INDUCED VOLTAGE ON GAS PIPELINE DUE TO ALTERNATING CURRENT TOTAL INTERFERENCE OF FAULTED OVERHEAD TRANSMISSION LINE

ALI I. EL GAYAR

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Electrical Engineering)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

JUNE 2017

To my beloved parents, my grandparents, my wife, my daughter, my son, and all family members for their encouragement and support”

ACKNOWLEDGEMENT

First of all, gratefulness of thanks to our Creator, “ALLAH”, who enabled us to complete this thesis.

Special thanks go to Prof. Dr. Zulkurnain Abdul-Malek, for giving this opportunity to work under his supervision and for sharing his great knowledge and experience with me.

Many thanks to the colleagues of the IVAT group, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, for their idea’s sharing and discussions.

Finally, Special thanks to my parents, my grandparents, my wife, my children, family and all my lovely friends for their continuous encouragement and support throughout the time.

ABSTRACT

In locations where a buried gas pipeline (PL) shares the same right-of-way with a high voltage overhead transmission line (TL), a relatively higher voltage than normally allowed may be induced in the pipeline due to the alternating current (AC) total interference between the TL and PL. The increase may damage the pipeline coating, connected pipeline equipment, as well as may pose a safety threat to pipeline service personnel. Key questions to be answered are how to evaluate, and minimise the AC total interference made up of inductive and conductive components and their related effects in the event of a power system fault occurring in the TL. This research investigated the pipeline induced voltage behaviour while simultaneously considering the inductive and conductive interferences. Different observation point profiles were considered to obtain various types of induced voltages such as metal ground potential rise (GPR), touch voltage, coating GPR, coating stress and earth surface GPR. A performance comparison between two computational methods, namely electromagnetic field (solutions to Maxwell's equations) and circuit-based (solutions to circuit equivalents of network configuration) approaches were carried out. The TL-PL AC total interference behaviour under various conditions were studied. These included the influence of complex soil structure, soil resistivity, defective pipeline coating, and several other critical parameters. A 30-km long, 115 kV TL and a 10 km long, 24-in PL were used. Results showed that the circuit-based approach performed as good as the field approach (within 5% error). The close agreement between the two approaches shows that the simulation and modelling works carried out in this work are valid. The TL-PL inductive interference increased with the fault current, but decreased with the TL-PL separation distance, the surrounding soil resistivity, and the tower footing resistance. Nevertheless, the conductive interference had to be considered when computing the pipeline induced voltages especially when the soil resistivity was low (< 10 Ω-m), the fault current was high (> 10 kA), the tower footing resistance was low (< 5 Ω), and the separation distance between the TL and PL was small (< 20 m). In addition, the effect of pipeline coating condition on the induced voltages was dependent on pipeline coating resistivity as well as the soil resistivity. High touch voltage poses threat to human and equipment safety, while high coating stress may accelerate pipeline coating deterioration and corrosion. The results also showed that the variation of the induced voltages in the pipeline buried in complex soil structure depended mainly on the thickness of the first horizontal layer, or the width of the middle vertical layer, or both. The complex soil structure can be replaced with a three-vertical-layer equivalent structure when the width of the middle layer is above 16 km and the thickness of the first horizontal layer is above 100 m. Adequate soil resistivity measurements must therefore be performed to provide the complete soil resistivity data for the complex as well as non-uniform soil models.

ABSTRAK

Lokasi di mana saluran paip (PL) gas berkongsi laluan yang sama dengan talian penghantaran atas voltan tinggi (TL), voltan melebihi tahap dibenarkan boleh diaruh dalam PL disebabkan jumlah gangguan arus ulang-alik (AC) antara TL dan PL. Kenaikan voltan boleh menyebabkan kerosakan salutan paip, peralatan paip, serta boleh menimbulkan ancaman keselamatan kepada kakitangan perkhidmatan saluran paip. Persoalan utama yang perlu dijawab adalah bagaimana untuk menilai dan mengurangkan jumlah gangguan AC (terdiri daripada komponen induktif dan konduktif) dan kesan yang berkaitan sekiranya berlaku kerosakan sistem kuasa pada TL. Kajian ini bertujuan untuk mengkaji tingkah laku voltan paip yang teraruh yang menyebkan kedua-dua gangguan induktif dan konduktif secara serentak. Profil titik pemerhatian yang berbeza digunakan bagi mendapatkan pelbagai jenis voltan teraruh seperti kenaikan potensi bumi (GPR) logam, voltan sentuh, GPR salutan, tekanan salutan dan GPR permukaan bumi. Perbandingan prestasi antara dua kaedah pengiraan, iaitu kaedah medan elektromagnet (penyelesaian kepada persamaan Maxwell) dan kaedah berasaskan litar (penyelesaian kepada litar setara konfigurasi rangkaian) telah dijalankan. Tingkah laku jumlah gangguan AC TL-PL dalam pelbagai keadaan telah dikaji. Ini termasuk pengaruh struktur kompleks tanah, kerintangan tanah, salutan paip yang rosak, dan beberapa parameter kritikal lain. Satu TL 115 kV sepanjang 30 km dan satu PL 24 inci sepanjang 10 km digunakan. Keputusan menunjukkan bahawa pendekatan berasaskan litar memberi prestasi yang sama dengan pendekatan medan (dalam ralat 5%). Persamaan antara kedua-dua pendekatan menunjukkan simulasi dan model yang dijalankan dalam kerja ini adalah sahih. Gangguan induktif TL-PL meningkat dengan arus kerosakan, tetapi berkurangan dengan jarak pemisahan TL-PL, kerintangan tanah, dan dengan rintangan tapak menara. Walau bagaimanapun, gangguan konduktif juga penting terutama apabila kerintangan tanah adalah rendah (< 10 Ω-m), arus kerosakan yang tinggi (> 10 kA), rintangan tapak menara yang rendah (< 5 Ω-m), dan jarak pemisahan TL-PL yang kecil (< 20 m). Di samping itu, kesan keadaan salutan paip pada voltan teraruh adalah bergantung kepada kerintangan salutan paip dan juga kerintangan tanah.. Voltan sentuh yang tinggi menimbulkan ancaman kepada keselamatan manusia dan peralatan, manakala tekanan salutan yang tinggi boleh mempercepatkan kemerosotan dan hakisan salutan paip. Keputusan juga menunjukkan bahawa perubahan voltan teraruh pada paip yang ditanam dalam struktur tanah kompleks bergantung terutamanya kepada ketebalan lapisan mendatar yang pertama, atau lebar lapisan menegak tengah, atau kedua-duanya. Struktur tanah yang kompleks boleh digantikan dengan struktur setara tiga-lapisan-menegak apabila lebar lapisan tengah melebihi 16 km dan ketebalan lapisan mendatar yang pertama melebihi 100 m. Ukuran kerintangan tanah yang mencukupi mesti dilakukan untuk memberikan data kerintangan tanah yang lengkap untuk model tanah kompleks dan tanah tak seragam.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

P	-	Carson's correction factor.
Q	-	Carson's correction for earth return and are given in form of infinite series.
L	-	Conductor nearest to pipeline
k	-	Correction factor
σ	-	Conductivity of the medium
θ	-	Complex conductivity of the medium
I	-	Current
J	-	Current density
R'_{dc}	-	DC resistance of the pipeline wall
δ	-	Depth of earth return path
h_P	-	Depth of pipeline underground
d	-	Distance between two conductors
D_{ij}	-	Distance between conductors *i* and the image of conductor *j*.
a	-	Distance between the transmission line and pipeline
E	-	Earth conductor
gmr_i	-	Effective radius (or geometric mean radius) of conductor *i*.
D	-	Electric flux density
E	-	Electric field intensity
D	-	Electric flux density
μ_B	-	Fictitious relative permeability of counterpoise
Z	-	Iimpedance
x	-	Individual location of a pipeline inside the exposure length.
l_{pp}	-	Length of parallel exposure between pipeline and overhead line
$\mathbf{Z}_{ij}$	-	Mutual-impedance between conductors *i* and *j*.
H	-	Magnetic field intensity
B	-	Magnetic flux density

N - Number of layer
r_P - Outer radius of the pipeline
k_P - Pipeline conductivity
d - Pipeline thickness
γ - Propagation constant
w - Probability factor
r - Radius of earth conductor
R - Resistance
R' - Resistance of earth wire per unit length
r' - Screening factor
$\mathbf{Z}_{ii}$ - Self-impedance of conductor *i* with ground return
ρ - Soil resistivity
μ_0 - The absolute permeability
h_L - The conductor height at the tower
$\bar{s}$ - The conductor sag
h_i - The height of conductor *i*.
h_S - The effective height of the conductor
μ_P - The fictitious relative permeability of the pipeline
l - Total length of pipeline
r_i - The internal resistance of conductor
$\boldsymbol{r}$ - The position of the observation point
r_B - The radius of counterpoise
r'_{tot} - Total screening factor

LIST OF ABBREVIATIONS

AC - Alternative Current
AGA - American Gas Association
ATP - Alternative Transients Program
CDEGS - Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis
ECCAPP - Electromagnetic and Conductive Coupling Analysis from Power Lines to Pipelines
EPRI - Electrical Power Research Institute
FEM - Finite-Element Method
GPR - Ground Potential Rise
OHTL - Over Head Transmission Line
PL - Pipe Line
ROW - Right of Way
SES - Safe Engineering Services
SRS - Soil Resistivity Structure
STD - Standard
TFR - Tower footing resistance
TL - Transmission Line
UTM - Universiti Teknologi Malaysia

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

Overhead transmission lines and gas pipelines are now commonly being installed together and sharing the same corridor, also known as "right-of-way" (ROW). Installing gas pipelines (PLs) in parallel with overhead transmission lines (TLs) may cause undesirable electromagnetic interference between the TL and PL. The electromagnetic interference may lead to the consequence of unsafe level of induced voltages within and around the pipeline. An induced voltage higher than the safe level may be dangerous to human or can be harmful to equipment attached to the pipeline such as those used for cathodic protection, various sensors, and control valves [1, 2]. The consequence of interference between the TL and the PL is now increasing in significance due to the environmental concerns which have been enforced on various companies. These are mainly aimed to reduce the influence posed by the interference on wildlife, nature and mankind [2, 3].

When a high current flows in the TL system as well as in the TL towers due to a power system fault, switching operations, or lightning, high voltages may be induced along the PL system. These induced voltages are as a result of some form of energy transfer from the TL system to the PL system through several paths between the two systems. The paths which exist as a result of various respective couplings in the commonly shared ROW are known as conductive, inductive, and capacitive paths [4]. The instantaneous or simultaneous resultant effect of the conductive, inductive, and capacitive couplings is commonly referred to as "the AC total interference" [5-7]. This work concerns the study of the AC total interference between an overhead high voltage transmission line (TL) and a buried gas pipeline (PL).

1.2 Research Background

As mentioned above, the overall electromagnetic interference between the transmission line and the gas pipeline consists of three mechanisms or components, namely, the conductive, inductive and capacitive interferences, which are in turn due to their respective couplings between the TL and PL. The resultant interference is also normally known as the AC total interference [8]. The conductive interference occurs when a fault current flows from the TL to the ground, during which some of the fault current may flow along the PL, and hence causes a potential rise in the pipeline. The inductive coupling occurs when the same fault current causes a magnetic coupling (instead of conductive coupling) between the TL system and the PL system and hence giving a potential rise in the pipe line [9, 10]. On the other hand, the capacitive coupling occurs due to any electric field interaction between the transmission line system and the gas pipeline system. However, this capacitive coupling can be neglected when dealing with a buried pipeline [11]. Apart from the fault current and its related parameters, the resultant potential rise or induced voltage in the pipeline due to the AC total interference is also dependent on several other influencing factors or other key parameters, such the surrounding soil condition within which the pipeline is buried. Typical magnitudes of the induced voltage in the pipeline due the TL-PL AC total interference are between several volts and several thousands of volts [12]. It is important to maintain the value of the induced voltage to be less than the values suggested by many standards and documents [13].

Two independent approaches are available to carry out an AC total interference study such that in the TL-PL interaction, which are the circuit-based approach and the electromagnetic field approach, or just field approach. In 2001, Dawalibi [14] studied the limitation of the circuit-based approach compared to the field approach when computing the inductive component of the TL-PL AC total interference. Similar to Dawalibi, many other studies had also considered only the inductive component and neglected the conductive component of the AC total interference [11, 15, 16]. It is to be noted that the conductive component of the AC total interference can only be neglected when the power system fault occurs in locations outside the commonly shared ROW, or remotely away from the pipeline system.

Within last several decades, the AC total interference related studies were extended to include several effects and major concerns. Many studies were carried out to determine the effects of several key parameters, such as soil resistivity, soil structure, fault current, and TL tower footing resistance, on the TL-PL inductive interference [11, 17-20]. Several methods to correctly compute the effects of those parameters on the TL-PL inductive interference were also proposed. The finite-element method (FEM) (field approach) was presented by several authors [15, 21-23]. A hybrid method consisting of both the FEM (field approach) and the circuit theory computation (circuit-based approach) todetermine the TL-PL inductive interference was also proposed [11, 17, 24]. However, these methods neglect the effects caused by the discontinuities at the TL-PL ends, or known as the end effects, and merely assumes the TL-PL arrangement as infinite in length. Clearly, this assumption is acceptable and applicable when computing the TL-PL inductive interference, but not the AC total interference. In short, most of the mentioned methods used when studying the effects of the key parameters on the TL-PL interference consider only the inductive component and neglect the conductive component, instead of the desired AC total interference.

An important aspect of the TL-PL interference study is on the effects of surrounding soil within which the pipeline is buried. The effect of soil structure on the conductive and inductive interferences is described by many previously published work. Despite of the existence of many published works, such as those described in [10], the effects of soil structure are still being studied. The importance of considering an accurate soil structure, when computing the TL-PL interference level, and when designing a mitigation system against high induced voltage for the pipeline, is described in [25]. Simulation work and relevant mathematical methods to determine the induced voltage on a pipeline were proposed with an assumption that the soil is uniform or homogeneous [8, 26]. Research has also shown that the soil structure and resistivity apparently have more significant impact on the conductive interference rather than on the inductive interference. Unlike the inductive interference (which can be correctly determined using just a uniform soil model), the TL-PL conductive interference can only be correctly computed if the soil structure is accurately modelled. Because of this, an accurate soil model (such as that with multi-layer structure) together with adequate soil resistivity data, is required when determining the TL-PL AC total interference along the ROW [11, 27].

When discussing about soil structure, soil resistivity plays the key characterizing factor. In a uniform soil structure, the soil resistivity is assumed to be constant [28]. Previous research agree on one fact, that is, the soil resistivity has a direct influence on the induced voltage in the pipeline. In particular, the induced voltage increases with the resistivity of the soil. It is known that in reality the soil is not uniform. In fact, the soil resistivity varies depending on the types of soil and additives present, as well as on the season of the year. Hence, the soil should actually be modelled as a non-uniform soil, for example, as a multi-layer soil, instead of a uniform soil. Each layer of the non-uniform soil model has its own resistivity. The influence of non-uniform soil on the inductive interference in a specific two conductor system was reported by Labridis [29]. The study observed the steady state interference between an AC electric traction line and nearby buried telecommunication cables. A similar study involving TL fault current and PL was carried out by Christoforidis [23], in which he reported the TL-PL inductive interference when the PL is buried in a two-layer soil. A comparison was also made between the induced voltages obtained with those obtained from a uniform soil equivalent [23]. In other researches, it was found that a non-homogeneous or non-uniform soil showed a significant effect on the behaviour of the inductive coupling or interference [30].

As previously mentioned, apart from the soil resistivity and soil structure, several other parameters may affect the overall behaviour of the AC total interference. One other key parameter is the pipeline coating and its condition. The pipeline lines are usually covered with an insulating coating layer to protect it from corrosion. Extreme stress or the presence of high voltages across the pipeline coating layer can result in its damage. The effects of coating defects and corrosion process in the pipeline are illustrated in [31, 32]. A pipeline buried in a homogenous soil having low resistivity is generally less vulnerable to corrosion and its subsequent damage compared to that buried in a homogenous soil having high resistivity [33]. The pipeline coating and its condition can potentially be a very significant factor in affecting the AC total interference. Nevertheless, majority of previous work assumed the pipeline coating resistance as either having a constant value or having a value similar to the perfect, or as new, coating [15, 34, 35]. If real conditions are to be taken into account, especially for old pipelines, the pipeline coating resistance should not be assumed as constant when carrying out the modelling work [15, 34, 35].

1.3 Research Problem Statement

In areas where the overhead high voltage transmission lines share the same corridor or right-of-way with gas pipelines, there exists several key issues. One of the key issues is how to minimise the interference and its related effects of a power system fault occurring in the TL on the nearby gas pipelines and their relevant infrastructures. The potential rise due to the interference has the capability to damage the pipeline coating and other related equipment. The induced voltage may also pose a threat to relevant pipeline service personnel. Therefore, it is important to determine the magnitude of the induced voltage and maintain the value to be less than the limit, above which it may jeopardize human safety, as suggested by many standards. The induced voltage is very much related to the study, analyses, and understanding of the behaviour of the TL-PL AC total interference. Many such studies were previously carried out to determine the induced voltage. However, most of those studies are limited to understanding only the inductive behaviour of the AC total interference [17, 35, 36]. Even though the effects of the conductive component can be neglected when the fault current occurred out of the parallel exposure lines or when the separation distance between the PL and TL is large, this is not true in the case of short PL-TL separation distance. It is therefore desired to determine the induced voltage in a buried pipeline due to simultaneous inductive and conductive interferences. Furthermore, the effects of key parameters, such as the tower footing resistance and the TL-PL separation distance, on the AC total interference behaviour have also not been widely reported.

When carrying out a study on the pipeline induced voltage, it is necessary to conduct a thorough study on the types of induced voltage that may arise, and to determine which types cause the most severe effect to the pipeline system and pipeline operators. In a simulation study, several observation profiles along the pipeline conducting path and its nearby regions, are usually selected for further analyses. Most previous studies concentrate on only one type of induced voltage, namely the pipeline metal ground potential rise, or metal GPR, which is measured using an observation profile within the conducting layer of the pipe [9, 10, 17, 20]. The behaviour of other types of induced voltages is barely studied. In particular, minimal data exists on the behaviour of the ground GPR (defined as the potential rise on the ground surface), the pipeline coating ground potential rise, or coating GPR (defined as the GPR on the outer surface of the coating layer), the coating stress (defined as the vector difference between the metal GPR and the coating GPR), and the touch voltage (defined as the vector difference between the metal GPR and the ground GPR).

The integrity of a gas pipeline is a critical issue in gas industries. Pipeline coating plays a key role in maintaining the pipeline integrity. The pipeline coating and hence its resistivity go through degradation process during its lifetime. Many previous works have reported the effects of pipeline coating resistivity on the TL-PL inductive interference [15, 34]. However, the effects of the variation in the pipeline coating, instead of the assumed ideal and constant coating in most studies, on the AC total interference behaviour, especially under varying soil resistivities are yet to be studied. Apart from the pipeline coating, the surrounding soil structure and soil resistivity are also significant in affecting the TL-PL AC total interference behaviour. Many studies examine the effects of soil resistivity on the induced voltage by assuming a homogenous soil structure. Studies on the TL-PL AC total interference behaviour using a complex soil structure, described as many interwoven horizontal and vertical layers, each with their respective resistivities, have yet to be carried out.

This work, aims to address the gaps in the above mentioned issues. Specifically, it attempts to determine the influence of complex soil structure on the TL-PL AC total interference. In addition, the effects of defective pipeline coating under varying soil resistivities, and the effects of several critical parameters on the simultaneous behaviour of inductive and conductive interferences would also be carried out.

1.4 Research Objectives

This research aims to study the pipeline induced voltage behaviour in different observation profiles while considering both the inductive and conductive interferences between an overhead high voltage transmission line and a buried gas pipeline. This study also aims to present a performance comparison between two different approaches used to compute the induced voltages, namely, the field and circuit-based approaches. The performance comparison helps in understanding the advantages and limitations of each approach when modelling and investigating the PL-TL AC total interference behaviour, especially in relation to the validity and accuracy of the results obtained.

The objectives of this study are listed below.

(i) To carry out a performance comparison between the field approach and the circuit-based approach for a TL-PL AC total interference behavioral study.

(ii) To determine the effects of critical parameters, namely, the TL fault current, the TL-PL separation distance, the surrounding soil resistivity, and the TL tower footing resistance, on the AC total interference behaviour.

(iii) To determine the effects of buried gas pipeline coating layer condition on the TL-PL AC total interference behaviour with varying surrounding soil resistivities.

(iv) To determine the effects of complex soil structures on the TL-PL AC total interference behaviour.

1.5 Research Scopes

The scopes of the work are summarized as follows.

(i) Based on the collected data for TL-PL right-of-way configuration, the study are limited to the following parameters. Three phases and single circuit overhead transmission lines with 115-kV, single-shield, single electrode tower footing grounding, sub-station feeding the TL from each end; gas pipelines: 24” diameter, 1-m burial depth, 1-mm thick insulating coating layer with 40-MΩ resistivity; maximum TL ROW: 30-km length, 50-m width.

(ii) In carrying out the performance comparison between the field approach and the circuit-based approach for a TL-PL AC total interference behavioral study, the following simulation software are used: SES-CDEGS for the field approach, and SES-ROW for the circuit-based approach.

(iii) In carrying out the study on the effects of critical parameters, namely, the TL fault current, the TL-PL separation distance, the surrounding soil resistivity, and the TL tower footing resistance, on the AC total interference behaviour, the following key limiting criteria were used. Maximum fault current: 20 kA; soil resistivity: 10 to 1000 Ω.m; maximum TL tower footing electrode length: 20 m.

(iv) The following induced voltages are considered based on different observation profiles, which are mostly located within and near the buried pipeline. The metal GPR, touch voltage, coating GPR, coating stress, and earth surface GPR. Two key induced voltages are the touch voltage and the coating stress.

(v) In carrying out the study on the effects of buried gas pipeline coating layer condition on the TL-PL AC total interference behaviour with varying surrounding soil resistivities, the following assumptions are made. Good pipeline coating resistivity range: 1 MΩ to 40 MΩ; defected coating: 0 to 1 MΩ.

(vi) In carrying out the study on the effects of complex soil structures on the TL-PL AC total interference behaviour, the following scopes are defined. Maximum number of horizontal and vertical layer: 3; maximum thickness of horizontal layers: 10 km; maximum width of vertical layers: 16 km.

1.6 Research Contributions

i. Comparison study between field and circuit-based approaches

The relative performance of the circuit-based and the field approaches is yet to be determined for the case of AC total interference. The comparison study between the field approach and circuit-based approach when computing TL-PL AC total interference was successfully carried out using several performance criteria, namely, right-of-way (ROW) configurations, TL-PL parallel length (along the ROW), TL-PL separation distance (across the ROW), TL fault (single phase to ground) current, and fault location. The circuit-based approach was found to be as good as the field approach in most cases, except for several specific conditions. Subsequent studies of the TL-PL AC total interference could be carried out based on this finding and guideline. The close agreement between the two approaches shows the simulation and modelling work carried out in this work are valid.

ii. Induced voltages on pipeline due to AC total interference

It is well known that induced voltages on pipeline occur due to the electromagnetic interference between the transmission lines and gas pipelines sharing the same right-of-way. The study of conductive and inductive coupling, or AC total interference, is important for evaluating the induced voltages. However, little data are available on induced voltage types and their behaviour with the variation of parameters affecting AC total interference. In this work, the influence conductive and inductive interference on various types of induced voltages was successfully studied. The effects of the fault current, the TL-PL separation distance, the surrounding soil resistivity, and the tower footing resistance, were analysed. Different observation point profiles were considered to obtain various types of induced voltages such as metal GPR, touch voltage, coating GPR, coating stress and earth surface GPR. Two key induced voltages are the touch voltage and the coating stress. This study accurately modelled, simulated and computed the effects of several parameters on the simultaneous conductive and inductive couplings between the TL and the PL in the form of AC total interference. The study shows the touch voltage and coating stress are mainly influenced by the inductive interference. The TL-PL inductive interference increases with the fault current, but decreases with the TL-PL separation distance, the surrounding soil resistivity, and the tower footing resistance. Nevertheless, the conductive interference is also significant especially when the soil resistivity is low, the fault current is high, the tower footing resistance is low, and the separation distance between the TL and PL is small. It is noted that an excessively high touch voltage poses threat to human and equipment safety. Similarly, high coating stress may accelerate pipeline coating deterioration and corrosion.

iii. Effects of defective coating on the AC total interference

The pipeline coating and hence its resistivity go through degradation process during its lifetime. Many previous works have reported the effects of pipeline coating resistivity on the TL-PL inductive interference. However, the effects of pipeline coating condition on the AC total interference under varying soil resistivities are yet to be studied. This study found that the effect of pipeline coating condition on the touch voltage and coating stress is dependent on its coating resistivity as well as on the soil resistivity. For a well coated pipeline (with coating resistivity above 1 MΩ), the touch voltage and coating stress are high (> 1000 V). The touch voltage and coating stress are also high (> 1200V) when the pipeline is buried in a low-resistivity (< 100 Ω.m) soil. The high touch voltage is a risk to human and equipment safety, and the high coating stress may lead to coating deterioration and pipeline corrosion. It is worth to mention that the induced voltages computed using the circuit-based and field approaches give similar results for all types of induced voltages. This shows that, for the pipeline coating effect study, any one of the two approaches may be used.

iv. The influence of complex soil structures on the induced voltage

When modelling a soil, the complexity of its structure need to be taken into consideration because it significantly affects the induced voltages in pipelines due to AC total interference. However, the influence of complex soil structure composed of interwoven vertical and horizontal layers have not been studied yet. Accurate simulation or model to represent the real soil structure is highly desired. This study has successfully examined the conditions when a complex soil structure can be represented by a vertical equivalent, or even further simplified to a uniform soil equivalent. Several key findings can be listed. Firstly, for a complex soil structure (anticline and syncline) consisting of three vertical and three horizontal layers interwoven between them, the variation of the induced voltages in the pipeline depends mainly on the thickness of the first horizontal layer, or the width of the middle vertical layer, or both. The complex soil structure can be replaced with an equivalent structure known as the three-vertical-layer equivalent when the width of the middle layer and the thickness of the first horizontal layer are above certain specified values. It is noted that a uniform soil equivalent, instead of the three-vertical-layer equivalent, is not possible due to the complexity of this case of soil structure. Also, the approximation of three vertical layers is not applicable for anticline and syncline structure with small thickness of the first horizontal layer and small width of the middle vertical layer. Secondly, a non-uniform (vertically and horizontally) soil structure can be replaced with an equivalent uniform soil when the thickness of the first layer (for horizontally layered structure) or the width of the middle layer (for vertically layered structure) are above certain specified values. For thicknesses or widths smaller than the specified values, a non-uniform soil structure must be used. Thirdly, to completely model a soil and hence ensure accuracy of the measured induced voltages, adequate soil resistivity measurements must be performed to provide the complete soil resistivity data for the complex as well as non-uniform soil models.

1.7 Thesis Outline

For a complete explanation of the work, this thesis is divided into five chapters consisting of thorough details of the study. Chapter 1 provides the research background, reasons to carry out this thesis, goals to meet to accomplish this work, research objectives, research scopes and research contributions.

Chapter 2 covers a comprehensive review on induced voltages on a metallic structure in vicinity of an overhead transmission line. It includes the background of the inductive and conductive interferences, thus the requirement to investigate more about AC total interference phenomenon and the effects of soil structures and defective pipeline coating. Many studies reported on the induced voltages on metallic structures, such as a gas pipeline, due to the electromagnetic interference with nearby overhead transmission lines. However, few researchers have tried to simulate and compute the AC total interference, which consists of inductive and conductive couplings computed simultaneously at different soil resistivities. Moreover, there is a lack of study on the effect of complex soil structure and the effect of pipeline coating resistivity. Some published works deliberated on the measurement of the induced voltages. However, due to limitation in experimental work, there are more reported work on the modelling of transmission line and pipeline right-of-way. The different approaches, such as FEM, ATP, and hybrid method, used to model the right-of-way, are described in this chapter. In recent research, the circuit-based approach and the field approach were introduced to have better observation of results and to provide a higher accuracy of simulation results.

Chapter 3 describes the methodology of the research. In this chapter several right-of-way models are developed to compare between the field approach and the circuit-based approach with respect to the AC total interference. In addition, a baseline model was developed and used for the evaluation and analysis of the induced voltages. The model considered the coating resistivity, parallel corridor, pipeline length, pipeline location, fault current, fault location, and other physical parameters such as the conductivity and permittivity of the pipeline. Critical parameters such as the soil structure and resistivity, which is important in the induced voltage phenomenon, are detailed for modelling. In this chapter, the flowchart of the simulation using the field approach and the circuit-based approach is detailed.

Chapter 4 discusses on the results, which are obtained from the simulation. At the beginning of this chapter, the comparison between the field approach and the circuit-based approach under steady-state and fault conditions, is explained. The results from the two approaches were obtained for several right-of-way configurations. The features and the limitation of each approach was studied to select the most suitable approach for each subsequent part of the study. The induced voltages along the pipeline are computed for different observation profiles. In addition, the effects of important parameters such as the magnitude of fault current, tower footing resistance, separation distance between the gas pipeline and TL, soil resistivity, and coating resistivity, are discussed. The anticline and syncline soil structure are used in this chapter to explain and understand the effects of complex soil structure on the induced voltage behaviour.

Chapter 5 presents the major findings of the study. Future work and recommendations are also highlighted in this chapter.

REFERENCES

1. H. M. Ismail. (2007). Effect of oil pipelines existing in an HVTL corridor on the electric-field distribution. *IEEE Transactions on Power Delivery*, vol.22 (4), pp. 2466-2472.
2. M. Adamek and Z. Vostracky. (2015). Interference from transmission lines to buried pipelines. *Electric Power Engineering (EPE), 2015 16th International Scientific Conference*. pp. 687-690.
3. J. A. Jardini, R. L. Vasquez‐Arnez, D. Kovarsky, R. Haik, and G. N. Zarpellon. (2014). Interference of a line‐commutated converter high‐voltage direct current system upon pipelines located in its vicinity. *International Transactions on Electrical Energy Systems*, vol. 24(12), pp. 1688-1699.
4. F. Dawalibi and R. D. Southey. (1990). Analysis of electrical interference from power lines to gas pipelines. II. Parametric analysis. *IEEE Transactions on Power Delivery*, vol. 5(1), pp. 415-421.
5. N. M. Abdel-Gawad, A. Z. El Dein, and M. Magdy. (2015). Mitigation of induced voltages and AC corrosion effects on buried gas pipeline near to OHTL under normal and fault conditions. *Electric Power Systems Research*, vol. 127(1), pp. 297-306.
6. J. Zhang, X. Wen, W. Li, H. Lu, and Y. Liu. (2015). Analysis of Electromagnetic Interference Effects on Gas Pipelines Due to a Nearby Parallel UHV Transmission Line. *Proceedings of the Second International Conference on Mechatronics and Automatic Control*, pp. 441-447.
7. I. Cotton, K. Kopsidas, and Y. Zhang. (2007). Comparison of transient and power frequency-induced voltages on a pipeline parallel to an overhead transmission line. *IEEE Transactions on Power Delivery*, vol. 22(3), pp. 1706-1714.

8. F. Dawalibi and R. D. Southey. (1989). Analysis of electrical interference from power lines to gas pipelines. I. Computation methods. *IEEE Transactions on Power Delivery*, vol. 4(3), pp. 1840-1846.

9. A. S. Al Shahri and N.-K. C. Nair. (2015). AC potential on pipelines nearby EHV power lines due to Low Frequency Induction. *2015 Australasian Universities Power Engineering Conference (AUPEC)*, pp. 1-5.

10. D. Tang, Y. Du, M. Lu, S. Chen, Z. Jiang, and L. Dong. (2015). Study on location of reference electrode for measurement of induced alternating current voltage on pipeline. *International Transactions on Electrical Energy Systems*, vol. 25(1), pp. 99-119.

11. G. C. Christoforidis, D. P. Labridis, and P. S. Dokopoulos. (2005). A hybrid method for calculating the inductive interference caused by faulted power lines to nearby buried pipelines. *IEEE Transactions on Power Delivery*, vol. 20(2), pp. 1465-1473.

12. S. C. Chia, A. Kadir, M. Z. Abidin, and M. Izadi. (2015). Evaluation of Gas Pipeline Induced Voltage Associated with Parallel Transmission Line. *Applied Mechanics and Materials*, vol. 793(1), pp. 90-94.

13. IEEE Guide for Safety in AC Substation Grounding. (1986), *ANSI/IEEE Std 80*-1986. Doi: 10.1109/IEEESTD.1986.81070

14. Y. Li, F. Dawalibi, and J. Ma. (2001). Effects of conductor length and angle on the accuracy of inductive interference computations. *Transmission and Distribution Conference and Exposition, IEEE/PES*, vol. 1(1), pp. 433-437.

15. K. Satsios, D. Labridis, and P. Dokopoulos. (1998). Currents and voltages induced during earth faults in a system consisting of a transmission line and a parellel pipeline. *International Transactions on Electrical Power*, vol. 8(3), pp. 193-199.

16. C. Munteanu, G. Mates, M. Purcar, V. Topa, I. Pop, L. Grindei, et al. (2012). Electromagnetic field model for the numerical computation of voltages induced on buried pipelines by high voltage overhead power lines. *The European Physical Journal Applied Physics*, vol. 58(3), p. 30902.

17. G. Christoforidis, D. Labridis, and P. Dokopoulos. (2003). Inductive interference calculation on imperfect coated pipelines due to nearby faulted parallel transmission lines. *Electric Power Systems Research*, vol. 66(2), pp. 139-148.

18. A. S. AlShahri, M. T. N. Dinh, and N. K. C. Nair. (2014). Induced voltage on pipeline located close to high voltage lines due to electromagnetic induction. *In 2014 Australasian Universities Power Engineering Conference (AUPEC)*, pp. 1-5.
19. J. Tang, X. Cui, L. Qi, T. Lu, L. Li, P. Zhu, et al. (2007). Analysis of transient inductive interference in underground pipelines due to faults on nearby power lines. *COMPEL-The International Journal for Computation and Mathematics in Electrical and Electronic Engineering*, vol. 26(5), pp. 1346-1363.
20. O. E. Gouda, A. Z. E. Dein, and M. A. H. El-Gabalawy. (2013). Effect of electromagnetic field of overhead transmission lines on the metallic gas pipe-lines. *Electric Power Systems Research*, vol. 103(1), pp. 129-136.
21. A. Racasan, C. Munteanu, V. Topa, I. Pop, and E. Merdan. (2011). 3D electromagnetic field model for numerical analysis of the electromagnetic interferences between overhead power lines and pipelines. *11th International Conference on Electrical Power Quality and Utilisation (EPQU)*, pp. 1-6.
22. C. Munteanu, V. Topa, G. Mates, M. Purcar, A. Racasan, and I. Pop. (2012). Analysis of the electromagnetic interferences between overhead power lines and buried pipelines. *International Symposium on Electromagnetic Compatibility (EMC EUROPE)*, pp. 1-6.
23. G. C. Christoforidis, D. P. Labridis, and P. S. Dokopoulos. (2005). Inductive interference on pipelines buried in multilayer soil due to magnetic fields from nearby faulted power lines. *IEEE Transactions on Electromagnetic Compatibility*, vol. 47(2), pp. 254-262.
24. G. C. Christoforidis, P. S. Dokopoulos, and K. E. Psannis. (2001). Induced voltages and currents on gas pipelines with imperfect coatings due to faults in a nearby transmission line. *IEEE Porto Power Tech Proceedings*, vol. 4(1), p. 6.
25. R. Southey, F. Dawalibi, and W. Vukonich. (1994). Recent advances in the mitigation of AC voltages occurring in pipelines located close to electric transmission lines. *IEEE Transactions on Power Delivery*, vol. 9(2), pp. 1090-1097.
26. S. Ogunade. (1981). Electromagnetic response of an embedded cylinder for line current excitation. *Geophysics*, vol. 46(1), pp. 45-52.

27. A. Samouëlian, I. Cousin, A. Tabbagh, A. Bruand, and G. Richard. (2005). Electrical resistivity survey in soil science: a review. *Soil and Tillage Research*, vol. 83(2), pp. 173-193.
28. M. Nassereddine, J. Rizk, A. Hellany, and M. Nagrial. (2015). Induced voltage behavior on pipelines due to HV AC interference under broken OHEW. *In 2015 IEEE 10th Conference on Industrial Electronics and Applications (ICIEA)*, pp. 1408-1413.
29. K. J. Satsios, D. P. Labridis, and P. S. Dokopoulos. (2000). The influence of nonhomogeneous earth on the inductive interference caused to telecommunication cables by nearby AC electric traction lines. *IEEE Transactions on Power Delivery*, vol. 15(3), pp. 1016-1021.
30. K. Satsios, D. Labridis, and P. Dokopoulos. (1999). Inductive interference caused to telecommunication cables by nearby AC electric traction lines. Measurements and FEM calculations. *IEEE Transactions on Power Delivery*, vol. 14(2), pp. 588-594.
31. E. D. Sunde. (1949). Earth conduction effects in transmission systems: *Dover Publications Inc.*
32. E. Sunde. (1968). Earth Conduction Effects in Transmission Lines. *ed: New York: Dover.*
33. C. Charalambous and I. Cotton. (2007). Influence of soil structures on corrosion performance of floating-DC transit systems. *IET, Electric Power Applications*, vol. 1(1), pp. 9-16.
34. D. P. Labridis and P. Dokopoulos. (1998). Finite element computation of field and eddy currents of a system consisting of a power transmission line above conductors buried in nonhomogeneous earth. *IEEE Transactions on Power Delivery*, vol. 13(3), pp. 876-882.
35. M. Nassereddine, J. Rizk, A. Hellany, and M. Nagrial. (2014). AC interference study on pipeline: OHEW split factor impacts on the induced voltage. *Journal of Electrical Engineering*, vol. 14(1), pp. 27-32.
36. T. Papadopoulos, G. C. Christoforidis, D. D. Micu, and L. Czumbil. (2014). Medium-voltage cable inductive coupling to metallic pipelines: A comprehensive study. *49th International Universities Power Engineering Conference (UPEC)*, pp. 1-6.

37. A. Peabody and A. Verhiel. (1970). The Effects of High Voltage Alternating Current (HVAC) Transmission Lines on Buried Pipe Lines. *Presented at the Petroleum and Chemical Industry Conference, Tulsa, Oklahoma*, No. PCI-70-32.
38. E. Kirkpatrick. (1997). Induced AC voltages on pipelines may present a serious hazard. *Pipeline and Gas Journal*, vol. 224(10), pp. 67-69.
39. J. Dabkowski. (1996). A statistical approach to designing mitigation for induced AC voltages on pipelines. *Materials performance*, vol. 35(8), pp. 9-12.
40. I. Metwally and F. Heidler. (2005). Mitigation of the produced voltages in AC overhead power - lines/pipelines parallelism during power frequency and lightning conditions. *International Transactions on Electrical Energy Systems*, vol. 15(4), pp. 351-369.
41. J. R. Carson. (1926). Wave propagation in overhead wires with ground return. *Bell System Technical Journal*, vol. 5(4), pp. 539-554.
42. F. Pollaczek. (1966). On the field produced by an infinitely long wire carrying alternating current. *Electrische Nachricten Technik*, vol. 3(9), pp. 339-359.
43. J. Pohl. (1966). Influence of high-voltage overhead lines on covered pipelines. *CIGRE Paper*, vol. 326(8), pp. 1090-1097.
44. A. Taflove and J. Dabkowski. (1979). Prediction Method for buried pipeline voltages due to 60 Hz AC inductive coupling Part I-Analysis. *IEEE Transactions on Power Apparatus and Systems*, vol. 3, pp. 780-787.
45. J. Dabkowski and A. Taflove. (1979). Prediction Method for Buried Pipeline Voltages Due to 60 Hz AC Inductive Coupling Part II--Field test Verification. *IEEE Transactions on Power Apparatus and Systems,* vol. 3(1), pp. 780-787.
46. K. C. Jaffa and J. B. Stewart. (1981). Magnetic field induction from overhead transmission and distribution power lines on buried irrigation pipelines. *IEEE Transactions on Power Apparatus and Systems,* vol. 3(1), pp. 990-1000.
47. I. R. Institute, J. Dabkowski, A. Taflove, and A. G. Association. (1978). Mutual design considerations for overhead ac transmission lines and gas transmission pipelines, *IIT Research Inst., Chicago, IL (USA)*, vol. 1, p. 904.

48. M. Frazier. (1983). Power line-induced AC potential on natural gas pipelines for complex rights-of-way configurations. *Rep./EPRI/Electric power Research Inst.* vol. 2(1), No.3106.

49. F. Dawalibi, R. Southey, Y. Malric, and W. Tavcar. (1987). Power line fault current coupling to nearby natural gas pipelines. *EPRI Report EL*, vol. 5472.

50. H.-J. Haubrich, B. Flechner, and W. Machczynski. (1994). A universal model for the computation of the electromagnetic interference on earth return circuits. *IEEE Transactions on Power Delivery,* vol. 9(3), pp. 1593-1599.

51. J. Dabkowski and M. Frazier. (1988). Power line fault current coupling to nearby natural gas pipelines. *Electric Power Research Institute*. Report EL-5472, AGA Cat, vol. 3, No. 51537.

52. F. P. Dawalibi and F. Donoso. (1993). Integrated analysis software for grounding, EMF, and EMI. *IEEE Computer Applications in Power,* vol. 6(2), pp. 19-24.

53. Y. Li, F. Dawalibi, and J. Ma. (2000). Electromagnetic interference caused by a power system network on a neighboring pipeline. *in Proceedings of the American Power Conference*, pp. 311-316.

54. F. Dawalibi, Y. Li, R. Southey, and J. Ma. (2000). On the mechanisms of electromagnetic interference between electrical power systems and neighboring pipelines. *Corrosion-National Association of Corrosion Engineers Annual Conference (NACE)*. Mar 26.

55. Computation of electromagnetic fields created by rectilinear current sources in stratified medium. *TD-80. Safe engineering services (SES).*

56. F. Dawalibi, D. Bensted, and D. Mukhedkar. (1981). Soil Effects on Ground Fault Currents. *IEEE Transactions on Power Apparatus and Systems*, vol. 7(1), pp. 3442-3450.

57. M. Nassereddine, J. Rizk, and G. Nasserddine. (2013). Soil resistivity structure and its implication on the pole grid resistance for transmission lines. *in Proceedings of World Academy of Science, Engineering and Technology*, vol. 1, pp. 19-23.

58. R. Southey and F. P. Dawalibi. (1998). Computer Modelling of AC Interference Problems for the Most Cost-Effective Solutions. *In Corrosion-National Association of Corrosion Engineers Annual Conference*.

59. F. P. Dawalibi, M. A. Joyal, J. Liu, and Y. Li. (2013). Realistic integrated grounding and electromagnetic interference analysis accounting for GIS, cables and transformers during normal and fault conditions. *In IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, pp. 1-6.
60. A. Osella, P. Martinelli, A. B. Favetto, and E. Lopez. (2002). Induction effects of 2-D structures on buried pipelines. *IEEE Transactions on Geoscience and Remote Sensing*, vol. 40, pp. 197-205.
61. A. Selby and F. Dawalibi. (1994). Determination of current distribution in energized conductors for the computation of electromagnetic fields. *IEEE Transactions on Power Delivery*, vol. 9, pp. 1069-1078.
62. F. Dawalibi and D. Mukhedkar. (1975). Optimum design of substation grounding in a two layer earth structure: Part I Analytical study. *IEEE Transactions on Power Apparatus and Systems*, vol. 94, pp. 252-261.
63. P. Lagace, J.-L. Houle, Y. Gervais, and D. Mukhedkar. (1988). Evaluation of the voltage distribution around toroidal HVDC ground electrodes in N-layer soils. *IEEE Transactions on Power Delivery*, vol. 3, pp. 1573-1579.
64. F. Dawalibi and D. Mukhedkar. (1977). Resistance calculation of interconnected grounding electrodes. *IEEE Transactions on Power Apparatus and Systems*, vol. 96, pp. 59-65.
65. F. Dawalibi and D. Mukhedkar. (1976). Multi step analysis of interconnected grounding electrodes. *IEEE Transactions on Power Apparatus and Systems,* vol. 95, pp. 113-119.
66. F. Dawalibi and D. Mukhedkar. (1979). Parametric Analysis of Grounding Grids. *IEEE Transactions on Power Apparatus and Systems*, PAS-98, vol. 5, pp. 1659-1668.
67. D. Tsiamitros, G. Christoforidis, G. Papagiannis, D. Labridis, and P. Dokopoulos. (2006). Earth conduction effects in systems of overhead and underground conductors in multilayered soils. *IEE Proceedings Generation Transmission and Distribution*, vol. 153(3), pp. 291-299.
68. E. Sawma, B. Zeitoun, N. Harmouche, S. Georges, M. Hamad, and F. H. Slaoui. (2010). Electromagnetic induction in pipelines due to overhead high voltage power lines. *International Conference on Power System Technology (POWERCON).* Oct 24, pp. 1-6.

69. IEEE Approved Draft Guide for Safety in AC Substation Grounding - Corrigendum 1Not Published -- *Incorporated into IEEE Std 80-2013. IEEE P80-2013/Cor1/D3*, December 2014, pp. 1-0, 2015.

70. A. J. Datta, R. Taylor, and G. Ledwich. (2015). Earth grid safety criteria determination with the standards IEEE-80 and IEC-60479 and optimization of installation depth. *In Australasian Universities Power Engineering Conference (AUPEC),* pp. 1-5.

71. J. Laver and H. Griffiths. (2001). The variability of soils in earthing measurements and earthing system performance. *Rev. Energ. Ren.: Power Engineering, School of Electrical Engineering, Cardiff University, UK.* Special Issue, Power Engineering, 2001. pp. 57-61.

72. F. Dawalibi and N. Barbeito. (1991). Measurements and computations of the performance of grounding systems buried in multilayer soils. *IEEE Transactions on Power Delivery,* vol. 6, pp. 1483-1490.

73. BS7354. (1990). Code of Practice for Design of High-Voltage Open-Terminal Stations. *ed: BSI.*

74. E. T. 41-24. (1992). *ed: Electricity Association.* Guidelines for the Design, Installation, Testing and Maintenance of Main Earthing Systems in Substations.

75. IEEE Guide for Safety in AC Substation Grounding. (2000). *IEEE Std 80-2000*, pp. 1-192.

76. E. Association. (1986). Engineering Recommendation S. 34) 1986:'A Guide for Assessing the Rise of Earth Potential at Substation Sites. *Electricity Association Services Limited, London.*

77. R. G. Van Nostrand and K. L. Cook. (1966). Interpretation of resistivity data. *US Govt. Print.* Off. 2330-7102.

78. F. Tagg.. (1964). Measurement of earth-electrode resistance with particular reference to earth-electrode systems covering a large area. *Proceedings of the Institution of Electrical Engineers,* vol. 111, pp. 2118-2130.

79. F. Dawalibi and D. Mukhedkar. (1974). Ground electrode resistance measurements in non uniform soils. *IEEE Transactions on Power Apparatus and Systems*, vol. 1, pp. 109-115.

80. D. D. Micu, L. Czumbil, G. C. Christoforidis, A. Ceclan, and D. Stet. (2012). Evaluation of induced AC voltages in underground metallic pipeline. *COMPEL: Int J for Computation and Maths. in Electrical and Electronic Eng.*, vol. 31, pp. 1133-1143.

81. J. H. Schön. (2015). Physical properties of rocks: fundamentals and principles of petrophysics. *Developments in Petroleum Science, Elsevier,* vol. 65, pp.2-497.
82. M. Kižlo and A. Kanbergs. (2009). The Causes of the Parameters Changes of Soil Resistivity. *Scientific Journal of Riga Technical University. Power and Electrical Engineering*, vol. 25, pp. 43-46.
83. R. Amorim, E. V. Brazil, F. Samavati, and M. C. Sousa. (2014). 3D geological modeling using sketches and annotations from geologic maps. *Proceedings of the 4th Joint Symposium on Computational Aesthetics, Non-Photorealistic Animation and Rendering, and Sketch-Based Interfaces and Modeling*, pp. 17-25.
84. H. Jenny. (1994). Factors of soil formation: a system of quantitative pedology: Courier Corporation. *Soil Science,* vol. 52(5), p. 415.
85. G. M. Bennison, P. A. Olver, and K. A. Moseley. (2013). An introduction to geological structures and maps. *Routledge*. Nov 26.
86. L. Niu and Y. Cheng. (2008). Development of innovative coating technology for pipeline operation crossing the permafrost terrain. *Construction and Building Materials*, vol. 22, pp. 417-422.
87. S. Guan. (2001). Corrosion protection by coatings for water and wastewater pipelines. *Appalachian Underground Corrosion Short Course, Water and Wastewater Program*, West Virginia University, PA.
88. L. T. Popoola, A. S. Grema, G. K. Latinwo, B. Gutti, and A. S. Balogun. (2013). Corrosion problems during oil and gas production and its mitigation. *International Journal of Industrial Chemistry*, vol. 4, pp. 1-15.
89. R. Singh. (2013). Arctic Pipeline Planning: Design, Construction, and Equipment. *Gulf Professional Publishing, Elsevier.*
90. K. Satsios, D. Labridis, and P. Dokopoulos. (1998). Finite element computation of field and eddy currents of a system consisting of a power

transmission line above conductors buried in nonhomogeneous earth. *IEEE Transactions on Power Delivery*, vol. 13, pp. 876-882.

91. G. C. Christoforidis, D. P. Labridis, and P. S. Dokopoulos. (2005). A hybrid method for calculating the inductive interference caused by faulted power lines to nearby buried pipelines. *IEEE Transactions on Power Delivery*, vol. 20, pp. 1465-1473.
92. A. Fu and Y. Cheng. (2010). Effects of alternating current on corrosion of a coated pipeline steel in a chloride-containing carbonate/bicarbonate solution. *Corrosion Science*, vol. 52, pp. 612-619.
93. L. Xu, X. Su, and Y. Cheng. (2013). Effect of alternating current on cathodic protection on pipelines. *Corrosion Science*, vol. 66, pp. 263-268.
94. Z. Y. Cui, L. W. Wang, Z. Y. Liu, C. W. Du, and X. G. Li. (2015). Influence of alternating voltages on passivation and corrosion properties of X80 pipeline steel in high pH 0.5 mol L− 1 NaHCO3+0.25 mol L− 1 Na2CO3 solution. *Corrosion Engineering, Science and Technology*, vol. 50, pp. 248-255.
95. O. E. Gouda, A. Z. El Dein, and M. A. El-Gabalawy. (2013). Effect of electromagnetic field of overhead transmission lines on the metallic gas pipelines. *Electric Power Systems Research*, vol. 103, pp. 129-136.
96. F. Dawalibi, D. Bensted, and D. Mukhedkar. (1981). Soil effects on ground fault currents. *IEEE Transactions on Power Apparatus and Systems*, vol. 12(3), pp. 3442-3450.
97. F. P. Dawalibi and R. D. Southey. (1989). Analysis of electrical interference from power lines to gas pipelines. I. Computation methods. *IEEE Transactions on Power Delivery*, vol. 4, pp. 1840-1846.
98. L. B. Martinho, V. C. Silva, M. L. P. Filho, M. F. Palin, S. L. L. Verardi, and J. R. Cardoso. (2014). 3-D Finite-Element Analysis of Conductive Coupling Problems in Transmission Line Rights of Way. *IEEE Transactions on Magnetics*, vol. 50, pp. 969-972.
99. N. M. K. Abdel-Gawad, A. Z. El Dein, and M. Magdy. (2015). Mitigation of induced voltages and AC corrosion effects on buried gas pipeline near to OHTL under normal and fault conditions. *Electric Power Systems Research*, vol. 127, pp. 297-306.

100. A. N. Z. Standard. (2000). Electric Hazards on Metallic Pipelines. *Australian/New Zealand Standard.* AS/NZS 4853.

101. IEEE Recommended Practice for Determining the Electric Power Station Ground Potential Rise and Induced Voltage from a Power Fault. (2012). *IEEE Std 367-1996,* pp. 1-144.

102. S. Al-Alawi, A. Al-Badi, and K. Ellithy. (2005). An artificial neural network model for predicting gas pipeline induced voltage caused by power lines under fault conditions. *COMPEL-The International Journal for Computation and Mathematics in Electrical and Electronic Engineering*, vol. 24, pp. 69-80.

103. F. Pollaczek. (1926). Uber das Feld einer unendlich langen wechselstromdurchflossen Einfachleitung. *ENT*, vol. 3, pp. 339-360.

104. F. Dawalibi and A. Selby. (1993). Electromagnetic fields of energized conductors. *IEEE Transactions on Power Delivery*, vol. 8, pp. 1275-1284.

105. F. P. Dawalibi, W. Ruan, and S. Fortin. (1995). Lightning transient response of communication towers and associated grounding networks. *in Proceedings of International Conference on Electromagnetic Compatibility, ICEMC '95 KUL, Kuala Lumpur, Malaysia*, pp. 95-102.

106. L. Grcev and F. Dawalibi. (1990). An electromagnetic model for transients in grounding systems. *IEEE Transactions on Power Delivery*, vol. 5, pp. 1773-1781.

107. S. Bruno, E. Tuglie, and L. SCALA M. (2007). Evaluation of the AC interferences between transmission lines and metallic underground structures. *ANCE*, vol. 4(6), pp. 134-139.

108. M. P. Kazmierkowski. (2007). Electromagnetic Compatibility in Power Systems (Lattarulo, F., ed.; 2007)-[Book Review]. *Industrial Electronics Magazine, IEEE*, vol. 1, pp. 42-45.

109. F. Dawalibi, J. Ma, and Y. Li. (1999). Mechanisms of electromagnetic interference between electrical networks and neighboring metallic utilities. *Illinois Inst. of Tech.*, Chicago, IL (United States).

110. J. Schlabbach. (2005). Short-circuit currents. *IEE Power and Energy Series: Institution of Electrical Engineers*, vol. 51.

111. A. a. o. VDEW. (1982). Technical recommendation No. 3 – Measures for construction of pipelines in the vicinity of HV/AC three-phase installations (German). *VWEW-Energieverlag, Frankfurt/Germany*, vol. 3.

112. A. a. o. VDEW. (1980). Technical recommendation No. 5 – Principles of calculation and measurement of reduction factor of pipelines and earth wires. *VWEW-Energieverlag, Frankfurt/Germany*.

113. HIFREQ Theory. *safe Engineering Services & Technologies Ltd.*, Montreal Canada.

114. F. P. Dawalibi. (1983). Champ Electromagnetique Cree par Dipole Electrique dans un Milieu Stratifie Horizontal. *Safe Engineering Services internal doucumentation*, vol. Unpublished.

115. Y. Li, F. P. Dawalibi, and J. Ma. (2002). Effect of conductor angle between transmission lines and neighboring utilities on the accuracy of inductive interference computations. *In Power System Technology, 2002. Proceedings International Conference on Power Energy*, vol. 2, pp. 2477-2481.

116. M. Nassereddine, J. Rizk, M. Nagrial, and A. Hellany. (2015). Induced Voltage Behavior on Pipelines Due to HV AC Interference: Effective Length Concept. *International Journal of Emerging Electric Power Systems*, vol. 16, pp. 131-139.

117. H. Zhang, G. G. Karady, and J. Hunt. (2011). Effect of various parameters on the inductive induced voltage and current on pipelines. *Power and Energy Society General Meeting, 2011 IEEE*, vol. 1, pp. 1-7.

118. R. DJEKIDEL and D. MAHI. (2014). Calculation and analysis of inductive coupling effects for HV transmission lines on aerial pipelines. *Przegląd Elektrotechniczny*, vol. 90, pp. 151-156.

119. M. Ouadah, S. Bouyegh, M. Zergoug, C. Dehchar, B. Boussiala, O. Touhami, et al. (2014). Impacts of Inductive and Conductive Interference due to High Voltage Power Lines on Metallic Pipelines. *4ème Conférence Internationale sur le soudage, le Contrôle Non Destructif et l'Industrie des Matériaux et Alliages, IC-WNDT-MI'14*.

120. M. Celin. (2015). Earth fault current distribution on transmission networks. *International Conference on Power System Technology (POWERCON)*. Nov 22, pp. 32-38.

121. M. Mapane. (2015). The effects of increased fault current on the existing substation grounding system-A case study. *IEEE 10th Conference on Industrial Electronics and Applications (ICIEA)*, pp. 906-911.

122. B. C. Paucar, J. R. Ortiz, J. P. Pinto, and P. Koltermann. (2007). Induced voltage on gas pipeline with angle between a transmission line. *Power Tech, 2007 IEEE Lausanne*, pp. 796-800.

123. W. Ruan, R. Southey, S. Tee, and F. Dawalibi. (2007). Recent advances in the modeling and mitigation of AC interference in pipelines. *NACE International, Corrosion 2007, 11-15 March, Nashville, Tennessee,* pp.1-10.