Wideband Parameter Estimation of Overhead Transmission Lines from Terminal Measurements

Fahad J. Alqahtani
Western Michigan University

Follow this and additional works at: https://scholarworks.wmich.edu/dissertations

Recommended Citation
https://scholarworks.wmich.edu/dissertations/3957

This Dissertation-Open Access is brought to you for free and open access by the Graduate College at ScholarWorks at WMU. It has been accepted for inclusion in Dissertations by an authorized administrator of ScholarWorks at WMU. For more information, please contact wmu-scholarworks@wmich.edu.
The accurate and efficient determination of electrical parameters of transmission lines is essential when performing computer-aided analyses of power systems, including power-flow, state estimation, short-circuit, transient stability, power quality, and electromagnetic transients.

In this dissertation, a novel technique for wideband parameter estimation of frequency-dependent single-phase, three-phase transposed, and three-phase untransposed overhead lines, is proposed. The proposed technique utilizes terminal measurements of transient voltages and currents and is based on an analytical approach to solve the frequency domain 2-port nodal model of the line for the series impedance and shunt conductance per unit length as a function of the frequency. The EMTP/ATP software tool is used to produce emulated terminal measurements of voltage and current to be used as an input in the method. Since the method is defined in the frequency domain, the time domain terminal measurements are transformed to the frequency domain using the numerical Laplace transform (NLT). The estimated parameters are compared to those calculated analytically, demonstrating high accuracy for a wide frequency range. The proposed method is aimed at its application in transmission line protection and fault location based on terminal transient response. In addition, the minimum norm least-squares (MNLS) method is used in the parameter estimation of three-phase untransposed lines to solve
an overdetermined system of equations resulting from the evaluation of the transmission line response for a set of tests producing distinct transient voltages and currents.
WIDEBAND PARAMETER ESTIMATION OF OVERHEAD TRANSMISSION LINES FROM TERMINAL MEASUREMENTS

by

Fahad Alqahtani

A dissertation submitted to the Graduate College in partial fulfillment of the requirements for the degree of Doctor of Philosophy
Electrical and Computer Engineering
Western Michigan University
June 2023

Doctoral Committee:

Dr. Pablo Gomez, Ph.D., Chair
Dr. Richard T Meyer, Ph.D.
Dr. Damon Miller, Ph.D.
ACKNOWLEDGMENTS

I'd like to express my heartfelt gratitude to my advisor, Dr. Pablo Gomez, for his continuous support of my Ph.D. studies and related research, as well as his patience, inspiration, and wide knowledge. His guidance and advice were invaluable during the research and writing of this dissertation.

In addition, I’d like to thank committee members, Dr. Damon Miller and Dr. Richard Meyer for their insightful comments and encouragement.

I'd like to thank my family for the support during the Ph.D journey. Especially Ohud, my wife, for encouraging me and patiently allowing me to pursue this endeavor. None of this would have been possible without her and my kids, Munirah and Omar.

Fahad Alqahtani
# TABLE OF CONTENTS

ACKNOWLEDGMENTS .................................................................................................................................................... ii

LIST OF TABLES ............................................................................................................................................................ vi

LIST OF FIGURES .......................................................................................................................................................... vii

CHAPTER

1. INTRODUCTION ........................................................................................................................................................... 1

    1.1. Background ........................................................................................................................................................... 1

    1.2. Literature Review .................................................................................................................................................. 4

    1.3. Problem Statement ........................................................................................................................................... 11

    1.4. Hypothesis ............................................................................................................................................................ 11

    1.5. Research Objectives ........................................................................................................................................... 12

2. PARAMETER ESTIMATION FOR SINGLE-PHASE TRANSMISSION LINE ....... 13

    2.1. Introduction .......................................................................................................................................................... 13

    2.2. Methodology ....................................................................................................................................................... 13

        2.2.1. Parameter Estimation from Terminal Measurements .......... 13

        2.2.2. Numerical Laplace Transform ................................................ 17

        2.2.3. Analytical Calculation of Frequency-Dependent Overhead Line Parameters for Verification Purposes ................................................................. 18

    2.3.1. Test Cases ....................................................................................................................................................... 20

    2.3.2. Topology 1 ......................................................................................................................................................... 21

    2.3.3. Case Study 1 .................................................................................................................................................... 23
### Table of Contents—Continued

#### CHAPTER

2.3.4. Case Study 2 ........................................................................................................25  
2.3.5. Topology 2 ..........................................................................................................27  
2.4. Summary .................................................................................................................30  

#### 3. PARAMETER ESTIMATION FOR THREE-PHASE TRANPOSED TRANSMISSION LINE..................................................................................31

3.1. Introduction ..............................................................................................................31  
3.2. Methodology ...........................................................................................................31  
3.3. Test Cases ...............................................................................................................35

3.3.1. Topology 1 ...........................................................................................................38  
3.3.2. Topology 2 ..........................................................................................................45  
3.4. Summary .................................................................................................................52  

#### 4. PARAMETER ESTIMATION FOR THREE-PHASE UNTRANSPOSED TRANSMISSION LINE ..............................................................................53

4.1. Introduction ..............................................................................................................53  
4.2. Methodology ...........................................................................................................53

4.2.1. Two-Port Model Reconstruction ........................................................................53  
4.2.2. Parameter Estimation from the Reconstructed Model ....................................57  
4.3. Test Cases ...............................................................................................................59

4.3.1. Single Conductor Case .......................................................................................61  
4.3.2. Conductor Bundles Case ....................................................................................69  
4.4. Summary .................................................................................................................76
Table of Contents—Continued

5. CONCLUSIONS AND FUTURE WORK ........................................................................... 78

5.1. Conclusions and Contributions .............................................................................. 78

5.2. Future Work ............................................................................................................. 80

REFERENCES ................................................................................................................. 82
LIST OF TABLES

2.1. Transmission line data .................................................................................................................. 20
3.1. Transmission line data .................................................................................................................. 37
3.2. Max percentage error of resistive load ......................................................................................... 44
3.3. Max percentage error for capacitive load ..................................................................................... 51
4.1. Transmission line data .................................................................................................................. 60
4.2. Conductor disposition for each tower configuration under study ............................................... 60
4.3. Max percentage error for each tower configuration ..................................................................... 68
4.4. Max percentage error for each tower configuration with bundle conductors ........................... 75
LIST OF FIGURES

2.1. Equivalent π circuit of a single-phase transmission line ......................................................... 14

2.2. EMTP/ATP test setups for generation of terminal measurements: topology 1 with DC source, resistive source impedance, resistive load, and line length of 100 km. ..................... 20

2.3. Terminal responses of the EMTP/ATP circuit for ground resistivity of 100 Ω·m:
   (a) voltages (per unit), (b) currents (per unit of voltage) ............................................................. 22

2.4. Magnitude of the element of the admittance model of the line for ground resistivity of 100 Ω·m:
   (a) |A|, (b) |B| .......................................................................................................................... 23

2.5. Transmission line parameters considering variation of ground resistivity:
   (a) resistance, (b) inductance, (c) capacitance ........................................................... 24

2.6. Transmission line parameters considering variation of conductor’s height above ground:
   (a) resistance, (b) inductance, (c) capacitance ............................................................... 26

2.7. EMTP/ATP test setups for generation of terminal measurements: topology 2 with AC source, inductive source impedance, capacitive load, and line length of 150 km. .... 27

2.8. Terminal response of the EMTP/ATP circuit for AC source with inductive impedance and capacitive load: (a) voltages (per unit), (b) currents (per unit of voltage). .. 28

2.9. Transmission line parameters considering variation in terminal conditions (source and load) and line length: (a) resistance, (b) inductance, (c) capacitance ............... 29

3.1. Conductor configurations used in the study. (a) triangular; (b) horizontal ......................... 36

3.2. ATP/EMTP circuit to generate terminal measurements: (a) resistive load.
   (b) capacitive load. .................................................................................................................... 37

3.3. Current and voltage waveforms for a transmission line of 100 km with triangular/horizontal conductor arrangement for resistive loading. (a) sending end; (b) receiving end ...................................................................................................................... 38

3.4. Current and voltage waveforms for a transmission line of 200 km with triangular/horizontal conductor arrangement for resistive loading. (a) sending end; (b) receiving end ...................................................................................................................... 39
3.5. Parameter estimation for a 100 km transmission line with triangular conductor arrangement as a function of earth resistivity. (a) Resistance, (b) Inductance, (c) Capacitance. ................................................................. 40

3.6. Parameter estimation for a 200 km transmission line with triangular conductor arrangement as a function of earth resistivity. (a) Resistance, (b) Inductance, (c) Capacitance. ........................................................................ 41

3.7. Parameter estimation for a 100 km transmission line with horizontal conductor arrangement as a function of earth resistivity. (a) Resistance, (b) Inductance, (c) Capacitance. ................................................................. 42

3.8. Parameter estimation for a 200 km transmission line with horizontal conductor arrangement as a function of earth resistivity. (a) Resistance, (b) Inductance, (c) Capacitance. ........................................................................ 43

3.9. Current and voltage waveforms for a transmission line of 100 km with triangular/horizontal conductor arrangement for capacitive loading. (a) sending end; (b) receiving end ................................................................. 45

3.10. Current and voltage waveforms for a transmission line of 200 km with triangular/horizontal conductor arrangement for capacitive loading. (a) sending end; (b) receiving end ................................................................. 46

3.11. Parameter estimation for a 100 km transmission line with triangular conductor arrangement as a function of earth resistivity. (a) Resistance, (b) Inductance, (c) Capacitance. ................................................................. 47

3.12. Parameter estimation for a 200 km transmission line with triangular conductor arrangement as a function of earth resistivity. (a) Resistance, (b) Inductance, (c) Capacitance. ........................................................................ 48

3.13. Parameter estimation for a 100 km transmission line with horizontal conductor arrangement as a function of earth resistivity. (a) Resistance, (b) Inductance, (c) Capacitance. ................................................................. 49


4.1. Schematic representation of the proposed parameter estimation method. .............................................. 57

4.2. Tower configurations under test: a) horizontal, b) triangular, c) vertical. .............................................. 60
4.3. Horizontal configuration. Self-elements: a) Resistance, b) Inductance, and c) Capacitance. ................................................................. 62

4.4. Horizontal configuration. Mutual elements: a) Resistance, b) Inductance, and c) Capacitance. ................................................................. 63

4.5. Triangular configuration. Self-elements: a) Resistance, b) Inductance, and c) Capacitance. ................................................................. 64

4.6. Triangular configuration. Mutual elements: a) Resistance, b) Inductance, and c) Capacitance. ................................................................. 65


4.9. Horizontal configuration. Self-elements: a) Resistance, b) Inductance, and c) Capacitance. ................................................................. 70

4.10. Horizontal configuration. Mutual elements: a) Resistance, b) Inductance, and c) Capacitance. ............................................................... 71

4.11. Triangular configuration. Self-elements: a) Resistance, b) Inductance, and c) Capacitance. ................................................................. 72


CHAPTER 1

INTRODUCTION

1.1 Background

Power generation plants are often installed away from consumers due to space availability and environmental concerns. Therefore, long high-voltage underground and overhead transmission systems are required to deliver electric power from the point of generation to the end users. It is vital for power utility companies to ensure that this transmission is reliable and of high quality; otherwise, can result substantial financial losses due to equipment damage or loss of service [1]. Furthermore, weather-related factors such as lightning strikes, high winds, and ice accumulation can cause damage to transmission lines and equipment in power transmission systems.

The calculation of electrical parameters in transmission lines plays an essential role in power system computer-aided analyses during steady and transient state conditions, e.g., power-flow, state estimation, short-circuit, transient stability, power quality, and electromagnetic transients [17]. Accurate transmission line parameter calculation is also critical to maintain safe operation of power systems given its direct impact on different aspects of protection design, such as selection and setup of distance relays [3,18]. For instance, the impedance relay, which is mostly associated with the length of lines and cables, is a type of distance protection that quickly responds to electrical parameters. These parameters are also used to determine the settings in protective equipment and perform condition monitoring [18].
When electrical and geometrical data are available, transmission lines parameters can be
determined using various analytical and numerical methods. The calculation of electrical
parameters is performed with respect to the physical characteristics of transmission lines, such as
phases and tower geometry, conductor and ground return properties, etc. For electromagnetic
transients, the skin effect in the wires and ground return current are given special attention since
they make the parameters frequency dependent [1,3]. One classical analytical technique used to
determine transmission line parameters is based on Bessel and Carson functions. In this
technique, approximations are applied to consider factors such as dispersive and non-
homogeneous conductivity of the soil, asymmetrical geometry of the lines, and changing
environmental conditions. However, these approximations can cause inaccuracies in the
transmission line models [1,14].

In many practical cases, geometrical and electrical data of a transmission system might be
unavailable or only partially available. In such instances, electrical parameters cannot be
calculated directly. Instead, they are estimated from system variables that can be measured or
monitored at specific positions of the transmission system, such as currents, voltages, or
frequency. One of the most common methods for estimating transmission line parameters is
based on voltage and current terminal measurements recorded by phasor measurement units
(PMUs). The advancement in PMU technology has allowed these devices to be used in line
parameter estimation for different applications [4]. The PMU device measures the angle and
magnitude of voltage and current at a particular location and indicates the time of the
measurement. Synchronized phasors installed in transmission systems allow accuracy-enhanced
estimation of parameters [4,20]. Alternatively, fault records from protective relays located at the
sending and receiving ends can also provide the necessary measurements. The performance of existing parameter estimation methods may differ due to factors such as system dynamics (steady or transient state), load profile, system characteristics, and transmission line geometrical configuration. Consequently, each estimation technique is effective for certain operating conditions of the power system.

Typically, estimation methods may be categorized into two basic classes: time-domain and frequency-domain. Most of these estimation methods have been developed to be used in transposed (the tower structure of the transmission line is geometrically symmetrical) transmission systems with vertically symmetrical lines, as well as for specific line lengths. In addition, the line parameters are approximated on the basis of synchronized measurements of current and voltage phasors at the line terminals [1,15].

Most of the available fundamental frequency phasor-based methods employ sequence line approaches. These approaches assume that the transmission line is perfectly transposed [36]. However, in practice line topologies are commonly untransposed. Therefore, studies have been conducted to take into account this asymmetry. Many researchers have proposed distributed parameter approaches for untransposed transmission lines to enhance accuracy in parameter estimation. Still, most methods developed to date are valid only for the nominal frequency of operation, making them useless for transient analysis of transmission systems, where oscillatory behavior of current and voltage signals is observed over a wide frequency range.
Although the most common line parameter estimation techniques previously studied have been based on the use of phasor current and voltage measurements obtained from PMUs, other methods proposed in the literature have focused on the examination and processing of time-domain terminal signals [21,23]. Still, methods proposed to date result in the estimation of constant line parameters at the nominal frequency of the system. These methods neglect the fact that, in practice, line parameters are frequency-dependent due to eddy currents in the conductors and in the ground plane [24]. This is particularly important for correct prediction of transient system response, such as for fault location when using traveling wave methods [25]. Furthermore, power electronic converters found in modern transmission systems introduce high-frequency harmonic content over a broad frequency spectrum even under steady-state conditions [26].

1.2 Literature Review

Several estimation methods can be used to determine relevant parameters from transmission lines. When electrical and geometrical data are available, transmission lines parameters can be determined using various analytical and numerical methods. In many practical cases, geometrical and electrical data of a transmission system might be unavailable or only partially available. In such instances, electrical parameters cannot be calculated directly. Instead, they are estimated from system variables that can be measured or monitored at specific positions of the transmission system, such as currents, voltages, or frequency. The estimation methods presently available can be classified into two basic types: (1) frequency-domain methods and (2) time-domain methods [1].
A combination of two methods is used in [1] to estimate parameters of a three-phase transmission line. The first one is based on the time-domain, where a three-phase $\pi$ circuit represents the transmission line, and the admittance and impedance parameters are represented by electrical circuit elements. The second method is based on the use of modal decoupling techniques to transform the system from the phase domain to the modal domain. The three-phase transmission line is decoupled into three independent propagation modes, and the modes are modeled using conventional $\pi$ circuits as three single-phase lines. However, the methodology is limited by the operating conditions of the transmission system, the physical characteristics of the transmission line, and electromagnetic phenomena. For example, the load profile, length, and geometry of the line may impact estimation accuracy.

A differential equation algorithm based on global positioning system (GPS) technology to measure live line inductance parameters of transmission lines, including mutual inductances, is proposed in [2]. Each end of the transmission line examined is fitted with a GPS receiver and an inductance sensor. The GPS receiver continuously measures the distance between the two ends and an inductance sensor measures the self-inductance of the line at that end. Using the measured self-inductances and GPS-measured distances, the mutual inductance between the two ends of the line is calculated. The mutual inductance is then used to calculate the transmission line parameters, such as its inductance per unit length and capacitance per unit length. The calculated inductance parameters can be used to evaluate the efficacy of the transmission line and design power compensation devices. However, the model assumes that the network is balanced, which may not always be the case in real-world scenarios. Furthermore, the model does not take into
account that the effect of the frequency dependence, which can impact the accuracy of the measurements. It is important to note that the accuracy of the measurements may be affected by the frequency range of the signals being measured. In particular, the model may not be able to accurately capture the behavior of the network at high frequencies, which can lead to errors in the measurements.

A method based on an optimization algorithm that minimizes the difference between the measured voltage and current signals and those predicted by a transmission line model is presented in [3]. The transmission line model is based on the telegrapher equations, which describe the relationship between transmission line voltages and currents. The optimization algorithm employs the Levenberg-Marquardt algorithm to find transmission line parameter values that minimize the difference between the measured and predicted signals. The method assumes that the measurements have a normal distribution, which is not always the case in practice. Moreover, it may be ineffective at identifying inaccurate measurements caused by systematic errors or biases.

A study in [4] compared several methods for estimating the parameters for transmission lines using synchro-phaser measurements. They investigated the methods under transposed and untransposed configurations, as well as under balanced and unbalanced conditions. The study was able to show that the positive sequence model of a transmission line has limitations when used to construct the defining equations for transmission lines. Furthermore, this study showed that parameter estimation methods based on the positive sequence model may perform poorly when applied to short untransposed and unbalanced transmission lines.
A simplified procedure to estimate the longitudinal resistances of transmission lines based on real-time load profile was presented in [5]. Resistance parameters were estimated from synchronized measurements of complex currents and voltages at the sending and receiving ends of transmission systems, which can be done in practice using phasor measurement units (PMUs). The estimation method revealed that the total apparent power and power factor are intrinsically related to the accuracy of the estimated values of the resistance parameters, resulting in inconsistent performance. Additionally, the method may require significant effort to ensure accurate synchronization of the PMU measurements, which can be challenging in some situations.

A method that uses a strong M-estimator to determine three-phase transmission line impedances based on synchro-phasor measurements is formulated in [6]. The synchro-phasor-based estimation is applied on both untransposed and transposed lines, and the model developed uses accurate measurements of voltage and currents that are time-synchronized at the line ends. The M-estimator in the study bypasses the unwanted spikes as well as complex noise by minimizing their influences on the measurements. This parameter determination method permits the omission of a separate bad data analysis that is computationally intensive. Therefore, the model used may not be able to represent all the complexities of the system being analyzed (various factors that can influence system behavior) such as noise, interference, and non-linear behavior. This can lead to inaccurate results.
Synchronized measurements are applied in [7] to formulate a parameter estimation method of untransposed overhead transmission lines. This method combines parameter tracking and state estimation to approximate the parameters of a completely coupled three-phase transmission line. The algorithm alternates between parameter tracking that uses recent state estimates to suppress current measurement noise, and state estimation to limit voltage and current measurement noises. However, the noise in measured voltages can affect the accuracy of the calculated parameters, especially at higher frequencies. The computational expense of evaluating coefficient matrix (Hv) can also become a bottleneck when dealing with wideband signals. Additionally, the rank deficiency of Hv can lead to instability in the calculated parameters, which can be exacerbated by the presence of high-frequency components.

Ref. [8] proposes a measurement-based approach for estimating transmission line parameters using an adaptive data selection strategy. The main idea is to select a subset of measured data points that are most relevant for estimating transmission line parameters, and then use these selected data points to fit a mathematical model of the transmission line. The data selection procedure is adaptive, meaning that it is modified iteratively based on the quality of the parameter estimates obtained at each iteration. The authors use a merit function to evaluate the quality of the parameter estimates, and they choose data points that are anticipated to enhance the merit function value. However, the model requires a large amount of data to estimate the transmission line parameters accurately. Moreover, the model assumes that the measurement errors are normally distributed, which may not be the case in practice.
Estimation of the entries of the longitudinal impedance matrix and the shunt admittance matrix at the rated system frequency for three-phase untransposed short transmission lines was performed in [9] using voltage/current synchro-phasor measurements obtained from PMUs. The line was modeled by the three-phase transmittance matrix, which was observed to be less sensitive to measurement noise than the admittance matrix. An accurate noise covariance matrix was also computed using the specifications of noise introduced by instrument transformers and phasor measurement units. Different least-squares-based estimation methods were derived based on a statistical model of estimation. The proposed approach assumes that the line is electrically short, which may not be the case for longer transmission lines. The proposed approach relies on accurate noise covariance matrix estimation, which may be challenging in practice due to the complexity of the noise sources and the need for accurate modeling of the measurement system.

A study in [10] proposed two new approaches based on the ordinary least-squares method and the total least-squares method to estimate the parameters of a balanced three-phase transmission line using voltage and current measurements from phasor measurement units. First, a new model for the steady-state phasorial equations of a medium-length transmission line is proposed. Then, the noises acting upon each measurement on the ordinary least-squares setup are considered, and for the total least-squares setup, noise acting upon the observation matrix in order to account for model uncertainties and non-linearities is also considered. The methods are tested in simulation data of a real medium-size transmission line. However, the approach only works for transmission lines that are balanced and of medium electrical length.
Another method is proposed in [11] for tracking the dynamic transmission line parameters of a power system using a Kalman filter. The authors first model the transmission line as a linear time-invariant system, meaning that the relationships between variables remain constant over time and can be described using linear equations. By combining the current estimate with new measurement data, they use a Kalman filter to estimate the state of the system (i.e., the transmission line parameters) at each time step. The Kalman filter utilizes a process model to describe the expected evolution of the system state over time and a measurement model to describe the relationship between the measured variables and the system's true state. Still, the proposed methods assume that the line parameters are time-varying but not frequency-dependent.

In another study [12], the whale optimization algorithm (WOA) is used to calculate the overhead AC transmission line parameters. The proposed technique is applied to single-phase and three-phase AC transmission lines. The researchers determined capacitance and inductance per unit length for three-phase lines using the proposed WOA algorithms with different bundle conductor arrangements. Nevertheless, the accuracy of the results may differ based on the number of tests conducted. The algorithm may not always be able to perform a comprehensive search and may become detained in local minima.

Previous studies on parameter estimation methods relied on phasor current and voltage measurements obtained from PMUs, while others examined and processed time-domain terminal signals. This leads to the estimation of constant line parameters at the nominal frequency of the system and disregards the frequency dependence of line parameters. This is particularly
important for correct prediction of transient system response. Unlike most methods proposed to date, the methodology proposed in this dissertation is capable of estimating parameters over a wide frequency range.

1.3 Problem Statement

The accurate determination of the parameters for overhead transmission lines over a wide frequency range is the main problem. Existing parameter estimation methods may not be suitable for frequency-dependent estimation over a wide frequency range due to issues with robustness, convergence, or computational efficiency, making them inappropriate for the transient analysis of transmission systems. Model assumptions and the availability of data may also pose a problem for the parameter estimation techniques.

The frequency-dependent nature of these parameters, however, makes their estimation difficult. Therefore, this study proposes a method for parameter estimation that takes the wide frequency range into account and yields accurate results.

1.4 Hypothesis

A frequency-dependent distributed parameter model of a transmission line in the frequency domain will enable an accuracy enhanced estimation of transmission line electrical parameters over a wide frequency range.
1.5 Research Objectives

In this dissertation, a novel procedure for wideband parameter estimation of transmission line based on transient terminal voltage and current measurements is proposed, executed, and evaluated. Specifically, this project aims to:

i. Develop a parameter estimation technique based on the frequency-dependent distributed parameter model of the line in the frequency domain.

ii. Implement an analytical parameter determination procedure for verification of the estimation method proposed.

iii. Simulate the terminal measurements of the line using EMTP/ATP simulation software under diverse terminal conditions.

iv. Test the accuracy and effectiveness of the procedure for a variety of transmission line topologies and terminal conditions.
CHAPTER 2

PARAMETER ESTIMATION FOR SINGLE-PHASE TRANSMISSION LINE

2.1 Introduction

This chapter describes the parameter estimation method for the case of single-phase transmission lines based on an analytical framework to solve a frequency domain 2-port nodal model. The proposed method estimates the elements of the line series impedance and shunt admittance per unit length, considering full frequency-dependent parameters over a wide frequency range. The EMTP/ATP software tool is used to produce emulated terminal measurements of voltage and current to be applied as inputs in the estimation method. Since the method is defined in the frequency domain, the time domain terminal measurements are transformed to the frequency domain using the numerical Laplace transform (NLT). The proposed parameter estimation approach is aimed at its application for accuracy-enhanced transmission line fault location using transient terminal responses.

2.2 Methodology

2.2.1 Parameter Estimation from Terminal Measurements

An analytical approach is employed here for the estimation of the frequency-dependent electrical parameters of a single-phase transmission line. It uses an equivalent circuit in the frequency domain and measurements of voltages and currents at both ends of the line. An equivalent π
model obtained from the solution of the telegrapher equations is employed to represent the transmission line. The equivalent Laplace-domain admittance matrix of the circuit in Fig. 2.1 is given by [27]

\[
\begin{bmatrix}
I_0^{(s)} \\
I_l^{(s)}
\end{bmatrix} = 
\begin{bmatrix}
A^{(s)} & -B^{(s)} \\
-B^{(s)} & A^{(s)}
\end{bmatrix}
\begin{bmatrix}
V_0^{(s)} \\
V_l^{(s)}
\end{bmatrix}.
\]  

(2.1)

where

\[
A = Y_0 \coth(\gamma l),
\]  

(2.2a)

\[
B = Y_0 \text{csch}(\gamma l).
\]  

(2.2b)

\[\text{Figure 2.1. Equivalent } \pi \text{ circuit of a single-phase transmission line.}\]

In Fig. 2.1, \(V_0\) and \(V_l\) are the voltages at the sending and receiving nodes of the line, while \(I_0\) and \(I_l\) are the currents at the same nodes. In addition, \(l\) is the length of the transmission line; \(Y_0\) is the characteristic admittance and \(\gamma\) is the propagation constant, which are obtained from the series impedance \(Z\) and shunt admittance \(Y\) of the line per unit length (p.u.l.):

\[
Y_0 = \sqrt{Y/Z},
\]  

(2.3b)
\[ \gamma = \sqrt{ZY}. \] (2.3a)

The proposed parameter estimation algorithm starts from the solution of (2.1) for the admittance matrix elements \( A \) and \( B \), assuming that terminal voltage and current measurements are known. This results in the following expressions to estimate the admittance model elements from terminal measurements:

\[ A = \left( \frac{I_L}{V_0} - \frac{I_0}{V_L} \right) / \left( \frac{V_L}{V_0} - \frac{V_0}{V_L} \right), \] (2.4a)

\[ B = \left( \frac{I_0}{V_0} - \frac{I_L}{V_L} \right) / \left( \frac{V_0}{V_L} - \frac{V_L}{V_0} \right). \] (2.4b)

The characteristic admittance \( Y_0 \) and propagation constant \( \gamma \) can be related to the estimated values of \( A \) and \( B \) using (2.2a) and (2.2b):

\[ \gamma = \left( \frac{1}{l} \right) \cosh^{-1} \left( \frac{A}{B} \right), \] (2.5a)

\[ Y_0 = \frac{A}{\text{coth}(\gamma l)}. \] (2.5b)

Eqs. (2.3a) and (2.3b) are then employed to estimate the line series and shunt elements \( Z \) and \( Y \) from \( Y_0 \) and \( \gamma \):

\[ Z = \frac{\gamma}{Y_0}, \] (2.6a)

\[ Y = \gamma Y_0. \] (2.6b)

Finally, the per unit length series resistance and inductance, as well as the per unit length shunt conductance and capacitance, are obtained from the real and imaginary components of \( Z \) and \( Y \):

\[ Z = R + j\omega L, \] (2.7a)
\[ Y = G + j\omega C. \]  

(2.7b)

where \( R \) is the series resistance per unit length (p.u.l.) corresponding to the series losses distributed along the line, \( L \) is the series inductance p.u.l. related to the magnetic flux produced by the current circulating along the conductor, \( G \) the shunt conductance p.u.l. associated with the transversal conduction current between the conductor and the reference, and \( C \) is the shunt capacitance corresponding to the transversal displacement current between the conductor and the reference [24].

The steps involved in the estimation of line parameters are as follows:

1. Transient current and voltage measurements are obtained for a certain line configuration considering an observation time window of interest. For the purpose of testing the estimation algorithm, software EMTP/ATP is used to produce emulated terminal measurements.

2. The measurements from Step 1 are transformed into the Laplace domain using the numerical Laplace transform [13, 28], as described in Section 2.2.2 of this dissertation.

3. The measurements in the Laplace domain are used as inputs in (2.4a) and (2.4b) to obtain the elements of the equivalent π circuit model of the line.

4. Admittance matrix elements \( A \) and \( B \) are substituted in (2.5a) and (2.5b) to obtain the characteristic admittance and propagation constant of the line as a function of the frequency.
5. Finally, $Y_0$ and $\gamma$ are used to obtain the series and shunt parameters of the line from (2.6a) and (2.6b). These parameters can be further divided into $R$, $L$, $G$ and $C$ according to (2.7a) and (2.7b).

### 2.2.2 Numerical Laplace Transform

Considering a real and causal time-domain function $f(t)$, such as a transient voltage or current measurement, and its image in the Laplace domain $F(s)$, the Laplace transform of $f(t)$ over an integration range $[0, T]$ is given by [13, 28]

$$F(s) = \int_0^T [f(t)e^{-ct}]e^{-j\omega t} \, dt.$$  \hspace{1cm} (2.8)

where $s = c + j\omega$ is the Laplace variable, $\omega$ is the angular frequency, $c$ is a damping factor, and $T$ is the observation time of the transient function $f(t)$. The numerical form of (2.8) from the definition of the fast Fourier transform (FFT), and the use of odd sampling, is given by [13, 28]

$$F_m = \sum_{n=0}^{N-1} f_n D_n \exp(-j2\pi mn/N).$$  \hspace{1cm} (2.9)

where:

$$m = 1, 3, 5, \ldots, 2N$$

$$n = 1, 2, 3, \ldots, N - 1$$

where:

$$F_m = F(c + jm\Delta\omega), f_n = f(n\Delta t)$$  \hspace{1cm} (2.10a), (2.10b)

$$D_n = \Delta t \exp(-cn\Delta t - in\pi/N)$$  \hspace{1cm} (2.10c)

$$\Delta\omega = \pi/T, \Delta t = T/N$$  \hspace{1cm} (2.10d), (2.10e)
\[ c = -\ln(\varepsilon)/T. \] (2.10f)

In (2.10f), \( \varepsilon \) is an empirical factor with a value between \( 1 \times 10^{-6} \) and \( 1 \times 10^{-3} \) (\( 1 \times 10^{-6} \) provided appropriate results for all the tests in this work), \( \Delta \omega \) is the frequency spectrum integration step, \( \Delta t \) is the time discretization step, and \( N \) is the number of discrete samples. A detailed description of the correct implementation of the NLT for appropriate results can be found in [13, 28].

2.2.3 Analytical Calculation of Frequency-Dependent Overhead Line Parameters for Verification Purposes

For the case of single-phase overhead lines, electrical parameters are calculated as described below. A detailed description of this analytical parameter calculation approach can be found in [24]. This analytical calculation is used for accuracy verification of the parameters estimated using the proposed method.

The series impedance per unit length can be divided into three parts: geometrical impedance, \( Z_G \), impedance due to the finite ground conductivity, \( Z_E \), and internal conductor impedance, \( Z_C \):

\[ Z = Z_G + Z_E + Z_C. \] (2.11)

The geometrical impedance is computed considering perfectly conducting ground and applying the method of images. This yields

\[ Z_G = \frac{\mu_0}{2\pi} \ln \left( \frac{2h}{r} \right). \] (2.12)

where \( \mu_0 \) is the permeability of free space, \( h \) is the conductor height above ground and \( r \) is its radius. The impedance due to finite ground conductivity is computed applying the method of
complex images, i.e., assuming that the ground return current is limited by a fictitious plane parallel to the earth plane and given by a complex penetration depth, $p$, defined as

$$p = \frac{1}{\sqrt{s\mu_0\sigma_E}}. \quad (2.13)$$

where $\sigma_E$ is the ground conductivity. From this definition, the impedance due to the finite ground conductivity is

$$Z_E = \frac{s\mu_0}{2\pi} \ln \left(1 + \frac{p}{h}\right). \quad (2.14)$$

The internal conductor impedance is due to the skin effect, which is the tendency of current to concentrate on the conductor surface as frequency increases. This phenomenon is approximated by means of the concept of complex penetration depth inside the conductor, $\delta$, expressed as

$$\delta = \frac{1}{\sqrt{s\mu_0\sigma_C}}. \quad (2.15)$$

where $\sigma_C$ is the conductivity of the conductor. Considering both DC and high-frequency components of the internal impedance [24]:

$$Z_C = \frac{\sqrt{4\delta^2 + \pi^2}}{2\pi r^2 \sigma_C \delta}. \quad (2.16)$$

On the other hand, the shunt capacitance of the line, also computed from the method of images, is given by

$$C = \frac{2\pi \varepsilon_0}{\ln\left(\frac{2h}{r}\right)}. \quad (2.17)$$

Finally, the shunt admittance of the line, neglecting $G$ as commonly done for overhead lines, is given by

$$\text{Finally, the shunt admittance of the line, neglecting } G \text{ as commonly done for overhead lines, is given by}$$
2.3.1 Test Cases

The initial EMTP/ATP circuit setup to obtain terminal measurements is shown in Fig 2.2. For testing purposes, the line is excited by a Thevenin equivalent with a unit step voltage source in series with a 10 Ω resistance and terminated in a 1 kΩ resistive load. Transmission line data employed in the EMTP/ATP simulation are listed in Table 2.1. The line model used in EMTP/ATP is the overhead single-phase distributed-parameter J. Marti setup, which considers frequency dependence of the line parameters [29]. A second topology with different terminal conditions and line length is used later on this section and is shown in Fig. 2.7.

![Figure 2.2. EMTP/ATP test setups for generation of terminal measurements: topology 1 with DC source, resistive source impedance, resistive load, and line length of 100 km.](image)

<table>
<thead>
<tr>
<th>Parameter [unit]</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor radius [m]</td>
<td>0.0272</td>
</tr>
</tbody>
</table>
2.3.2 Topology

Figs. 2.3a and 2.3b show the transient voltages and currents obtained at the terminals of the line using EMTP/ATP under the conditions mentioned above and shown in Fig. 2.2a. These emulated measurements are transformed into the Laplace domain using the NLT and used as inputs for the parameter estimation algorithm, as described in Section 2.2.
Figure 2.3. Terminal responses of the EMTP/ATP circuit for ground resistivity of 100 Ω·m: (a) voltages (per unit), (b) currents (per unit of voltage).

Figs. 2.4a and 2.4b show the magnitude of the admittance parameters $A$ and $B$ of the nodal line model for the configuration listed in Table 2.1. The estimation obtained by the proposed algorithm matches very closely with the definition of $A$ and $B$ obtained from the analytical calculation of parameters over a wide frequency range (from 25 Hz to 100 kHz).
Figure 2.4. Magnitude of the element of the admittance model of the line for ground resistivity of 100 Ω·m: (a) \(|A|\), (b) \(|B|\)

2.3.3 Case Study 1

Figs. 2.5a, 2.5b, and 2.5c show the estimated resistance, inductance, and capacitance as a function of the frequency. Besides the ground resistivity of 100 Ω·m listed in Table 1, the results for other ground resistivities are included to illustrate the ability of the proposed algorithm to estimate parameters under different electrical conditions affecting the frequency dependence of the series impedance of the line.
Figure 2.5. Transmission line parameters considering variation of ground resistivity: (a) resistance, (b) inductance, (c) capacitance.
The results reveal an excellent match for a variety of resistivities. In addition, Fig. 2.5c shows that the capacitance per unit length is correctly estimated as independent from the frequency or the ground resistivity, as defined analytically in (2.17). The small variations in Fig. 2.5c when estimating capacitance for different ground resistivities are negligible for practical purposes.

2.3.4 Case Study 2

To further explore the ability of the estimation approach to handle different line conditions, Figs. 2.6a, 2.6b, and 6c show the results for resistance, inductance and capacitance obtained considering the variation of the conductor height above ground from 10 m to 40 m (with the ground resistivity fixed at 100 Ω·m).
According to Figs 2.6, the proposed approach is able to provide an accurate estimation of the behavior of the parameters with frequency, although some deviation is observed in the inductance at high frequency for a height of 10 m above ground. This is attributed to differences in the way in which the series impedance of the line is calculated in EMTP/ATP with respect to the analytical calculation used in this work. EMTP/ATP employs Carson series, while the analytical calculation in this paper is based on the concept of complex penetration depth.
Previous studies has shown that the use of complex penetration depth provides more accurate parameters at frequency range compared with Carson approximation.

2.3.5 Topology 2

A final test is included to demonstrate the robustness of the estimation method by modifying the terminal conditions, as well as the length of the line. This modified topology is shown in Fig. 2.7. In this case, the Thevenin equivalent includes an AC source in series with a 100 mH inductance, while the load at the receiving node corresponds to a capacitance of 50 μF. The length of the line has increased to 150 km. Figs. 2.8a and 2.8b show the transient voltages and currents obtained via EMTP/ATP for this case. The transient response is evidently different from the one obtained for the first circuit topology.

![Figure 2.7. EMTP/ATP test setups for generation of terminal measurements: topology 2 with AC source, inductive source impedance, capacitive load, and line length of 150 km.](image)
Figure 2.8. Terminal response of the EMTP/ATP circuit for AC source with inductive impedance and capacitive load: (a) voltages (per unit), (b) currents (per unit of voltage).

Figs. 2.9a, 2.9b, and 2.9c compare the line resistance, inductance and capacitance estimated under the terminal conditions and length of topology 1 (Fig. 2.2) with respect to those obtained considering the terminal conditions and length of topology 2 (Fig. 2.7).
Figure 2.9. Transmission line parameters considering variation in terminal conditions (source and load) and line length: (a) resistance, (b) inductance, (c) capacitance.
Figs. 2.9 present the parameters resistance, inductance and capacitance under different line condition in topology 1 and the line condition considered in topology 2. The proposed method provides an accurate estimation between the estimated parameters and the analytical parameters proposed in this study. It is evident that the parameter estimation per unit length is not affected by the terminal conditions or the line length, with very similar frequency plots in both cases, demonstrating the robustness of the proposed method.

2.4 Summary

This chapter proposes an accurate parameter estimation method for single-phase transmission lines considering full frequency range. The proposed method is based on an analytical framework to solve a 2-port nodal model for the series impedance and shunt conductance per unit length in the frequency domain. According to the plots, the proposed method provides an accurate estimation of the frequency-dependent behavior of the parameters, although with some deviations. This is due to differences between how the series impedance of the line is calculated in EMTP/ATP and the analytical calculation used in this study. EMTP/ATP uses the Carson series, while the analytical calculation depends on the concept of complex penetration depth. Previous work has shown that the use of complex penetration depth provides more accurate parameters at a wide frequency range compared with Carson’s approximation.
CHAPTER 3

PARAMETER ESTIMATION FOR THREE-PHASE TRANSPOSED TRANSMISSION LINE

3.1 Introduction

In this chapter, a parameter estimation method for a transposed three-phase transmission line is presented, which is based on the application of Clarke’s transformation to decouple the system of equations defining the transmission line model for this case. Clarke’s transformation method is used to obtain three decoupled components and apply them in the estimation of parameters as three separate single-conductor systems. EMTP/ATP software is used to generate the terminal measurements of voltage and current required as inputs in the estimation method. Transformation of the time domain terminal measurement to the frequency domain is done by means of the numerical Laplace transform (NLT).

3.2 Methodology

An analytical approach is employed to determine the frequency-dependent electrical parameters of a three-phase fully-transposed transmission line. The parameters are obtained from the π equivalent circuit of the line by employing voltage and current measurements at both ends of the line.
The analytical solution of the telegrapher equations for a non-ideal transmission line produces a 2-port admittance matrix model of the transmission line across the sending (0) and receiving (l) ends, which can be expressed as:

\[
\begin{bmatrix}
I_0 \\
I_l \\
\end{bmatrix} =
\begin{bmatrix}
A & -B \\
-B & A \\
\end{bmatrix}
\begin{bmatrix}
V_0 \\
V_l \\
\end{bmatrix}
\]  

Equation (3.1)

where, \(I_0, I_l\) and \(V_0, V_l\) are 3×1 vector corresponding to the three-phase terminal currents and voltages, respectively. The admittances \(A\) and \(B\) in eq. (3.1), which are scalars for a single-phase transmission line, become 3×3 matrices in the case of a three-phase transmission line. In contrast to the single-phase case described in Chapter 2, eq. (3.1) cannot be solved directly for \(A\) and \(B\) from the terminal voltages and currents since it would result in an underdetermined system of equations. This is because \(A\) and \(B\) (both symmetrical matrices), have 6 distinct values each for a total of 12 unknown values, but the total number of equations defining (3.1) is 6. In this chapter, a fully-transposed three-phase transmission line is considered to simplify the solution for the admittances in eq. (3.1) by employing an analytical approach similar to the single-phase case.

The Clarke transformation is used to eliminate coupling components and transform the admittances into diagonal matrices:

\[
\begin{bmatrix}
I_0^{(s)} \\
I_l^{(s)} \\
\end{bmatrix} =
\begin{bmatrix}
A^{(s)} & -B^{(s)} \\
-B^{(s)} & A^{(s)} \\
\end{bmatrix}
\begin{bmatrix}
V_0^{(s)} \\
V_l^{(s)} \\
\end{bmatrix}
\]  

Equation (3.2)

where:

\[
I_x^{(s)} = T I_x
\]  

Equation (3.3a)
\[ V_x^{(s)} = TV_x \]  \hspace{1cm} (3.3b)

\[ A^{(s)} = TAT^{-1} \]  \hspace{1cm} (3.3c)

\[ B^{(s)} = TBT^{-1} \]  \hspace{1cm} (3.3d)

where \( x = \{0, l\} \), superscript \( (s) \) denotes that quantities have been transformed from phases to modes, and the power-invariant Clarke transformation matrix \( T \) is defined as:

\[
T = \begin{bmatrix}
1 & 0 & \frac{1}{\sqrt{2}} \\
\frac{1}{\sqrt{2}} & \frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \\
-\frac{1}{\sqrt{2}} & \frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}}
\end{bmatrix}.
\]  \hspace{1cm} (3.4)

In the case of a fully-transposed transmission line, \( A^{(s)} \) and \( B^{(s)} \) are diagonal modal matrices and the estimation of parameters described in Chapter 2 for single-phase lines can be applied to each mode separately, as in the case of a single-phase transmission line. It should be noted that the computation of \( A^{(s)} \) and \( B^{(s)} \) is repeated for each frequency component resulting from the application of the numerical Laplace transformation to the time domain terminal voltage and current measurements.

The solution of the telegrapher equations provides the relationships between the modal admittances in eq. (3.2) and the modal characteristic admittance matrix \( Y_o^{(s)} \) and the propagation constant matrix \( \Psi^{(s)} \), respectively:

\[
A^{(s)} = Y_o^{(s)} \coth(\Psi^{(s)}l) \]  \hspace{1cm} (3.5a)

\[
B^{(s)} = Y_o^{(s)} \operatorname{csch}(\Psi^{(s)}l). \]  \hspace{1cm} (3.5b)
Eq. (3.5) can be solved for $Y_o^{(s)}$ and $\Psi^{(s)}$ using the estimated values of $A^{(s)}$ and $B^{(s)}$, as follows:

\[
\Psi^{(s)} = \left(\frac{1}{l}\right) \cosh^{-1} \left( A^{(s)} B^{(s)^{-1}} \right) \quad (3.6a)
\]

\[
Y_o^{(s)} = A^{(s)} \left[ \coth(\Psi^{(s)} l) \right]^{-1}. \quad (3.6b)
\]

The following relationships can be employed to estimate the elements of the per-unit length impedance $Z$ and admittance $Y$:

\[
Z = T^{-1} Z^{(s)} T = T^{-1} \Psi^{(s)} Y_o^{(s)^{-1}} T \quad (3.7a)
\]

\[
Y = T^{-1} Y^{(s)} = T^{-1} \Psi^{(s)} Y_o^{(s)} T. \quad (3.7b)
\]

In the case of a fully-transposed transmission line, $Z$ and $Y$ can be defined as

\[
Z = \begin{bmatrix} Z_s & Z_m & Z_m \\ Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_s \end{bmatrix} \quad (3.8a)
\]

\[
Y = \begin{bmatrix} Y_s & Y_m & Y_m \\ Y_m & Y_s & Y_m \\ Y_m & Y_m & Y_s \end{bmatrix}. \quad (3.8b)
\]

The terms on the main diagonals are the self-impedances $Z_s$ and self-admittances $Y_s$, and the off-diagonal terms are mutual impedances $Z_m$ and admittances $Y_m$, which represent the couplings between phases; $Z$ consists of frequency-dependent resistance and inductance components, while $Y$ includes shunt capacitance and conductance components. These components can be obtained from the real and imaginary parts of the elements of $Z$ and $Y$:

\[
Z = R + j\omega L \quad (3.9a)
\]
\[ Y = G + j\omega C \]  

(3.9b)

where \( R \) is the series resistance matrix per unit length (p.u.l.) corresponding to the series losses distributed along the line, \( L \) is the series inductance matrix p.u.l. related to the magnetic flux produced by the current circulating along the conductor, \( G \) the shunt conductance p.u.l. associated with the transversal conduction currents between the conductors and the reference ground plane (commonly neglected for overhead lines); and \( C \) is the shunt capacitance corresponding to the transversal displacement currents between the conductors and the reference ground plane [24]. \( R \) and \( L \) elements are frequency dependent due to the skin effect in the conductors and in the ground plane [24].

The parameter estimation method described in this chapter was implemented in MATLAB™ to investigate its accuracy for different transmission tower topologies under the assumption of line transposition. ATP-EMTP is used to obtain emulated time domain measurements of the terminal voltages and currents of the line. The results obtained are compared to values computed from analytical expressions for the geometrical, conductor and earth return impedances and shunt admittances of a 3-phase transposed line.

### 3.3 Test Cases

The results of the analytical method described above for the calculation of the parameters of a fully-transposed three-phase transmission line are presented in this section. An ATP/EMTP simulation is employed to obtain the measurement of voltages and currents at the sending and
receiving ends of the transmission line, which are used as inputs for testing purposes. A MATLAB™ script was developed to perform the calculation of the transmission line parameters. Additionally, an analytical model of the transmission line derived from the telegrapher equations is used as a reference for comparison with the estimated parameter values. Numerical Laplace transform is used to transform terminal currents and voltages from time domain to the frequency domain.

Different tower configurations, line lengths, and terminal conditions are considered for testing the performance of the estimation method, i.e., two different conductor configurations: triangular conductor arrangement and horizontal conductor arrangement (see Fig. 3.1); two transmission line lengths: 100 km and 200 km; and two loading conditions: resistive load and capacitive load, as shown in Fig. 3.2. The parameters and conditions used are listed in Table 3.1.

![Figure 3.1. Conductor configurations used in the study. (a) triangular; (b) horizontal.](image)

Figure 3.1. Conductor configurations used in the study. (a) triangular; (b) horizontal.
Table 3.1. Transmission line data

<table>
<thead>
<tr>
<th>Parameter [unit]</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor radius [m]</td>
<td>0.0272</td>
</tr>
<tr>
<td>Conductor resistivity (Aluminum) [Ω·m]</td>
<td>$2.61 \times 10^{-8}$</td>
</tr>
<tr>
<td>Ground resistivity [Ω·m]</td>
<td>10/30/60/100</td>
</tr>
<tr>
<td>Line length [km]</td>
<td>100/200</td>
</tr>
</tbody>
</table>

Figure 3.2. ATP/EMTP circuit to generate terminal measurements: (a) resistive load. (b) capacitive load.
3.3.1 Topology 1

The ATP/EMTP circuit shown in Fig. 3.2a is considered for this case to obtain emulated terminal measurements for four cases that consider line lengths of 100 km and 200 km, and tower configurations of triangular and horizontal type, all with resistive load of 1 kΩ ohms per phase. The tests are conducted for various earth resistivities, including the four scenarios presented in this section. Figs. 3.3 and 3.4 show the plots of terminal measurements for the cases evaluated in this topology. The parameters and conditions listed in Table 3.1 are used in this case.

![Figure 3.3. Current and voltage waveforms for a transmission line of 100 km with triangular/horizontal conductor arrangement for resistive loading. (a) sending end; (b) receiving end.](image-url)
The results of parameter estimation for resistance, inductance and capacitance considering different earth resistivities and resistive loads are presented as follows:

- Fig. 3.5: 100 km long line with triangular configuration,
- Fig. 3.6: 200 km long line with triangular configuration,
- Fig. 3.7: 100 km long line with horizontal configuration, and
- Fig. 3.8: 200 km long line with horizontal configuration.
Figure 3.5. Parameter estimation for a 100 km transmission line with triangular conductor arrangement as a function of earth resistivity. (a) Resistance, (b) Inductance, (c) Capacitance.
Figure 3.6. Parameter estimation for a 200 km transmission line with triangular conductor arrangement as a function of earth resistivity. (a) Resistance, (b) Inductance, (c) Capacitance.
Figure 3.7. Parameter estimation for a 100 km transmission line with horizontal conductor arrangement as a function of earth resistivity. (a) Resistance, (b) Inductance, (c) Capacitance.
Figure 3.8. Parameter estimation for a 200 km transmission line with horizontal conductor arrangement as a function of earth resistivity. (a) Resistance, (b) Inductance, (c) Capacitance.
Table 3.2 Max percentage error for resistive load

<table>
<thead>
<tr>
<th>Elements</th>
<th>100 km</th>
<th>200 km</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Horizontal</td>
<td>Triangular</td>
</tr>
<tr>
<td>Resistance</td>
<td>1.90%</td>
<td>2.00%</td>
</tr>
<tr>
<td>Inductance</td>
<td>1.11%</td>
<td>1.18%</td>
</tr>
<tr>
<td>Capacitance</td>
<td>0.25%</td>
<td>0.31%</td>
</tr>
</tbody>
</table>

Figures 3.5 to 3.8 represent the self and mutual elements of the resistance, inductance and capacitance matrices for resistive load, testing different tower configuration and line lengths under a variety of ground resistivities. The arrows in the figures indicate the values of the self elements, while the plots with lower values at the bottom of the figures correspond to the mutual elements. The results indicate an excellent match between the estimated parameters and the analytical parameters. Table 3.2 represents the highest percentage error between the estimated resistance, inductance and capacitance and the analytical parameters. The results demonstrate the accuracy of the parameter estimation, showing very low percentage error. Table 3.2 also reveals a slightly higher percentage error for resistance estimation, as expected. Similar to the single-phase case, this is due to the fact that the line series impedance is calculated in ATP/EMTP using Carson series, while the analytical calculation of the same parameter is based on the concept of complex penetration depth.
3.3.2 Topology 2

The ATP/EMTP circuit shown in Fig. 3.3b is now considered to obtain emulated terminal measurements for the same four cases evaluated in Section 3.3.2, but with capacitive load of 50µF per phase. Figs. 3.9, 3.10 show the plots of terminal measurements for the cases in this topology. The parameters and conditions listed in Table 3.1 are used in this case.

Figure 3.9. Current and voltage waveforms for a transmission line of 100 km with triangular/horizontal conductor arrangement for capacitive loading. (a) sending end; (b) receiving end.
Figure 3.10. Current and voltage waveforms for a transmission line of 200 km with triangular/horizontal conductor arrangement for capacitive loading. (a) sending end; (b) receiving end.

The results of parameter estimation for resistance, inductance and capacitance considering different earth resistivities and capacitive load are presented as follows:

- Fig. 3.11: 100 km long line with triangular configuration,
- Fig. 3.12: 200 km long line with triangular configuration,
- Fig. 3.13: 100 km long line with horizontal configuration, and
- Fig. 3.14: 200 km long line with horizontal configuration.
Figure 3.11. Parameter estimation for a 100 km transmission line with triangular conductor arrangement as a function of earth resistivity. (a) Resistance, (b) Inductance, (c) Capacitance.
Figure 3.12. Parameter estimation for a 200 km transmission line with triangular conductor arrangement as a function of earth resistivity. (a) Resistance, (b) Inductance, (c) Capacitance.
Figure 3.13. Parameter estimation for a 100 km transmission line with horizontal conductor arrangement as a function of earth resistivity. (a) Resistance, (b) Inductance, (c) Capacitance.
Figure 3.14. Parameter estimation for a 200 km transmission line with horizontal conductor arrangement as a function of earth resistivity. Resistance, Inductance, Capacitance.
Table 3. Max percentage error for capacitive load

<table>
<thead>
<tr>
<th>Elements</th>
<th>Horizontal</th>
<th>Triangular</th>
<th>Horizontal</th>
<th>Triangular</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100 km</td>
<td>200 km</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistance</td>
<td>1.88%</td>
<td>2.04%</td>
<td>2.36%</td>
<td>2.55%</td>
</tr>
<tr>
<td>Inductance</td>
<td>1.10%</td>
<td>1.18%</td>
<td>0.95%</td>
<td>1.02%</td>
</tr>
<tr>
<td>Capacitance</td>
<td>0.27%</td>
<td>0.31%</td>
<td>0.22%</td>
<td>0.21%</td>
</tr>
</tbody>
</table>

Figures 3.9 to 3.14 represent the self and mutual elements of the resistance, inductance and capacitance matrices for capacitive load, testing different tower configuration and line lengths under variety of ground resistivities. The results in this case are very similar to those obtained in the previous topology (resistive loading), indicating an excellent match between the estimated and analytical parameters. This also shows that the parameter estimation method is not affected by different terminal conditions and line lengths. Table 3.3 represents the highest percentage error between the estimated and analytical resistance, inductance and capacitance. The results prove the accuracy of the analytical parameters as it shows low percentage error between the two methods. Table 3.3 also reveals that the highest percentage error was observed for resistance, with less percentage error for the inductance and capacitance, as expected.
3.4 Summary

This chapter proposes an accurate parameter estimation method for transposed three-phase transmission lines that considering full frequency range. The proposed method utilizes an analytical framework to solve a 2-port nodal model in the frequency domain for the series impedance and shunt admittance of a line using Clarke's transformation to decouple the system into three separate single-conductors. The method is tested under various conditions including different tower configuration over varies earth resistivity.

Even though the conditions considered in the analysis for Topologies 1 and 2 result in widely differing current and waveform waveforms, the estimation method provides practically the same values. The results demonstrate accurate estimation under varying line lengths, tower configurations, and loading conditions for various earth resistivity values. The results also show a very small mismatch in some parameters, which can be explained to some extent by the disparity between the two software tools used in the testing process. In general, the results show a good agreement between estimated parameters and the values obtained from the analytical model for all the conditions considered in this study.
CHAPTER 4

PARAMETER ESTIMATION FOR THREE-PHASE UNTRANSPOSED TRANSMISSION LINE

4.1 Introduction

This chapter focuses on transmission line model reconstruction and parameter determination by introducing a novel wideband parameter estimation method for untransposed three-phase overhead transmission lines with frequency-dependent parameters. Starting with terminal measurements obtained from a set of tests, the method reconstructs the 2-port nodal model of the line over a wide frequency band. The overdetermined mathematical system resulting from these tests is solved using the minimum norm least-squares method. Then, the reconstructed 2-port model is solved directly in the phase domain for the line parameters (series impedance and shunt admittance matrices), avoiding the use of the modal decomposition discussed in Chapter 3. Terminal voltage and current measurements used as inputs for the estimation method are simulated using software ATP/EMTP for several cases that consider different tower configurations, in order to assess the accuracy and generality of the proposed approach.

4.2 Methodology

4.2.1 Two-Port (Admittance) Model Reconstruction

The proposed estimation method starts from the definition of a frequency-domain admittance model given by the relationship between the voltages and the currents measured at both ends of the line, defined as
\[
\begin{bmatrix}
I_0^{(s)} \\
I_l^{(s)}
\end{bmatrix} = \begin{bmatrix}
A^{(s)} & -B^{(s)} \\
-B^{(s)} & A^{(s)}
\end{bmatrix} \begin{bmatrix}
V_0^{(s)} \\
V_l^{(s)}
\end{bmatrix}
\]  

(4.1)

where \(I_0, I_l, V_0\) and \(V_l\) are the frequency domain vectors of phase voltages and currents, obtained by means of the application of the numerical Laplace transform (NLT) [28] to the corresponding time domain measurements:

\[
V_0 = \text{NLT}\{[v_{0A} v_{0B} v_{0C}]^T\},
\]

(4.2a)

\[
V_l = \text{NLT}\{[v_{lA} v_{lB} v_{lC}]^T\},
\]

(4.2b)

\[
I_0 = \text{NLT}\{[i_{0A} i_{0B} i_{0C}]^T\},
\]

(4.2c)

\[
I_l = \text{NLT}\{[i_{lA} i_{lB} i_{lC}]^T\},
\]

(4.2d)

while the admittance submatrices \(A\) and \(B\) (for an untransposed 3-phase line) are given by

\[
A = \begin{bmatrix}
A_{11} & A_{12} & A_{13} \\
A_{12} & A_{22} & A_{23} \\
A_{13} & A_{23} & A_{33}
\end{bmatrix},
\]

(4.3a)

\[
B = \begin{bmatrix}
B_{11} & B_{12} & B_{13} \\
B_{12} & B_{22} & B_{23} \\
B_{13} & B_{23} & B_{33}
\end{bmatrix},
\]

(4.3b)

\(A\) and \(B\) are symmetrical matrices; consequently, each of them contains six different elements.

Therefore, (4.1) can be rewritten as the following set of equations:

\[
I_{0A} = A_{11}V_{0A} + A_{12}V_{0B} + A_{13}V_{0C} - B_{11}V_{lA} - B_{12}V_{lB} - B_{13}V_{lC},
\]

(4.4a)

\[
I_{0B} = A_{12}V_{0A} + A_{22}V_{0B} + A_{23}V_{0C} - B_{12}V_{lA} - B_{22}V_{lB} - B_{23}V_{lC},
\]

(4.4b)

\[
I_{0C} = A_{13}V_{0A} + A_{23}V_{0B} + A_{33}V_{0C} - B_{13}V_{lA} - B_{23}V_{lB} - B_{33}V_{lC},
\]

(4.4c)

\[
I_{RA} = -B_{11}V_{0A} - B_{12}V_{0B} - B_{13}V_{0C} + A_{11}V_{lA} + A_{12}V_{lB} + A_{13}V_{lC},
\]

(4.4d)
\( I_{RB} = -B_{12}V_{0A} - B_{22}V_{0B} - B_{23}V_{0C} + A_{12}V_{lA} + A_{22}V_{lB} + A_{23}V_{lC}, \) \hspace{1cm} (4.4e)

\( I_{RC} = -B_{13}V_{0A} - B_{23}V_{0B} - B_{33}V_{0C} + A_{13}V_{lA} + A_{23}V_{lB} + A_{33}V_{lC}. \) \hspace{1cm} (4.4f)

The system defined by (4.4) can be expressed in matrix form as shown in (4.5), given that the voltages and currents are known but the admittance components are unknown.

\[
\begin{bmatrix}
  V_{0A} & 0 & 0 & -V_{lA} & -V_{lB} & -V_{lC} & 0 & 0 & 0 \\
  0 & V_{0A} & V_{0B} & 0 & -V_{lA} & 0 & -V_{lB} & -V_{lC} & 0 \\
  0 & 0 & V_{0B} & V_{0C} & 0 & -V_{lA} & 0 & -V_{lB} & -V_{lC} \\
  -V_{lA} & -V_{lB} & -V_{lC} & 0 & 0 & V_{0A} & V_{0B} & V_{0C} & 0 \\
  0 & -V_{lA} & 0 & -V_{lB} & -V_{lC} & 0 & 0 & V_{0A} & V_{0B} & V_{0C} \\
  0 & 0 & -V_{lA} & 0 & -V_{lB} & -V_{lC} & 0 & 0 & V_{0A} & V_{0B} & V_{0C}
\end{bmatrix}
\begin{bmatrix}
  A_{11} \\
  A_{12} \\
  A_{13} \\
  A_{22} \\
  A_{23} \\
  A_{33} \\
  B_{11} \\
  B_{12} \\
  B_{13} \\
  B_{22} \\
  B_{23} \\
  B_{33}
\end{bmatrix}.
\hspace{1cm} (4.5)

Eq. (4.5) can be represented in compact form as:

\[
[I]_{6\times1} = [V]_{6\times12}[\mathbf{Y}_\pi]_{12\times1},
\] \hspace{1cm} (4.6)

where column vector \( \mathbf{Y}_\pi \) contains the elements of the \( \mathbf{A} \) and \( \mathbf{B} \) matrices to be obtained from the terminal currents in column vector \( \mathbf{I} \) and terminal voltages in rectangular matrix \( \mathbf{V} \). The system in (4.6) is underdetermined; it contains 6 equations and 12 unknowns; therefore, there are solution is not unique. To solve (4.6) for vector \( \mathbf{Y}_\pi \) in such a way that the reconstructed admittance is unique, we propose to obtain terminal measurements for a variety of tests. Two tests would yield the system in (4.7) with the same number of equations than unknowns:

\[
\begin{bmatrix}
  I_{test\; 1} \\
  I_{test\; 2}
\end{bmatrix}_{12\times1} =
\begin{bmatrix}
  V_{test\; 1} \\
  V_{test\; 2}
\end{bmatrix}_{12\times12}[\mathbf{Y}_\pi]_{12\times1}.
\] \hspace{1cm} (4.7)

However, the 12\(\times\)12 matrix of voltages in Eq. (4.7) will in general be singular, precluding the direct solution of this system. This can be solved by adding an additional test to achieve an
overdetermined system as follows:

\[
\begin{bmatrix}
 I_{\text{test }1} \\
 I_{\text{test }2} \\
 I_{\text{test }3}
\end{bmatrix}_{18 \times 1} = 
\begin{bmatrix}
 V_{\text{test }1} \\
 V_{\text{test }2} \\
 V_{\text{test }3}
\end{bmatrix}_{18 \times 12} \begin{bmatrix}
 Y_{\pi}
\end{bmatrix}_{12 \times 1}.
\] 

(4.8)

Eq. (4.8) is solved here by applying the minimum norm least-squares (MNLS) approach [39], which calculates a vector \( Y \) that minimizes \( \| VY - I \| \). For the system to be solved, it was determined that 3 tests that generate distinct terminal voltages and currents are sufficient to accurately reconstruct the admittance matrix of the transmission lines under test.

The tests applied can be illustrated by the excitation of the system in Fig. 4.1 for different switching combinations at \( t = 0 \). The proposed sequence of tests is as follows:

- Test 1: \( sw_A \): ON, \( sw_B \) OFF, \( sw_C \): OFF.

- Test 2: \( sw_A \): ON, \( sw_B \): ON, \( sw_C \): OFF.

- Test 3: \( sw_A \): ON, \( sw_B \): OFF, \( sw_C \): ON.

The load remains unchanged during all tests.
4.2.2 Parameter Estimation from the Reconstructed Model

From transmission line theory [40], the \( A \) and \( B \) elements of a distributed parameter multiconductor transmission line admittance model are defined as follows:

\[
A = Y_0 \coth(\Psi l), \tag{4.9a}
\]

\[
B = Y_0 \text{csch}(\Psi l). \tag{4.9b}
\]

where \( l \) is the length of the line, while \( Y_0 \) and \( \Psi \) are given by

\[
Y_0 = Z^{-1}\Psi, \tag{4.10a}
\]

\[
\Psi = \sqrt{ZY}. \tag{4.10b}
\]

where \( Z \) and \( Y \) are the series impedance and shunt admittance matrices of the line. Considering that \( A \) and \( B \) are known from the model reconstruction described in Section 4.2, a series of
algebraic steps allows to obtain the parameters of the line from $\mathbf{A}$ and $\mathbf{B}$. First, (4.9a) and (4.9b) are combined and solved for $\Psi$:

$$\Psi = \cosh^{-1}(\mathbf{B}^{-1}\mathbf{A}) / l. \quad (4.11)$$

Then, (4.11) is substituted into (4.9a), which is solved for $\mathbf{Y}_0$:

$$\mathbf{Y}_0 = \mathbf{A} \{ \coth[\cosh^{-1}(\mathbf{B}^{-1}\mathbf{A})] \}^{-1}. \quad (4.12)$$

Lastly, (4.10a) and (4.10b) are solved for $\mathbf{Z}$ and $\mathbf{Y}$:

$$\mathbf{Z} = \Psi \mathbf{Y}_0^{-1}, \quad (4.13a)$$

$$\mathbf{Y} = \mathbf{Y}_0 \Psi. \quad (4.13b)$$

For the parameter estimation method, matrices $\Psi$ and $\mathbf{Y}_0$ are first obtained from $\mathbf{A}$ and $\mathbf{B}$ according to (4.11) and (4.12), and then $\mathbf{Z}$ and $\mathbf{Y}$ are obtained from $\Psi$ and $\mathbf{Y}_0$ according to (4.13a) and (4.13b). Finally, resistive, inductive and capacitive matrices of the line are calculated as

$$\mathbf{R} = \text{Re}\{\mathbf{Z}\}, \quad (4.14a)$$

$$\mathbf{L} = \text{Im}\{\mathbf{Z}\}/\omega, \quad (4.14b)$$

$$\mathbf{C} = \text{Im}\{\mathbf{Y}\}/\omega, \quad (4.14c)$$

where $\omega$ is the angular frequency.
4.3 Test Cases

The results of the parameter estimation method described above are presented in this section. ATP software [41] is employed to simulate the measurements of voltage and current at the sending and receiving ends of the transmission line. For the 3 distinct tests simulated, the load (receiving end) is kept constant at 1 kΩ, and the sending node is excited in 3 different ways, as the tests applied can be illustrated by the excitation of the system in Fig. 4.1 for different switching combinations at \( t = 0 \). The proposed sequence of tests is as follows:

- Test 1: \( sw_A : \) ON, \( sw_B : \) OFF, \( sw_C : \) OFF.
- Test 2: \( sw_A : \) ON, \( sw_B : \) ON, \( sw_C : \) OFF.
- Test 3: \( sw_A : \) ON, \( sw_B : \) OFF, \( sw_C : \) ON.

In all cases the excitation is a step voltage source with source impedance of 10 Ω. The three-phase overhead line model used for the ATP simulations is based on a distributed-parameter and frequency-dependent representation (J. Marti setup [29]). The numerical Laplace transform [28] is applied to convert the simulated terminal measurements from the time domain to the frequency domain.

To further investigate the capability of the estimation method to handle diverse line topologies, three different tower configurations are considered: horizontal, vertical, and triangular, as shown in Fig. 4.2. The line parameters for all cases are listed in Table 4.1. Coordinate \((x,y)\) location of conductors for each case is defined in Table 4.2.
Figure 4.2. Tower configurations under test: a) horizontal, b) triangular, c) vertical.

Table 4.1. Transmission line data

<table>
<thead>
<tr>
<th>Parameter [unit]</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor radius [m]</td>
<td>0.0272/0.01210</td>
</tr>
<tr>
<td>Conductor resistivity (Al) [$\Omega\cdot m$]</td>
<td>$2.61\times10^{-8}$</td>
</tr>
<tr>
<td>Ground resistivity [$\Omega\cdot m$]</td>
<td>100</td>
</tr>
<tr>
<td>Line length [km]</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 4.2. Conductor disposition for each tower configuration under study

<table>
<thead>
<tr>
<th>Phase</th>
<th>Horizontal</th>
<th>Triangular</th>
<th>Vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(x,y) location in meters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>(-3,12)</td>
<td>(-5,25)</td>
<td>(0,36.64)</td>
</tr>
<tr>
<td>B</td>
<td>(0,12)</td>
<td>(0,30)</td>
<td>(0,30.72)</td>
</tr>
<tr>
<td>C</td>
<td>(3,12)</td>
<td>(5,25)</td>
<td>(0,4,24.80)</td>
</tr>
</tbody>
</table>
4.3.1 Single Conductor Case

Plots for each case, comparing analytical and estimated results, are divided in self elements and mutual elements as follows:

- Horizontal configuration case: Figs. 4.3 (self) and 4.4 (mutual).
- Triangular configuration case: Figs. 4.5 (self) and 4.6 (mutual).
- Vertical configuration case: Figs. 4.7 (self) and 4.8 (mutual).

The frequency range for all cases is 10 Hz to 15 kHz. Although not obvious in some cases due to overlapping of curves, each plot shows 3 analytical and 3 estimated curves: (1,1), (2,2), (3,3) for self elements and (1,2), (1,3) and (2,3) for mutual elements. Besides conductor disposition, most data remain unchanged between cases, as given by Table 4.1, except for conductor radius, which is given by 0.0272 m for horizontal and triangular configuration, and by 0.0121 m for vertical configuration. The conductor disposition for each tower configuration considered in this study is presented in Table 4.2.

Figures 4.3 to 4.8 show that the estimated resistance and inductance follow the expected variation with frequency due to skin effect in the conductors and in the earth-return path. On the other hand, no frequency-dependence is considered in the capacitances by the analytical model, which is estimated correctly, with slight variation around the analytical values.
Figure 4.3. Horizontal configuration. Self-elements: a) Resistance, b) Inductance, and c) Capacitance.
Figure 4.4. Horizontal configuration. Mutual elements: a) Resistance, b) Inductance, and c) Capacitance.
Figure 4.5. Triangular configuration. Self-elements: a) Resistance, b) Inductance, and c) Capacitance.
Figure 4.6. Triangular configuration. Mutual elements: a) Resistance, b) Inductance, and c) Capacitance.
Figure 4.7. Vertical configuration. Self-elements: a) Resistance, b) Inductance, and c) Capacitance.
Figure 4.8. Vertical configuration. Mutual elements: a) Resistance, b) Inductance, and c) Capacitance.
According to Figs. 4.3 to 4.8, the results of diagonal and off-diagonal elements of resistance, inductance and capacitance reveal high accuracy for the analytical approach under different tower configuration compared with the estimated parameters. The highest percentage error between the estimated parameters and the analytical approach is presented in Table 4.3. The Table proves the accuracy of the proposed method as it indicates low percentage error between the estimated parameters against the analytical approach. An increasing mismatch in the $R$ and $L$ elements with frequency observed in the plots and in larger percentage errors in Table 4 (particularly for resistance elements) can be explained to some extent by the fact that the parameter calculation in ATP and with the analytical formulas used in this work are not identical.
4.3.2 Bundled Conductors Case

To further investigate the robustness of the method and to reflect practical conditions, the previous cases are retested with the addition of conductor bundles (a number of subconductors per phase), which is a very typical configuration in transmission towers to reduce losses and increase transmission capacity. The same three tower configurations (horizontal, vertical, and triangular) are considered in this case, as shown in Fig. 4.2, with line parameters and coordinate \((x,y)\) location of conductors for each case listed in Tables 4.1 and 4.2. The bundled conductor arrangement considered for all cases contains three conductors per phase with a 12 cm distance between them, forming an equilateral triangle. Plots for each case, comparing analytical against estimated results, are divided in self-elements and mutual elements as follows:

- **Horizontal configuration case**: Figs. 4.9 (self) and 4.10 (mutual).
- **Triangular configuration case**: Figs. 4.11 (self) and 4.12 (mutual).
- **Vertical configuration case**: Figs. 4.13 (self) and 4.14 (mutual).
Figure 4.9. Horizontal configuration. Self-elements: a) Resistance, b) Inductance, and c) Capacitance.
Figure 4.10. Horizontal configuration. Mutual elements: a) Resistance, b) Inductance, and c) Capacitance.
Figure 4.11. Triangular configuration. Self-elements: a) Resistance, b) Inductance, and c) Capacitance.
Figure 4.12. Triangular configuration. Mutual elements: a) Resistance, b) Inductance, and c) Capacitance.
Figure 4.13. Vertical configuration. Self-elements: a) Resistance, b) Inductance, and c) Capacitance.
Figure 4.14. Vertical configuration. Mutual elements: a) Resistance, b) Inductance, and c) Capacitance.

Table 4.4. Max percentage error for each tower configuration with bundle conductors

<table>
<thead>
<tr>
<th>Elements</th>
<th>Horizontal</th>
<th>Triangular</th>
<th>Vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance (self)</td>
<td>4.24%</td>
<td>3.75%</td>
<td>7.8%</td>
</tr>
<tr>
<td>Inductance (self)</td>
<td>0.93%</td>
<td>0.91%</td>
<td>1.25%</td>
</tr>
<tr>
<td>Capacitance (self)</td>
<td>0.29%</td>
<td>0.21%</td>
<td>0.28%</td>
</tr>
<tr>
<td>Resistance (mutual)</td>
<td>4.5%</td>
<td>3.6%</td>
<td>6.05%</td>
</tr>
</tbody>
</table>
Table 4.4—Continued

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductance (mutual)</td>
<td>1.9%</td>
<td>1.4%</td>
<td>2.1%</td>
</tr>
<tr>
<td>Capacitance (mutual)</td>
<td>0.65%</td>
<td>0.61%</td>
<td>0.73%</td>
</tr>
</tbody>
</table>

According to Figs. 4.9 to 4.14, the results of diagonal and off-diagonal elements of resistance, inductance and capacitance reveal high accuracy again for the case of conductor bundle for the analytical approach under different tower configuration compared with the estimated parameters. The highest percentage error between the estimated parameters and the analytical approach is presented in Table 4.4. This table proves the accuracy of the proposed method as it indicates low percentage error between the estimated parameters against the analytical approach. An increasing mismatch in the $R$ and $L$ elements with frequency observed in the plots and in larger percentage errors in Table 4 (particularly for resistance elements) can be explained to some extent by the fact that the parameter calculation in ATP and with the analytical formulas used in this work are not identical.

4.4 Summary

This chapter presents a novel method for determining the parameters of untransposed three-phase overhead transmission lines over a wide frequency range. Using the minimum norm least-squares method, the 2-port nodal model of the line is reconstructed from terminal measurements obtained for a set of tests. The reconstructed model is then solved without modal decoupling techniques for the series impedance and shunt admittance matrices. Simulations of terminal
voltage and current measurements for various tower configurations are used to demonstrate the accuracy of the proposed method. The results of diagonal and off-diagonal elements of $R$, $L$ and $C$ show high accuracy for different tower configurations, according to Figs. 4.3 to 4.14 and Tables 4.4 and 4.5. An increasing mismatch in the $R$ and $L$ elements with frequency observed in the plots and in larger percentage errors in the tables (particularly for resistance elements) can be explained to some extent by the fact that the parameter calculation in ATP and with the analytical formulas used in this work are not identical. Analytical formulas used for comparison follow the concept of complex penetration depth proposed by Gary [42], while ATP applies Carson’s method [43]. It has been shown that these two methods can diverge at high frequencies [30].
CHAPTER 5

CONCLUSIONS AND FUTURE WORK

5.1 Conclusions and Contributions

based on the results presented in the dissertation we can confirm the hypothesis that frequency-dependent distributed parameter model of the line in the frequency domain will enable the accuracy enhanced estimation of transmission line electrical parameters over a wide frequency range. Wideband parameter estimation methods have been introduced and evaluated in this dissertation for frequency-dependent single-phase, three-phase transposed and three-phase untransposed overhead lines using terminal measurements of transient currents and voltages, employing an analytical framework to solve a frequency domain 2-port nodal model for the series impedance and shunt admittance considering full frequency dependence over a wide frequency range. The proposed analytical approaches have been derived from the transmission line equivalent π circuit in the frequency domain. The terminal measurements required as inputs are obtained from simulations using the well-known electromagnetic transient simulation program EMTP/ATP, and the application of the numerical Laplace transform (NLT).

A parameter estimation method for single-phase transmission lines using an analytical framework was introduced to solve a 2-port nodal model in the frequency domain for the line's series impedance and shunt admittance per unit length, considering full frequency-dependent parameters over a wide frequency range. The results obtained for the single-phase method were compared against the analytical calculation of frequency dependent electrical parameters of
overhead lines, demonstrating very high accuracy and robustness of the proposed estimation approach over a wide frequency band under diverse conditions, including variations in geometrical and electrical parameters, as well as in the terminal connections of the line.

The aforementioned single-phase method was extended using the Clarke transformation to enable electrical parameter estimation for fully transposed three-phase transmission lines. The method demonstrates accurate estimation for fully-transposed three-phase transmission lines under various conditions, including different tower configuration that used over various earth resistivity under assumption of transposition, which improves the accuracy of parameter estimation in the transposed three-phase transmission lines.

A novel method for estimating the transmission line parameters for untransposed three-phase overhead transmission lines over a wide frequency range was proposed in this dissertation. The method involved reconstructing the 2-port nodal model of the line from the terminal measurements obtained from a set of tests for solving an overdetermined mathematical system using the minimum norm least-square method. The series impedance and shunt admittance matrices are then solved for the reconstructed model without the need for the model decoupling technique. Simulations of terminal voltage and current measurements for various tower configurations are used to demonstrate high accuracy in this estimation method when compared with analytical frequency-dependent parameters.
The estimation methods proposed here have potential use in a variety of practical applications, including designing and optimizing transmission line systems, analyzing, identifying, and monitoring transmission line problems (e.g., fault conditions, sagging due to icing, installation defects, etc.), and enhancing power system reliability and safety.

5.2 Future Work

- The parameter estimation method can be further extended for a variety of applications, such as power system analysis or fault diagnosis, combining the estimation with other types of analysis, such as load flow or stability studies.
- The robustness of the estimated method can be further evaluated considering noise or measurement errors.
- The reconstructed model from the parameter estimation method can be useful in a variety of applications, such as:
  - To predict transmission line behavior under various operating conditions. For instance, the model can be used to predict the voltage and current on the line during various transient events or under various load conditions.
  - Optimizing transmission line design. By adjusting model parameters, it is possible to evaluate various design options and select the one that provides the best performance.
  - To evaluate the transmission line performance. By comparing model predictions to actual measurements taken on the line, it is possible to identify deviations from the expected behavior and investigate their cause.
• To troubleshoot transmission line issues. If the line is not performing as expected, the reconstructed model can be used to determine the root cause of the problem and propose potential solutions.
REFERENCES


