ELECTROMAGNETIC INTERFERENCE CAUSED BY A HIGH VOLTAGE TRANSMISSION NETWORK ON BURIED PIPELINES & COMMUNICATION CABLES

BY

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DEDICATION

This Thesis is Gratefully Dedicated To

My Parents

ACKNOWLEDGMENT

In the name of God, the Compassionate, the Merciful

All praise is for Allah, Lord of the Worlds, Master of the Day of Judgment whom we do worship, and whose pleasure and aid we seek. Blessings and peace of Allah be upon his last Prophet and Messenger Mohammed and upon his Family and Companions.

The contents of this thesis have been developed and improved by the contributions of numerous people.

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THESIS ABSTRACT

NAME: BANDER JUBRAN AL-GAHTANI

TITLE: ELECTROMAGNETIC INTERFERENCE CAUSED BY A HIGH VOLTAGE TRANSMISSION NETWORK ON BURIED PIPELINES & COMMUNICATION CABLES

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Electromagnetic fields, produced by the transmission lines on nearby oil and gas buried pipelines and underground communication cables, generate uncontrolled voltages which can be a safety problem and distort communications. This research evaluates and analyzes the electromagnetic interference effects on oil and gas buried pipelines and underground communication cables created by the nearby high voltage transmission lines in the Eastern Province of Saudi Arabia. The study revealed that the maximum induced voltage on all buried pipelines and communication cables during the steady state condition is within the standard limit. However, the results during the short circuit condition exceed the safety limits on some buried pipelines. A mitigation system using gradient control wires has been simulated to reduce the pipeline potential to the safety limit.

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خلاصة الرسالة

الاسم الكامل : بندر جبران القحطاني

عنوان الرسالة : أثر التداخلات الكهرومغناطيسية المتولدة من خطوط نقل الطاقة ذات الجهد العالي على خطوط الأنابيب والاتصالات المدفونة

التخصص : الهندسة الكهربائية

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تتأثر خطوط أنابيب الزيت والغاز وخطوط الاتصالات المدفونة والمتواجدة بالقرب من خطوط نقل الطاقة ذات الجهد العالي بالمجالات المغناطيسية المتولدة عنها حيث تتسبب هذه المجالات في توليد فولتية (فرق جهد) على هذه الأنابيب وخطوط الاتصالات مما قد يؤثر سلباً على السلامة و يعمل على تشويش الاتصالات. سيتم في هذا البحث تقييم و تحليل أثر التداخلات الكهرومغناطيسية المتولدة من خطوط نقل الطاقة ذات الجهد العالي في شرق المملكة العربية السعودية على خطوط أنابيب الزيت والغاز وخطوط الاتصالات القريبة والمدفونة. لقد أوضحت الدراسة أن تأثيرات التداخلات الكهرومغناطيسية كان ضمن المعايير المسموح بها دولياً و محلياً أثناء الظروف العادية. بينما سجلت أرقام عالية جداً على بعض خطوط الأنابيب في حالة وجود قصر كهربائي مما يتوجب عمل إجراءات وقائية للحد و التقليل من هذه التأثيرات لتتوافق مع المقاييس العالمية و المحلية.

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CHAPTER I

INTRODUCTION

1.1 RESEARCH OBJECTIVES

The intention of this research is to conduct a comprehensive study on the electromagnetic interference effects on oil and gas buried pipelines and underground communication cables. This research also updates the previous studies, done years ago, to analyze the inductive interference in a wide area of Saudi Electric transmission lines and nearby oil and gas buried pipelines. The present area has been changed drastically since new transmission lines were erected and some pipelines were removed. The objectives of this research are to determine what are the induced voltages at all locations along buried pipelines and communication cables, which remain within the vicinity of transmission lines for significant distances, and to check whether these induced voltages are within standards' safe limit. The research will include the present steady-state conditions as well as the transient-state conditions. Moreover, the present study will cover the effect of the tower grounding resistance, soil resistivity, and distance between the transmission lines and buried pipelines and communication cables on the reduction of EMI effects on these pipelines and cables.

1.2 RESEARCH METHODOLOGY

The research started by collecting the required updated data from Saudi Electricity Company (SEC) and Saudi Aramco (such as transmission line conductors, tower configuration coordinates and characteristics, transmission lines loading, soil resistivity, leakage, ground footing resistances, pipelines and communication cables layout drawings, diameter, material, etc.). Due to the complexity of the case-study, which includes more than one transmission lines and many oil and gas buried pipelines and underground communication cables, it was difficult to calculate the induced voltages by hand calculation. Thus, the case-study has been carried out through the following major steps using the modeling and simulation of Current Distribution, Electromagnetics, Grounding, and Soil Structure Analysis (CDEGS) software developed by the Safe Engineering Services & Technologies (SES):

1. Determine the self and mutual impedances of all conductors under study.
2. Using the circuit model established with the impedance obtained in step 1, determine the induced voltage in the buried pipelines and communication cables.
3. Determine the stress voltages across the insulation or coating of the buried pipelines and communication cables.
4. Analyze the effects of various mitigation measures.

1.3 RESEARCH CONTRIBUTIONS

This research will present a rigorous background to help engineers understand the importance of the EMI problem, through the collection of data on the standards available, and the modeling and simulation of practical cases.

The major benefits envisaged from this research are as follows:

1. Identify the technical merits of applying, planning and analyzing the interference mechanism.
2. Encourage safe and reliable solutions to interference problems.
3. Calculate the induced voltage on the buried pipelines and communication cables and compare them with standards.
4. In the case of excess over standards, conduct and implement a mitigation analysis.
5. Provide utility planners with new alternatives for installation of new transmission lines and pipelines.
6. Allow safe and secure distances to a buried pipeline from a given transmission line.
7. Provide a basis for continually updated studies and contracts/agreements; whereby both the utility and end-users can benefit from electromagnetic investigations.

1.4 THESIS ORGANIZATION

Chapter 1 addresses the objective and methodology of this research, and it provides general background about the EMI mechanisms and effects.

Chapter 2 gives a brief history of electromagnetic interference studies, including inductive and conductive couplings between pipelines and power lines. Also, special consideration is given to the available software used to conduct the electromagnetic interference studies.

Chapter 3 briefly discusses some theoretical essentials and calculations for inductive and conductive interferences. It also considers the position of the pipelines or communication cables which might comprise a succession of parallelisms, oblique approaches and crossings with reference to the power lines.

The EMI Analysis for the investigation area is introduced in Chapter 4, and it covers the geographical area of the 380 KV transmission lines between Faras and Qurayyah power plants that are used to feed the power to several oil and gas facilities owned by Saudi Aramco.

Chapter 5 presents the simulation results of the EMI analysis for the Faras-Qurayyah case-study, and then Chapter 6 proposes a mitigation technique to limit the EMI interference to the acceptable safe levels that meet the local and international standards.

Chapter 7 contains the conclusion and the summary of the research analysis, and it highlights the future work.

1.5 GENERAL BACKGROUND

Metal pipelines are largely used to convey fluids and especially liquid or gaseous hydrocarbons (i.e. oil or natural gas). Their length can reach several hundreds and even thousands of kilometers. The pipelines are generally buried at shallow depths but they can also be aerial. In order to prevent electrochemical corrosion of the metal, the underground pipelines are provided with an outside insulating coating and connected to a cathodic protection installation. For the sake of the cathodic protection, insulating flanges can interrupt the electrical conduction of the pipeline at different places.

Because of the continuous growth of energy consumption, and of the tendency to site power lines and pipelines along the same routes, high voltage structures are more and more frequently located in the vicinity of metallic pipelines. Moreover, short-circuit current becomes higher as electric networks increase in size and power. Therefore, there has been and still is a growing concern about the following possible hazards resulting from the influence of H.V. systems on metal pipelines [7, 38]:

- safety of people entering in contact with the pipeline

- risks of damage of the pipeline
- risks of destruction of equipment connected with pipeline.

Metal pipelines and communication cables form conductors insulated from the earth, and they may be on a part of their length exposed to influences of nearby high voltage lines. Influences of H.V. lines can result from three types of couplings: capacitive, inductive and conductive. Under fault conditions, the voltages on influenced pipelines can reach a magnitude between several hundred volts and a few kilovolts. In normal operation, influences are normally much lower, but nevertheless they can make problems. Since the capacitive effect is negligible for the buried pipelines and communication cables, only the inductive and conductive couplings are considered in this research. [9, 26]

1.6 MECHANISMS OF ELECTROMAGNETIC INTERFERENCE (EMI)

1.6.1 INDUCTIVE COUPLING MECHANISM

Buried pipelines or communication cables that run parallel to or in close proximity to transmission lines are subjected to induced voltages caused by the time-varying magnetic fields produced by the transmission line currents (Figure 1.1). The induced e.m.f.s cause currents to flow in the buried pipeline and communication cable and also voltages between them and the surrounding earth. [4]

The inductive influence of a H.V. line on a nearby pipeline depends basically on three parameters:

- Power transmission line currents and operating conditions. Under short circuit conditions, induced e.m.fs depend on the fault current. The induced voltages can be much higher than in normal situations but their duration is very short. [4]

- Distance between electrical line and pipeline. The separation between the transmission line and the pipeline is an important factor influencing the induced voltage level, which is reduced with increasing separation. [37]

- Exposure length. The length of exposure is the length of the zone where the influence is significant. The influence is considered significant when the induced e.m.f. due to a fault current with earth-return is higher than 10 V/km x kA, or in other words when a 1 kA current with earth return produces an electromotive force higher than 10 V per kilometer. Such values correspond approximately to distances (in m) between the electrical line and the pipeline less than $200\sqrt{\rho}$ (with ρ soil receptivity in Ωm). [16]

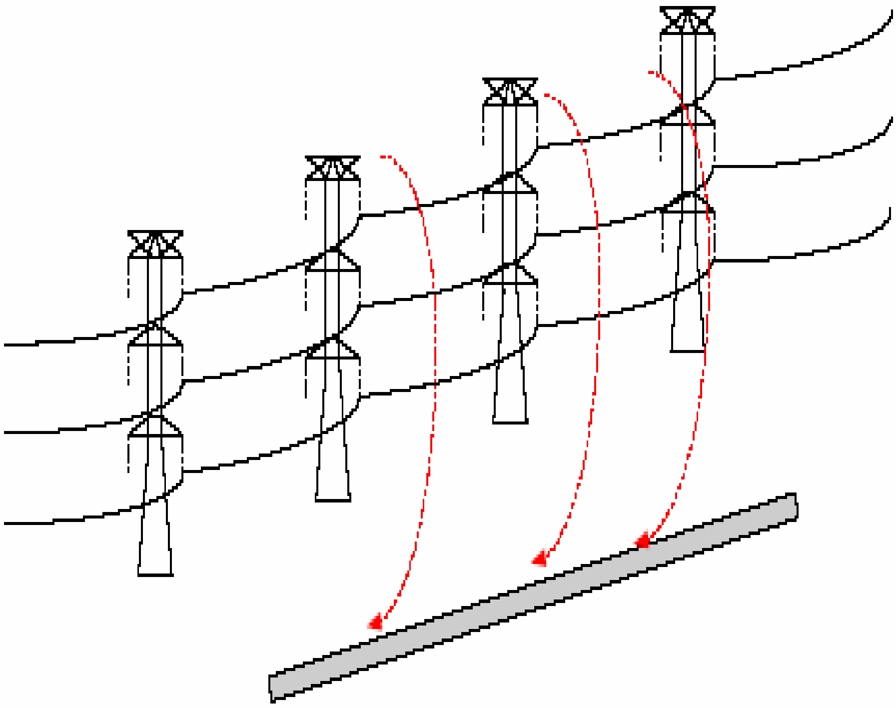

Figure 1.1 Inductive Coupling. [3]

Although the total e.m.f increases with the exposure length, induced voltages increase with the exposure lengths only where these are short (from 1 up to a few kilometers depending on the pipeline coating). For long exposure lengths, there is a limitation of the induced voltages due to the leakage impedance of the coating. [16]

For the communication cables, the inductive coupling occurs via the mutual inductance between the power lines and the communication cables. The magnetic flux, produced by the transmission line current, may induce noise voltage into an adjacent communication cable, generating a loop current in the disturbed circuit. The geometry of the conductors, as well as the geometric range between the power lines and communication cables, determines the value of the mutual impedance and, consequently, the intensity of the inductive coupling. [53]

1.6.2 CONDUCTIVE COUPLING MECHANISM

When a ground fault occurs at a power line tower (or in a power substation), there is conductive coupling between the line tower (or a power substation) and a nearby pipeline if the pipeline is directly connected to the ground electrode of the H.V. system (i.e. inside a power station) or if the pipeline enters the “zone influence” of the tower (or power substation), i.e. a noticeable ground potential rise (GPR) appears at the pipeline location because of the fault current flowing into the soil. In practice, conductive coupling most often results from the second case (ground potential rise at pipeline location). [4]

In so far as a pipeline is not influenced by capacitive or inductive coupling, its potential can be assumed to remain very close to the reference potential of remote earth. Therefore, any GPR (ground potential rise) at the pipeline location is directly applied to the pipeline insulating coating. Problems may appear when the GPR exceeds the coating dielectric strength: in such a case, permanent, but usually very limited, puncturing of the pipeline coating can be observed. Melting of the pipeline steel may even occur, but only when the pipeline is very close to a tower grounding electrode. [31]

When the coating material is not perfectly insulating (i.e. bitumen), or if the pipeline is intentionally grounded inside the zone of influence of the faulted tower (or substation), leakage currents flow from the soil into the pipeline. Thus a fraction of the GPR is transferred to the metallic pipeline. This transferred potential can be transmitted by the pipeline to a remote point such as an insulating flange, a pipeline access point, or a cathodic protection system. Depending upon its amplitude, this transferred potential may generate a dielectric stress upon the insulating flange or upon the cathodic protection system, or it may create touch and step voltages which may be applied to workers touching the pipeline at access points or staying nearby. A similar situation appears when a pipeline section is directly bonded to the earth electrode of a power station. [3]

Thus, touch voltages (between the pipeline and the earth) appear within and outside the station. If safety precautions are not taken, such voltages might represent a risk to workers (in the station) and to the public (outside the station). In addition, the ground potential rise of the station is transmitted along the pipeline and, before decreasing to a safe value, it can be applied to an insulating flange. [3, 4]

In the case of communication cable, the conductive coupling occurs when transmission lines and communication cable have a common branch. The conductive coupling is fairly common when the bonding and grounding systems used for the power and telecommunications are not sufficiently isolated. [53]

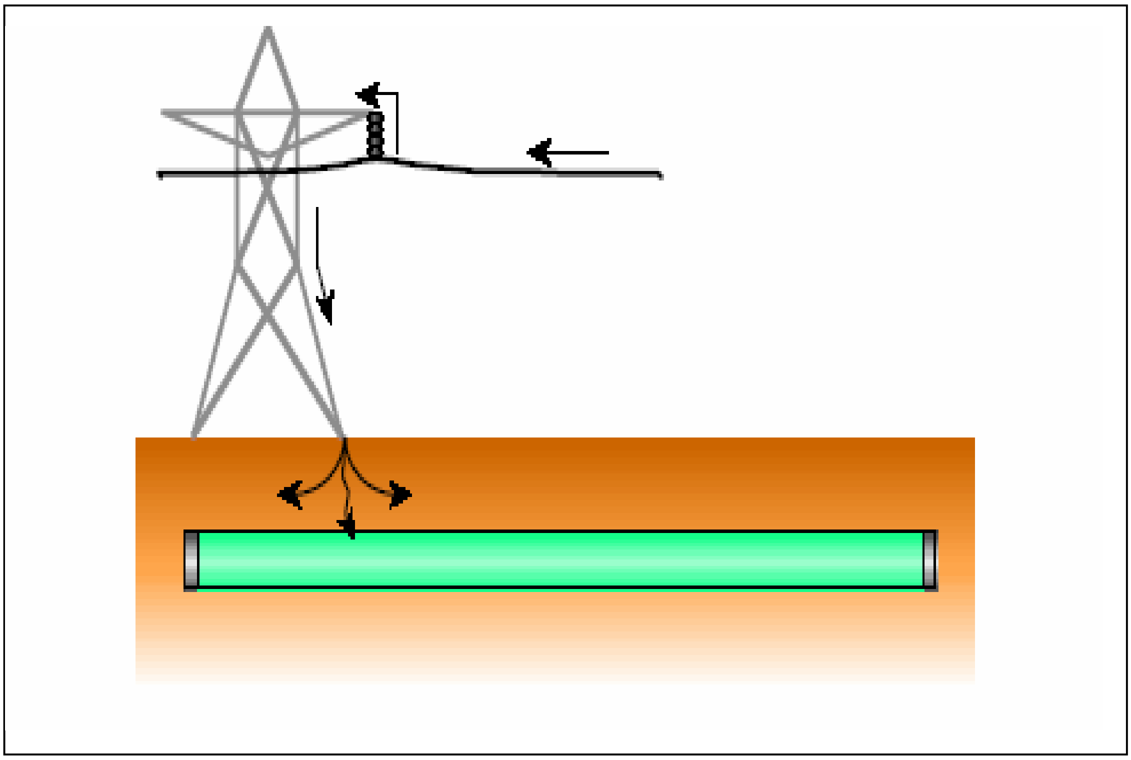

Figure 1.2 Conductive coupling during line-to-ground fault condition. [4]

1.7 EFFECTS OF EMI

1.7.1 EFFECTS OF INDUCTIVE COUPLING

Induced voltages can be responsible for safety problems for people in contact with an aerial or underground pipeline – situated in the vicinity of H.V. lines. Most national regulations insist that safety measures have to be taken when the voltages on the pipeline exceed 50 or 65V under steady-state conditions. During H.V. faults to the earth, much higher voltages are admissible, as the fault produces a short duration stress and the admissible voltage depends on the stress duration. Risks due to faults are limited, because of the limited rate of faults and the low probability that somebody is in contact with the pipeline at the very moment when the danger level is exceeded. Also, during H.V. earth faults, voltages on the pipeline can exceed the withstand voltage level of the insulating flanges. The same danger exists for equipment connected to the pipeline, especially for cathodic protection apparatus. [26]

The electromagnetic interference may cause electrical and electronic malfunctions and can prevent the proper use of the radio frequency spectrum. In data communication, excessive electromagnetic interference hinders the ability of remote receivers to successfully detect data packets. The end result is increased errors, network traffic due to packet retransmissions, and network congestion. [53]

1.7.2 EFFECTS OF CONDUCTIVE COUPLING

When the transferred potential develops along a pipeline, workers touching the pipeline (or staying close to it) may be subjected to electrical shock, which can eventually result in ventricular fibrillation. The risk depends upon many factors: duration of the fault, voltage amplitude, combined probability for people to be in an exposed position during a phase-to-earth fault, voltage distribution around the access point, quality of gloves and shoes that workers wear, etc. [9]

Any voltage difference between the metallic pipeline and the surrounding soil is applied to the insulating coating. Investigations have shown that relatively low voltage values (1000 to 2000 V) result in glow and arc discharges on the whole area of bitumen coatings. During such phenomena, the pipeline's transverse admittance to the earth is increased (i.e. the coating becomes more conductive). If the coating degradation is irreversible, it will further result in an increased current consumption by the cathodic protection systems, and also in a smaller pipeline a voltage increase in the case of inductive coupling with a H.V. line. Damage to polyethylene coating will be usually more localized. [4]

High-intensity current passing through a small-size coating puncture would heat up the pipeline steel and, in theory, could make it melt. Experiments and calculations have shown that such a puncturing process cannot result from the sole "transferred potential" mechanism: it can happen only if the pipeline is so close to the H.V. tower footing (or the substation grounding grid) that an electric arc appears in the soil and, by establishing a zero-resistance path between the electrode and the pipeline, makes it possible for a large current to flow directly into the pipeline. [16]

Voltage transferred into a pipeline section can result in a dielectric stress across an insulating flange. If the flange dielectric strength is exceeded, flashover will occur, with the destruction of the insulating flange as a possible result. However, such an accident is rather unlikely to occur, since voltages transferred by resistive coupling are most often much lower than voltages resulting from inductive coupling against which insulating flanges are dimensioned. [16]

Active cathodic protection system, including semi-conductor rectifiers (SCRs) can be damaged by high voltage resulting from transferred potential if no protective measures are taken. [4]

CHAPTER II

LITERATURE REVIEW

2.1 GENERAL REVIEW

Electromagnetic interference caused by electric transmission and distribution lines on neighboring metallic utilities such as gas and oil pipelines became a major concern in the early 60s due to the significant increase in the load and short-circuit current levels needed to satisfy the energy required by the phenomenal industrial growth of Western nations. Another reason for increased interference levels originates from the more recent environmental concerns which obligate various utilities to share common corridors in an effort to minimize the impact on wildlife and other related threats to nature. [11]

Electromagnetic interference problems were analyzed in the early days of telegraph and telephone mainly as an inductive coupling problem between telecommunications circuits (crosstalk) and between electric lines and telecommunications lines (electric noise). However, it is only in the mid 60s that the first detailed investigations of a realistic interference analysis, including power lines and pipelines, were published by Favez et al. [15]

2.2 EMI INTERFERENCE

The interference of power lines to closely located metallic structures, buried pipelines and telecommunication cables has been a topic of interest over the past *25* years. The inductive and conductive interferences were examined by researchers who produced various reports, papers, and standards [1-56]. The widely known Carson's relations were the basis for the initial attempts to study these interferences [12]. A technical recommendation was developed in Germany based on these studies, which was revised later, by utilizing more advanced and sophisticated analytical models in a computer program [15].

During the late 1970s and early 1980s, two research projects of the Electrical Power Research Institute (EPRI) and the American Gas Association (AGA) introduced practical analytical expressions that could be computerized or programmed on handheld calculators [18]. In the following years, EPRI and AGA jointly developed a computer program that utilizes equivalent circuits with concentrated or distributed elements with the self and mutual inductances being calculated using classic formulas from Carson et al [27]. Furthermore, CIGRE's Study Committee 36 produced a report detailing the different regulations existing in several countries and, some years later, published a general guide on the subject, with a summary of its most important parts [16]. Moreover, a universal algorithm was proposed that may be used to simulate uniformly both the inductive and conductive interferences, whereas a more general method may be applied to pipeline networks with complex geometries [6].

More recently, a finite-element method (FEM) was adopted to calculate the induced voltages on pipelines. This method removes certain approximations that previous approaches used. However, due to the large solution area of the problem, only two-dimensional (2-D) FEM calculations were performed. This made the method applicable only to symmetrical cases (e.g., parallel routings) and to cases where the pipeline has a perfect coating, which is a situation rarely encountered in reality. Defects on pipeline coatings are a common fact, especially in old pipelines, and they can range from a few millimeters to several decimeters. In order to overcome the above limitations, an improved hybrid method was introduced later, utilizing both FEM calculations and circuit theory, that is capable of calculating unknown parameters of the problem, such as the induced currents or voltages, and it was validated by comparing it with other published results. [17,19]

During 1990-2001, the electromagnetic field method (EFM) and the conventional circuit method (CCM) were proposed by the Safe Engineering Services & Technologies (SES) Group to analyze electromagnetic interference between transmission lines, railways, pipelines, communication lines or other metallic structures parallel to the transmission lines. In the EFM case, the total interference level is obtained in one step without the need to compute separately each individual component such as inductive and conductive components. The main limitation of EFM is that it is difficult to handle very long right-of-ways with many circuits. In the CCM case, interference levels due to induction and conduction are computed separately. The total interference level is then obtained by combining the inductive and conductive components, which is always a time-consuming process. When the victim circuit is connected to the electrical substation grounding grid, which is usually connected to the overhead ground wires, the total interference level can no longer be computed accurately by CCM. Recently, the SES Group has adopted the CCM approach where the total interference level can be computed efficiently and accurately even where pipelines are connected to electric substation grounding systems. [2, 14]

In 1994, Charge Simulation Method (CSM) was developed for calculating the induced voltages on fence wires/pipelines underneath AC power transmission lines. The calculated induced voltages compare favorably with those measured experimentally. [40]

In 2003, a local case study was conducted to analyze and evaluate the inductive effects on some old parts of Saudi Aramco pipelines created by the operation of SEC 380KV power lines in the some parts of the Eastern province of Saudi Arabia. A mathematical model is given for the computation of the electrostatic effect of the power line on the pipelines. [3]

Nodal network analysis was used in 2004 to analyze the induced voltage on the buried gas pipelines. The induced voltage on the 71.3 km long gas pipeline running parallel to the 22.9 kV power line is analyzed, and the maximum induced voltage is 4.78 V at the starting point of the longest parallel segment. [54]

In 2005, a new technique was presented on the basis of the development of an artificial neural network (ANN) model for predicting the electromagnetic interference effects on gas pipelines shared right-of-way (ROW) with high voltage transmission lines. It was demonstrated that the ANN-based model developed can predict the induced voltage with high accuracy. The accuracy of the predicted induced voltage is very important for designing mitigation systems that will increase overall pipeline integrity and make the pipeline and equipments connected to pipeline safe for operating personnel. [55]

The influence of strong electromagnetic fields of power lines on telecommunication lines was studied in two characteristic cases: when the power line is used only for power transportation, and when the power line is used for transporting data. [53]

Study of the influence of the electrostatic and magnetostatic fields from a power transmission line over a gas pipeline distribution system, for a non-parallel configuration was published in 2008. That study was based on the nodal model analysis for power line, quantifying the capacitive and self and mutual impedance effects, due to the geometrical configuration of both systems, as they depend on the power line voltage and on the current in conductors, respectively. [5]

Longitudinal induction voltage measurement on communication cables running parallel to overhead lines was presented in April 2008. It aimed to briefly highlight the effect of induced voltage in the telecommunication cables, and to explain methods by which the longitudinal induced voltage can be measured, and to introduce a new method for this measurement. [1]

The most recent study was conducted in November 2008, and it focused on the possibilities of studying the electromagnetic interferences in common corridors shared by electric transmission lines and other utilities, such as pipelines, by using professional analysis and modeling software. The study confirmed the possibility of obtaining an accurate modeling of extremely long common corridors, along which various parameters may change, such as soil resistivity, power line current magnitude, fault location, and victim line characteristics. [2]

2.3 SAFETY STANDARDS

Several international standards provide a methodology for determining the maximum acceptable touch and step voltages, and they are all based on the minimum current required to induce ventricular fibrillation. In addition, many national standards are set by many countries to provide their own safety limits. In general, there is no worldwide consensus on a maximum safe touch voltage level. Table 2.1 lists different countries and standards for the maximum allowable touch voltage level. [41-44]

Unfortunately, Saudi Arabia has no national code standard to determine the maximum safe limits for touch and step voltages. Instead, the Saudi Electricity Company (SEC) and Saudi Aramco Company refer to the IEEE 80 standard for the maximum touch voltage limit.

TABLE 2.1 Standards of Maximum Allowable Touch Voltage Level

Standards/Countries	Steady State Max. Voltage (V)	Fault State	
		Max. Time	Max. Voltage (V)
IEEE 80-2000	15	0.5	287
IEC-479		0.45	220
NACE RP0177-2000	15	No guidance	
Saudi Arabia	According to IEEE 80-2000		
United States	25	According to IEEE 80-2000	
Germany	65	0.5	1000
Sweden	15	0.5	600
Switzerland	50	0.3	300
South Africa	50	> 0.35	430
International Telecommunication Union's guidelines	60	0.5	430

2.4 MITIGATION OF EMI EFFECTS

A mitigation system designed to protect the buried pipeline and communication cable subject to EMI interference must achieve several objectives. Under worst case power-line load conditions, the buried pipeline or communication cable potentials with respect to local earth must be reduced to acceptable levels for the safety of operating personnel and the public. The mitigation system must ensure the safety of the public and operating personnel at exposed sites during fault conditions in the power line.

The mitigation system must also ensure that pipeline coating stress voltages remain within acceptable limits to prevent damage to the coating or even to the pipeline steel. Following are the most common mitigation techniques that can control induced voltage on an influenced buried pipeline and communication cable.

2.4.1 LUMPED GROUNDING

The simplest method to lower EMI interference levels in the buried pipeline or communication cable is to connect it to an earth electrode at certain locations. This method is known as lumped grounding or a “brute force method”.

The soil resistivity in the area can affect the size of the required electrode significantly. For example, 50 m vertical rod in 100 Ωm soil achieves 3 Ω. But 0.3 Ω can be achieved by six 100 m long vertical rods spaced 100 m apart and connected with a horizontal conductor. If soil resistivity increases to 1000 Ωm, these dimensions increase tenfold. While it can still work well for mitigation systems with low impedance requirements and in a very low soil resistivity, in many practical cases this method is impractical and very expensive. [10]

2.4.2 CANCELLATION WIRE

Cancellation wire as a method was developed in the late 1980s. It consists of a long buried wire parallel to the transmission line, often on the side of the transmission line opposite to the buried pipeline or the communication cable, so that the transmission line is located between the buried pipeline and the cancellation wire. With proper positioning, the voltages induced in the wire are out-of-phase with voltages induced into the pipeline. As one end of the cancellation wire is connected to the pipeline, these voltages cancel each other when the other end of the wire is left free.

The problems with this method are that it cancels only the inductive component of the fault currents, and it may transfer excessive voltages to its unconnected end. The method requires the purchase of additional land for the placement of the wire. [31]

2.4.3 INSULATING JOINTS

Insulating joints divide the pipeline into several electrically isolated parts so that induced voltage cannot reach high levels. Local ground is then connected to the pipeline at each side of the insulating joint. Each earthing electrode is connected to the pipeline through a surge diverter, which operates only when the voltage on the pipeline is higher than its breakdown level. With this method, the pipeline is protected from stray currents that can cause corrosion, and cathodic protection currents are prevented from leaking out. The combination of insulating joints and permanent earths can be quite an effective way of mitigating the induced voltages on the pipeline. But insulating joints are more complicated in relation to maintenance. They can be shorted during operation (this case has already been reported in the field). Insulating joints are tested only in the laboratory, and thus their performance in the field during faults or lightning cannot be predicted. Sealing and installation of the joints maybe difficult, and may lead to future leaks. Use of insulating joints appears to be an old technique for mitigation of induced voltages in pipelines. [31]

2.4.4 GRADIENT CONTROL WIRE

The latest method for mitigating induced voltages on the buried pipelines and communication cables is the use of gradient control wire. It consists of one or two zinc wires buried in parallel with the buried pipeline or communication cable, with regular electrical connections to the pipeline or the communication cable. The connections should be made through surge diverters, as in the case of insulating joints. Two insulating joints are also present at the start and at the end of the protected structure.

Gradient control wires provide grounding to the protected structure in relation to inductive interference. They also raise the potential of the local earth, reducing the touch and coating stress voltages. Similarly, in relation to conductive interference, these wires reduce the potential difference between the buried pipeline or communication cable and the local earth by allowing the current to flow between them. [10, 35]

2.5 REVIEW OF AVAILABLE SOFTWARE FOR EMI STUDY

Solving problems that involve power system electromagnetic fields (EMF), electromagnetic interference (EMI), and grounding tends to be complex, and many interrelations exist among these three areas. Almost any attempt to simulate problems involving current circulating outside phase conductors (i.e., in earth, neutral ground wires, metal pipes, etc.) should take into account many aspects of EMF, EMI, and grounding simultaneously.

The early analysis tools were limited in several ways, which have been overcome by more recent research. While earlier software was based on the assumption of essentially parallel facilities, cases arise in practice in which both the electric power lines and the pipelines follow curved paths which intersect one another, diverge, re-converge, etc., making them difficult to model accurately. Recently, field-theory based software does away with the parallel assumption, and it accounts simultaneously for the inductive and conductive couplings between the electric power lines and the pipelines. [21]

During a research project sponsored jointly by the Electric Power Research Institute (EPRI) and the Pipeline Research Committee (PRC) of the American Gas Association (A.G.A.) in 1989-1990, the ECCAPP software package was developed to analyze the electromagnetic and conductive coupling effects between transmission lines and nearby pipelines. ECCAPP enables users to predict electrical effects on gas pipelines produced by normal-load and ground-fault currents from electrical transmission lines, and also to design mitigation systems whenever these effects exceed tolerable levels. ECCAPP has been utilized in some projects and studies, such as the capacitive coupling between 750-KV single circuit and nearby pipelines. Also, it has been used to study the effect of the earth layer and resistivity on the performance of the EMI mitigation system. [27]

In 1991, the DECOP software package was developed using the Decoupled method. DECOP decouples and reduces the equivalent ladder circuit by using circuit techniques introduced in the Decoupled method. [13]

Over the past twenty years, Safe Engineering Services & Technologies (SES) has been developing the Current Distribution, Electromagnetics, Grounding, and Soil Structure Analysis (CDEGS) software package. CDEGS includes six specific engineering applications modules that can analyze soil resistivity, design of grounding, and EMF & EMI. References show different projects, studies and researches conducted with the

CDEGS software. A few years ago, SES developed an integrated software package, as part of CDEGS, called “Right-Of-Way”. It consists of several engineering application packages which analyze EMI interference and mitigation analyses, and a variety of other engineering studies involving electrical power systems. [21]

The available software packages for EMI studies have been evaluated to select the most appropriate one for our study. It was found that the “Right-Of-Way” package is the best for the EMI interference and mitigation analysis. This selection is based on many facts. “Right-Of-Way” has been proved by many studies and projects to be ideal for accurately computing voltages and currents transferred from electric power lines and cables (by inductive, capacitive and conductive coupling) to pipelines, railways, communication lines and other such utilities, whether buried or above ground. It is especially designed to simplify and to automate the modeling of complex right-of-way configurations. It can automatically create phase-to-ground faults along any transmission line at regular intervals throughout the right-of-way corridor, as specified by the user.

The “Right-Of-Way” software is used by more than 200 large well-known companies such as Pacific Gas and Electric Company (California), Lower Colorado River Authority (Texas), Houston Power and Light (Texas), Florida Power and Light, South Carolina Electric and Gas, Rochester Gas and Electric (New York), Ontario Hydro, Manitoba Hydro, TransAlta Utilities (Alberta), ARAMCO (Texas and Saudi Arabia), SNC Group, Consulting Engineers (Quebec). [22]

Three modules in “Right-Of-Way” software are used to perform EMI analysis [22]:

1. The TRALIN module calculates the self and mutual impedances of buried and above-ground conductors such as transmission line phase wires, shield wires, pipelines, and communication cables.
2. The SPLITS module determines the current distribution in the transmission line conductors, and the induced voltages on nearby buried pipelines and cables, by performing circuit reduction using the double-sided elimination technique which remains accurate for large numbers of transmission line sections and for large numbers of conductors.
3. The MALZ module performs the EMI analysis during the transient condition.

In more detail, an inductive and conductive interference analysis using the TRALIN module along with the SPLITS and MALZ modules consists of the following steps:

1. Produce a single map showing in detail the transmission lines and all buried pipelines and communication cables of interest in the study.
2. Measure the relative coordinates of the endpoints of all nonparallel transmission line and buried pipeline or communication cable segments. Measure the spacing between parallel transmission line conductors and buried pipelines or communication cables.
3. Determine the equivalent pipeline shunt or coating leakage resistances to ground.
4. Run the TRALIN module to get self and mutual impedances of phase bundles.

5. Run the SPLITS module to obtain the induced voltages in all buried pipeline and communication cables.

6. Run the MALZ program to determine the EMI effect on buried pipelines and communication cables during the transient condition.

7. Analyze the effects of the mitigation system.

CHAPTER III

EMI THEORETICAL ESSENTIALS & CALCULATIONS

3.1 INDUCTIVE INTERFERENCE

Calculation of the voltages appearing on the pipelines is normally worked out in two steps:

- Determination of the electromotive forces (e.m.f.) induced along the pipeline.
- Calculation of voltages to earth in response to the induced e.m.f.s and calculation of the circulating currents

A clear distinction has to be made between e.m.fs and voltages appearing on the pipeline. E.m.fs are virtual electric generators inside the pipeline resulting from the influence of the inductive coupling. These e.m.fs produced voltages on the pipeline, and only these voltages represent the actual stresses on the pipeline and its equipment.

The zone of influence generally comprises a succession of parallelisms, approaches and crossings. Expressions giving electromotive forces are given for parallelisms between pipelines and disturbing circuits. For the calculation of induced voltages, approaches and crossings may be assimilated to parallelisms, provided they are subdivided into short lengths. All equations and calculations listed in the following sections are extracted from the Power System Analysis [23] and the handbook of Cathodic Corrosion Protection [24].

3.1.1. DETERMINATION OF THE ELECTROMOTIVE FORCES

Two different situations of the power network have to be considered:

- Fault conditions giving rise to the highest e.m.fs but only during rare and short periods of time.
- Normal operation producing smaller but permanent e.m.fs.

3.1.1.1. Fault Conditions. Among the different kinds of faults, short circuits between one phase and the earth produce the most severe influences. Calculation is then applied to the evaluation of the coupling between two circuits having the earth as return conductor.

In the simplest configuration, where the electrical line is not provided with earth wire(s), and in the absence of other metallic conductors in the vicinity, the electromotive force E affecting the circuit pipeline/earth per unit length is related to the fault current I circulating in the phase conductor by the following expression [24]:

$$E = -\ Z_m I \qquad (3.1)$$

where Z_m represents the mutual impedance per unit length of the circuits phase conductor/earth and pipeline/earth (Ω / m) and it can be calculated by using the Carso-Clem expression [24]:

$$Z_m(\Omega/\text{m}) = \frac{\mu_o \omega}{8} + j\mu_o f\left[\ln\frac{2}{g\alpha d} + \frac{1}{2}\right] \qquad (3.2)$$

where $\mu_o = 4\pi 10^{-7}$ H/m

f = frequency (Hz)

g = 1.7811- Euler's constant

$\alpha = \sqrt{\frac{\omega \mu_o}{\rho}}$

ρ = soil resistivity ($\Omega \cdot$ m)

d = geometrical distance between conductors (m)

The validity of the calculations depends, among other things, on the knowledge of the inducing currents. With modern meshed electrical networks, calculations of fault currents are relatively complicated, and they require special computer programs. Electricity utilities are familiar with such calculations, and values of currents to be used are available from these companies.

Metallic conductors in the vicinity of the HV line or of the pipeline can reduce disturbances. The current induced in such conductors by the HV line produces on the pipeline an e.m.f. which partially cancels the e.m.f. due to the fault current. The screening factor represents the ratio between the e.m.f. induced in presence of the conductor and the e.m.f. induced in absence of the conductor. The main reduction effect is generally produced by the earth wire(s) which equip the line. It is generally around 0.7 – 0.75 for one earth wire and 0.5 – 0.55 for two earth wires. Wires placed along the pipeline (especially bare wires) can also be efficient.

3.1.1.2. Normal Operation. Different situations are to be considered. The simplest case concerns a line without earth wires, when the currents are balanced.

A balanced system means the same amplitude with phase differences equal to 120° and 240° [23],

$$I_1 = I \ , \qquad I_2 = \frac{I}{2}\left(-1 - j\sqrt{3}\right), \qquad I_3 = \frac{I}{2}\left(-1 + j\sqrt{3}\right)$$

The residual e.m.f. comes from the difference in the distances between the pipeline and each of the phase conductors. Formulas for calculations are given in [16].

Curve A of figure 3.1 shows the evolution with the distance of the 50 Hz e.m.f. produced in a steady-state operation by a 400 kV line with vertical configuration of the conductors. The emf decreases fast with the distance.

If the line is provided with earth wire(s), the current forced in the earth wire(s) can reach 10% of the phase current in each earth wire in the case of vertical configuration. It thus creates a second e.m.f., which can increase stresses on the pipeline. Curve B of figure 3.1 shows the effect of the earth wires on a 400 kV line with vertical configuration of the conductors.

Generally the currents are unbalanced, because of the different capacitances between the phase conductor and the earth, and because of unbalanced loads. Supplementary e.m.f.s can then be produced, which are a function of the unbalanced current. For unbalanced systems, calculation will be preferably carried out by using the decomposition of the currents in symmetrical components: positive, negative and zero-sequence components.

For close proximities between the line and the pipeline, the e.m.f. depends mainly on the different distances between the pipeline and each phase conductor, while for greater distances it results from the unbalanced current. Curve C of Figure 3.1 shows the influence of a 400 kV line, with vertical configuration crossed by a current presenting a positive sequence current equal to 1 kA and a zero-sequence current equal to 0.1 kA.

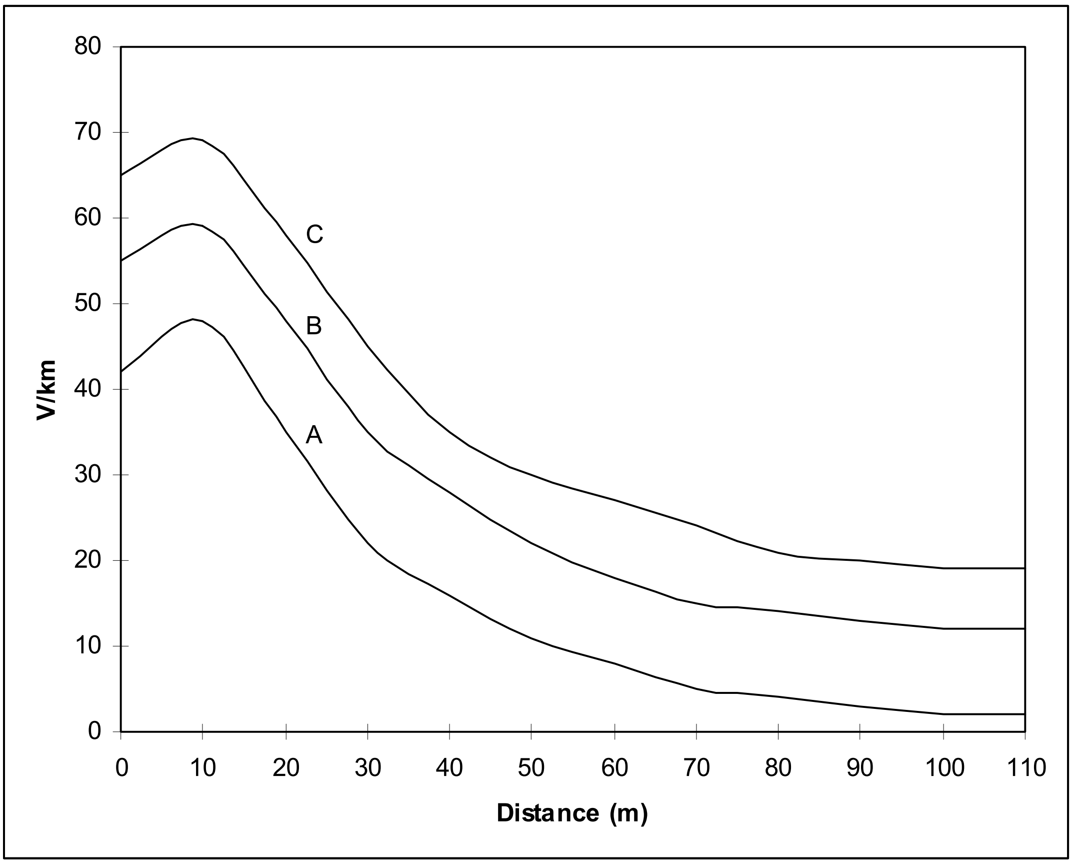

Figure 3.1 Example of e.m.f. induced in normal situation. [16]

Curve A – line without earth wire – balanced currents (1000 A)

Curve B – line with earth wire – balanced currents (1000 A)

Curve C – line with earth wire – unbalanced currents (positive seq. current= 1000A & zero seq. current = 100 A)

3.1.2. CALCULATION OF THE VOLTAGES ON THE PIPELINE

The following concerns the calculation of the response of the pipeline-earth electrical circuit to the e.m.f.s. The voltage calculation method will be first demonstrated for the simple theoretical case of a "perfect" parallelism. The principles for the general case will be given in 3.1.2.2.

3.1.2.1. Perfect Parallelism Between The Electrical Line and Pipeline. The calculation presented here is based on the following assumptions:

- The pipeline is parallel to the disturbing line.
- The leakage admittance of the pipeline is constant, i.e. for underground pipelines, the coating resistance per unit length of the pipeline is uniform and independent of the applied voltage.
- The soil resistivity along the parallel routing is constant.

On the basis of the above assumptions, the equations of the circuit pipeline-earth are [16]:

$$\frac{dV(x)}{dx} + z\,I(x) - E(x) = 0 \qquad (3.3)$$

$$\frac{dI(x)}{dx} + y\,V(x) \qquad = 0 \qquad (3.4)$$

where

z = impedance per unit length of the circuit pipeline-earth

y = admittance per unit length of the circuit pipeline-earth

E(x) = e.m.f. induced on the pipeline per unit length

This equation is the so-called "transmission line" equation, whose solution can be found in the text books. It is only briefly recalled here for three particular cases which are worth examining. [16]

Case I: The pipeline extends for a few kilometers beyond the parallel routing without earthing:

$$V(x) = \frac{E}{2\gamma}\left(e^{-\gamma\,(L-x)} - e^{-\gamma x}\right) \qquad (3.5)$$

$$I(x) = \frac{E}{2Z}\left(2 - e^{-\gamma\,(L-x)} - e^{-\gamma x}\right) \qquad (3.6)$$

with $\gamma = \sqrt{zy}$ propagation coefficient of the circuit pipeline earth.

The maximum pipeline potential occurs at the ends of the parallel routing at x = L and x = 0

$$\left|V_O\right| = \left|V_L\right| = V_{R\ max} = \frac{E}{2\gamma}\left(1 - e^{-\gamma L}\right) \qquad (3.7)$$

Outside the exposure, the pipeline potential declines according to the exponential function:

$$V_R = V_{R\ max}\ e^{-\gamma x} \qquad (3.8)$$

with x= co-ordination outside the subdivided suction

Case II: the pipeline extends beyond the parallel routing at one extremity (A) and stops at the other extremity (B) without earthing:

$$V(x) = \frac{E}{2\gamma}\left[e^{\gamma x}\left(2e^{-\gamma L} - e^{-2\gamma L}\right) - e^{-\gamma x}\right] \qquad (3.9)$$

$$V_{max} = \frac{E}{\gamma}\left(1 - e^{-\gamma L}\right) \qquad (3.10)$$

$$V(o) = \frac{-E}{2\gamma}\left(1 + e^{-2\gamma L} + 2\,e^{-\gamma L}\right) \qquad (3.11)$$

$$V(L) = V_{max} = \frac{E}{\gamma}\left(1 - e^{-\gamma L}\right) \qquad (3.12)$$

Case III: The pipeline is perfectly earthed at one extremity of the parallelism (A) while it extends to the other extremity (B):

$$V(x) = \frac{E}{2\gamma}\left(e^{\gamma x} - e^{-\gamma x}\right)e^{-\gamma L} \qquad (3.13)$$

$$V_{max} = \frac{E}{2\gamma}\left(1 - e^{-2\gamma L}\right) \qquad (3.14)$$

$$V(o) = 0;\ V(L) = V_{max} = \frac{E}{2\gamma}\left(1 - e^{-2\gamma L}\right) \qquad (3.15)$$

3.1.2.2. Non-Parallelisms Between The Electrical Line and Pipeline. The zone of influence generally comprises a succession of parallelisms, oblique approaches and crossings. Determination of e.m.f.s along the zone of influence requires a subdivision of the pipeline into sections which will be assimilated to parallelisms.

The simplest evaluation consists in assimilating the complete zone of influence to a parallelism, with a constant equivalent emf per unit length. This equivalent emf is given by the expression [16]:

$$E = \frac{1}{L} \sum_{i=1}^{n} E_i \; L_i \qquad (3.16)$$

where E_i = e.m.f. per unit length in section i

L_i = length of section i

n = number of sections

L = total length of the zone of influence $L = \frac{1}{L} \sum_{i=1}^{n} L_i$

The maximum induced voltages are then given by applying expressions 3.7, 3.12 or 3.15 according to the cases: extension of the pipeline outside the zone of influence, earthing at one extremity. Such a rough estimate is generally insufficient, but it helps to determine whether admissible limits are likely to be exceeded, and thus whether a more precise evaluation of the stresses is necessary. As this estimate is conservative, no more calculations are needed if limits are not exceeded.

3.2 CONDUCTIVE INTERFERENCE

Electric stresses resulting from conductive coupling can be calculated in order to predict the effects of conductive coupling to a buried pipeline. For this purpose, one has to determine various electrical quantities: GPR at pipeline location, voltage applied to the pipeline coating, voltage transferred to the metallic pipeline, voltage applied to insulating flanges and to cathodic protection systems. The following paragraphs will provide simplified methods for an approximate determination of these quantities. More accurate, but more complex, methods are available in various software packages.

3.2.1 VOLTAGE TRANSFERRED TO A PIPELINE CLOSE TO A TOWER OR A SUBSTATION

Because in practice coatings are not perfectly insulating, some voltage is transferred to a metallic pipeline if a ground fault occurs on a nearby transmission line tower. The magnitude of this transferred voltage obviously depends on the GPR at the pipeline location and on the pipeline coating admittance. The variations of transferred potential along the pipeline can be derived [16]:

For $x > 0$: $V(x) = V_o e^{-\gamma x}$ (3.17)

For $x < 0$: $V(x) = V_o e^{\gamma x}$ (3.18)

where $V_o = \gamma \int_0^{\infty} V_e(x)\,dx$

with:

x : abscissa along the pipeline route (the origin is taken at the closest point to the tower)

V(x) : GPR along the pipeline at the abscissa x

V(x) : pipeline voltage at abscissa x (with reference to remote earth)

γ : propagation constant of the buried insulated pipeline ($\gamma = [zy]^{1/2}$)

These simple analytical expressions still require the numerical integration of GPR V(x) along the pipeline route. They show in a qualitative manner the influence of the pipeline coating admittance y on the variations of transferred voltages V_o and V(x). The higher is y (the poorer the coating insulation), the higher will be the maximum transferred voltage V_o and the faster will be the transferred voltage V(x) decrease apart from abscissa x = 0.

3.2.2 VOLTAGE ACROSS THE PIPELINE INSULATING COATING

Since, in a resistive coupling, the voltage transferred to the pipeline is always low (as compared to GPR), one can make the simplifying assumption that the voltage across the coating equals the GPR at the pipeline location.

3.2.3 VOLTAGE TRANSFERRED TO A PIPELINE BONDED TO A GROUND ELECTRODE INSIDE A STATION OR A SUBSTATION

- Case I: the pipeline is electrically connected to the station ground mat, and it extends outside the station area. If there is no interruption of the electric continuity of the pipeline, the pipeline voltage can be assumed to decrease exponentially, and it is therefore given by the following equation [16]:

$$V(x) = V_S\, e^{-\gamma x} \tag{3.19}$$

where:

x : abscissa along the pipeline route outside the perimeter of the station (the origin is taken at the outer limit of the station ground electrode, and the abscissa is positive outwards from the station limit)

$V(x)$: pipeline voltage at abscissa x

V_S : potential rise of the station earth electrode

The equation 3.19 is valid as long as no insulating flange has been installed on the pipeline “close” to the station (“close” meaning closer than 3 to 4 times the characteristic length $\lambda = 1/\gamma$ of the insulated pipeline).

If there is an insulating flange at a distance x_f “close” to the station, an additional term must be added to equation 3.19 to take into account the reflection at x_f :

$$V(x) = V_S\, \frac{e^{-\gamma x} + e^{-\gamma (x - 2 x_f)}}{1 + e^{2 \gamma x_f}}\, e^{-\gamma x} \tag{3.20}$$

The voltage applied to the insulating flange is given by the value of the difference between $V(x_f)$ and the pipeline voltage on the other side of the flange. In most practical cases, this difference equals $V(x_f)$ since the pipeline extends far beyond the insulating flange and its voltage is negligible on this part (assuming no other coupling mechanism is involved).

- Case II: The pipeline is electrically interrupted by an insulating flange at the station outer limit. The situation is then similar to the case of transferred potential analyzed in section 3.2.1, and the equations 3.17 and 3.18 may be used.

3.2.4 VOLTAGE ACROSS AN INSULATING FLANGE

Voltage appears across an insulating flange (separating two sections of a pipeline) when one of those sections is being submitted to transferred potential resulting from either a GPR along the pipeline route or a direct bonding of the pipeline to a ground mesh (i.e. inside a power station). In the first case, voltage across the flange can be estimated from equations 3.17, 3.18, 3.19. In the second case, the mesh ground potential rise can be computed by using methods presented in reference [16].

3.2.5 CURRENT FLOWING INTO THE PIPELINE THROUGH COATING DEFECTS

As an example, consider a situation where a pipeline is buried near a H.V. tower, and let us assume that the pipeline coating has a single defect: a hole with a cross-section. At the defect point, the pipeline has a resistance to earth whose approximate value is (considering the hole as an earth electrode having the form of a disk) [24]:

$$r = \frac{\rho}{4}\sqrt{\frac{\pi}{s}} \qquad (3.21)$$

If the GPR value is Ve at the pipeline location, the current flowing through the coating defect is [24]:

$$I = \frac{V_e}{r} \qquad (3.22)$$

Thus the current density I_d through the coating defect is [24]:

$$I_d = \frac{I}{s} \qquad (3.23)$$

Taking typical values (ρ=100 Ωm, s=1 mm^2, Ve= 5000 V), it can easily be shown that d has such a low value that the metal pipeline temperature is not significantly increased during a phase-to-ground fault on a H.V. system.

However, this conclusion is no longer true if soil ionization allows a high intensity arc current to flow directly from the power system earth electrode into the pipeline. Because of the high value of the disruptive electric field in the soil, such a discharge cannot occur when the distance between the earth electrode and the pipeline exceeds approximately 0.5 meters, unless it is initiated by a high amplitude impulse current resulting from a stroke of lightning to a H.V. tower.

3.3 CALCULATION OF THE INDUCED VOLTAGES ON COMMUNICATION CABLES

When designing the power system, engineers take into account the currents, which may flow into conductors due to normal operating conditions and more importantly due to fault conditions. Faults may include earth, which cause the earth currents to rise rapidly.

Earth faults will cause current flow in earth-wires, and these currents generate induce voltages on other conductors. The current in the shield is calculated as the shield produces an induced voltage which opposes the voltage created by the phase wire. The shield current, however, can decrease farther from the fault if the cable has ground contact along its length. The resultant induced voltage is the difference between the voltage induced by the faulted phase conductor and the shield. The value of induced voltage is calculated by using the following formula [1]:

$$V = C.L.I.K \qquad (3.29)$$

where:

V: induced longitudinal voltage [V]

C: mutual impedance per unit length [ohm/km]

L: length of exposure (between power and communication cable) [km]

I: fault current [A]

K: shielding factor {K=1 for no shielding}

The mutual impedance, C, of two parallel circuits having earth returns is given by

$$C = 2\pi f\left[\log_e\left(1+\frac{6\,x\,10^5\,\rho}{d^2 f}\right)\right]x\,10^{-4}\quad [\text{ohm/km}] \qquad (3.30)$$

where:

d: geometric separation between earth return circuits in meters

ρ: earth resistivity in ohm-meter

f: system frequency in Hz

If the shield is not grounded on both ends, the shield current is zero and the shielding factor K is 1.

CHAPTER IV

EMI ANALYSIS FOR 2007 INVESTIGATION AREA

4.1 Introduction

As mentioned earlier, the main objective of this research is to study and analyze the electromagnetic interference effects on Saudi Aramco buried pipelines and underground communication cables created by the operation of SEC 380 KV power lines in the Kingdom's eastern province.

The area of investigation is about 130 x 55 km, and it covers the geographical area of the 380 KV transmission lines between Faras and Qurayyah power plants that feed the power to several oil and gas facilities owned by Saudi Aramco. This study is an update for a similar study conducted twenty years ago by the Safe Engineering Services (SES) Company. The old study did not consider the 380 KV Shedgum-Qurayyah transmission lines which run parallel with the Faras-Qurayyah transmission lines for about 45 km. Also, over the last twenty years, several buried pipelines and underground communication cables have been removed or relocated.

One very important and time-consuming task, which must be performed in electromagnetic interference analysis, is the collection and classification of large amounts of data. As illustrated in the following section, various data/materials for the EMI study have been collected. Briefly they can be classified as follows:

1. Conductor coordinates:
   - Height or burial depth of all conductors
   - Horizontal separation distances between all parallel conductors
   - Entire geographical area of interest, showing all conductors under study.

2. Conductor characteristics:
   - Physical dimensions of all conductors: overall radius, core radius, number and radius of strands (if any), wall thickness, inner and outer radii of all coaxial conductors (as in a cable), thickness of insulating coating (if any).

   - Resistivity and permeability of all conductors.
   - Conductivity and permittivity of insulating material (if any) making up each conductor.

3. Soil resistivity and leakage resistance:
   - Soil resistivity values or estimates for the entire geographical region of interest.
   - Ground resistance values or estimates for all transmission line towers.

- Impedance values of all regularly occurring grounds along non-energized conductors.

4. Termination impedances:
   - Ground impedances of all installations which provide grounding for non-energized conductors in the study.
   - How each non-energized conductor in the study is terminated. If the conductor terminates outside the geographical area of interest, equivalent shunt impedance will be calculated.
   - Which conductors are bonded together.

5. Boundary conditions:
   - Voltage magnitude and angle at phase buses of all transmission substations involved in the study.
   - Magnitude and angle of current or power in each phase of the transmission line.
   - Ground impedance of all substations involved in the study.

Figure 4.1 indicates the buried pipelines of interest in this study. These nine pipelines were chosen because of their long lengths of exposure to the Faras-Qurayyah transmission line and their proximity to the interference source. In addition to these buried pipelines, an underground communication cable has also been modeled. It was chosen for the same reason as those related to the pipelines.

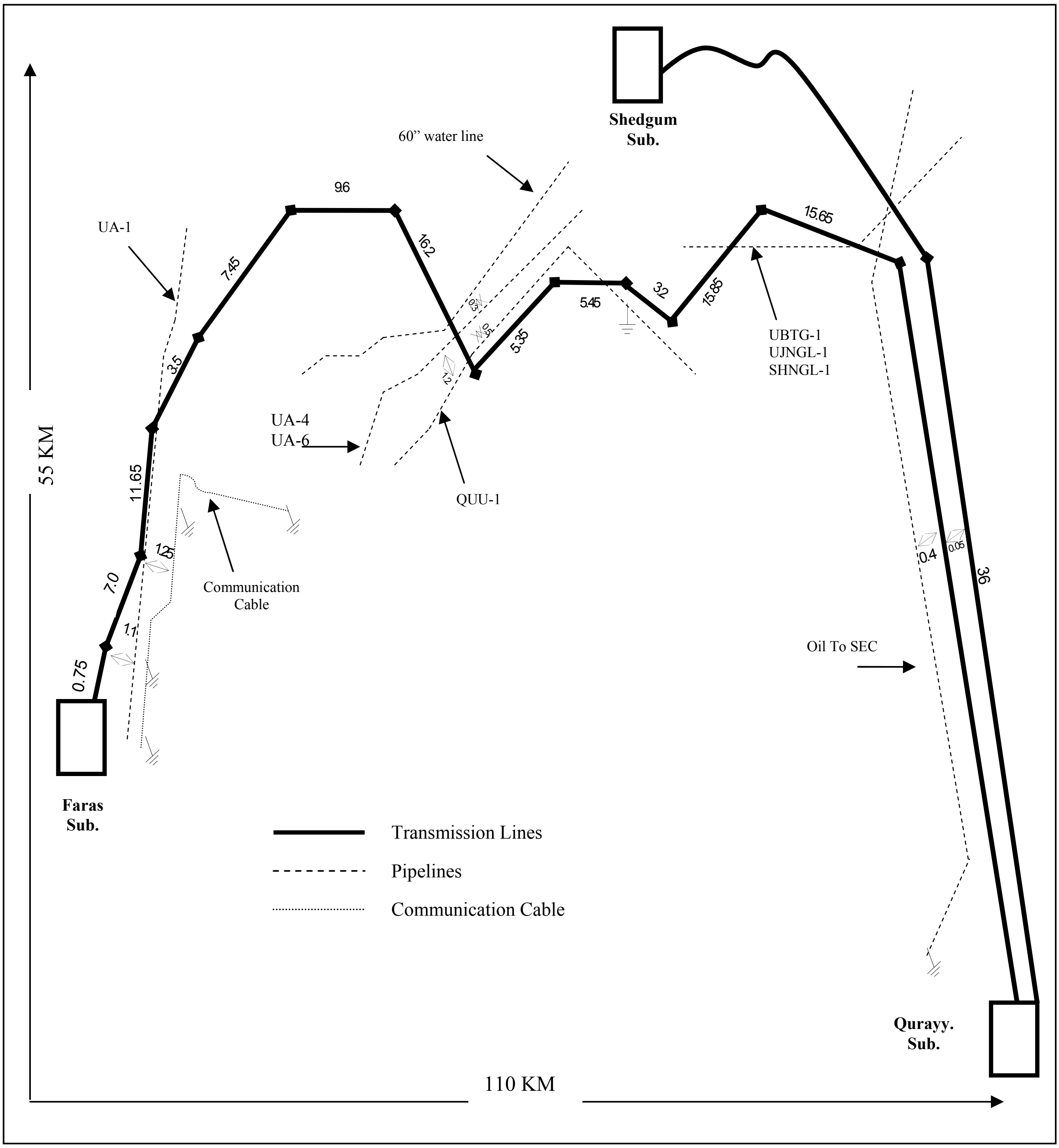

Figure 4.1 380 KV network with buried pipelines & cables to be modeled. (All numbers are in km)

4.2 TERMINOLOGY

The following terms will frequently appear in the discussion which follows. It is best, therefore, that they be clearly defined immediately.

Conductor: A conductor can be any of the following: a transmission line phase conductor, a transmission line neutral conductor or shield wire, a pipeline, a copper strand in a communication cable, the aluminum shield of a communication cable, the steel armour of a communication cable, a transmission line counterpoise, etc.

Line Path: A line path is a group of conductors that are associated together for the purpose of the easier management of right-of-way conductors. At any given point along the transmission right-of-way, a line-path is composed of one or several parallel conductors (or none) in which one of them is expected to be the principal conductor while all other conductors are defined as satellite conductors. For example, a single circuit transmission line contains three phases: A, B, and C. If Phase A is the principal conductor, then the other two phases are satellites of Phase A. A line-path is not necessarily continuous: one group of conductors representing the line-path may terminate at some point, while another group of conductors representing the line-path may begin at a later point.

Principal Conductor : There may be several principal conductors in a right-of-way. One principal conductor is chosen from each line path bundle of conductors (a bundle is a group of parallel conductors). The relative coordinates of a principal conductor are specified; the positions of other conductors in the same bundle are specified as relative spacing from the principal conductor, i.e. they become satellites of the principal conductor.

Satellite Conductor : A satellite conductor is any conductor that is parallel to the main conductor or to a principal conductor and whose position is specified as relative spacing from one of these. For instance, line-path 11 consists of pipelines UBTG-1, UJNGL-1 and SHNGL-1. During the measurement of the coordinates, UBTG-1 was used for the measurement and therefore becomes a "principal" conductor; UJNGL-1 and SHNGL-1 then become satellites. Only the coordinates of principal conductors are entered in TRALIN software; whereas the satellites are specified in terms of their spacing from their associated principal conductors.

Phase (bus): All conductors having the same potentials are assigned a phase number. Each phase bundle is ultimately replaced by a single equivalent conductor for the circuit analysis to be performed by the circuit modeling (SPLITS) module.

Region: A region is a portion of the transmission line right-of-way where the main path (usually the transmission line) is straight, and where no significant change occurs in the characteristics of any of the line-paths under study except that a line-path need not exist throughout the region. The characteristics of the path include the number of conductors, conductor diameters, coating resistances, soil resistivity, etc.

Attribute Set: An attribute set defines the characteristics of all conductors in a line path and the relative position of satellite conductors within a path. Several regions can be associated to a given attribute set, even if the positions of the line paths relative to each other are different from one region to the other. It is practical to divide the transmission line right-of-way into attribute sets that are referenced by the regions. An attribute set consists of an integral number of transmission line sections.

Section: The Right-of-Way program subdivides the transmission line regions into sections, based on a nominal section (span) length specified by the user. A section usually corresponds to an actual transmission line span.

Based on these definitions, the phases and line paths of the Faras-Qurayyah right-of-way along with nearby buried pipelines and underground communications cables can be defined as follows:

Phase 1: 380 KV Transmission Line Phase A Conductors

Phase 2: 380 KV Transmission Line Phase B Conductors

Phase 3: 380 KV Transmission Line Phase C Conductors

Phase 4: 380 KV Transmission Line Sky wires

Phase 5: Pipeline UA-1

Phase 6: Pipelines UA-4/UA-6

Phase 7: Pipeline 60” WATER

Phase 8: Pipeline QUU-1

Phase 9: Communication Cable Cores

Phase 10: Communication Cable Shields/Armours

Phase 11: Pipelines UBTG/UJNGL/SHJNGL

Phase 12: Pipeline SEC OIL

Phase 13: 380 KV Shedgum-Qurayyah Transmission Line Phase A Conductors

Phase 14: 380 KV Shedgum-Qurayyah Transmission Line Phase B Conductors

Phase 15: 380 KV Shedgum-Qurayyah Transmission Line Phase C Conductors

Phase 16: 380 KV Shedgum-Qurayyah Transmission Line Sky wires

Also, based on the above definitions, the transmission line right-of-way has been divided into 340 sections, 30 regions and 10 attribute sets.

4.3 CONDUCTOR COORDINATES

The coordinates of the line paths under study in the Faras-Qurayyah right of way have been measured by a special program (part of the generated map is shown in figure 4.2).

The coordinates of the transmission lines were measured first, after dividing the transmission line into a series of straight-line segments or regions such that the transmission line changes in one axis direction (e.g. x-axis). Then, the principal conductors of each line path that contains buried pipeline or underground communication cable were measured with respect to the transmission line coordinates.

Based on the above mentioned definition of the region and the software methodology, the Faras Qurayyah right of way has been divided to 30 regions as shown in the table 4.1.

Table 4.1 lists the coordinates of the transmission lines with a multiplicative factor of 0.5 which converts grid unit to km. For example, in region 26 as shown in table 4.1, the SEC Oil pipeline is running parallel with power transmission lines for about 22.75 km (45.5 grid units) and it is separated by 400 m (0.8 grid units).

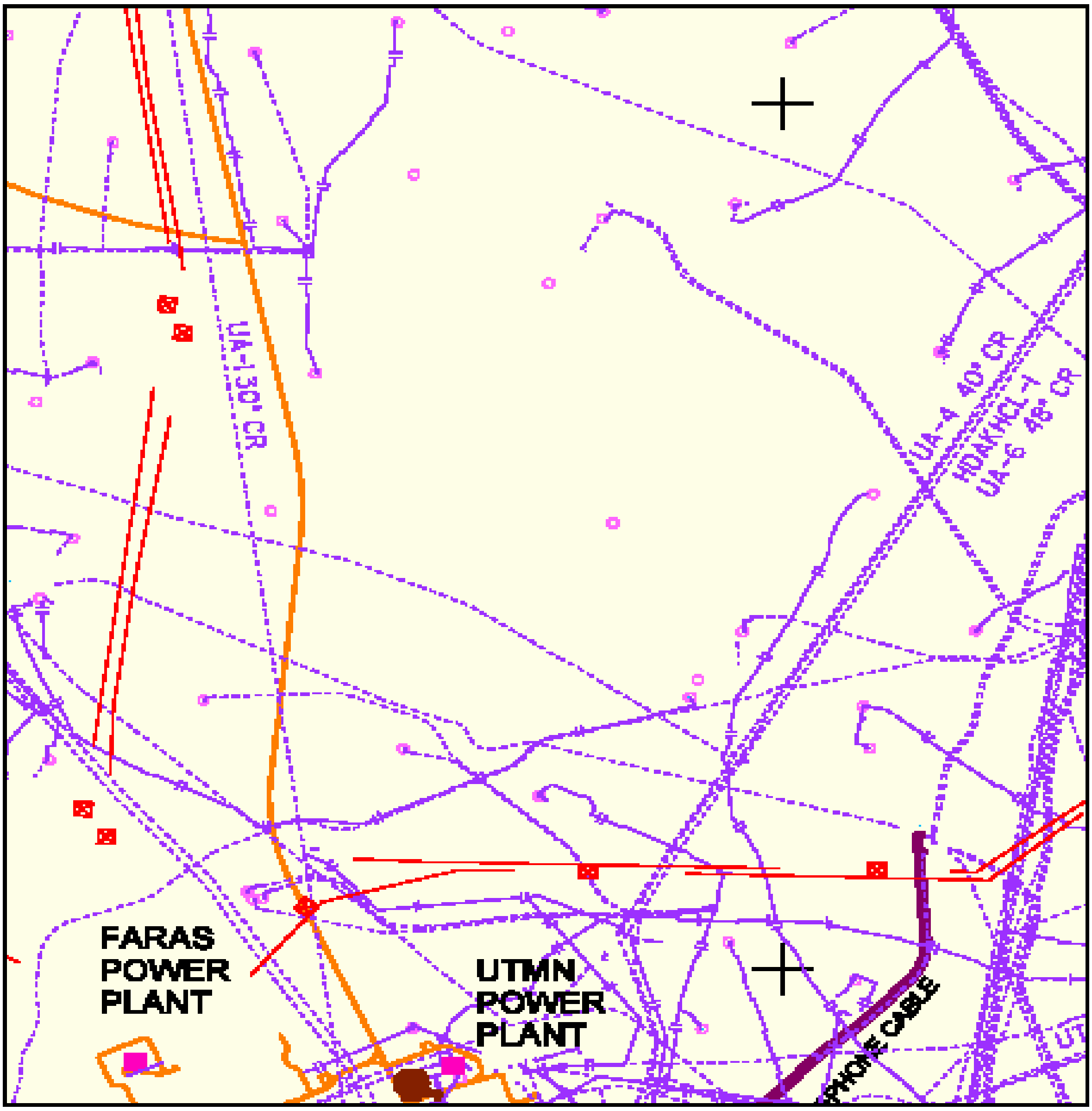

Figure 4.2 Partial map generated by special program to measure the coordinates

TABLE 4.1 Line-Path coordinates measured in Faras-Qurayyah Right-of-Way

Region#	Transmission Line coordinates	Relative Line-Path Coordinates (Grid units)					
	Phase 1-4 (Grid units)	Phase 5	Phase 6	Phase 7	Phase 8	Phase 11	Phase 12
R1	(0.0, 0.0) (1.5, 0.0)	(0.0, -2.0) (1.4, -2.2)					
R2	(0.0, 0.0) (7.0, 0.0)	(0.6, -2.3) (7.1, -0.2)					
R3	(0.0, 0.0) (7.0, 0.0)	(-0.1, 0.3) (4.0, -0.2) (6.8, -0.6)					
R4	(0.0, 0.0) (13.0, 0.0)	(0.1, -0.5) (12.7, 2.9)					
R5	(0.0, 0.0) (10.3, 0.0)	(0.0, 3.0) (10.5, 2.2)					
R6	(0.0, 0.0) (7.0, 0.0)	(-0.3, 2.2) (6.7, 3.3)					
R7	(0.0, 0.0) (8.2, 0.0)	(0.4, 3.4) (1.5, 3.2) (8.2, 4.1)					
R8	(0.0, 0.0) (6.7, 0.0)	(0.0, 4.1) (7.3, 4.8)					
R9	(0.0, 0.0) (14.8, 0.0)	(-0.6, 4.8) (14.6, 10.0)					
R10	(0.0, 0.0) (4.4, 0.0)	(-4.8, 8.9) (-0.5, 13.5)					
R11	(0.0, 0.0) (5.2, 0.0)	(-12.4, 7.5) (-10.0, 11.5)					
R12	(0.0, 0.0) (11.0, 0.0)						
R13	(0.0, 0.0) (8.7, 0.0)			(-0.5, -2.8) (7.5, -2.8)	(-3.0, -14.5) (3.5, -11.5)		
R14	(0.0, 0.0) (7.5, 0.0)		(1.1, -4.5) (4.5, -1.5) (6.3, 1.8)	(0.7, -2.6) (4.7, 0.0) (6.0, 2.3)	(2.8, -12.1) (7.6, -3.0) (7.9, -0.7)		

Region#	Phase 1-4 (Grid units)	Phase 5	Phase 6	Phase 7	Phase 8	Phase 11	Phase 12
R15	(0.0, 0.0) (10.7, 0.0)		(1.2, 1.8) (11.2, 1.3)	(1.5, 2.4) (12.7, 4.5)	(0.5, -0.7) (3.5, 0.5) (10.1, 0.3)		
R16	(0.0, 0.0) (10.9, 0.0)		(-0.4, 1.3) (7.9, 6.4)	(-1.0, 5.0) (1.8, 7.8) (5.6, 11.2)	(0.1, 0.3) (4.5, 2.5) (10.5, 0.8)		
R17	(0.0, 0.0) (3.0, 0.0)				(0.1, 0.8) (2.3, -1.5)		
R18	(0.0, 0.0) (3.4, 0.0)				(0.4, -1.4) (2.5, -1.5) (3.9, -1.2)		
R19	(0.0, 0.0) (11.0, 0.0)				(-0.5, -1.2) (8.2, -9.5)		
R20	(0.0, 0.0) (3.0, 0.0)						
R21	(0.0, 0.0) (17.7, 0.0)					(2.1, 3.4) (17.4, -2.4)	
R22	(0.0, 0.0) (5.6, 0.0)					(0.5, -2.4) (5.3, -2.5)	
R23	(0.0, 0.0) (18.6, 0.0)					(0.2, -2.5) (15.2, 1.1) (18.6, 5.5)	
R24	(0.0, 0.0) (7.1, 0.0)						(3.2, 9.5) (7.1, -0.73)
R25	(0.0, 0.0) (10.0, 0.0)						(0.0, -0.8) (10.0, -0.8)
R26	(0.0, 0.0) (45.5, 0.0)						(0.0, -0.8) (45.5, -0.8)
R27	(0.0, 0.0) (5.0, 0.0)						(0.0, -0.6) (5.0, -5.3)
R28	(0.0, 0.0) (5.7, 0.0)						
R29	(0.0, 0.0) (4.0, 0.0)						
R30	(0.0, 0.0) (2.0, 0.0)						

4.3.1 TRANSMISSION LINE CONDUCTOR

The Faras-Qurayyah transmission line is a single circuit, with 4-bundle conductors per phase, mounted in horizontal configuration on a lattice steel structure as illustrated by figure 4.3. On the other hand, the Shedgum-Qurayyah Transmission line is a double circuit, with 4-bundle conductors per phase, mounted in vertical configuration on a lattice steel structure as shown in figure 4.4.

Tables 4.2 and 4.3 list, respectively, the physical characteristics of the transmission line phase conductors as well as ground wire conductors such as sectional area, overall diameter, strands number and GMR. The conductors of both transmission lines have the same characteristics. The coordinates of the transmission lines are specified to the TRALIN package in terms of their average absolute heights and their X coordinates relative to the reference conductor.

4.3.2 BURIED PIPELINES & COMMUNICATION CABLES

All pipelines under study are buried so that their centers are 1.5 m below the earth's surface, while all communication cables are buried 0.6 m below the earth's surface Tables 4.4 to 4.12 list the characteristics for all buried pipelines such as radius, wall thickness, length, coating thickness and the carrying liquid or gas type. Table 4.13 lists the characteristics of the underground communication cable.

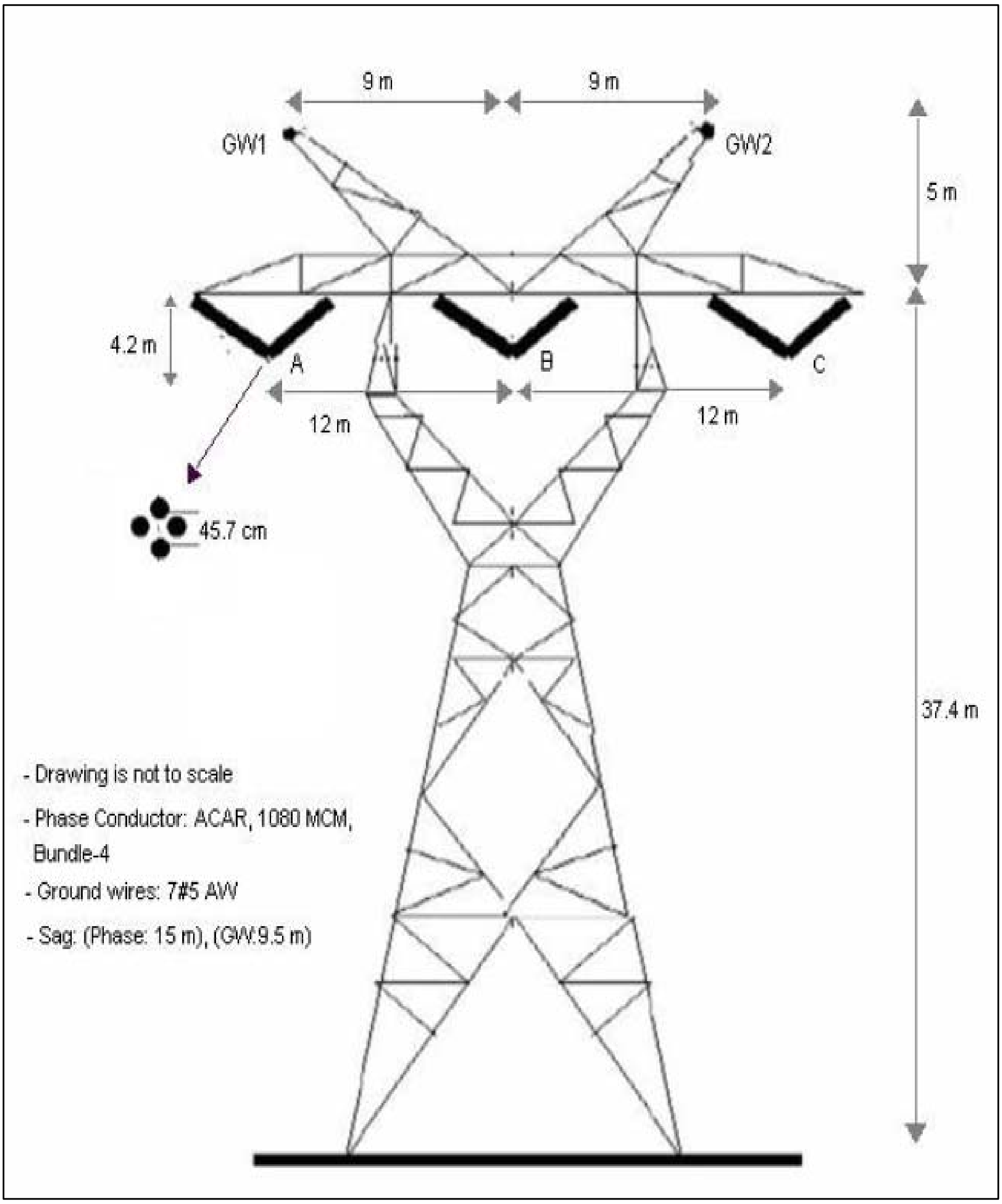

Figure 4.3 Cross section of 380 KV Faras-Qurayyah Transmission Lines

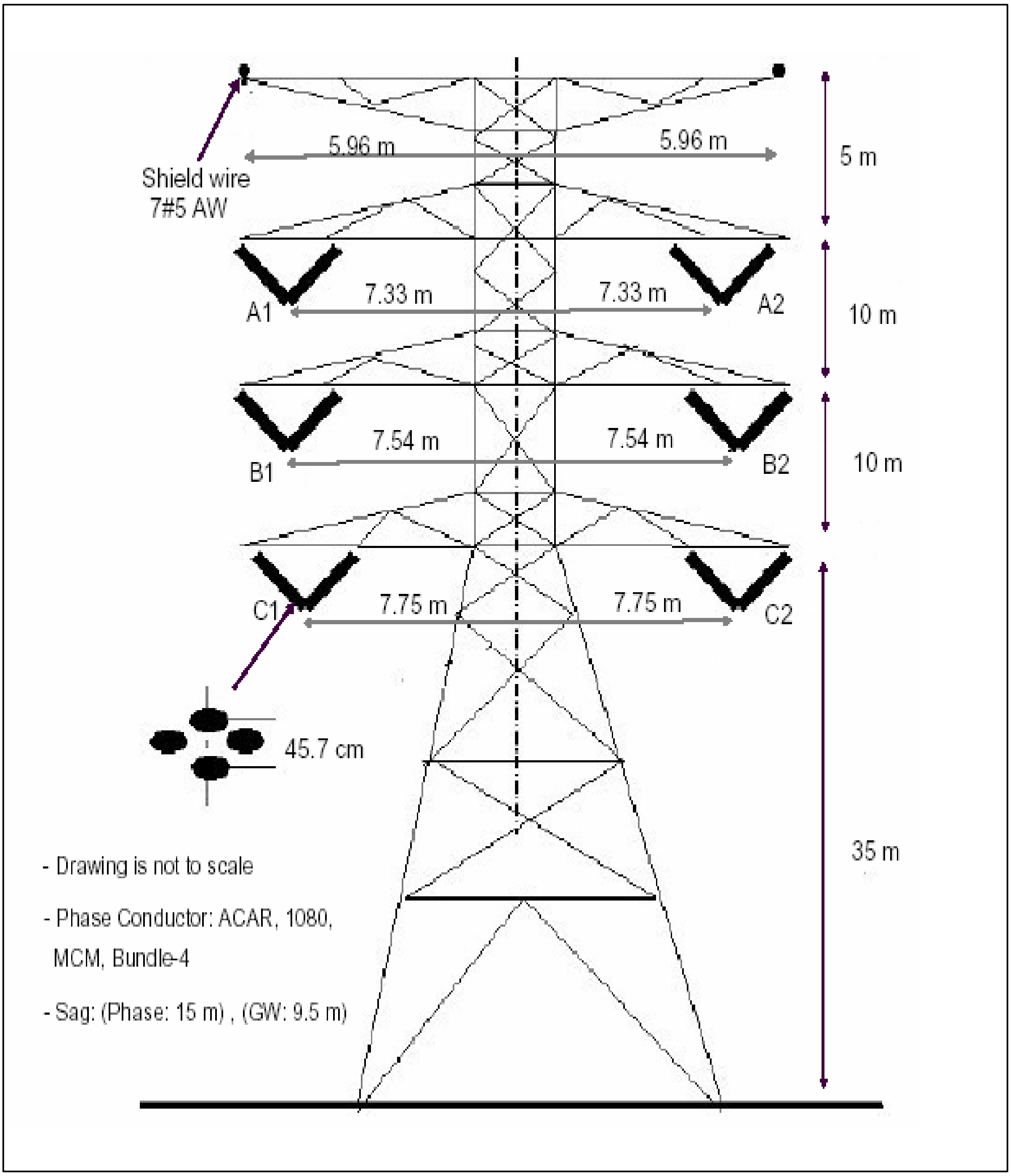

Figure 4.4 Cross section of 380 KV Shedgum-Qurayyah Transmission Lines

TABLE 4.2 Physical Characteristics of Transmission Line Phase Conductors

Parameter	Data
Type	ACAR
Sectional area	547.4
Overall diameter	30.4 mm
Overall radius	15.2 mm
Conductor weight	1.506 kg/m
Ultimate tensile strength	12338 kg
Maximum sag	15 m
Number of outer strands	18
Number of inner strands	19
Outer strands radius	2.17 mm
AC resistance (@25˚C)	0.0582 Ω-km
GMR	0.0117 m
Core radius	0.01085 m

TABLE 4.3 Physical Characteristics of Transmission Line Ground Wire Conductors

Parameter	Data
Type	7/5 AWG AS
Sectional area	170.18
Overall diameter	13.9 mm
Overall radius	6.95 mm
Conductor weight	0.8006 kg/m
Ultimate tensile strength	13256 kg
Maximum sag	9.5 m
Number of strands	7
Outer strands radius	2.31 mm
AC resistance (@25˚C)	1.037 Ω-km
GMR	9.02×10^{-4} m
Core radius	2.31 m

TABLE 4.4 UA-1 Pipeline Characteristics

Parameter	Data
Service	Arab Light Crude
Radius	0.381 m
Wall thickness	0.00635 m
Material GR. Of pipe	X52
Length	46400 m
Flange rating	300#
Max. operating pressure	600 PSIG
Design temperature	171 ºF
Coating resistance	6503 Ω-m^2
Coating thickness	0.01 m
r_{whole}	0.391 m
r_{outer}	0.381 m
r_{inner}	0.37465 m
$\rho_{conductor}$	17.0 ρ_{cu}
$\mu_{conductor}$	250.0 μ_0
$\rho_{coating}$	658797 Ω-m
$\varepsilon_{coating}$	E_0
$Y_{coating}$	3.68 x 10^{-4} siemens/m

TABLE 4.5 QUU-1 Pipeline Characteristics

Parameter	Data
Service	Seawater
Radius	0.762 m
Wall thickness	0.0127
Material GR. Of pipe	X60
Length	50570 m
Flange rating	300#
Max. operating pressure	720 PSIG
Design temperature	170 ºF
Coating thickness	0.01 m
Coating resistance	6503 Ω-m^2
Coating thickness	0.01 m
r_{whole}	0.772 m
r_{outer}	0.762 m
r_{inner}	0.7507 m
$\rho_{conductor}$	17.0 ρ_{cu}
$\mu_{conductor}$	250.0 μ_0
$\rho_{coating}$	654558 Ω-m
$\varepsilon_{coating}$	E_0
$Y_{coating}$	7.36 x 10^{-4} siemens/m

TABLE 4.6 UBTG-1 Pipeline Characteristics

Parameter	Data
Service	Sweet Gas
Radius	0.533 m
Wall thickness	0.0159 m
Material GR. Of pipe	X60
Length	16240 m
Flange rating	400#
Max. operating pressure	960 PSIG
Design temperature	120 ºF
Coating resistance	7432 Ω-m^2
Coating thickness	0.01 m
r_{whole}	0.543 m
r_{outer}	0.533 m
r_{inner}	0.5171 m
$\rho_{conductor}$	17.0 ρ_{cu}
$\mu_{conductor}$	250.0 μ_0
$\rho_{coating}$	750170 Ω-m
$\varepsilon_{coating}$	E_0
$Y_{coating}$	4.51 x 10^{-4} siemens/m

TABLE 4.7 UJNGL-1 Pipeline Characteristics

Parameter	Data
Service	NGL $C2^+$ Gas
Radius	0.381 m
Wall thickness	0.013 m
Material GR. Of pipe	X60
Length	133930 m
Flange rating	600#
Max. operating pressure	900 PSIG
Design temperature	120 ºF
Coating resistance	7432.2 Ω-m^2
Coating thickness	0.01 m
r_{whole}	0.391 m
r_{outer}	0.381 m
r_{inner}	0.368 m
$\rho_{conductor}$	17.0 ρ_{cu}
$\mu_{conductor}$	250.0 μ_0
$\rho_{coating}$	752931 Ω-m
$\varepsilon_{coating}$	E_0
$Y_{coating}$	3.22 x 10^{-4} siemens/m

Table 4.8 SHNGL-1 Pipeline Characteristics

Parameter	Data
Service	NGL $C2^{+}$ Gas
Radius	0.381 m
Wall thickness	0.0111 m
Material GR. Of pipe	X60
Length	130012 m
Flange rating	600#
Max. operating pressure	1225 PSIG
Design temperature	200 ºF
Coating resistance	11148 Ω-m^2
Coating thickness	0.01 m
r_{whole}	0.391 m
r_{outer}	0.381 m
r_{inner}	0.369 m
$\rho_{conductor}$	17.0 ρ_{cu}
$\mu_{conductor}$	250.0 μ_0
$\rho_{coating}$	1129367 Ω-m
$\varepsilon_{coating}$	E_0
$Y_{coating}$	2.15 x 10^{-4} siemens/m

TABLE 4.9 UA-4 Pipeline Characteristics

Parameter	Data
Service	Arab Light Crude
Radius	0.533 m
Wall thickness	0.0159 m
Material GR. Of pipe	X60
Length	52496 m
Flange rating	300#
Max. operating pressure	649 PSIG
Design temperature	150 ºF
Coating resistance	7432 Ω-m^2
Coating thickness	0.01 m
r_{whole}	0.543 m
r_{outer}	0.533 m
r_{inner}	0.5171 m
$\rho_{conductor}$	17.0 ρ_{cu}
$\mu_{conductor}$	250.0 μ_0
$\rho_{coating}$	750170 Ω-m
$\varepsilon_{coating}$	E_0
$Y_{coating}$	4.51 x 10^{-4} siemens/m

TABLE 4.10 UA-6 Pipeline Characteristics

Parameter	Data
Service	Arab Light Crude
Radius	0.5842 m
Wall thickness	0.0159 m
Material GR. Of pipe	X60
Length	17090 m
Flange rating	300#
Max. operating pressure	585 PSIG
Design temperature	170 ºF
Coating resistance	7432 Ω-m^2
Coating thickness	0.01 m
r_{whole}	0.5942 m
r_{outer}	0.5842 m
r_{inner}	0.5683 m
$\rho_{conductor}$	17.0 ρ_{cu}
$\mu_{conductor}$	250.0 μ_0
$\rho_{coating}$	749563 Ω-m
$\varepsilon_{coating}$	E_0
$Y_{coating}$	4.94 x 10^{-4} siemens/m

TABLE 4.11 SEC Oil Pipeline Characteristics

Parameter	Data
Service	Oil
Radius	0.3048 m
Wall thickness	0.0061 m
Material GR. Of pipe	X52
Length	52400 m
Flange rating	300#
Max. operating pressure	600 PSIG
Design temperature	170 ºF
Coating resistance	13935 Ω-m^2
Coating thickness	0.01 m
r_{whole}	0.3148 m
r_{outer}	0.3048 m
r_{inner}	0.29845 m
$\rho_{conductor}$	17.0 ρ_{cu}
$\mu_{conductor}$	250.0 μ_0
$\rho_{coating}$	1416236 Ω-m
$\varepsilon_{coating}$	E_0
$Y_{coating}$	1.37 x 10^{-4} siemens/m

TABLE 4.12 60” Water Pipeline Characteristics

Parameter	Data
Service	Water
Radius	1.52 m
Wall thickness	0.015
Material GR. Of pipe	X60
Length	12350 m
Flange rating	300#
Max. operating pressure	900 PSIG
Design temperature	130 ºF
Coating thickness	0.01 m
Coating resistance	6503 Ω-m^2
Coating thickness	0.01 m
r_{whole}	1.53 m
r_{outer}	1.52 m
r_{inner}	1.505 m
$\rho_{conductor}$	17.0 ρ_{cu}
$\mu_{conductor}$	250.0 μ_0
$\rho_{coating}$	654558 Ω-m
$\varepsilon_{coating}$	E_0
$Y_{coating}$	7.36 x 10^{-4} siemens/m

Table 4.13 Communication Cable characteristics

Cable Radius	0.019 m
Core Inner Radius	0.0 m
Core Outer Radius	0.000455 m (19 AWG)
ρ_r Core	1.0 (relative resistivity – with respect to annealed copper)
μ_r Core	1.0 (relative permeability)
σ_r Core Insulation	0.0 (conductivity)
ε_r Core Insulation	1.0 (relative permittivity)
Sheath Inner Radius	0.013 m
Sheath Outer Radius	0.0132 m
ρ_r Sheath	1.5625 (aluminum)
μ_r Sheath	1.0
σ_r Sheath Insulation	0.0
ε_r Sheath Insulation	1.0
Armour Inner Radius	0.016 m
Armour Outer Radius	0.01615 m
ρ_r Armour	17.0 (Steel)
μ_r Armour	250.0
σ_r Armour Insulation	0.0
ε_r Armour Insulation	1.0

4.4 CONDUCTORS GROUNDING

The CDEGS program requires the soil resistivity in each region set of the right-of-way, in order to determine accurately the self impedances of all line-paths. Table 4.14 lists the soil resistivity value applicable for each region set.

Also, the CDEGS program requires the values of any diffuse or regularly occurring impedances between the line-paths and the earth. These take the form of transmission phase wire capacitances, pipeline coating resistances or ground resistances of splice points on communication cables. Since great care is taken to isolate transmission line phase wires from earth, only capacitive impedance exists. The value of this impedance can be obtained by running the TRALIN program for the ACAR phase wire bundles. The capacitive impedance of all transmission line phases is approximately -j 26664000.0 Ω-m.

For irregularly occurring grounds on buried pipelines, following are the large grounding installations for pipelines:

1. QUU-1 pipeline is bonded to the pump house ground (0.06 Ω) at Jadidah Booster Station
2. SEC Oil pipeline is bonded to seawater treatment plant ground (0.05 Ω).

TABLE 4.14 Soil Resistivities

Region Set	Region	Starting Section	Ending Section	Soil Resistivity (Ω-m)
1	1	1	2	21
	2	3	11	
2	3	12	19	27
	4	21	35	
	5	36	48	
3	6	49	57	22
	7	58	67	
4	8	68	75	90
	9	76	93	
	10	94	98	
	11	99	104	
	12	105	118	
5	13	119	129	27
	14	130	138	
	15	139	151	
	16	152	164	
	17	165	168	
	18	169	172	
6	19	173	186	51
7	20	187	190	13
	21	191	212	
	22	213	219	
8	23	220	242	13
9	24	243	251	13
10	25	252	263	16
	26	264	319	
	27	320	325	
	28	326	332	
	29	333	337	
	30	338	340	

CHAPTER V

CASE STUDY SIMULATION & RESULTS

5.1 INTRODUCTION

The case study explained in the previous chapter has been modeled and simulated by using CDEGS software to calculate the induced voltages along the concerned pipelines due to inductive and conductive interferences during both steady-state and transient conditions. The following sections will analyze the simulation results of the induced voltages on all buried pipelines and underground communication cables.

5.2 VALIDATION OF SOFTWARE RESULTS

The simulation results obtained by CDEGS software have been verified by comparing the induced voltages calculated by CDEGS with the field-measured ones performed by the pipeline department in Saudi Aramco on QUU-1 pipeline (11 Km long). Figure 5.1 and table 5.1 show the results of the comparison. Fortunately, the measurement was done during the peak load on the 380 KV Faras-Qurayyah transmission lines where the current reached 900 A per phase. The comparison revealed acceptable convergence between the measured induced voltages and the simulated ones under the same condition.

Moreover, extensive scientific validations of the CDEGS software, by using field tests and comparisons with analytical or published research results, have been conducted by Safe Engineering Services & Technologies Ltd. (SES) as well as other independent researchers, and they have shown excellent agreement between the simulation results and the reference ones. These validation tests have been documented in tens of technical papers and scientific researches published in prestigious international journals. [27-33]

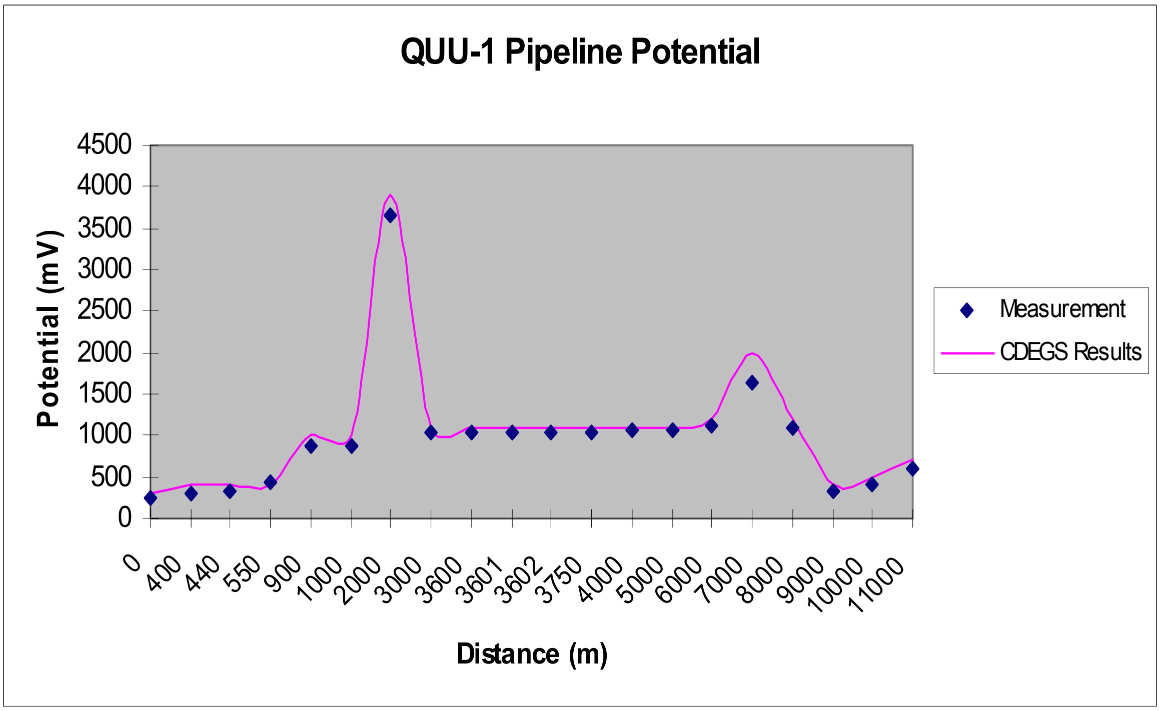

Figure 5.1 Pipeline potential along the axial length of the QUU-1 Pipeline

TABLE 5.1 Pipeline Potential along the QUU-1 Pipeline

Location (Meter)	Measured value (mV)	Computed value (mV)	Error %
0	245	300	18.3
400	310	400	22.5
440	340	400	15.0
550	450	400	12.5
900	885	1000	11.5
1000	870	1000	13.0
2000	3650	3900	6.4
3000	1050	1100	4.5
3600	1035	1100	5.9
3750	1040	1100	5.5
4000	1055	1100	4.1
5000	1060	1100	3.6
6000	1130	1190	5.0
7000	1640	2000	18.0
8000	1090	1200	9.2
9000	330	400	17.5
10000	410	500	18.0
11000	590	700	15.7

5.3 STEADY-STATE CONDITION

The rights-of-way of 380KV Faras-Qurayyah and Shedgum-Qurayyah were modeled under worst-case steady-state conditions, with a maximum current of 900 A and 1200 A per phase, respectively, as shown in figures 5.2 & 5.3. These values were obtained from the SEC Dispatcher during different loading cycles.

The induced voltages along the buried pipelines under study have been calculated by the software. The touch voltage is the difference between the pipeline potential and earth surface potential. Because the earth surface potential is very small (close to 0 V), the touch voltage is actually very close to the pipeline potential.

The resulting induced voltage along the crude oil buried pipeline UA-1 is shown in figure 5.4. The zone of influence comprises parallelisms, approaches and crossings between the power transmission lines and the buried pipeline which greatly affects the induced voltage level on the pipeline. The induced voltage began to increase from 2 V at 5 km from the Faras Substation, where the pipeline is 400 m away from the right-of-way (ROW), to 15 V at 7.6 km where the separation between the buried pipeline and the transmission lines is 50 m. Then, it decreased to below 2 V where the pipeline crosses and runs away from the ROW.

The UA-1 Pipeline recorded the highest induced voltage among all buried pipelines under study, and it reached the maximum allowable touch voltage 15 of volts. This relative high induced voltage was expected, due to the vicinity and the extensive parallel exposure of the UA-1 pipeline to the power transmission lines.

Figure 5.5 shows the calculated induced voltage along the SEC Oil buried pipeline. Although it runs parallel with power transmission lines for about 30 km, the induced voltage was in the order of 6 volts. However, this relatively low induced voltage was expected, because the buried pipeline is mostly located 400-500 m away from the power transmission lines and it is also bonded to the Seawater Treatment Plant ground. The maximum induced voltage occurs at the bending points of the pipeline. This is because the strong discontinuity of the EMF at these points forces a large leakage current from the pipeline, resulting in higher pipeline potentials at these points.

The computed induced voltages along the other buried pipelines (crude pipeline UA-4, water pipeline QUU-1, 60" water pipeline, and gas pipeline) were in the order of 2-6 volts. These results are realistic since these pipelines are run far away from the power transmission lines and do not have perfect parallelism along the right of way. Also, the underground communication cables that mostly located 500 meters away from the power lines have a maximum induced voltage of 6 volts.

Figure 5.6 shows the induced voltage along the gas pipeline that smoothly approaches and crosses the Faras-Qurayyah transmission lines. The maximum induced voltage occurred in the crossing area, and it reached 13 volts.

Figures 5.7, 5.8 & 5.9 show the induced voltages along the QUU-1 and UA-4 pipelines. Both pipelines behave quite similarly in terms of approaching and crossing the ROW. However, compared with the gas pipeline in figure 5.6, the induced voltages were much lower because these pipelines cross the ROW sharply. As expected, the maximum induced voltage occurred in the crossing area, and it reached 3.5 and 1.8 volts on the QUU-1 and UA-4 pipelines, respectively.

Figure 5.10 shows the induced voltage along the underground communication cable that is located mostly more than 500 meters away from the ROW, but it approaches the transmission lines once where the horizontal separation is about 200 meters. The maximum induced voltage reached 5.5 volts at the closest point between the communication cable and the transmission lines.

Based on the simulation results, the maximum touch voltages along all buried pipelines and underground communication cables do not exceed 15 volts, and therefore no mitigation is required according to the Saudi Electricity Company, IEEE and IEC standards.

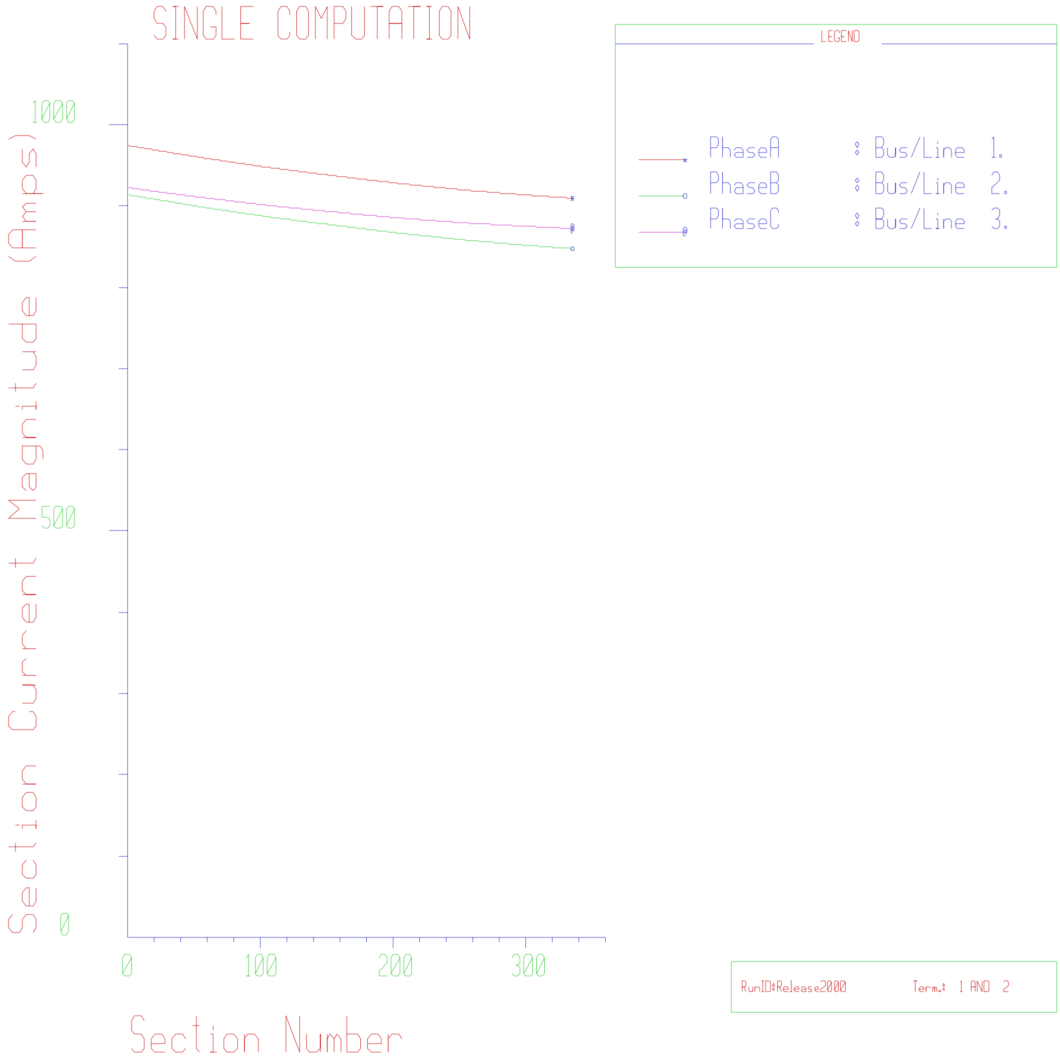

Figure 5.2 Current level on 380KV Faras-Qurayyah Transmission Lines

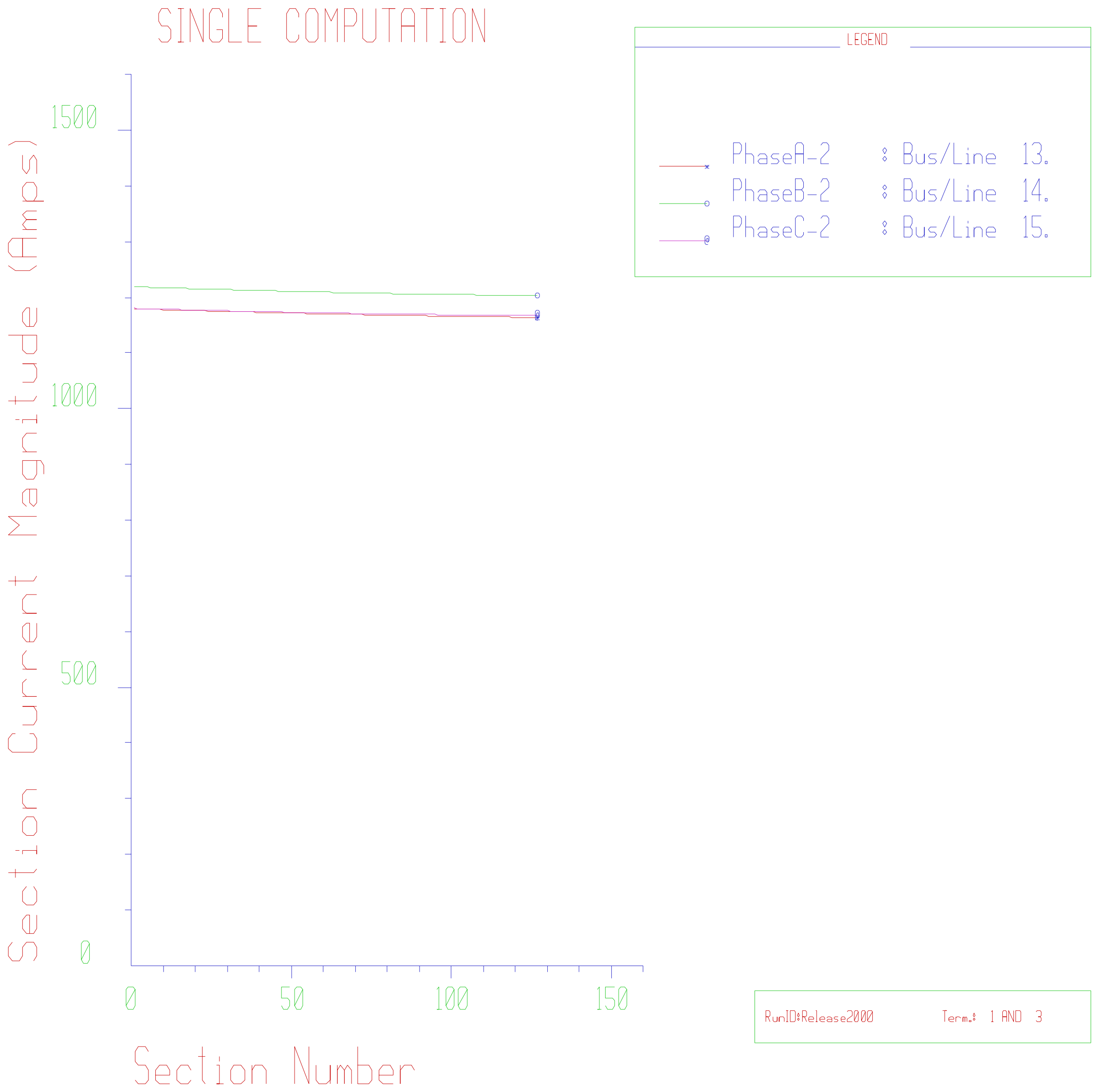

Figure 5.3 The current level on 380KV Shedgum-Qurayyah Transmission Lines

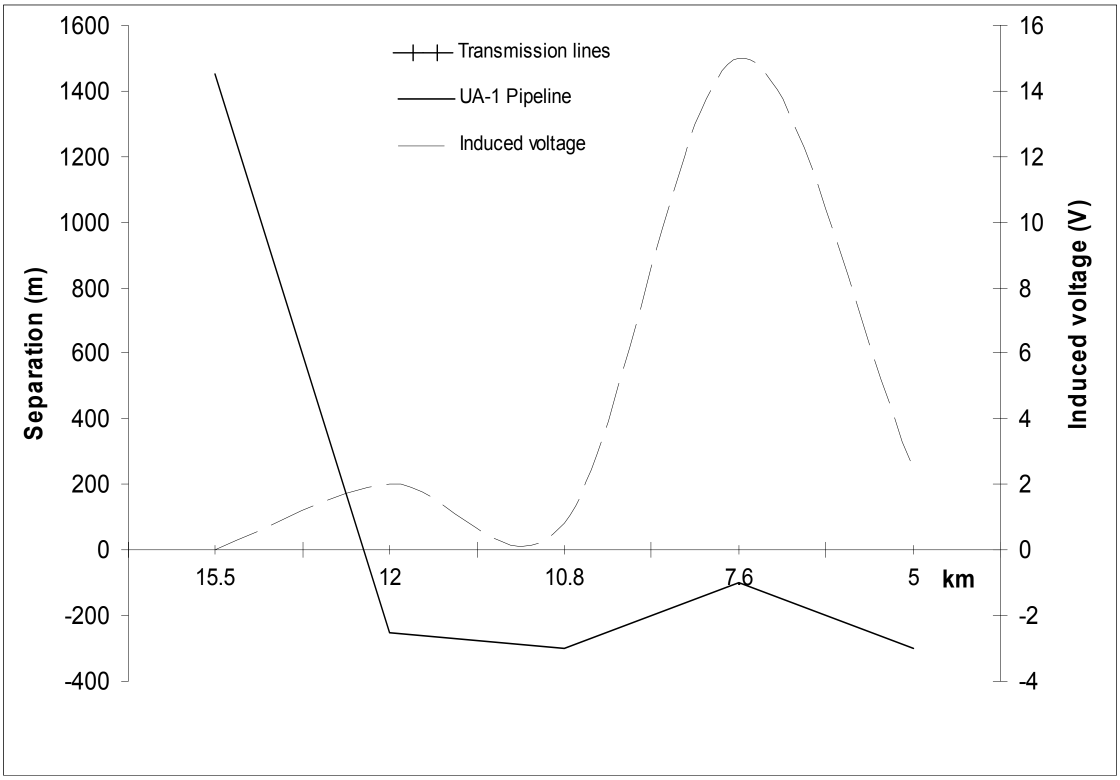

Figure 5.4 Pipeline potential along the axial length of the UA-1 Pipeline

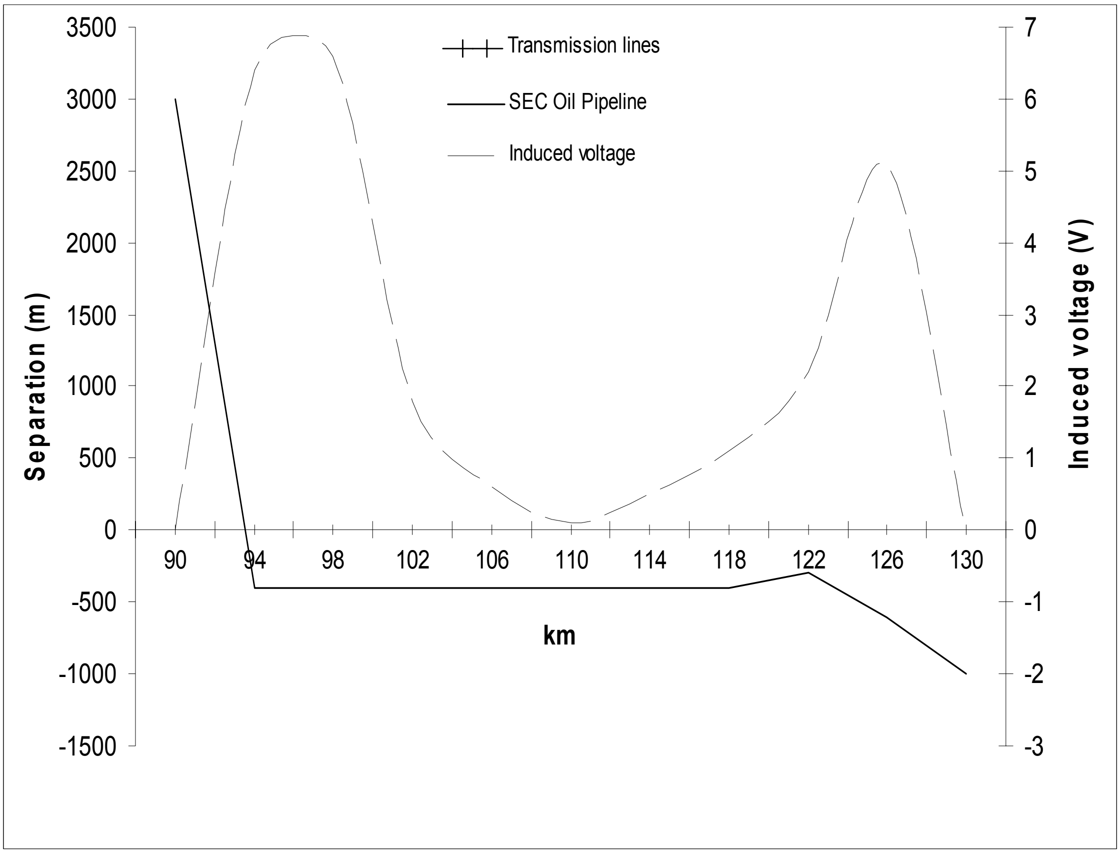

Figure 5.5 Pipeline potential along the axial length of the SEC Oil Pipeline

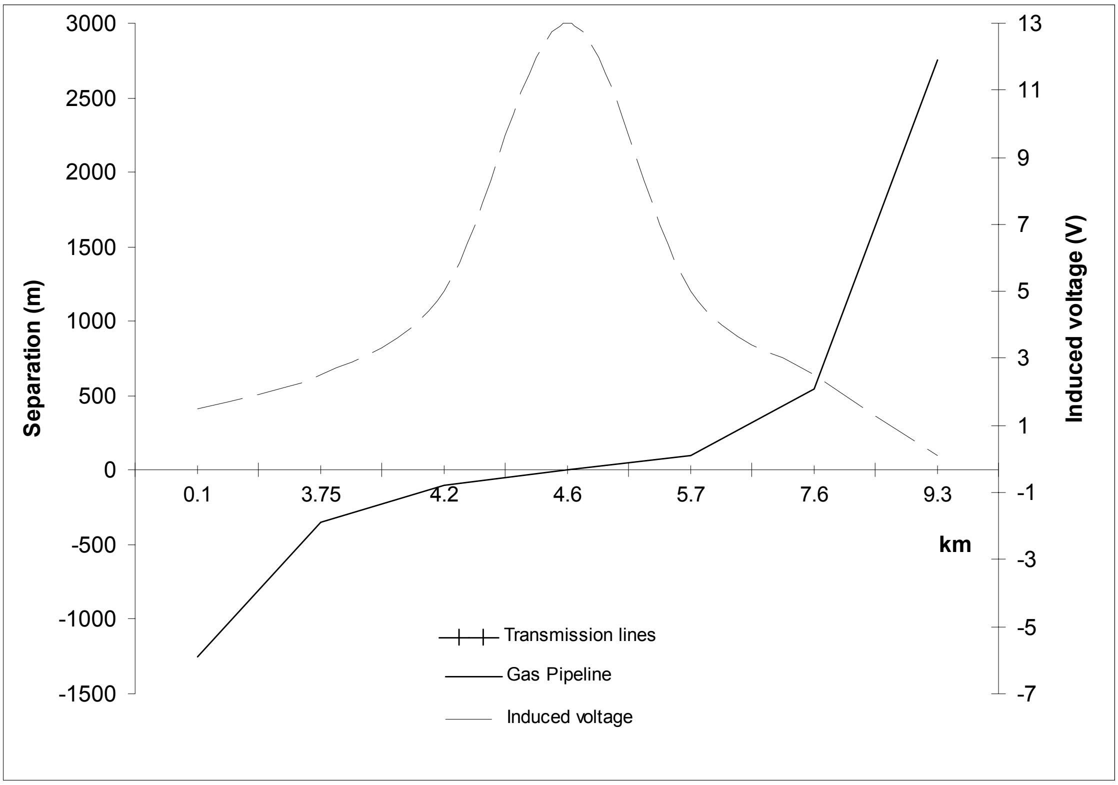

Figure 5.6 Pipeline potential along the axial length of the Gas Pipeline

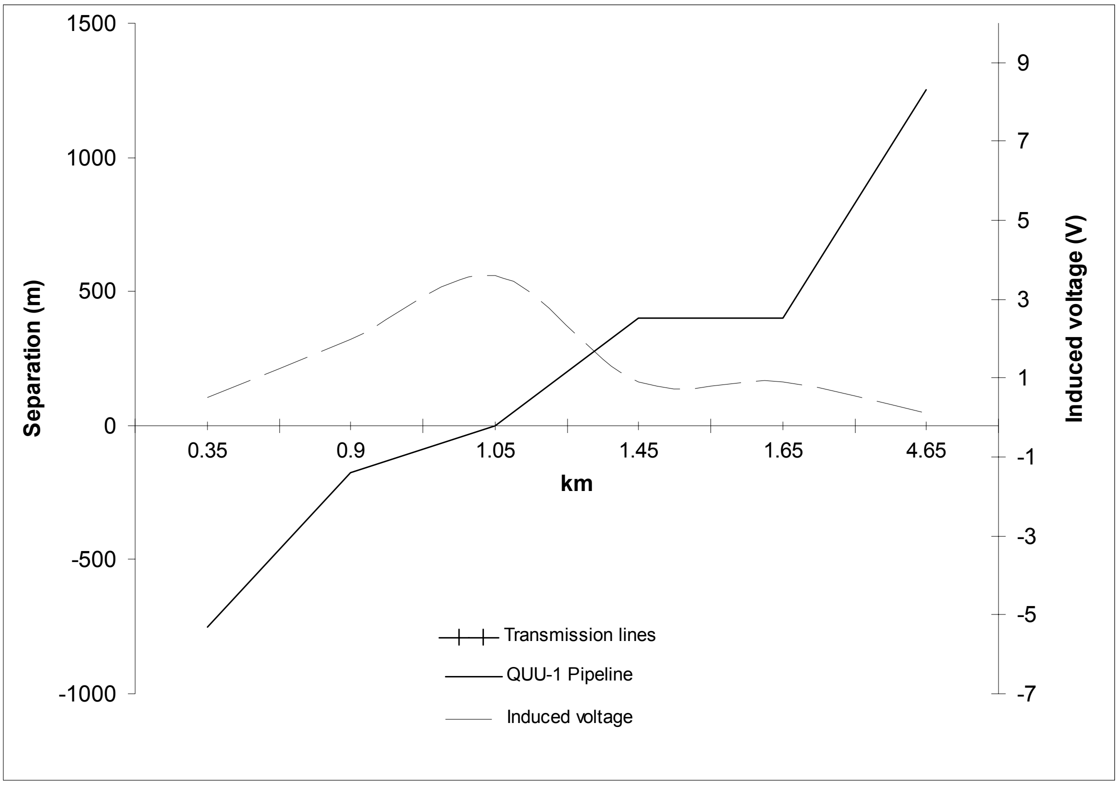

Figure 5.7 Pipeline potential along the axial length of the QUU-1 Pipeline (Case-1)

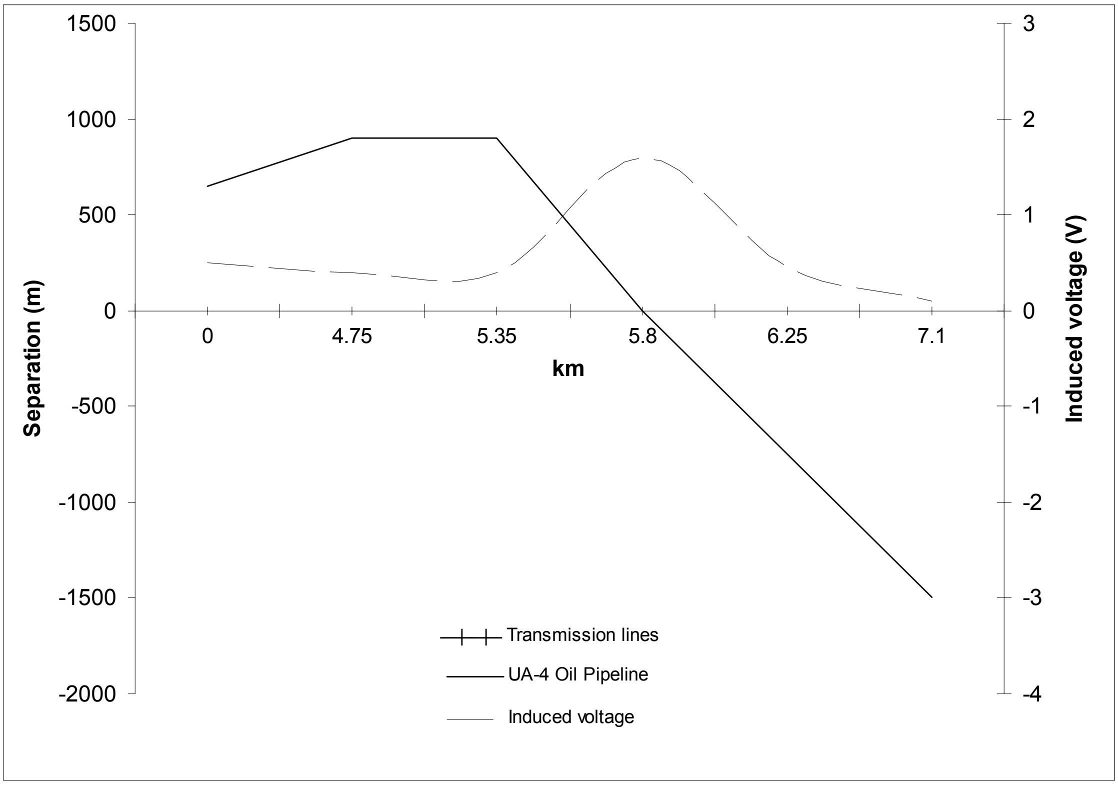

Figure 5.8 Pipeline potential along the axial length of the UA-4 Oil Pipeline

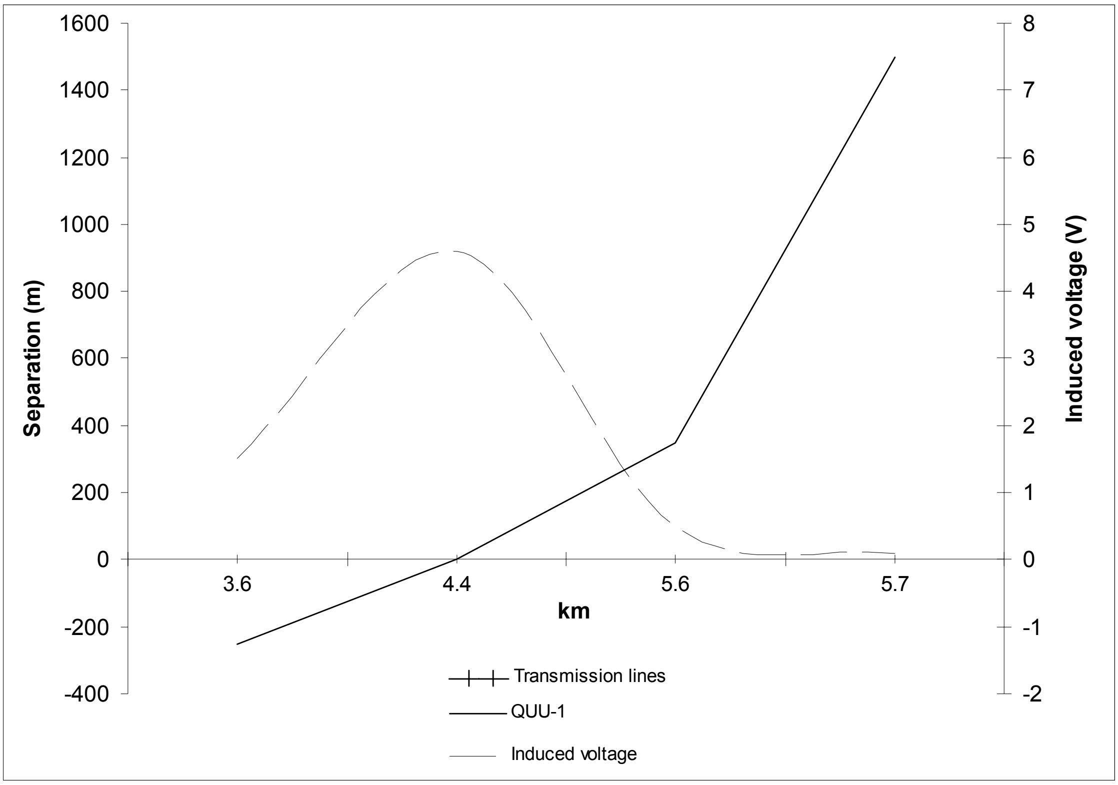

Figure 5.9 Pipeline potential along the axial length of the QUU-1 Pipeline (Case-2)

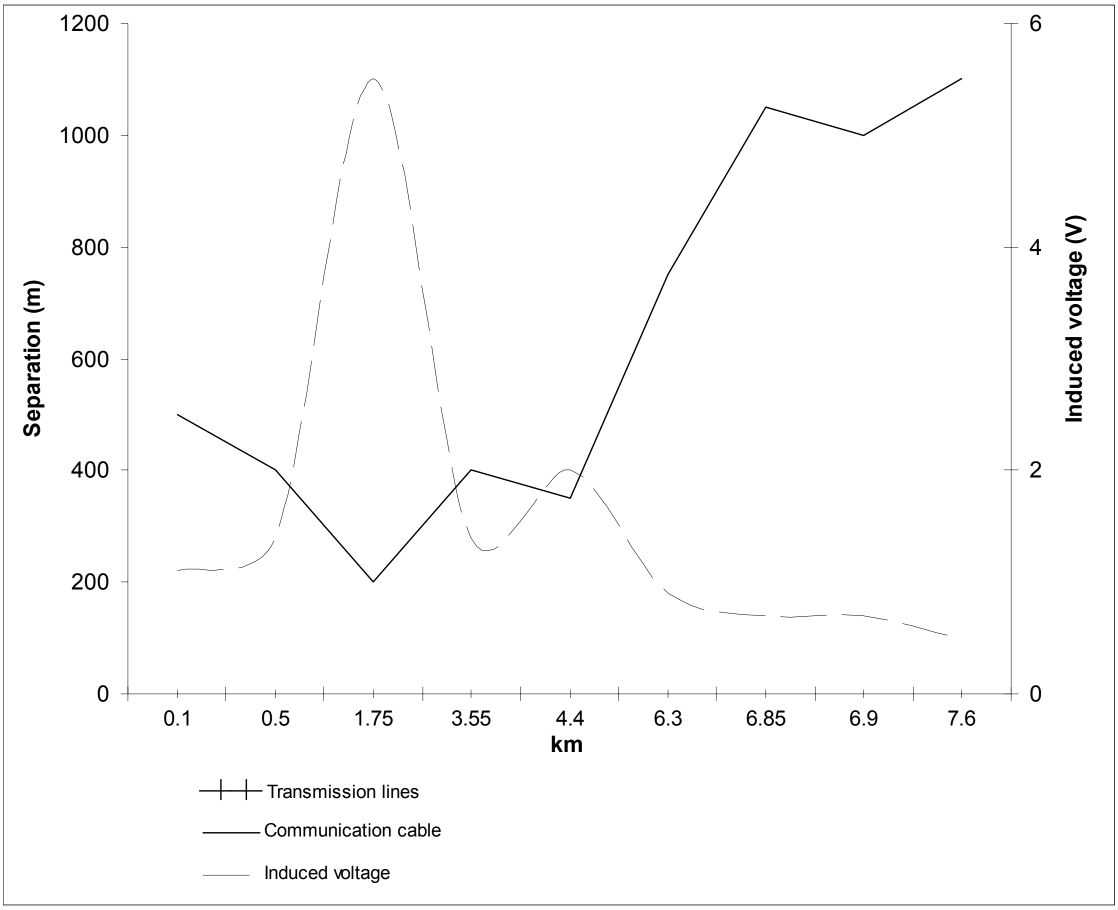

Figure 5.10 Induced voltage along the communication cable

5.4 Transient Condition

Single line-to-ground fault has been simulated at 10% intervals throughout the Faras-Qurayyah transmission lines. The fault current level computed by the CDEGS software matches the actual levels provided by SEC as shown in the table 5.2.

The following sections show the touch voltages along all buried pipelines and underground communication cables during single line-to-ground fault at 10% intervals throughout the Faras-Qurayyah transmission line starting with a fault at Faras substation.

The maximum safe touch voltage limit can be calculated according to the following ANSI/IEEE 80 equation as well as the IEC-479 standard:

$$V_{touch} = \frac{116 + (0.17\rho)}{\sqrt{t}}$$

where:

ρ = Surface soil resistivity in ohms-meters

t = Fault duration in seconds.

Therefore, for 500 ohm-meter top soil resistivity and 0.5 second fault clearing time, the safe touch voltage limit is 287 volts for a person whose weight is 50 kg.

The simulation results, as predicted, have shown that the touch voltage levels are directly proportional to the soil resistivity, while they are inversely proportional to the separation distance. Following is the summarized results analysis of the touch voltage along all the pipelines during the proposed fault locations:

1) The touch voltages along all buried pipelines and communication cables except the UA-1 and SEC oil pipelines were below the safety touch voltage limit 287 volts. This result was expected, because these buried pipelines are mostly located more than 500 m away from the ROW, and they are far away from the power substations. Moreover, the soil resistivities at the locations of these pipeline are relatively low (20-50 Ω·m).

2) The touch voltage reaches 870 V on the nearby UA-1 pipeline during the fault at 10% from the Faras Substation, as shown in figure 5.7. Also, it exceeds the safety limit during the simulated faults at 20-50% from the Faras Substation. This high touch voltage resulted from the pipeline being close to the faulted transmission line towers (70 m away) as well as the Faras Substation (8 km away).

3) The touch voltage reaches 650 V on the nearby SEC-Oil pipeline during the fault at 90% from the Faras Substation, as shown in figure 5.8. Also, it exceeds the safety limit during the simulated faults at 60-90% from the Faras Substation. The pipeline is mostly 400-500 m away from the transmission lines, but one of its ends crosses the ROW near the transmission line tower, which highly affects the touch voltage levels.

The coating stress voltage is expected to be in the order of touch voltage, since most of the potential drop between the earth surface and the pipeline steel occurs across the pipeline coating. There is no problem regarding the pipeline coating stress voltage, because these pipelines have a coating of fusion bonded epoxy which can withstand voltage up to 3000 V.

TABLE 5.2 Fault Currents Level for Faras-Qurayyah 380KV Transmission Line

Terminal	Fault Location		SEC Current (A)	CDEGS Current (A)
	% From Faras	Section Number		
Faras	25	85	7644	7550
	50	170	4490	4440
	75	255	2987	2965
Qurayyah	25	85	3241	3225
	50	170	4859	4870
	75	255	8576	8310

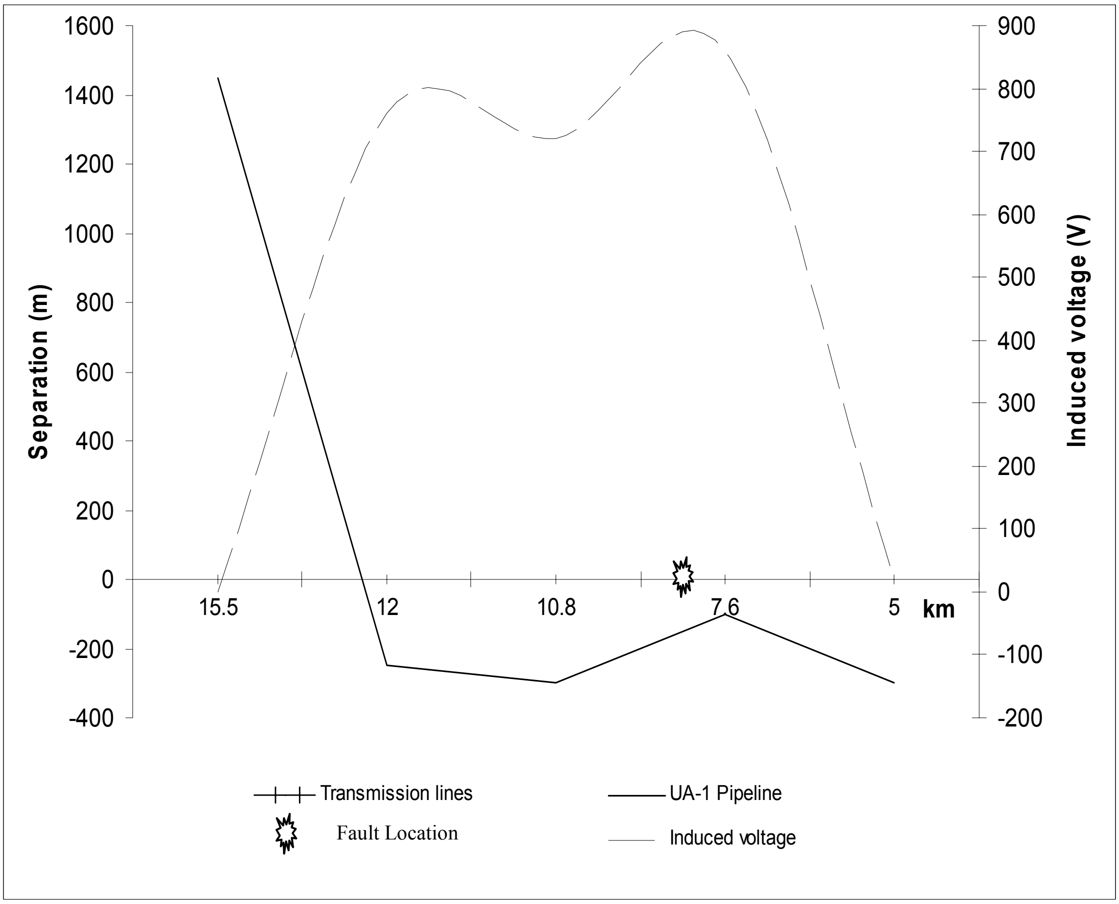

Figure 5.11 Touch voltage along the axial length of the UA-1 Pipeline

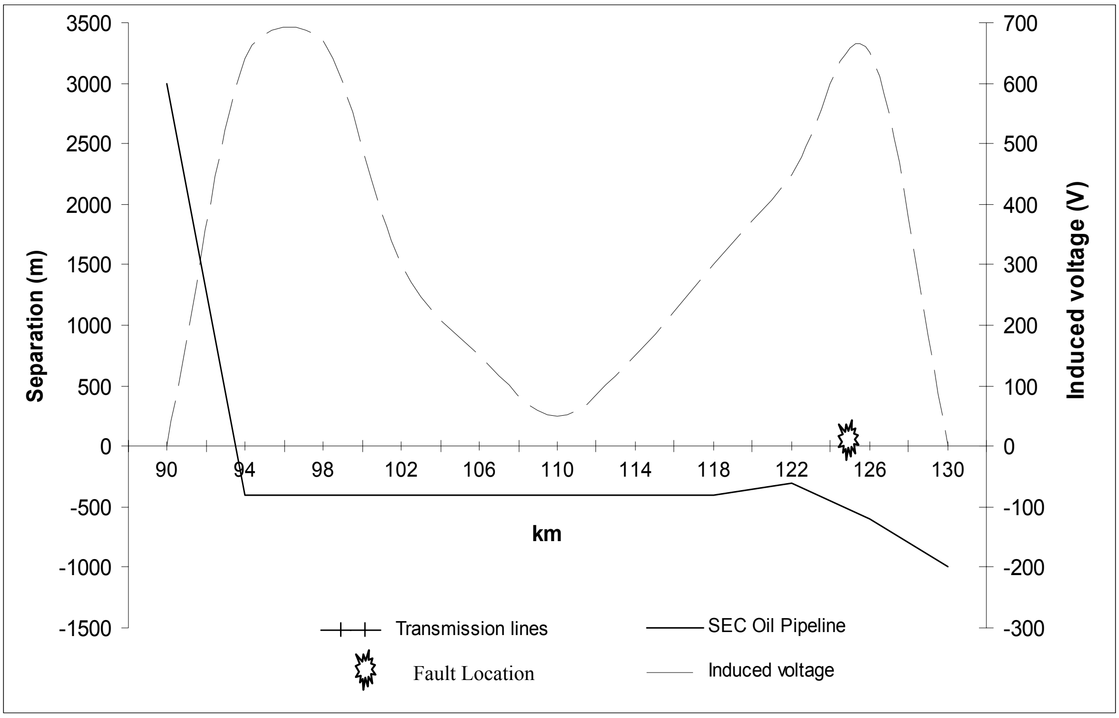

Figure 5.12 Touch voltage along the axial length of the SEC Oil Pipeline

CHAPTER VI

MITIGATION OF EMI INTERFERENCE

The simulation results of the system show that a high level of touch voltages has existed in some pipelines, which need to be reduced to the touch voltage limit as per the IEEE and ICE standards (the other standards refer to IEEE for this limit).

Various techniques have been developed to mitigate AC voltages on buried pipelines, such as lumped grounding, cancellation of wires, bonding across isolation flanges and ground mats. However, the most popular and cost effective mitigation technique is the application of gradient control wire. The gradient control wires are generally made of bare zinc extruded over a thin gauge steel wire. The mitigation typically consists of one or two bare wires / ribbons, buried parallel to the pipeline to be protected, and connected to the pipeline at regular intervals. Figure 6.1 shows a schematic arrangement of pipeline connected to the zinc ribbon for mitigation of EMI interference. The mitigation wire reduces the effects of inductive and conductive interference. The gradient control wires provide grounding for the pipe, decreasing the induced pipe potential rise at the same time as the potential of the local earth is raised due to the gradient control wires, thus reducing the potential difference between the earth and the pipe. [34, 35]

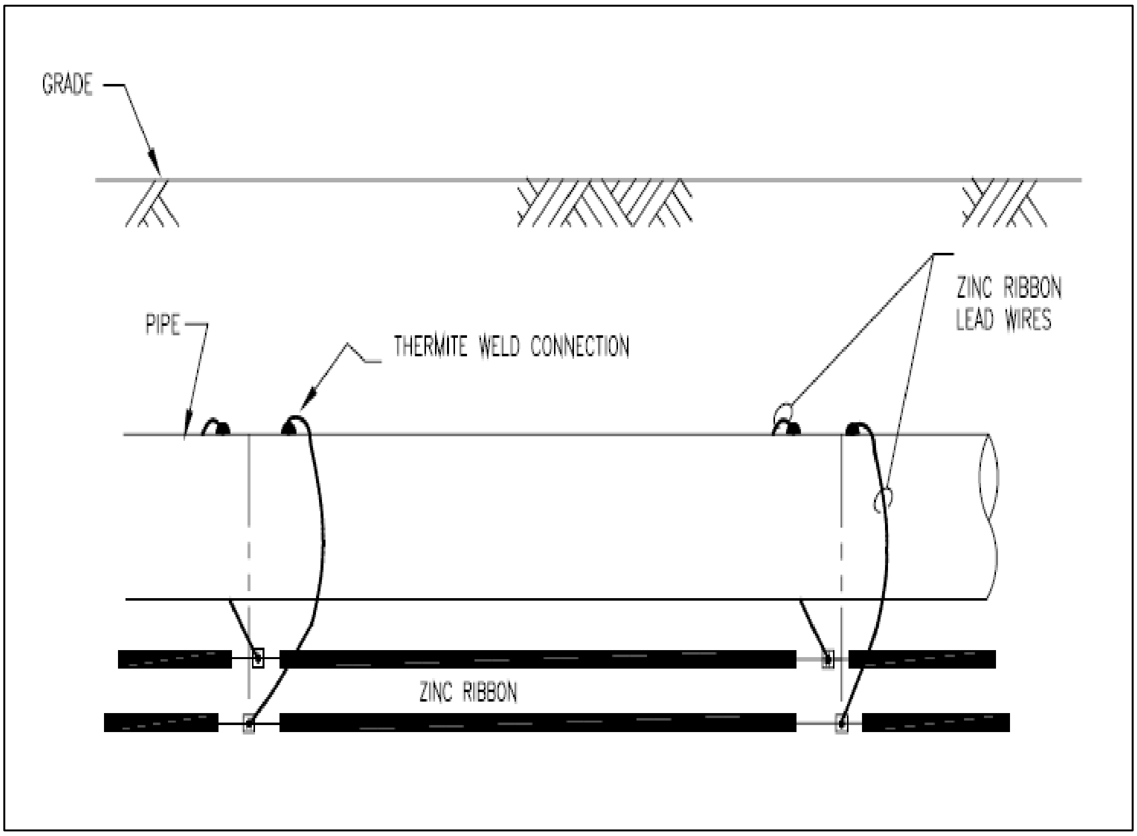

Figure 6.1 Typical gradient control wire installation. [35]

The simulation results have been analyzed to find out the best cost-effective locations to install the gradient control wire for the pipelines that need mitigation. Following is a summary of the maximum touch voltages on these pipelines that exceed the touch voltage limit:

4) The touch voltage reaches 870 V on the UA-1 pipeline during the fault at 10% from the Faras Substation.
5) The touch voltage reaches 650 V on the SEC-Oil pipeline during the fault at 90% from the Faras Substation.

So, by using CDEGS software, the following proposed installations of gradient control wires have been simulated to check their mitigation performance:

1 1050 m gradient control wire installed on UA-1 pipeline between tower # 7 to tower #10 from Faras Substation.

2 1050 m gradient control wire installed on UA-1 pipeline between tower # 17 to tower #20 from Faras Substation.

3 1050 m gradient control wire installed on UA-1 pipeline from tower # 30 to tower #33 with reference to Faras Substation.

4 350 m gradient control wire installed on SEC Oil pipeline between tower # 252 to tower #253 from Faras Substation.

5 700 m gradient control wire installed on SEC Oil pipeline between tower # 271 to tower #273 from Faras Substation.

6 700 m gradient control wire installed on SEC Oil pipeline between tower # 304 to tower #306 from Faras Substation.

7 1050 m gradient control wire installed on SEC Oil pipeline between tower # 317 to tower #320 from Faras Substation.

Figures 6.2 and 6.3 show the simulation results for the above mentioned pipelines after installing the proposed gradient control wires.

The touch voltages on the UA-1 and SEC Oil pipelines have been reduced to 180V and 144V respectively, which are far below the safe touch voltage limit (287 V).

The rough cost estimate of installing gradient control wires is about $ 25,000 per kilometer including the materials and the installation cost [31]. So, the proposed mitigation system for the UA-A and SEC Oil Pipelines costs around $ 125,000.

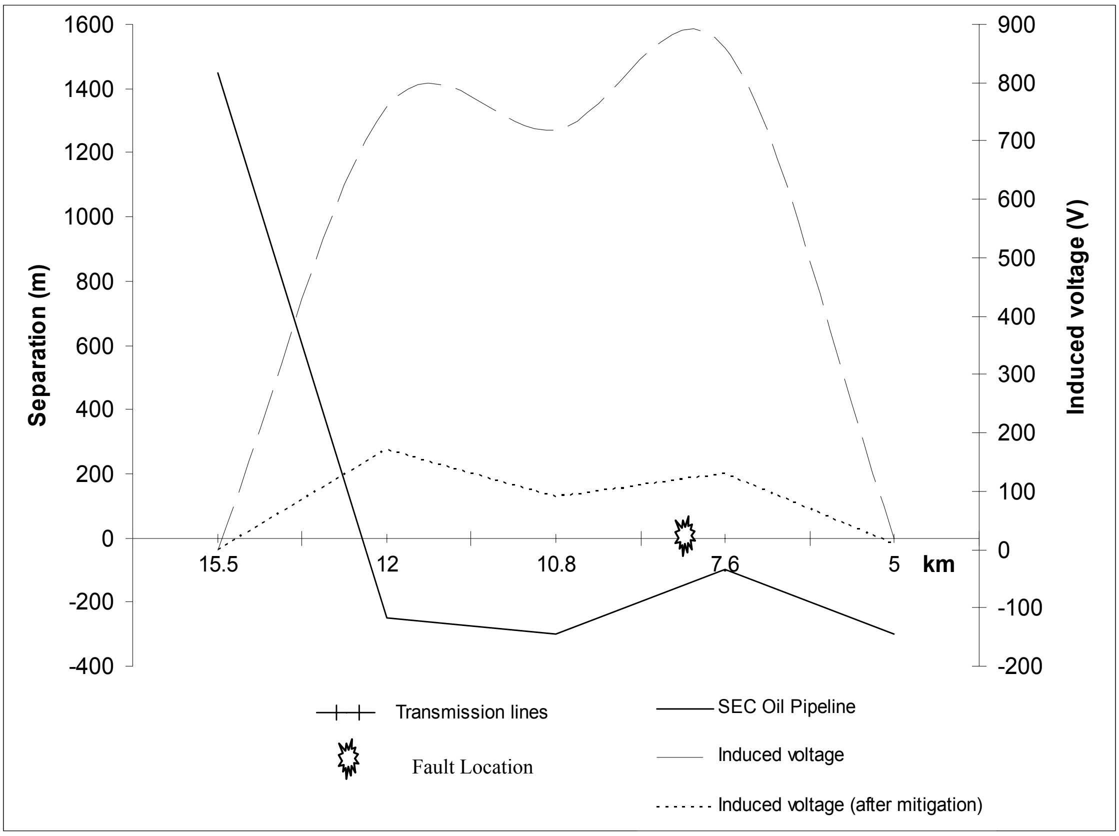

Figure 6.2 Touch voltage along the UA-1 Pipeline after mitigation

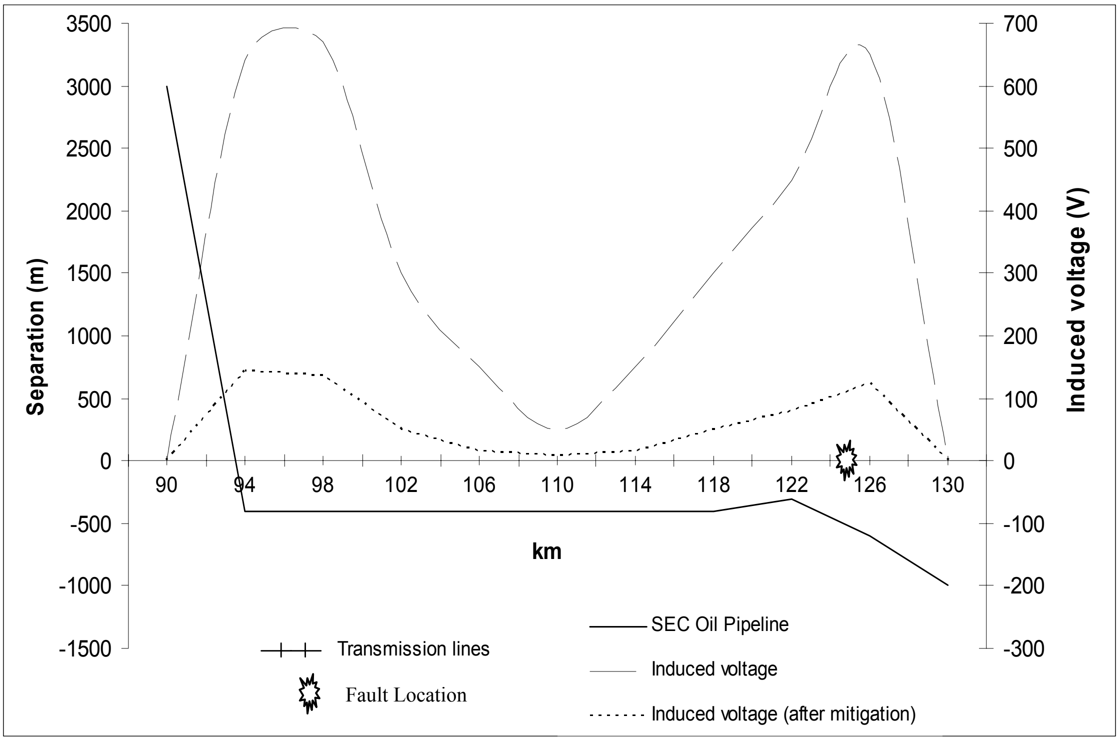

Figure 6.3 Touch voltage along the SEC Oil Pipeline after mitigation

CHAPTER VII

CONCLUSION

Electromagnetic fields, produced by the transmission lines on nearby pipelines and communication cables, generate uncontrolled voltages which can be a safety problem and distort communications. Therefore, there has been and still is growing concern about possible hazards resulting from the influence of High Voltage systems on metal pipelines.

This research covered the basis of electromagnetic field interference (EMI) theory, and it illustrated an actual comprehensive local case-study by using well known software which was acquired to assist in the simulation and evaluation of such EMI problems. It calculated, evaluated and analyzed interference effects on buried pipelines and underground communication cables, due to the nearby high voltage transmission lines.

The local case-study focused on the electromagnetic interference effects on Saudi Aramco buried pipelines and underground communication cables created by the nearby two 380 KV transmission lines operated by SEC in the Eastern Province of Saudi Arabia. Due to the complexity of the case-study, which includes more than one transmission lines and many buried pipelines, it was difficult to calculate the induced voltage by hand calculation. Thus, it was carried out using a well-known software program. The program was subjected to a validation test where the program simulation result was compared with the field measurements result. The test has shown good agreement between the simulated and measured values.

The local case-study of a 380KV transmission network with the nearby buried pipelines and underground communication cables was modeled, simulated, evaluated, and analyzed to ensure that the calculated induced voltages on these pipelines and communication cables are within international standards such as IEEE 80-2000 and IEC-479 and/or whether they need some mitigation measures.

The study revealed that the maximum induced voltage on all buried pipelines and underground communication cables during the steady state condition is within the standard limit and ranging between 0.06 and 15 volts. Most of these pipelines and communication cables are located more than 400 m away from the ROW, except one pipeline that runs close to the ROW for about 3.5 km and recorded a maximum of 15 volts.

However, the resulting touch voltages during the short circuit condition exceed the safety limits on two pipelines, and they reached 650-870 volts. These pipelines cross the ROW near the transmission line towers, and they run parallel with the transmission lines for a significant distance. The other buried pipelines and communication cables recorded low touch voltages, because they are mostly located more than 500 m away from the ROW, and they are far away from the power substations. Moreover, the soil resistivities at the locations of these pipelines are relatively low (20-50 Ω·m).

A mitigation system using gradient control wires has been simulated to reduce the pipeline potential to the safety limit. The proposed mitigation system significantly reduced the touch voltages on the two concerned pipelines during the short circuit condition. The mitigated touch voltages were much below the standard's safe limits.

While there has been a significant level of research on the performance of the mitigation systems for the EMI effects on the buried pipelines during the steady-state and fault conditions, little is known about their performance during lightning strikes. The EMI analysis and the mitigation system performance during the lightning condition is a direction for future research.

NOMENCLATURE

ACAR: Aluminum Conductor Alloy Reinforced

AWG: American Wire Gauge

C: Capacitance per unit length (F/m)

d: Geometrical distance between conductors (m)

E: Electromotive force induced per unit length (V/m)

E_F: Electrical field (V/m)

f: Frequency (Hz)

g: Euler's constant g = 1.7811

GMR: Geometric mean radius

h: Height of the pipeline

I: Current intensity (A)

I_F: Fault current (A)

I_d: Current density (A/m^2)

j: $\sqrt{-1}$

L: Length (of a circuit, of the zone of influence) (m)

R: Resistance (Ω)

r_{whole}: Radius of the pipeline including the coating layer

r_{outer}: Outer radius of the pipeline

r_{inner}: Inner radius of the pipeline

s: Area of coating defect

V: Voltage induced on a conductor

y: Admittance of a circuit per unit length $(\Omega/m)^{-1}$

Z: Impedance (Ω)

Z_m: Mutual impedance of two circuits per unit length (Ω/m)

z: Impedance of a circuit per unit length (Ω/m)

α: $\sqrt{\frac{\omega\mu_o}{\rho}}$

γ: $\sqrt{zy}$ = propagation coefficient of a circuit $(m)^{-1}$

ε: Electrical permeability of the air

$\varepsilon_o = 8.85 \times 10^{-12}$ F/m

μ_o: Magnetic permeability of the air

$\mu_o = 4\pi\ 10^{-7}$ H/m

ρ: Soil resistivity (Ωm)

ω: $2\pi f$ (rad/s)

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