华北电力大学

硕士学位论文

交流输电线路对埋地金属管道的电磁影响研究

Influence of Electromagnetic Field Generated by HVAC Transmission Lines on Nearby Underground Metal Pipelines

Giovanni DUSHIMIMANA

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硕 士 研 究 生：　Giovanni DUSHIMIMANA
导　　师：　Prof. Qi Lei
申 请 学 位：　工学硕士
专 业 领 域：　电力系统及其自动化
培 养 方 式：　全日制
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Candidate： Giovanni DUSHIMIMANA

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Giovanni DUSHIMIMANA

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摘 要

高压交流输电线路会对同走廊的地下天然气/石油金属管道感应产生很大电压，尤其是在输电线路发生故障时产生的影响更加严重。高压交流输电线路在天然气/石油地下金属管道上产生的电磁场会产生有害电压，对人员、管道及其相关保护设备（如阴极系统）造成威胁。如果感应电压不符合标准，则必须采取抑制措施，将这些感应电压降至对人员和管道安全的水平。

本文研究了 500kV 交流输电线路的电磁场效应。针对交流输电线路稳态运行和接地故障故障两种不同工况下产生的电磁干扰，使用CDEGS软件进行了全面的分析。对于稳态运行的工况，计算获得的大部分结果与 GB 6830-1986 标准保持一致。但是，由于交流输电线路单相接地短路产生的高电流，使得地下管道及其邻近土壤发生电位抬升，感应电压超出 ITU-T DL / T 5033-2006 中规定的标准限值。

为了解决这个问题，分析了两种不同类型的抑制措施（梯度控制线和接地电极）。通过仿真，发现所提出的抑制措施在不同水平的单相接地故障条件下都能大大降低两种情况下的感应电压。然而，梯度控制线技术能够将感应电压降低到比采用接地电极措施时更低的水平，因此建议采用前一种抑制措施，以将管道涂层感应电压降低到安全标准限值。

关键词: 交流干扰, 同走廊, 高压输电线路, 感应电压,

Abstract

High voltage AC (HVAC) power lines can induce significant amount of voltages on underground gas/oil metal pipelines in areas where they share similar Right of Way, the situation becoming more serious particularly in case of fault conditions. Electromagnetic field generated by the HVAC transmission lines on these gas/oil underground metal pipelines, generate unwanted voltages which present threats to personnel, the pipeline and its associated protective equipment such as cathodic systems. In cases where the induced voltages don't meet the standards, the application of mitigation is necessarily compulsory to minimize these induced voltages to levels that are safe for personnel and the pipeline.

This research studies the effect of electromagnetic field from a 500kV AC power line. A comprehensive interference analysis was performed on two different cases under steady state and fault condition using CDEGS software package. For the steady state condition, most of the results obtained are in agreement with GB 6830-1986 standard. However, due to high currents generated under single phase to ground short circuit, rising the potential of adjacent soil including the underground pipeline; induced voltages were found to be beyond the standard limits as stated in ITU-T DL/T 5033-2006.

To provide a solution to this problem, two different type of mitigation systems are analyzed (the gradient control wire and earth electrode). After simulation, the proposed mitigation systems are found to greatly reduce the induced voltages on both studied cases under single phase to ground fault condition at different levels. However, the gradient control wire technique reduces these voltages to much lower voltage levels than earth electrodes, the former mitigation technique is suggested for the implementation to lessen the pipeline coating voltage stress to safe standard limits.

Key words: AC interference, Right of Way, High voltage power lines, induced voltage, phase to ground fault

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List of Abbreviations

AC: Alternating Current
A.G.A: American Gas Association
API: American Petroleum Institute
ASTM: American Society for Testing and Materials
CDEGS: Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis
CP: Cathodic Protection
ECCAP: Electromagnetic and Conductive Coupling Analysis from Power lines and Pipelines
EFM: Electromagnetic Analysis Method
EMI: Electromagnetic Interferences
EPRI: Electric Power Research Institute
FEM: Finite Element Method
FDTD: Finite Difference Time Domain Method
HVAC: High Voltage Alternating Current
HVPL: High Voltage Power Line
ISO: International Organization for Standardization
LEF: Longitudinal Electric Field
MoM: Method of Moment
NACE: National Association of Corrosion Engineers
OHEW: Overhead Earth Wire
RMS: Root Mean Square
ROW: Right of Way
TEM: Transverse Electromagnetic

CHAPTER 1: General Introduction

1.1 Background

Electromagnetic interference (EMI) between high voltage transmission lines and metal pipelines has been a main concern in developed countries as people are in need of a lot of power, resulting in the high load demand. In fact, this concern has been raised since the 1960's. Environmental regulations, targeting to safeguard the ecosystem. Additionally, the fact was the unceasing growth of energy utilization conducting to the trend of locating power lines and pipelines along the same pathways. This has necessitated different utilities to share close or even common corridors for both power lines and pipelines due to an increase of the cost of rights-of-ways. That is why, today situations where a pipeline positioned in proximity to a transmission line for some kilometers are frequent [1], [2], [3].

Furthermore, the growth in human population every year, and with technology advancement and amelioration of the norms of living, new industries being installed specifically in cities, demanding the rise of energy demand. Due to this, electric power generation companies are forced to constantly expand their generation to meet the load demand. As energy demand rises, there is an associated rise in load demand which leads to the rise in balanced load current alongside the power lines. The rise in the transmission line currents enhance magnetic fields close to the power lines which regularly interferes with the surrounding metal pipelines [4]. The effect of electromagnetic field from transmission line affecting nearby buried metal pipeline is mainly concerned with the protection of personnel, pipeline safety and its protective system which is gradually becoming noticeable pulling the consideration of the relevant departments to apply new national standard for AC interference [5]. Because of this, there is an arising concern about the potential hazards that may result from the influence of electrical systems, resulting in huge economic loss due to high maintenance and repair costs of the pipelines. Thus, it is not surprising that there is a big concern for analyzing AC interference [6].

Moreover, interference between power transmission lines and pipeline normally comprises of an inductive, a capacitive and a resistive (conductive) part. The inductive part results from the magnetic field produced by power line, and may appear during steady state and faults operating conditions or during unbalanced phase currents situations [7]. Capacitive coupling is found to have effect only on the aboveground pipeline; due to the capacitance created between transmission line and earth, whereas for pipeline buried below the ground cannot experience this effect because the ground shields it. Resistive coupling between transmission line and pipeline appears only during phase to ground fault and lightning strike, which is followed by a significant drift of current into the earth through tower groundings rising the tower ground potential, and this may affect the coating of the surrounding underground pipeline [8].

Electromagnetic interference exists during both normal operating and faults conditions. Operations personnel in contact with the pipeline or appurtenances can be dangerously and potentially vulnerable due to the AC voltage is induced on a pipeline. In fact, high voltages can be induced to close pipelines, particularly during fault conditions, even when the fault occurs far away from the section close to the pipeline. Furthermore, the pipeline coating, insulating flanges or cathodic protection systems maybe highly damaged. In this way, the long-term interference may cause AC corrosion on pipelines as an outcome of the AC discharge from the pipeline generally for voltages between 4 and 10 V [9].

Over the previous years, scholars examined the above-mentioned problem; this resulted in several reports, manuscripts, and standards. Early tries to analyze this interference started with the well-known Carson's relations and Maxwell's equations using numerical methods (e.g. the finite-difference time-domain (FDTD) technique or the method of moments (MoM)) [1], [10]. Many other mathematical analyses were applied to compute mutual impedances and the induced voltages between the transmission lines and pipeline such as those proposed by Pollaczek and Sunde comprising semi-infinite integrals to evaluate semi-infinite integral terms with novel numerical integration scheme, built on good combination of numerical integration methods to overcome successfully the difficulties caused by the extremely oscillatory form of the infinite integrals [11]. Describing complex electromagnetic field problems with the application of finite elements method (FEM) for the solution of Maxwell's equations lead to valuable conclusions [12].

In 1976, Electric Power Research Institute (EPRI) and American Gas Association (A.G.A) both started a research project that produced a hand calculator program to calculate inductively induced voltages on pipelines parallel to transmission lines. Advanced research was done after in a continuation research program to develop a computer software which can deal with practical right-of-way in which transmission lines and pipelines are not permanently parallel. Later founding by EPRI and AAR emphasizing on interference to railroad facilities and computer program named CORRIDOR was made available. This program was qualified of calculating induced voltages on pipelines and railroad facilities under normal operating conditions. In the late 80's, Electromagnetic and Conductive Coupling Analysis from Power lines and Pipelines (ECCAP) was made available to calculate both inductive and conductive interference during fault states, a problem that was not able to be examined using the CORRIDOR software [13].

Lately, the development of software further expanded using the same database as input for AC mitigation simulations [6]. This deeply explains why industries showed a demand for the accessibility of user-friendly simulation software that would offer abilities for forecasting and mitigating inductively coupled voltages on underground pipelines paralleling high-voltage electric-power transmission lines. Still, most existing computer programs such as the CORRIDOR, ECCAPP, and PRCI program showed restrictions in modeling abilities to parallel or near parallel geometries.

Furthermore, most of the existing programs had restrictions in the number of pipelines, transmission lines, and (direct) connections that can be modeled. Because most of the complexity of system to be analyzed, this constraint becomes serious since in many corridors some pipelines are welded together (e.g., for cathodic protection reasons) [14]. The ECCAPP computer program, which was designed by the EPRI/A.G.A research program, merged a powerful input data preprocessor with a computation algorithm that was able to precisely calculate the effects conductive and inductive coupling for conductors positioned randomly above-ground and underground which could happen in the rights-of-way [15].

Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis (CDEGS) is a software suite of packages consisting of eight powerful and accurate computation engines (modules) devoted to precisely study problems implicating grounding, electromagnetic fields, EMI containing AC/DC interference mitigation studies and diverse aspects of cathodic protection and anode bed analysis with a complete assessment, starting exactly from the ground up [16]. This software that overcome the restrictions faced by previous software was designed by Safe Engineering Services & technologies ltd. The same software will be used in this project to analyze the effect of EMI on nearby underground metal pipeline.

This research aims to study the influence of electromagnetic field generated by HVAC transmission line on nearby underground metal pipeline under steady-state and single phase to ground fault condition. Updated research studies will be used to study inductive and resistive interference at all positions alongside the buried pipelines that remain within the neighborhood of transmission lines for significant distances. Furthermore, the effect of different parameters including: tower grounding resistance, soil resistivity, distance between the transmission line and underground pipeline, line load current, pipeline coating resistance and crossing angle will be analyzed using CDEGS software package. Results will be checked if they agree with Chinese standards and ITU-T DL/T 5033-2006. Mitigation systems will be taken into account where necessary to improve the safety of people, pipelines and appurtenances connected to them.

1.2 Research Status of Domestic and Overseas

The study of wave propagation throughout the ground has a history dating back to the beginning of the 20th century. Initial study attempts of this interference started with the well-known Carson's relations and Maxwell's equations using numerical methods, such as the Finite-Difference Time-Domain (FDTD) technique and the Method of Moment (MoM) [1], [10]. In 1926, Carson defined this problem by computing the values of distribution parameters for a quasi-transverse electromagnetic mode for a transmission line assuming the solution to be applied to very low frequencies and/or perfectly conducting earth [17]. In his paper published in 1944, Feinberg demonstrated a calculation derived from an integral equation that treated the problem of radiation over a planar earth having irregularities of terrain.

His demonstration revealed that the influence of small height irregularities would decrease the apparent conductivity of the earth. Detailed derivation of his publication was not presented, and his results did not demonstrate the effect of that finite earth conductivity [18].

Related improvements were published by Sunde, 1949 in his outstanding manuscript on earth conduction effects in power-line systems. Further advanced works have addressed to the high frequency behavior (kikuchi, 1956). In 1977, Kuesterand Chang demonstrated the first usage of full wave theory for a wire over a two-layer medium [18]. Recently, Ametani et al, 2015 examined how Carson's and Pollaczk formulae could deal with displacement currents based on a stratified earth impedance by assuming an earth-return admittance and studied high frequency wave propagation. The results showed that Carson's and Pollaczk formulae could deal with displacement currents when the relative earth permittivity is one [19].

In his paper, Satsios et al, 1997 analyzed the influence of a multi-layer ground on the electromagnetic field and on the inductive interaction between an overhead transmission line and underground pipeline. A different method applying finite-element method (FEM) for the solution of Maxwell's equations was suggested to resolve the problem of two dimensional electromagnetic field of a faulted overhead transmission line in the existence of underground conductors and multi-layer ground; this method were found to be valuable since it led to suitable solutions [12]. Nevertheless, owing to the large solution space of the problem, only two-dimensional (2-D) FEM computations were accomplished. The technique was also found to only be applicable to symmetrical cases (e.g., parallel routings) and to conditions where the pipeline has an ideal coating, which is a condition that is hardly met in reality [1].

Different methods attempting to develop more accurate models and compute the frequency dependent impedance of overhead transmission lines using different analytical approaches were reported in the literature [20]. A different methodology, intending the computation of the earth conduction effects on both the series impedances and the shunt admittances was suggested by Wise. Nakagawa further upgraded the semi-infinite homogeneous earth model, and prolonged the formulas for the series impedances earth modification terms for situations of multi-conductor lines and for earth structures containing of numerous horizontal layers with different electromagnetic properties, considering the displacement currents in the earth [21]. In the paper published in 2008, GUO Jian et al mentioned that in China the Department of electrical and plumbing are closely linked to adjust the electromagnetic effects to the limited value and regulate the electromagnetic effect of practical threshold to assure the safe operation, the control of project investment of great impact to support the construction of electricity and oil and gas transportation engineering [22].

At national and industry levels, China has started a sequence of national and industry standards comprising specifications of all topics that cover entire pipeline life cycle stages. The process begins from the design of pipeline, procurement and manufacture covering pipeline operation, maintenance and rejections.

These standards have strictly reinforced the work of pipeline construction and operation in China. Comprehensive changes were made regarding the improvement of pipeline design and manufacturing standards, thus increasing the overall pipeline construction technology.

In relation with international standardization organizations, Natural Gas and Pipeline Company has set up successful communication and interchange mechanisms with standardization organizations such as the American Petroleum Institute (API), International Organization for Standardization (ISO), American Society for Testing and Materials (ASTM), and National Association of Corrosion Engineers (NACE). This dynamically took part in standardization research by tracking and implementing state-of-the-art international, national and industry standards. From 2011 to 2015, a full review and publication of 62 industry standards, 12 national standards were made available, including [23]:

- GB 50251-2015 "Code for design of gas transmission pipeline engineering"
- GB/T 31032-2014 "Welding and acceptance standard for steel piping and pipelines"
- GB 50253-2014 "Code for design of oil transportation pipeline engineering"
- GB 50369-2014 "Code for construction and acceptance of oil and gas long-distance transmission pipeline engineering"
- SY/T 4109-2013 "Nondestructive testing standard of oil and gas steel pipeline"
- SY/T 0086-2012 "Electrical isolation of cathodically protected pipelines"
- GB/T 50698-2011 "Standard for AC interference mitigation of buried steel pipelines"

AC induced corrosion experienced an increasing concern in Germany in 1986, when cathodically protected gas pipeline was discovered punctured attributing the failure to induced AC voltages. In 1987, another gas pipeline in Switzerland showed analogous breakdown which was also credited to AC. Later, comparable incidents were also described in the US, Canada and France [24].

In the United States (U.S), pipeline proprietors and operators have the responsibility to safeguard their properties in regions where it is sensible to anticipate the discharge of electrical currents into the earth, for example owed to substations or high-voltage transmission lines ground-faults, or lightning strikes. Practical situations have been recognized and studies showed that put down power lines can produce electric arcs emerging through the soil via resistive coupling and attack underground pipelines, therefore affecting their coating. In the past 20-year period from 1988 through 2008, corrosion has been accountable for 18% of the major incidents (both onshore and offshore) reporting failure of materials to 22.9% in the same period. Protection against corrosion in the U.S is mandatory for transmission pipelines carrying natural gas and risky liquids (e.g. oil) to avoid their deliberate discharge into the ecosystem. The release of such products can seriously affect neighboring residents, properties, and also cause ecological destruction followed by high economic loss [25].

Australian standard established two distinct categories of acceptable voltage limits for metal pipelines. These are classified as Category A and Category B, describing normal touch voltages based on the category of contact.

Category A touch voltage parameters are categorized as limits valid for the parts of pipeline reachable by the public whereas Category B touch voltage parameters are categorized as limits valid for the parts of the pipeline with restricted public access.

These limits are found by combining the current level and their applied time. Normal induced voltage limits have been outlined in the Australia/New Zealand standards 853:2000, Electrical Hazards on Metallic Pipelines and AS/NZS 3835.1, Earth potential rise protection of telecommunications network users. The allowable voltage limits are summarized in Table 1-1. [26].

Table 1- 1: Low frequency interference (LFI) limit under fault condition

	Limit category	
	Category A	Category B
Fault duration	≤ 350 ms	≤ 500 ms
LFI hazard voltage limits	1500 V	1000 V

European standard CEN/TS 15280 provides the following recommendations for AC corrosion:

The pipeline is believed to be safe from AC corrosion when the Root Mean Square (RMS) alternating current density is lesser than 30 A/m^2. Basically, the likelihood of AC corrosion is assessed on a wider basis:

- current density lower than 30 A/m^2: no or low likelihood of AC corrosion,
- current density between 30 and 100 A/m^2: medium likelihood of AC corrosion,
- current density higher than100 A/m^2: very high likelihood of AC corrosion.

Currently in the U.S., AC mitigation is generally determined by the safety attentions with prime emphasis of reducing the induced AC voltage below 15V with respect to surrounding soil for balanced power system operation on above-grade portions where people could interact with the pipeline or appurtenance, to guarantee the agreement with the NACE Standard RP0177. In Germany, the maximum acceptable voltage limit is set to 65V (Technical Recommendation N^0. 7, "Measures for the installation and operation of pipelines in the vicinity of three-phase high voltage systems and single-line traction systems") and 60V in China as stated in the national standard GB 6830-86 "telecommunication lines from power lines allow the dangerous effects of the specified value" [22].

1.3 Layout of the thesis

Chapter 1, outlines the background of the study and research status of domestic and overseas.

Chapter 2, gives the literature review on EMI mechanism between power lines and underground pipelines, limit values for the safety of personnel and pipeline, mitigations used, and mathematical calculations of EMI and the description of CDEGS software.

Chapter 3, presents comprehensive computation of EMI under steady state operating conditions of the power line and application of mitigations.

Chapter 4, presents the calculation of EMI under single phase to ground fault conditions of the power line and the implementation of mitigations.

Chapter 5, presents the simulation results for the project application case study under steady state and fault condition and the application of mitigation system.

Chapter 5, presents the conclusion of this research and suggestion of the future work research.

CHAPTER 2: Literature Review

2.1 Electromagnetic Interference Mechanism (Modes)

In several situations, due to the electromagnetic field produced by these high voltage lines, the metal pipelines placed near the high voltage line are exposed to induced voltage and alternating current. Operating personnel may experience the danger of these induced voltages and currents, while the pipeline structure may lose its integrity due to corrosion effects. Interferences resulting from high voltage power line are classified into three types as detailed below [27].

2.1.1 Inductive (Electromagnetic) Interference

The evaluation of inductive Interference effects needs to distinguish between the inductive coupling during steady state and fault operational states of the power transmission lines.

A. Effects under normal operating conditions

During the steady state conditions, the vector sum of the three phase currents in overhead transmission line is zero. Induced voltages in the pipeline neighboring the overhead power line result from the irregular position of the power line conductor configuration and the pipeline. The voltage will be the sum of the magnetic fields generated by the current in the overhead line. The magnitude of the potential induced in the pipeline is affected by [28]:

- The distance separating power line and pipeline;
- The length of parallelism;
- The load current of the overhead transmission line;
- The overhead transmission line configuration (e.g., single or three phases with or without earth conductor and vertical or horizontal configuration);
- The magnitude of the zero-sequence current;
- The size of the pipeline (diameter);
- The resistivity of the soil neighboring the pipeline; and
- The resistance and reactance of the pipeline.

B. Effects during fault conditions

When a single-phase to earth fault appears in the power line (i.e., one of the three live wire is shorted to the transmission line structure or substation grounding system), induced voltages in the pipeline can reach thousands of volts when no mitigation system applied, due to the extreme magnetic field produced by the high current flowing in the defective wire. In the study of AC inductive interference, it is crucial to give serious attentions to power lines that are 300 meters or more away from the power line under consideration [13].

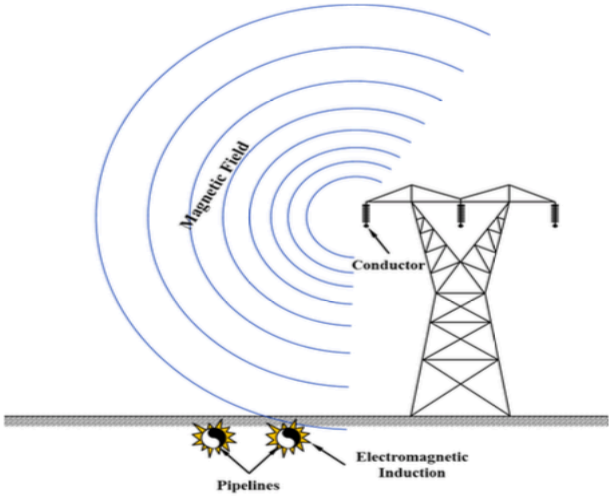


Figure 2- 1: Illustration steady state AC inductive interference

2.1.2 Resistive (Conductive) Interference

This type of interference occurs when lightning strikes a transmission line, or when there is a phase-ground fault. When this happens, induced high voltages appear on neighboring pipelines, even when the fault appears in distant zone of contact with the pipeline section [29]. This leads to the increase of the pylon base potential and that of nearby earth with respect to the distant earth, resulting in a significant stress voltage across the pipeline coating, Due to the formation of the arc, it may cause damage to the coating or even the pipeline itself [8].

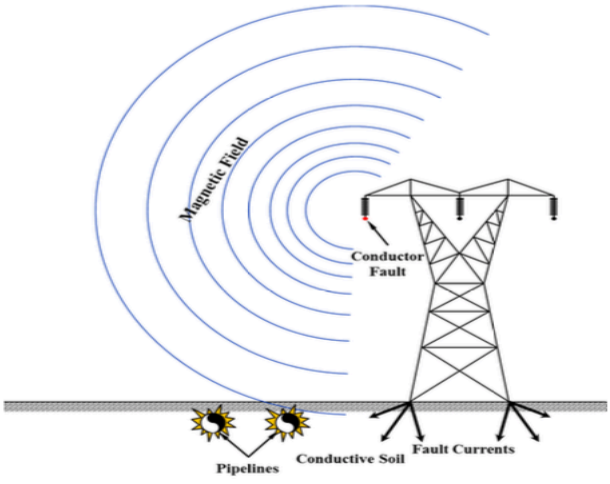


Figure 2- 2: Illustration of resistive interference

2.1.3 Electrostatic (Capacitive) Interference

This type of capacitive interference is caused by a capacitance created between the AC transmission lines and the above-ground pipeline, in series with the capacitance created between the above-ground pipeline and nearby soil. The electric field tends to transfer electrons from the ground to the pipeline and also from the pipeline to the overhead power line.

Underground pipelines don't experience this type of interference because the capacitance formed between the pipeline and ground is small, even when dielectric welded coatings are used [30].

Electrostatic or capacitive interference are mostly experienced during the construction when the welded pipeline is placed on a good insulated basis close to high voltage power lines; the induced voltage might attain level able to be threaten the personnel. This phenomenon is avoided by grounding the welded pipeline every 100 m [31].

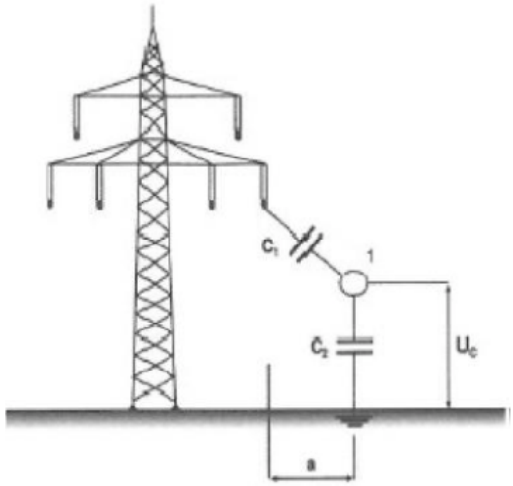


Figure 2- 3: Illustration of capacitive interference

2.2 Electromagnetic Interference Limits

2.2.1 Personal Safety Voltage

A. During normal operation of transmission line

In 1972, IEEE Working Group studied on the critical value of human current, when it flows through the body at 50Hz/60Hz. The results showed that, no pain was felt for Alternating Current less than 6mA even for women and children. GB 6830-86, for the telecommunication line suffering from the danger of strong electric power line, the permissible value of the power line at normal operating condition under the allowable value of the longitudinal electromotive force on the communication wire is 60V. The above criteria consider the safety voltage limit that is loaded into the human body when a telecommunication worker touches a communication line. As stated in GB 3805-93 and GB 6830-1986, the safe voltage for human body long-time is 33V (general public) and 60V (professional staff) respectively. Therefore, in this study we use 60V as the human body long-time safety voltage limit as determined according to professional personnel. Long-time effect of the human body safety voltage limit standards are shown in table 2-1 [32].

Table 2- 1: Human body long time safety voltage standards

Related standards	Safety Voltage limit (V)
United States NACE RP 0177-95	15
CSA Standard C22.3 No.5-M1991	15
SY/T0032-2000	15
GB 3805-93	33
IEC 61201	33
GB 50054-1995	50
German Afk third standard	65
GB 6830-1986	60
ITU-T	60
CIGRE guide,1995	50-65
CCITT standard,1989	60 (Piping without any precautions) 150 (Security measures are in use)
TB/T 2832-1997 (China's railway industry standards)	60

B. During a short-circuit fault in the transmission line

Generally, the possibility of personnel being seriously exposed to the pipeline under fault state is minor. Yet, because the fault current can be transferred alongside the pipeline for certain distance from the faulted tower position, the safety of personnel must stay an essential consideration [33]. This gravity of the personnel hazard is generally proportionate to the magnitude of the potential difference between the structure and the earth or between different structures and varies with the exposure duration [34]. Presently, China's new power transmission lines have high reliability making the probability of failure to be very small. In addition, in the case of a failure of the line the probability of the relevant workers to be in contact with the bare metal parts of the pipeline is very small. Therefore, the national standard adopted DL/T 621-1997 as the standard of personal safety voltage in short-circuit fault of transmission line [32]. Standards for Instantaneous safety voltage of human body under short term action are shown in table 2-2

Table 2- 2: Instantaneous safety voltage standard of human body under short term action

Related standards	Voltage Limit Value (V)
DL/T 621-1997	$U_S = \frac{174 + 0.17\rho}{\sqrt{t}}$
IEEE	$U_S = (1000 + 1.5\rho)\frac{0.157}{\sqrt{t}}$
GB6830-1986 CCITT（ITU-T Pre-title)	t＞0.5，430 t＜0.5，650
ITU-T DL/T 5033-2006	0.5＜T ≤1.0，430 0.35＜T ≤0.5，650 0.2＜T ≤0.35，1000 0.1＜T ≤0.2，1500 T ≤0.1，2000

2.2.2 Pipeline Safety

A. Safe Operation Voltage of Pipeline

Germany Afk standard N^03 for high voltage AC equipment and communication requires actions to be taken during the installation and operation of pipelines in railways facilities. Interference between equipment of the German Railways, Deutsche Post and German Power Stations considers that for short term failure with no protective measures, the acceptable short-term disturbance voltage to be up to 1 kV and for asphalt covered pipelines, short-term allowable maximum voltage limit not greater than 1.5 kV, in this situation grounding measures may not be taken into consideration. Referring to foreign standards, paper [22] suggested 1kV to be taken as the safe voltage limit of the pipeline during the assessment of transient voltage caused by short time faults [22].

2.2.3 AC Corrosion (Leakage Current)

In the past decades, soil corrosiveness showed a main danger to the integrity of the underground metal pipelines, and this has become a main concern for pipeline proprietors [35]. AC current density has been found to be a valuable parameter for determining the rate of corrosion caused by AC interference. To lessen chance of pipeline corrosion occurrence in the presence of AC interference, the measured voltage between the pipeline and soil at a particular point alongside the length of the pipeline at any time should not go beyond 10V when the earth resistivity is higher than 25Ωm, and 4V when the earth resistivity is lower than 25Ωm [4].

Moreover, corrosion level of the metal pipeline and the corrosion resistance of the corroded layer is also measured according to the density of the current flow in the pipeline to the soil. Maximum current density recommended by the ISO standard is $3mA/cm^2$. The maximum values of pipeline voltage and leakage current density set by various standards and regulations for AC corrosion of metal pipelines are shown in table 2-3.

However, during the assessment of pipeline corrosion level, it is suggested to use 3mA/cm^2 as recommended by ISO 15589-1-2003 standard [22].

Table 2- 3: Limit values about voltage or leakage current relative to corrosion of pipeline

Relevant standard	Voltage limit/V	Leakage current density/mA/cm^2
SY0032-2000	8	-
ISO 15589-1-2003	-	3
A concise handbook on cathodic protection	-	5
Institute of physical structure Chinese Academy of Sciences	-	5

2.3 Electromagnetic Interference Mitigation

Mitigation systems usually includes the installation of one or more grounding devices to let AC current to quickly discharge off of the pipeline therefore protecting the pipeline and the personnel. They are planned to decrease induced currents, voltages and coating stress voltages to safe values during steady state and fault operating conditions of the power line [36]. Several types of mitigation approaches have been used however some of them were found to be either ineffective or costly. The following part explains different protective methods applied to mitigate AC impact on metal structures exposed to AC interference hazards.

2.3.1 Insulating Joints

They are inserted between the sections of the pipeline to decrease propagation of induced voltage. The pipeline is split into segments allowing the affected section in case of cathodic protection system failure to be electrically isolated from others. Due to the proportionality existing between induced voltage and the length of the section parallel to the power line, this makes insulating joints to be effective in reducing the effect of AC interference on the metal pipeline when the electrical length of the pipeline exposed to power lines is small. To protect the joint and the pipeline, polarization cells or surge arresters are fixed across the joint to divert this energy to ground [37].

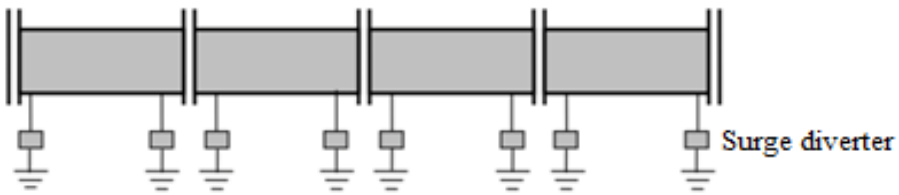


Figure 2- 4: Insulating joints method

2.3.2 Lumped Grounding

This is the easiest and old method also called "brute force method" used to drop AC interference values on pipeline by connecting the pipeline to earth electrode at certain positions. The size of the required electrode is considerably affected by the earth resistivity in the

considered zone [38]. The impedance of the grounding system is sufficiently kept low, therefore reducing the pipeline potential at the connected point to whichever desired value. Rising the soil resistivity results in the increase of the systems size. Moreover, these systems should be fitted at many positions which makes the system to be both costly and almost unpractical. However, in regions with low earth resistivities, this technique can lead to adequate protection system [39].

2.3.3 Cancellation Wires

This method is built on a theoretical concept of carefully positioning cancellation wire at positions where induced voltage in the cancellation wire will be at dissimilar phase angle than the voltage induced the pipeline therefore, reducing the voltage induced in the pipeline. The cancellation wire is an uncovered underground conductor positioned parallel to the power line at an optimal separation distance to get highest induced voltage cancellation. In much situations, the cancellation wire is placed on the position of the transmission line opposed to the pipeline [40]. This method has a drawback of only canceling inductive part of the fault currents and this result in transferring unsafe voltages to the isolated termination. This method also necessitates purchasing extra terrain for the settlement of the conductor therefore, increasing the implementation cost [38].

2.3.4 Gradient Control Wire

Current developments in interference mitigation led to gradient control wire technique. This technique involves uninterrupted and extended earth wire or wires fixed horizontally and parallel to the pipeline section at planned lengths with unvarying connection gaps. Their purpose is to offer security to the structure and pipeline coating during normal and fault conditions from close power transmission lines. Gradient control wires are able to decrease the steady-state voltages and the likelihood of piercing the coating or structure under fault conditions [34]. They achieve their task by counter-balancing the difference between the pipeline and earth potential.

During the occurrence of inductive interference, gradient control wires deliver extra earthing for the pipeline, consequently declining the induced voltage increase to the pipeline. Directly, neighboring earth potentials are increased by these wires leading to smaller touch and coating stress voltages. In the situation of conductive interference, gradient control wires reduce the ground potential growth in the vicinity of the pipeline immediately rising the pipeline potentials. This also leads to the decrease of touch and stress voltages [13].

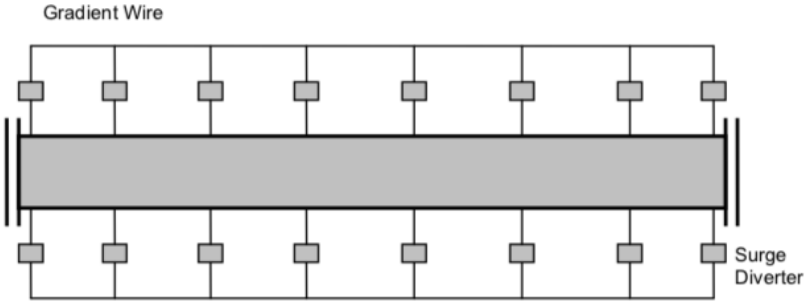


Figure 2- 5: Gradient control wire method

2.4 EMI Calculation Method and CDEGS Software

2.4.1 Calculation of induced voltage using Telegraph and Carson's Equations

A. Telegraph Equations Formulation

The approximation of the pipeline to ground voltage at every location along the parallel length of the underground pipeline can be done using an equivalent circuit applied to the pipeline transmission line circuit. The pipeline is modelled as a lossy transmission line comprising series impedance and shunt admittance together with a voltage source which is equal to the longitudinal EMF induced on the pipeline. The equivalent circuit of a section of the pipeline with length L running parallel to an overhead high voltage power line is shown in figure 2-6 [41].

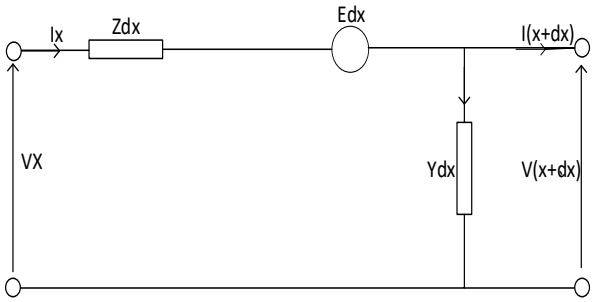


Figure 2- 6: Equivalent circuit for a section of a transmission line model of the pipeline earth electrical circuit

$Zd(x)$ = impedance from sending end point of the line; $V(x)$ =potential from sending end point of the line; $V(x+dx)$ = potential from receiving end point of the line; $I(x)$ = current at the sending end point of the line; $I(x+dlx)$ = current at the sending end point of the line; Ydx : admittance of the line; $E(x)\,dx$: induced Emf on the pipeline PUL (V/m).

From figure 2-6, by applying Kirchhoff's voltage and current law, the corresponding transmission-line equations, are derived as follows: [42], [3], [43]

$$V(x) - Zd(x)I(x) + E(x)d(x) - [V(x) + dV(x)] = 0 \tag{2-1}$$

$$I(x) - [I(x) - dI(x)] - YdxV(x) = 0 \tag{2-2}$$

Dividing (2-1) and (2-2) by *dx* we get:

$$\frac{dV(x)}{dx} = -ZI(x) + E(x) \tag{2-3}$$

$$\frac{dI(x)}{dx} = -YV(x) \tag{2-4}$$

Differentiating (2-3) and (2-4) and combine them give the second-order differential equation for the induced voltage and current:

$$\frac{d^2V(\mathrm{x})}{dx^2} = \gamma^2 V(\mathrm{x}) + \frac{dE(\mathrm{x})}{dx} \tag{2-5}$$

$$\frac{d^2I(\mathrm{x})}{dx^2} = YZI(\mathrm{x}) - \mathrm{E}(\mathrm{x}) \tag{2-6}$$

Z: series impedance Per Unit Length (PUL) of the pipeline-earth circuit

Y: parallel admittance Per Unit Length (PUL) of the pipeline-earth circuit
E: induced Emf on the pipeline PUL

Equations (2-5) and (2-6) are written as follow:

$$V(\mathrm{x}) = (\mathrm{A}e^{\gamma x} + B\,\mathrm{e}^{-\gamma x}) \tag{2-7}$$

$$I(\mathrm{x}) = \frac{E}{Z} + \frac{1}{Z_c}(\mathrm{A}e^{\gamma x} - B\,\mathrm{e}^{-\gamma x}) \tag{2-8}$$

where $Z_c = \sqrt{\frac{Z}{Y}}$, is characteristic impedance of the pipeline-earth circuit and $\gamma = \sqrt{ZY}$, the propagation constant of the pipeline-earth circuit.

$$A = \frac{E(1+\mathrm{v}_1)\mathrm{v}_2 - (1+\mathrm{v}_2)\mathrm{e}^{\gamma L}}{2\gamma(\mathrm{v}_1\mathrm{v}_2 - \mathrm{e}^{2\gamma L})} \tag{2-9}$$

$$B = \frac{E(1+\mathrm{v}_1)\mathrm{e}^{2\gamma L} - \mathrm{v}_1(1+\mathrm{v}_2)\mathrm{e}^{\gamma L}}{2\gamma(\mathrm{v}_1\mathrm{v}_2 - \mathrm{e}^{2\gamma L})} \tag{2-10}$$

The constants A and B depend on the boundary conditions at the ends of the pipeline, where:

$v_1 = \frac{Z_A - Z_c}{Z_A + Z_c}$ Reflection factor at the beginning of the pipeline

$v_2 = \frac{Z_B - Z_c}{Z_B + Z_c}$ Reflection factor at the end of the pipeline

The E(x) is the induced electromotive force generated by the transmission line on the unit length pipeline. Under normal operation, the disturbing current is constant along the zone of influence. Impedance and admittance parameters are computed using the following formula [3], [14]:

$$Z = \frac{\sqrt{\rho_p \mu_o \mu_r \omega}}{\pi D\sqrt{2}} + \frac{\mu_o \omega}{8} + j\left[\frac{\sqrt{\rho_p \mu_o \mu_r \omega}}{\pi D\sqrt{2}} + \frac{\mu_o \omega}{2\pi}\ln\frac{3.7\sqrt{\rho\omega^{-1}\mu_o^{-1}}}{D}\right] \tag{2-11}$$

$$Y = \frac{\pi D}{\rho_c \delta_c} + j\omega \frac{\varepsilon_o \varepsilon_r \pi D}{\delta_c} \tag{2-12}$$

ρ_p Resistivity of the pipeline Ωm; μ_o magnetic permeability of the air $4\pi \times 10^{-7}$ H/m; μ_r relative permeability of the pipeline; ρ resistivity of the soil Ωm; D diameter of the pipeline (m); ρ_c resistivity of the coating Ωm; δ_c thickness of the coating (m); ε_o electrical permittivity of the air 8.85×10^{-12} F/m; ε_r relative permittivity of the pipeline coating. Formulas (2-12) is normally used for above ground pipelines but it is also valid for underground pipelines (except for uncovered pipelines or pipelines with low values of the specific coating resistance r_c .

B. Carson's Equations Formulation

Low Frequency Interference depends upon the physical circuits configuration (distance between transmission line circuits and pipeline, earth return circuit, soil resistivity) [44]. For underground pipeline parallel with transmission line carrying alternating current of frequency 50 Hz, Carson's formula is used to calculate the self and mutual impedances between the transmission line and the pipeline [45]. Thereafter, these impedances are used to calculate inductive interference between power lines and the pipeline.

Mutual impedance between the i[th]-phase conductor of the transmission line and the pipeline $Z_{ph(\mathrm{i})_p}$ is given by (1) [46], [4]:

$$Z_{ph(\mathrm{i})_p} = \mu_0 \times \frac{\omega}{8} + j\left(\mu_0 \times \frac{\omega}{2\pi}\right) \times \ln\left(\frac{D_{ex}}{D_{ph(\mathrm{i})_p}}\right) \tag{2-13}$$

where ω is the angular frequency; μ_0 is the permeability of the vacuum; and $D_{ph(\mathrm{i})_p}$ represents the distance between the i[th]-phase conductor and the pipeline. The depth of earth return-path (m) is given as: $D_{ex} = 658.5\sqrt{\frac{\rho}{f}}$, ρ is resistivity of the soil; f :system frequency (Hz). For an overhead earth wire with earth return resistance R_E and geometric mean radius of R_{GM}, self-impedance of the overhead earth-wire (OHEW) Z_E can be computed as follows:

$$Z_E = R_E + \left(\mu_0 \times \frac{\omega}{8}\right) + j\left(\mu_0 \times \frac{\omega}{2\pi}\right) \times \left(\frac{1}{4} + \ln\left(\frac{D_{ex}}{R_{GM}}\right)\right) \tag{2-14}$$

For the parallelism length between the high voltage power line (HVPL) and underground pipeline of length L, the total induced voltage on the pipeline with overhead earth wire is given by:

$$V_p = \sum_{i=1}^{n} Z_{ph(i)_p} \times I_i \times L \tag{2-15}$$

2.4.2 CDEGS software

This software package was released by SES-tech in 1970's, it has been extensively used all over the world, in the study of electrical induction and conduction problems appearing in varying three-dimensional lossy environments (e.g. air and soil) while time-harmonic currents are introduced into different locations of the network of randomly positioned conductors in the same location [47], [37].

The package encompasses numerous independent modules aimed to solve different problems. The widely used modules integrated in the software package for our study of electromagnetic interference are described below [8], [44], [37], [48]:

1. The module of HIFREQ developed based on the electromagnetic analysis method (EFM) is used in calculation of the interferences between HVPL and neighboring metal structures.

2. The module of Right-of-Way is used to compute the inductive and capacitive components and can also be used to design mitigation systems of electromagnetic interferences.

3. The MALZ module calculates EMI during the transient condition.

4. The TRALIN module determines the self and mutual impedances of underground and overhead wires including transmission line phase conductors, ground conductors, pipelines, and communication lines.

5. SPLITS module calculates steady state and fault current distributions in each segment or span of the power line networks defined in the TRALIN module, whether balanced or not.

Study Procedure

The analysis of EMI between HVPL and buried pipelines should consider the entire system and not just the pipeline alone. Usually a typical complete study should include the following tasks:

Data Collection: the foremost step in the study of the interference problems is the collection of pipelines and to the transmission line parameters.

1. Pipeline Data

a. System overview of the region under study describing the following data:

- Length of pipelines under study,
- Length of power lines close to the pipeline under study,
- Pipeline appurtenances (e.g. metering valves, insulating joints, earthing and anode beds linked with the pipeline),
- Vertical and horizontal distances between pipelines and power lines.

b. Pipeline parameters:

- Burial depth
- Wall Thickness
- Coating Resistivity

- coating thickness
- Relative Resistivity
- Outer Diameter
- Inner Diameter
- Relative permeability

2. **Transmission line parameters**

- Transmission line voltage (kV)
- Normal operating load current (kA)
- Number of circuits and bundle spacing
- average height of conductors (phase and ground conductors)
- Number phase and ground conductors
- Conductor parameters (e.g. resistance, permeability, permittivity)
- Fault current parameters

3. Soil resistivity at multiple depths and locations at exposed structures along the Right of Way.

2.5 Summary of the chapter

In this chapter, the effect of electromagnetic interference and their mode of interference were discussed. In this field area, inductive and conductive interferences are most dominant. These are found to be more harmful not only on the metal pipelines close to transmission lines but also to personnel that might be in contact with the pipeline due to the considerable voltage generated especially in fault conditions. The level of impact depends on the duration of contact, the weight of the person and the soil resistivity. Mitigation systems generally applying the installation of grounding devices to protect the pipeline and Personnel are also discussed in this chapter.

Advancement in modeling and mathematical analysis were not left behind to investigate EMI. It is in that case, researchers started to analyze this problem using different mathematical analysis methods. Carson were the first to study these interferences using numerical integration methods. Later on, different methods such as FDTD, MoM and FEM technique were used and found to be effective in different situations. This chapter focused on Carson and Telegraph equations for transmission lines to compute the induced voltage on underground metal pipelines as they are used in this research to compute these interferences. Furthermore, this chapter outlined different modules of the CDEGS software used in this research together with procedures and data required for the analysis of EMI.

CHAPTER 3: EMI Analysis under Normal Condition

3.1 Description of the Case Study

As defined before, this research intends to analyze the effect of EMI created by HVAC transmission line on nearby underground metallic pipelines. In our case study, a 50 Hz, 500 kV AC double vertical circuit line running parallel to an underground metal pipeline for a distance of 20 Km and extending for 5 km outside the parallel routing at both terminations as indicated in figure 3-1, is modelled and analyzed under steady state operating condition. Under this condition, the voltage generated on the pipeline is normally associated with the power line and pipeline structure, and parameters. In the calculation, a double vertical circuit line configurated in reverse phase sequence (ABC-CBA), a horizontal and triangular circuit with the span of 500 m are examined to analyze the effect of the generated electromagnetic field on the pipeline. The phase conductors of the double vertical circuit are configured with 4-bundle conductors per phase, fixed in vertical configuration on a steel tower structure with bundle spacing of 400 mm. The equivalent radius of the phase conductor is 188 mm, relative resistivity ρ=9.67 S/m and relative permeability ε_r=1. The two overhead earth conductors are at 65m above ground with an equivalent radius of 5.7 mm, relative resistivity ρ=9.67 S/m and relative permeability 636. In this analysis, it is assumed that the earth conductor is continuously and periodically grounded.

The underground metallic pipeline is buried at 1.6 m below the ground, with inner radius of 485 mm and outer radius of 505 mm. The thickness of the anti-corrosive layer is 3 mm while the resistivity of the anti-corrosion layer is $3*10^4$ Ωm^2. The relative resistivity ρ=9.67 Ωm and the relative permeability ε_r=300, with a relative dielectric constant of 2.3. The soil is assumed to be homogenous with a resistivity of 100 Ωm. The tower is nearly formed by 4 vertical thin conductors each with the resistivity of 1.66×10^{-7} Ωm, equivalent radius of 6 mm and relatively magnetic permeability of 636. The conductors made of steel are buried at the depth of 0.6 m, with a radius of 6 mm, resistivity of 1.66×10^{-7} Ωm, and a magnetic permeability of 636. The horizontal length between the power line and the pipeline is 200 m.

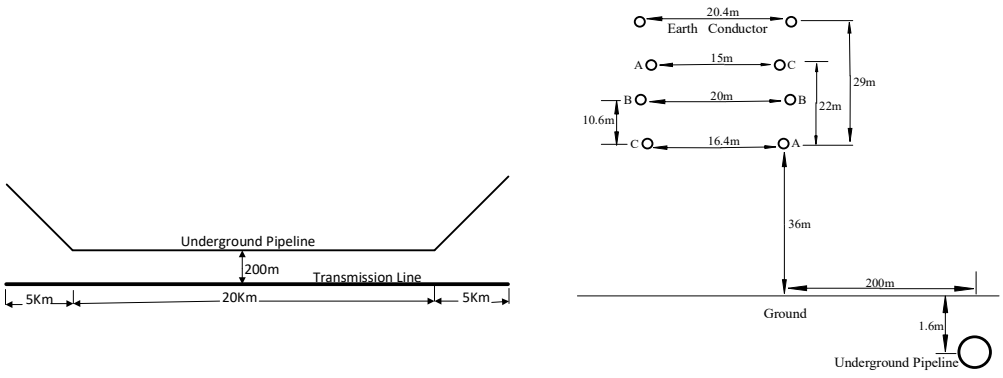


Figure 3- 1: Model of shared corridor of transmission line and underground pipeline

3.2 Case Study Simulation and Results Interpretation

The simulation of the aforementioned case study is modeled using CDEGS software package to determine induced voltages on the underground pipeline caused EMI during normal conditions. In situation of steady state operating condition of the power line, the voltage induced on the pipeline is mostly affected by power line and pipeline parameters, their configuration and earth resistivity surrounding the pipeline. In this section different parameters influencing the pipeline integrity are analyzed under normal operating condition with a balanced load current of 2 kA.

From figure 3-2, it is observed that the voltage induced on the pipeline is in inverse proportion to the lateral distance between the power line and the pipeline. By varying the distance from 50 m to 500 m the peak induced voltage decreases from 33 V to 9 V. This is because the farther the pipeline is from the power line, the better the overall symmetry of the power line relative to the pipeline, therefore, lower induced voltage on the pipeline. However, the maximum voltage appears at the extremities of parallelism, and this voltage decreases exponentially where it reaches zero at the center of the pipeline. This is agrees with the author in [49] where in his research stated that, the maximum induced voltage occurs at both terminations of the pipeline where it is electrically disconnected from the rest of the pipeline for cathodic protection purposes. Therefore, we can conclude by saying that pipeline should be installed far away from transmission lines to avoid problems of induced voltage.

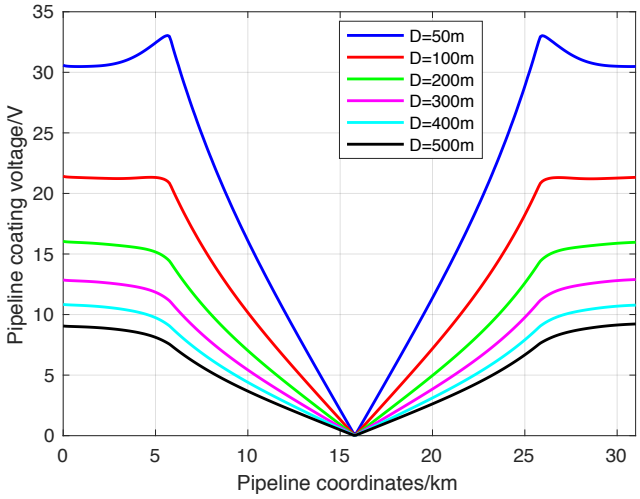


Figure 3- 2: Effect of distance between power line and pipeline

The effect of earth resistivity is observed from figure 3-3, induced voltage on account of variation of earth resistivity is much more important than other parameters. These induced voltages are in proportion with the earth resistivity. High soil resistivity means high system impedance and this results to the rise of the induced voltage [39]. Therefore, the higher the earth resistivity, the larger induced voltage on the pipeline leading to high stress of the pipeline coating. It is observed that for earth resistivities above 1000 Ωm, the change in induced voltages become slight. The results are in agreement with authors in [44], [50].

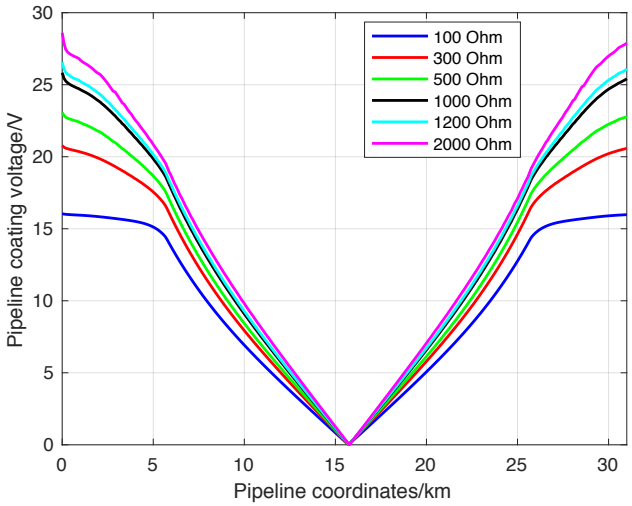


Figure 3- 3: Effect of earth resistivity

Figure 3-4 illustrates the impact of steady load current on the induced voltage. From the figure it is observed that induced voltage rises with the rise of load current, this is caused by the rise in magnetic field formed near the power line conductors when the load current is increased therefore, leading to high induced voltage on the pipeline. The results coincide with the author in [51].

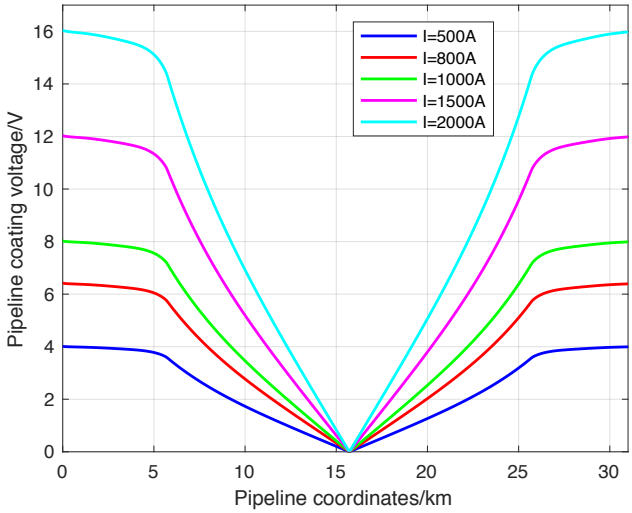


Figure 3- 4: Effect of load current

Figure 3-5 illustrates the impact of the distance of parallelism, where it is changed from 5 to 30 Km. The analysis demonstrates that the peak induced voltage on the pipeline increases progressively with the expansion of the pipeline length. It is observed that when the maximum voltage attains a particular value, it starts to decline lightly and tend to be stable. At this point where the highest voltage occurs corresponds to saturated length of the pipeline; this is the pipeline length that makes the maximum induced voltage on the pipeline attain its maximum value [32] and the results match with author in [8].

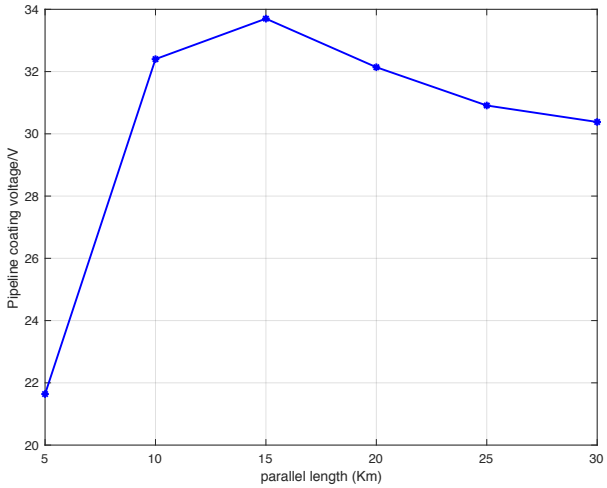


Figure 3- 5: Effect of parallel length

Figure 3-6 displays the change of curves of the induced voltage on the pipeline with diverse phase sequence arrangement type of the double vertical circuit power line. During the simulation, the left side is in ABC sequence while the right-side is arranged in 6 different phase sequence (ABC, ACB, BAC, BCA, CAB, CBA). It is observed that the arrangement of the power line in different phase sequence arrangement has great impact on the voltage induced on the pipeline. This is caused by the magnetic field being canceled out in the power lines depending on the phase angle of current in the power line conductors.

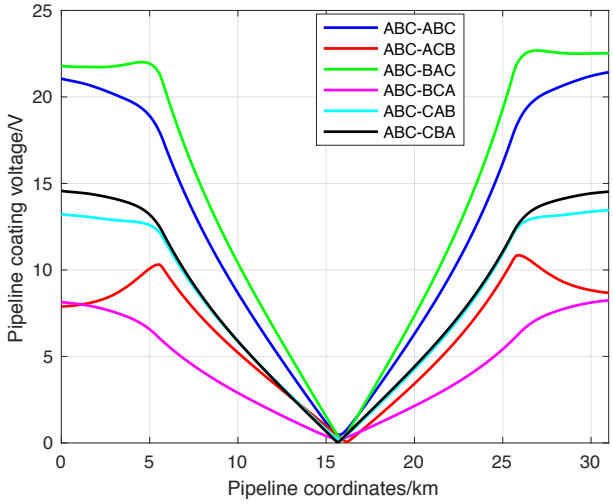


Figure 3- 6: Effect of phase sequence

Figure 3-7 shows influence of pipeline diameter on the change of voltage induced on the pipeline. 3LPE and FBE anti-corrosion layer are analyzed at different diameter size as follows: 108 mm, 219 mm, 406 mm, 660 mm, 813 mm, and 1016 mm. From the figure, it is observed that the bigger the pipeline diameter, the lesser the voltage induced on the pipeline coating. This is caused by the proportionality existing between the diameter of the pipeline and the propagation constant of the pipeline which leads to the decline of the impedance per unit length of the coating.

We can also see that voltage induced on the pipeline with FBE coating to be upper than that of 3LPE coating, this is because the resistivity of the ant-corrosion layer is proportional to the induced voltage, the greater the resistivity the superior the induced voltage. The results are in agreement with author in [32].

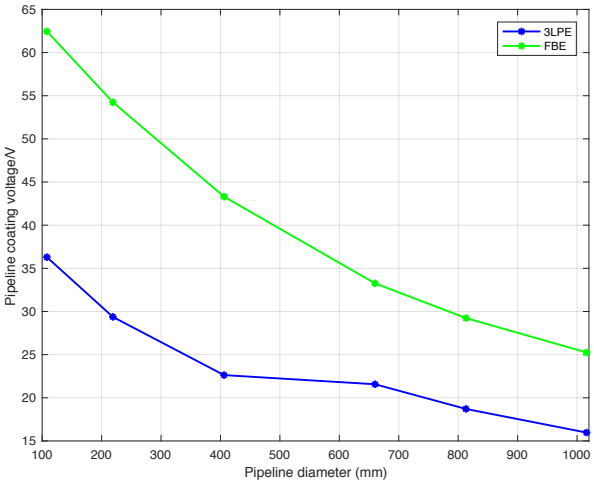


Figure 3- 7: Effect of pipeline diameter

Figure 3-8 illustrates the change in induced voltage on the pipeline with different resistivity of the pipeline anti-corrosion layer. It is observed that the greater the resistivity of the anti-corrosion layer, the more the induced voltage on the pipeline coating. This is on account of the resistivity of the anti-corrosion layer which is in inverse proportion to the propagation constant of the pipeline which results in the increment of the impedance per unit length of the anti-corrosion layer, therefore producing larger induced voltage on the pipeline coating. Pipelines that have low coating resistance, due to being buried underground for a long time, are less disposed to inductive interference from nearby power lines. However, the leakage currents flowing through the leakage resistances become much larger [50].

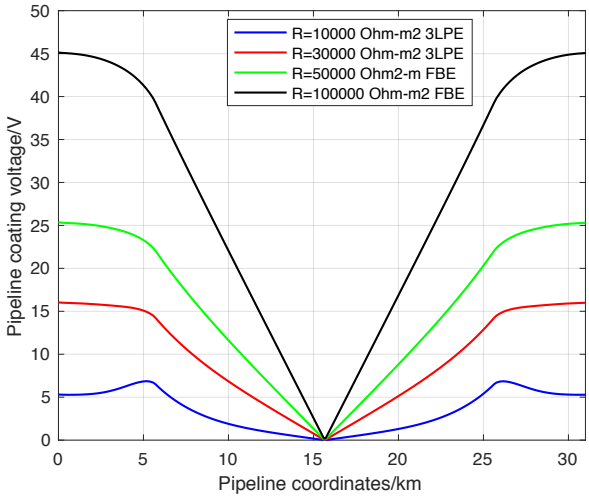


Figure 3- 8: Effect of resistivity of pipeline coating

Figure 3-9 illustrates the profile of induced voltage on the pipeline with different type of tower configuration. From the figure it is observed that the induced voltage produced by the horizontal circuit tower on the adjacent pipeline is the largest, followed by triangular tower, and the double vertical circuit tower generating the lowest among the other configurations. It is clear to mention that for the double vertical circuit, the two-circuit conductor are designed in reverse phase sequence. Therefore, the configuration of the power line has a significant effect on the voltage induced on the pipeline since it goes with phase sequence and phase angles of the lines which are found in return to have effect on EMI generated by the power line. The results are in agreement with author in [32].

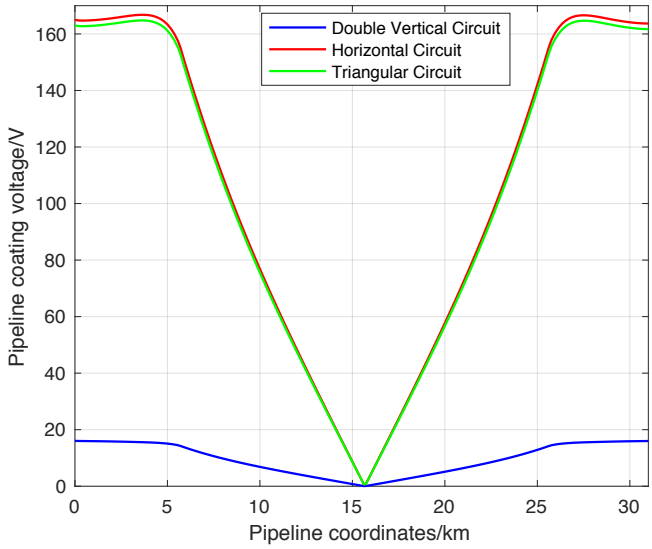


Figure 3- 9: Effect of tower type

Figure 3-10 shows the maximum anti-corrosion layer voltage of the pipeline under different ground resistivity and cross-over angle. The earth resistivity is 100 Ωm, 300 Ωm, 500 Ωm, 800 Ωm, 1000 Ωm, 1200 Ωm and 2000 Ωm respectively. The two conductors of the double vertical circuit are structured in reverse phase sequence, and the pipeline crosses the transmission line at different angle: 15^0, 25^0, 30^0, 45^0, 60^0,75^0, and 85^0 and extends far away at both ends. From the figure it is observed that the angle at which the pipeline intersects the power line has a great impact on the voltage induced on the pipeline coating. The maximum induced voltage is in inverse proportion with the cross-over angle; the smaller the angle the larger the voltage. As the angle between the pipeline and power line expands, the magnitude of induced voltage drops as the segment of the pipeline exposed to induction reduces. The voltage induced on the pipeline is effectively minimized when the pipeline crosses the power line at or near 90° because the effective parallel length is minimized [52].

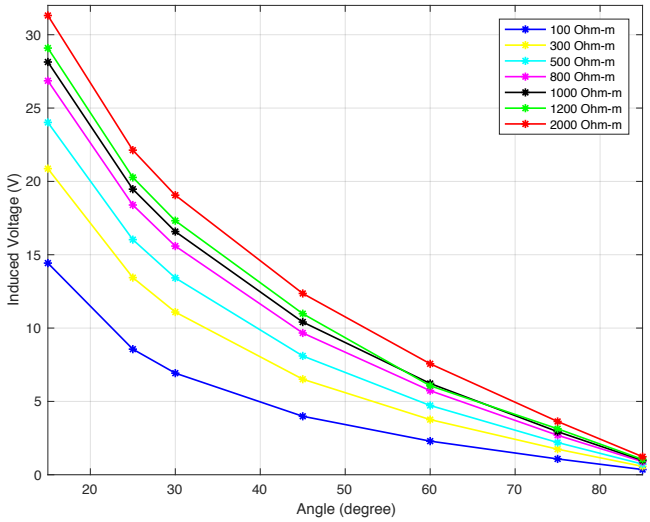


Figure 3- 10: Effect of cross-over angle

Figure 3-11 describes the change of the induced voltage on the pipeline owing to the variation of length between phase conductors for a horizontal circuit power line. Figure 3-12 illustrates the variation of the induced voltage under different phase conductor height to ground for the double vertical circuit. Form both figures, it is observed that the farther the line conductors are from the ground and the smaller the phase spacing, the lower the voltage is induced on the pipeline. This is due to the fact that the exterior phase conductor gets more distant from the pipeline which decreases the phenomenon of interference. Similarly, it is due to the fact that the mutual effect of the two nearer conductors is decreased as they get more close to each other [45].

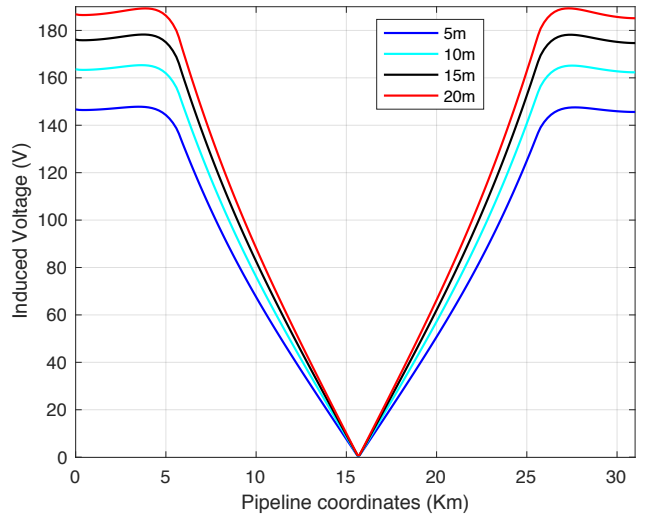


Figure 3- 11: Effect of phase conductors spacing

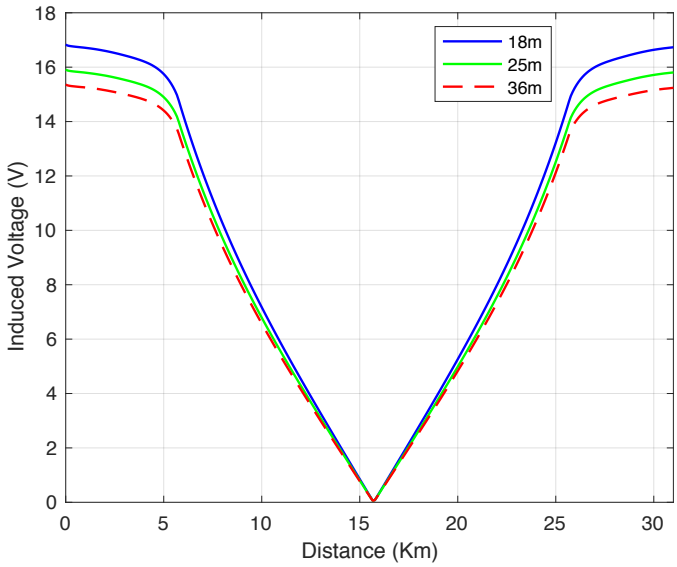


Figure 3- 12: Effect of average height to ground of phase conductors

Figure 3-13 shows the level of influence of the overhead earth conductor on the voltage induced on the pipeline under steady state operating conditions. By considering the effect of ground conductor and not considering the effect of ground conductor; it is observed that the voltage induced on the pipeline anti-corrosion layer with ground conductor is greater than the voltage induced without ground conductor. This is justified by the fact that the presence of the ground conductor interrupts the magnetic field balance of the power line leading to higher induced AC voltage on the buried pipeline [53].

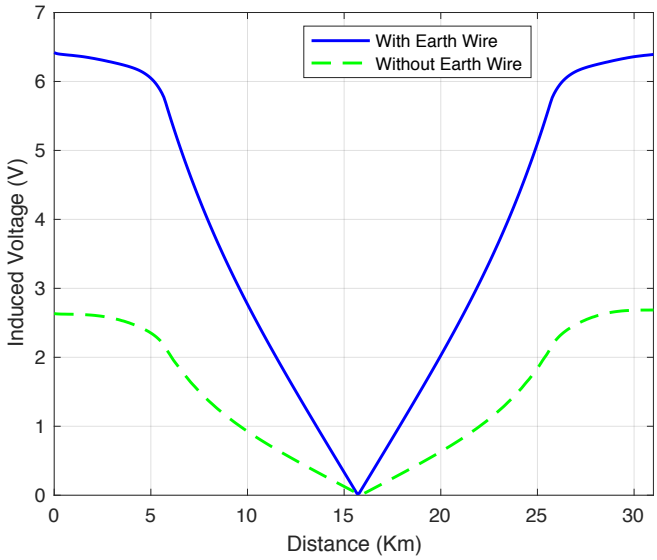


Figure 3- 13: Effect of overhead ground conductor

3.3 Application of Mitigation Systems

Simulations indicated that for most parameters analyzed, the peak voltage induced on underground pipeline under normal condition was in agreement with GB 6830-1986 standard, except for pipeline with FBE anti-corrosion coating layer, horizontal circuit tower type, triangular tower type and phase wire spacing. Therefore, this section deals with the application of mitigation systems to diminish these voltages to the level which cannot destroy the pipeline. Gradient control wire mitigation technic is proposed and applied to minimize the danger of these voltages. This method consists of a pair of 10Ω bare copper wire buried parallel to the pipeline at the depth of 1.6 m and connected to the pipeline at unvarying intervals.

Figure 3-14 shows the application of mitigation for voltage induced when spacing between phase wires is 20m known the worst-case scenario as it is observed from figure 3-11. The figure is subdivided into 3 subplots. In subplot 1, the gradient control wire has 316 welding connections with pipeline at unvarying intervals, subplot 2 has 78 welding connections and subplot 3 with 32 welding connections. From the figure it is observed that when the number connections are 32 induced voltage is 63.8V and for 78 connections the voltage decreases to 60.5V, while for 316 connections the voltage decreases to 59.3V. From these voltage profiles, we can deduce that the voltage induced on the pipeline diminishes with the increase in number of bonding.

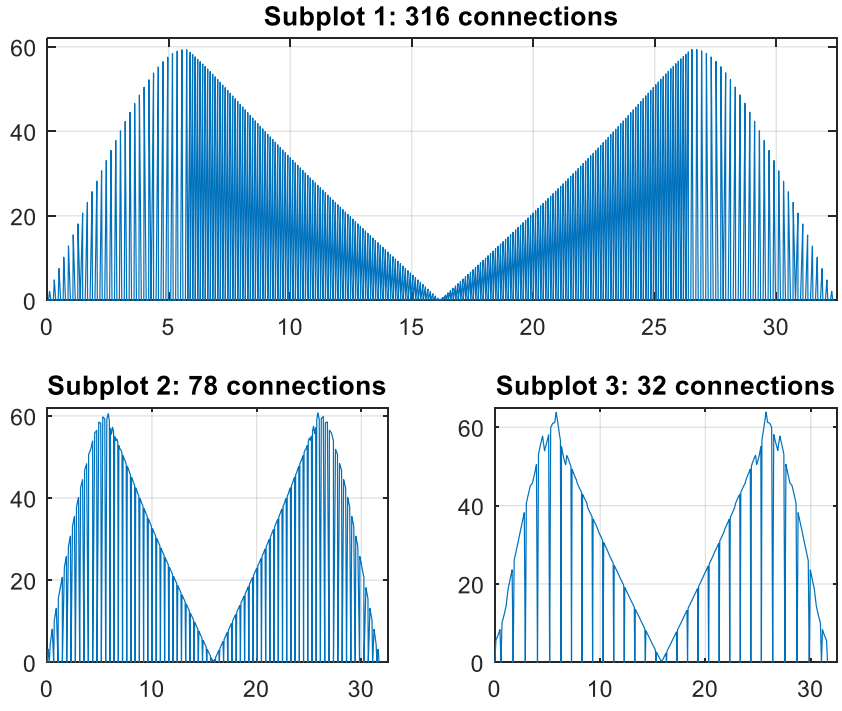


Figure 3- 14: Effect of phase conductors spacing

Figure 3-7 shows influence of pipeline diameter on the change of voltage induced on the pipeline. From the figure, it is observed that pipeline with FBE ant-corrosion layer at a diameter equal to 108mm to induce the highest voltage that goes beyond standards.

Figure 3-15 shows the voltage profile after the application of mitigations. From the same figure it can be observed that these voltages reduced significantly to safe values which are not harmful to personnel.

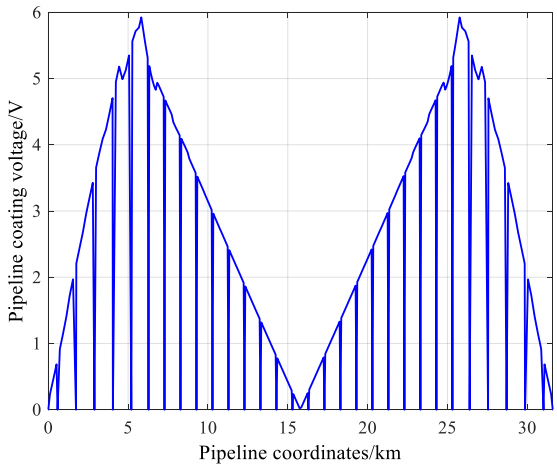


Figure 3- 15: Effect of pipeline diameter (FBE type)

Figure 3-16 and 3-17 show the induced voltage profiles after applying mitigations to the case of horizontal and triangular circuit tower type. Referring to figure 3-9 it is observed that gradient control wire achieved its purpose where it decreased these voltages significantly to levels below 60V which is considered to be safe value for personnel under long term exposition to EMI from AC power lines. These voltages decreased from 166.8V to 56.75V (%) for horizontal circuit tower type and from 164.8V to 55.11V (%) for triangular circuit tower type.

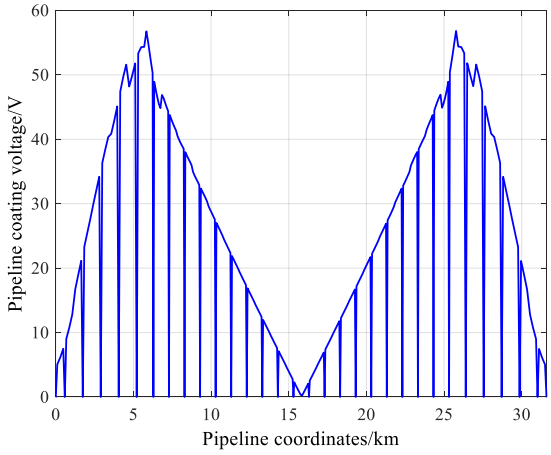


Figure 3- 16: Effect of tower type (Horizontal circuit)

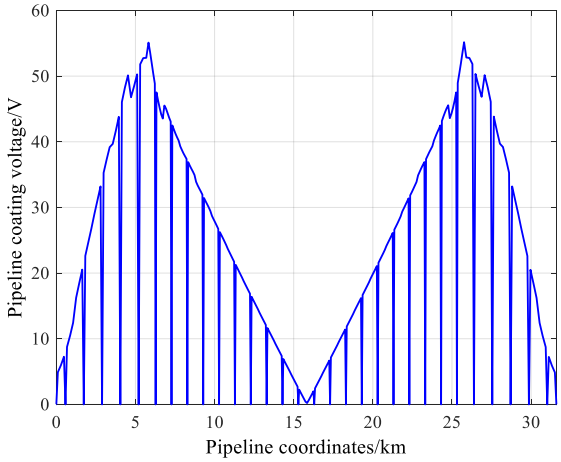


Figure 3- 17: Effect of tower type (Triangular circuit)

3.4 Summary of this Chapter

This chapter described the case study of power line running parallel to an underground pipeline which is modeled and analyzed using CDEGS software package under steady state conditions. Numerous parameters (e.g. earth resistivity, pipeline diameter, resistivity of ant-corrosion layer, distance between phase conductors, length of parallelism) that affect the pipeline next to power transmission line were analyzed.

It revealed that these parameters affect the pipeline at different level of significance. FBE anti-corrosion coating layer, horizontal circuit tower type, triangular tower type and phase wire spacing were the parameters that induced voltage greater than 60V on the pipeline which are beyond the standard limits for personnel safety as stated in GB 6830-1986. Therefore, gradient control wire method was applied to these cases to minimize the level of the voltage induced on the pipeline to safe values. This method was found to be efficient because it achieved this purpose.

Chapter 4: EMI Analysis under Single Phase to Ground Fault

4.1 Introduction

Generally, fault current loads particularly phase to ground faults present major impact on the degree of AC interference induced in the adjacent metal structures. When a single-phase to ground short-circuit fault arises in the power line, the fault current produces higher magnetic field around the conductor compared to the normal condition resulting in increased level of threat to the underground pipeline. The fault occurring on the tower creates large currents that travel down to the ground via the tower grounding structure causing the neighboring ground potential to increase; these fault currents generate resistive interference effect on the pipeline.

4.2 Simulation Results and Discussion

This part studies the effect of different factors that affect the pipeline safety under a single phase to ground fault on the double vertical circuit. In this case study, a transmission line routes parallel to a pipeline for a distance of 10 Km, and then prolongs outside the parallel routing at both terminations for a distance of 2.5 km. The horizontal length between power line and pipeline is 400 m while other parameters remain the same as for steady state condition.

Figure 4-1 illustrates voltage induced on the pipeline once a single phase to ground fault appears on each phase of the power line. It is observed that the level of fault current differs with the faulted phase. In our model, phase conductors are aligned in ABC sequence from up to down. It observed that the highest voltage to be induced on the lower conductor and decreases as we move up. We can say that, the closer the phase conductor to ground, the higher voltage induced on the pipeline. This is caused by the distance travelled by the fault currents since these currents varies with tower grounding resistance; the longer distance, the higher the resistance thus, low voltage induced on the pipeline, and vice versa. In the situation of fault, the typical "V" shaped curve is got more clearly, this is due the effect of the electromagnetic field generated by the unfaulted phases which is too low compared to the one generated by the faulted phase. This is in agreement with author in [51].

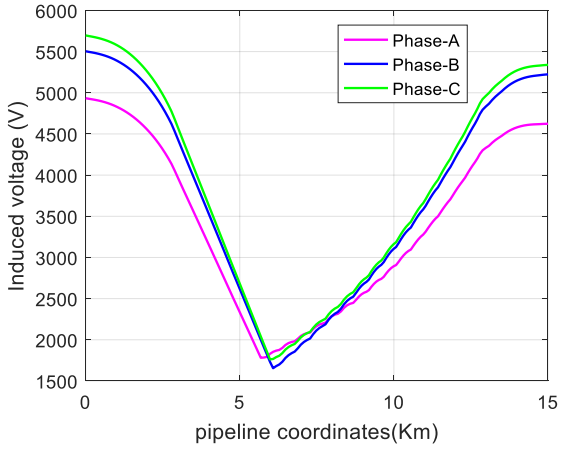


Figure 4- 1: Effect of short circuit fault on different phases

The magnetic field produced by transmission lines in fault state is in proportion with the fault current flowing in the faulted phase conductors to the ground and in inverse proportion with the horizontal length separating the power line and pipeline. From figure 4-2, it is observed that by extending the horizontal length D from 100 m to 600 m decreases the voltage induced on the pipeline by 62%. Apparently, the longer the separation length between power line and adjacent pipeline, the lesser the voltage induced on the pipeline. This is clarified by the fact that the induced voltage on pipeline rises when the separation distance reduces, since increasing the separation results in a lower interference interaction between power line and the pipeline, therefore leading to a lower induced voltage [39].

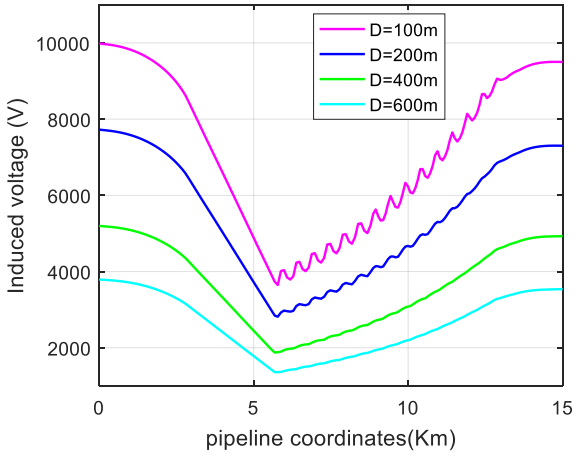


Figure 4- 2: Effect of distance between power line and pipeline

Figure 4-3 shows the maximum induced voltage on the pipeline as a function of earth resistivity. During calculation the ground resistivity is 100 Ωm, 300 Ωm, 500 Ωm, 1000 Ωm, and 2000 Ωm, respectively. From the figure it is observed that, the maximum induced voltage on the pipeline rises gradually with the rise of the earth resistivity. It is again noticed that when the ground resistivity is less than 1000 Ωm, the maximum voltage changes significantly with the rise of the earth resistivity. When the ground resistivity is greater than 1000 Ωm, the variation in the maximum voltage changes slightly becoming almost flat. This is caused by the proportionality existing between the resistivity and the impedance. Low soil resistivity implies low mutual impedance between the power line and the pipeline and this results in lower induced voltage created on the pipeline [54].

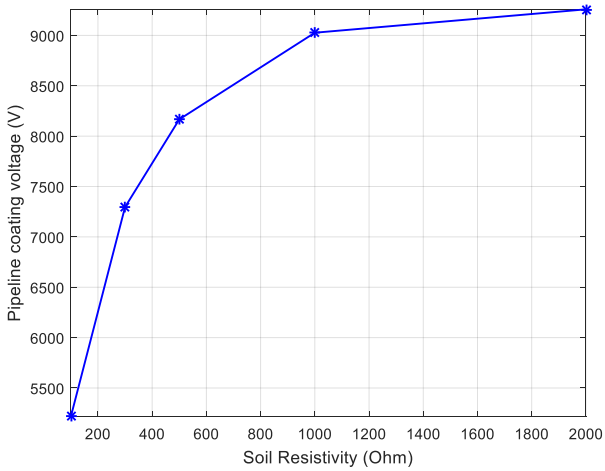


Figure 4- 3: Effect of earth resistivity

Figure 4-4 shows induced voltage on the pipeline with change in pipeline diameter. During calculation, the pipeline diameter (outer radius/inner radius) is respectively 40.65 cm/39.55 cm, 50.5 cm/48.5 cm, and 60.95 cm/50.95 cm. It is observed that the induced voltage decreases somewhat with the enlargement of the pipeline diameter. This is due to the fact that a larger diameter of the pipeline will normally have a lower effective resistance to ground, and therefore tends to induce lower voltage on the pipeline [52].

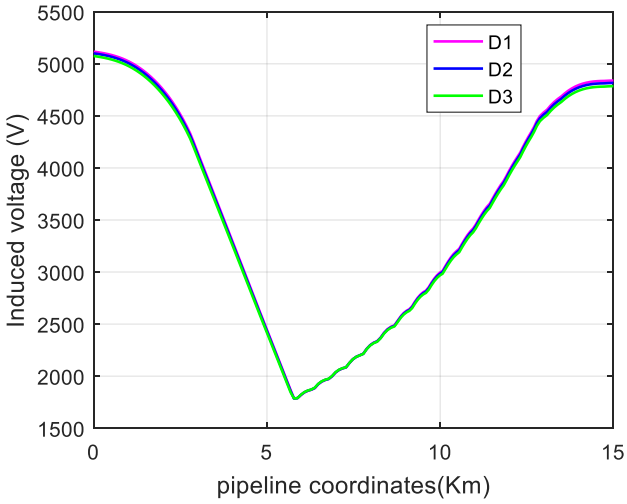


Figure 4- 4: Effect of pipeline diameter

The parallel length is one of the influencing factors required to be studied when a single-phase to ground fault occurs in a power line. During the simulation, the parallel lengths between the power line and the pipeline are calculated as 4km, 6km, 8km, and 10km respectively, other calculation parameters remaining unchanged. Figure 4-5 shows the maximum induced voltage on the pipeline as a function of the parallel length between the power line and the pipeline. It is observed that the maximum induced voltage progressively rises with the rise of the parallel length. The parallel length affects the magnitude of induced voltage collected on the pipeline as it defines the length of the pipeline exposed to the Longitudinal Electric Field (LEF) of the phase conductors [52].

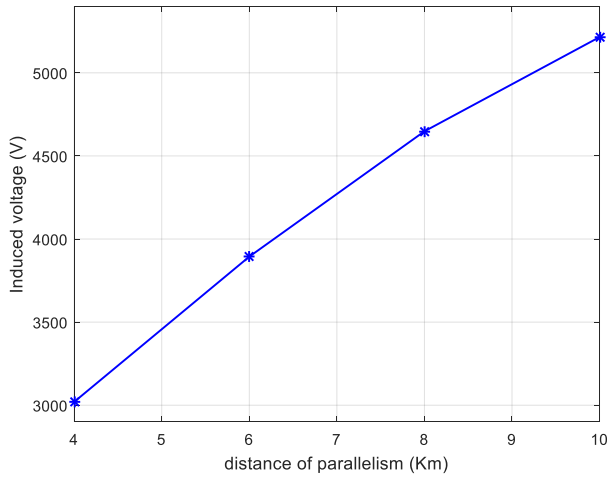


Figure 4- 5: Effect of parallel length

During analysis, the values of the grounding resistance are 1 Ωm, 5 Ωm, 10 Ωm, 15 Ωm, and 20 Ωm, respectively. Figure 4-6 demonstrates the influence of earthing resistance on the highest value of the induced voltage on the pipeline. It is observed that this value declines with the rise of the earthing resistance value. Generally, when a fault occurs in the power line, generated large currents flow into the ground through the grounding structures of the tower. Therefore, grounding resistance is of big importance in the computation of the induced voltage on the pipeline. Certainly, the greater the grounding resistance of the power line, the lower short-circuit current will be, and this will induce low voltage on the pipeline. This is due to the fact that under fault condition, induced voltage on the pipeline is affected by the current reaching the ground neighboring the tower and the pipeline. Therefore, this voltage decreases because the increase in grounding resistance decreases the amount of fault currents reaching the ground. This is also in agreement with author in [54].

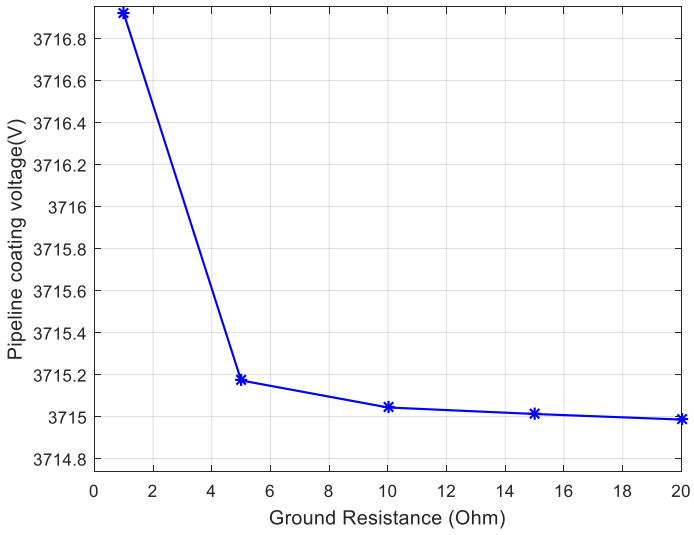


Figure 4- 6: Effect of tower grounding resistance

Figure 4-7 shows the maximum anti-corrosion layer voltage of the pipeline under different cross-over angles between the power line and pipeline. The two-phase wires of the double vertical circuit are structured in reverse phase sequence, and the pipeline crosses the transmission line at 15^0, 25^0, 30^0, 45^0, 60^0, 75^0, and 90^0 respectively, extending far away at both ends. It is observed that the angle at which the pipeline intersects the power line has a great impact on the voltage induced on the pipeline coating. The smaller the angle the larger the voltage induced on the pipeline. As the angle between the pipeline and power line expands, the magnitude of induced voltage drops as the segment of the pipeline exposed to induction reduces. The voltage induced on the pipeline is effectively minimized when the pipeline crosses the power line at or near 90° because the effective parallel length is minimized [52].

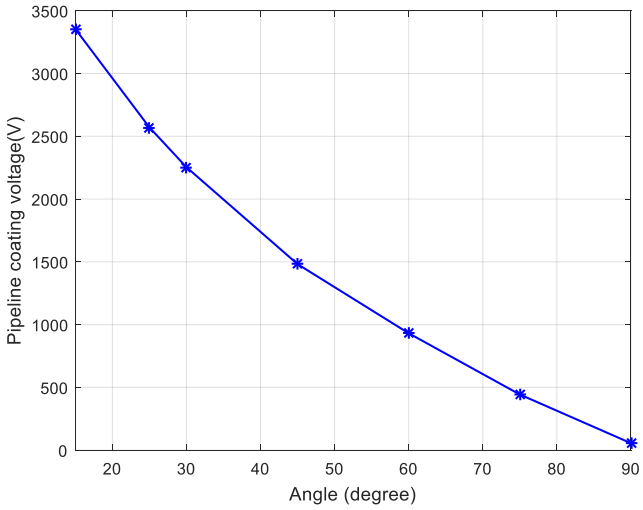


Figure 4- 7: Effect of intersection angle between line and pipeline

Figure 4-8 illustrates the curve of maximum resistive stress voltage induced on the pipeline coating for different locations of the phase to ground fault on the power line. When analyzing, the position of the points is respectively located at the 2^{nd}, 4^{th}, 6^{th}, 8^{th}, and 10^{th} tower of the transmission line, other computation parameters remaining unchanged. It is observed that the maximum resistive voltage induced on the pipeline coating due to single phase to ground faults does not change with the change in the position of the fault in the transmission line. The results agree with author in [32].

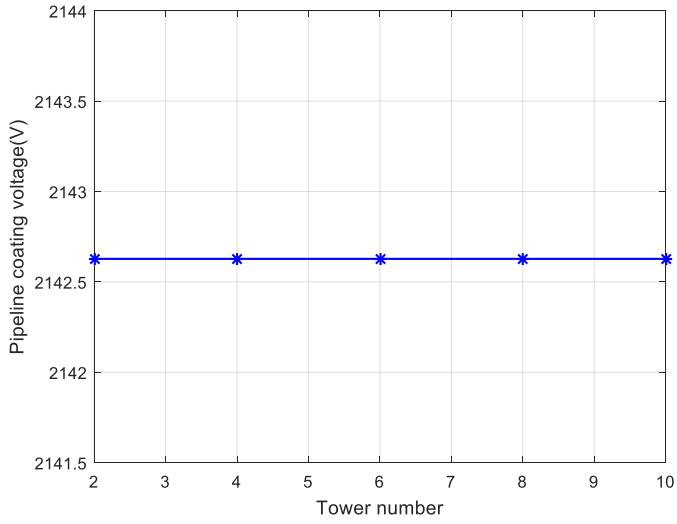


Figure 4- 8: Effect of fault location

Figure 4-9 exhibits the voltage induced on the pipeline coating with different phase to ground fault currents ratio from both substations ends of the power line. Different analyzed situations are: Case 1: I_{a1} = 1 kA, I_{a2} = 1 kA; Case 2: I_{a1} =1.5 kA, I_{a2} =0.5 kA; Case 3: I_{a1} =1.2 kA, I_{a2} = 0.8 kA; Case 4: I_{a1} =0.2 kA, I_{a2} =1.8 kA; and Case 5: I_{a1} = 0.6 kA, I_{a2} = 1.4 kA.

From the figure it is observed that the induced voltage on the pipeline coating caused by resistive interference mostly relies on the overall fault current from both substations terminations of the power line. Table 4-1 illustrates the maximum voltage induced on the pipeline coating; it is observed that the maximum value of the voltage is independent from the current ratio from both substations ends. The results are agreement with author in [32].

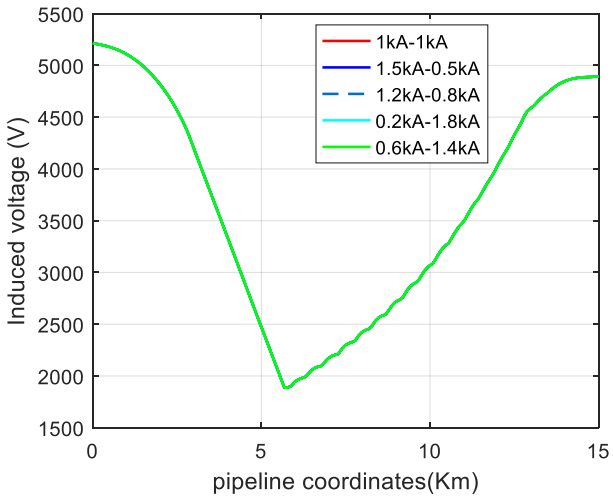


Figure 4- 9: Effect of supply current ratio at both substations ends

Table 4- 1: Maximum resistive coupling voltage of pipes under different conditions

Supply current at both ends of substation	Left1kA	Left 1.5kA	Left 1.2kA	Left 0.2kA	Left 0.6kA
	Right 1kA	Right 0.5kA	Right 0.8kA	Right 0.8kA	Right 1.4kA
Maximum resistive coupling voltage of pipe	5215V	5215V	5215V	5215V	5215V

In the computation, the resistivities of the anti-corrosion layer of a three-layer PE and FBE coating of the pipeline are $1\times10^4\ \Omega m^2$, $3\times10^4\ \Omega m^2$, $5\times10^4\ \Omega m^2$ and $1\times10^5\ \Omega m^2$, respectively. Generally, the perfect the coating, the bigger the induced voltage because current doesn't easily outflow from a well-coated pipeline. From figure 4-10, it is clear that the anti-corrosion coating resistivity has a major impact on the induced voltage during single phase to ground fault. The voltage induced on the pipeline rises with the rise of the resistivity of the anti-corrosion layer. Pipelines that have low coating resistance, due to being buried underground for a long time, are less disposed to inductive interference from nearby power lines. However, the leakage currents flowing through the leakage resistances become much larger leading to high induced voltage on the pipeline [50].

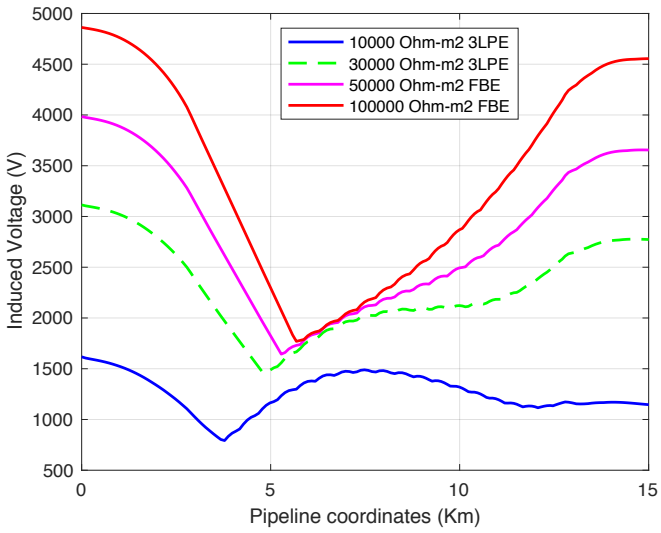


Figure 4- 10: Effect of pipeline coating resistivity

4.3 Application of Mitigation Systems

Under single phase to ground fault it is observed that voltages reach higher values capable of threatening the pipeline integrity. Therefore, mitigation systems are necessary to be put into action to diminish these voltages to the level which cannot damage the pipeline. This section two types of mitigations (gradient control wires and grounding electrodes also known as lumped grounding) are proposed and analyzed to compare their performance. The technic found to be efficient will be to the next cases.

Figure 4-11 and 4-12 show the application of mitigations to the worst scenario of single phase to ground short circuit when the pipeline runs parallel to the power line. Through the observation of voltage profiles in figure 4-2 under single phase to ground fault condition, we notice that the voltages have their maximum values at beginning and ending point of the pipeline reaching very high levels able to destroy the pipeline coating.

Two types of mitigation systems (grounding electrodes and gradient control wires) are suggested, with the purpose of reducing the voltage at both terminations to safest limits. The first method contains a pair of 10Ω bare copper wire buried parallel to the pipeline at the depth of 1.6 m connected to the pipeline at constant distances. The second method consists of 10Ω bare copper earthing electrode connected to both terminations of the pipeline. From figure 4-11 it is observed that voltage at the ends decreases but increases in the middle of the distance of parallelism being maximum at the fault location. The peak voltage reaches 7131V when the lateral length between pipeline and power line is 100 m taken as the worst scenario and 2572V when the horizontal length between pipeline and power line is 600 m. From the figure, it is noticed that the voltage induced on the pipeline is significantly influenced by the lateral distance between the power line and the pipeline.

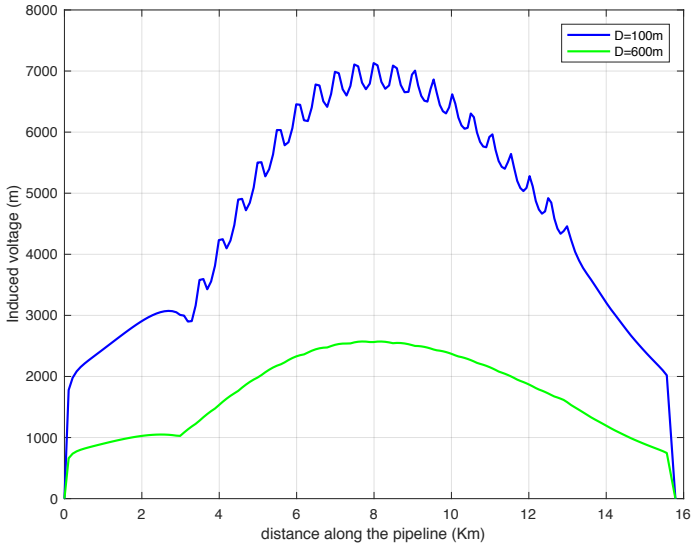


Figure 4- 11: Induced voltage along the pipeline under fault condition: grounding electrodes present

Figure 4-12 shows the induced voltage when a pair of bare copper wires are placed in parallel with the pipeline at a depth of 1.6m and connected to the pipeline at different constant intervals. From the figure it is observed that the peak voltage reaches 2621V when the lateral distance between pipeline and power line is 100 m and 818V when the lateral distance between pipeline and power line is 600 m. From the figure, we notice that the induced voltage is affected by both lateral length between pipeline and power line and also these voltages differ according to the type of mitigation system used.

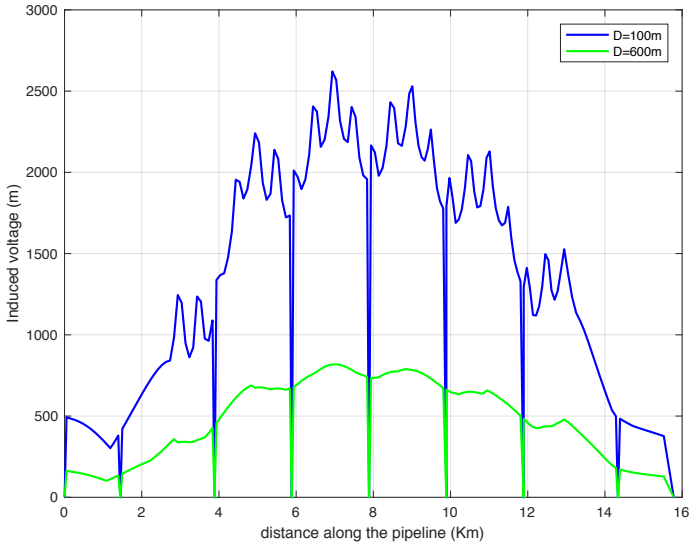


Figure 4- 12: Induced voltage along the pipeline under fault condition: gradient control wires present

Figure 4-13 shows the application of gradient control wire mitigation system to the highest voltage induced on the pipeline with the variation of earth resistivity through the observation of voltage profiles in figure 4-3. From the figure, it is observed that the voltage reduced to values below 1500V along the length of parallelism where it becomes maximum at the ends of parallel routing. From table 2-1: ITU-T DL/T 5033-2006 states that induced voltage can reach 2000V when T ≤0.1, where T is the duration time of contact. Therefore, we can assure the safety of the personnel since the probability of being the exact point where the voltage is a little higher than 2000V is very low. The security of the pipeline is also assured because recent development in pipeline coatings made pipeline coating able to withstand voltage ranging between 3kV and 5kV to be in use.

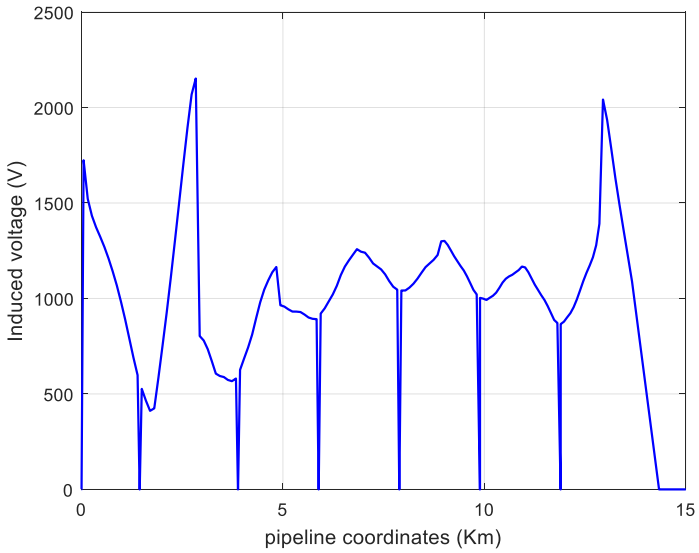


Figure 4- 13: Effect of earth resistivity

Figure 4-14 demonstrates the application of gradient control wire mitigation system to the maximum voltage induced on the pipeline with the variation of pipeline diameter as observed in figure 4-4. Generally, induced voltage increases with the decrease of the pipeline diameter, mitigation was applied the lowest pipeline diameter 40.65cm/39.55cm (outer radius/inner radius) which induced maximum voltage on the pipeline. ITU-T DL/T 5033-2006 also states that the personnel are safe for voltage below 1500 when contact time T is between 0.1 and 0.2 second. Therefore, the mitigation technic achieved its purpose because the maximum voltage induced on the pipeline reaches 1093V which is very low compared to 1500V.

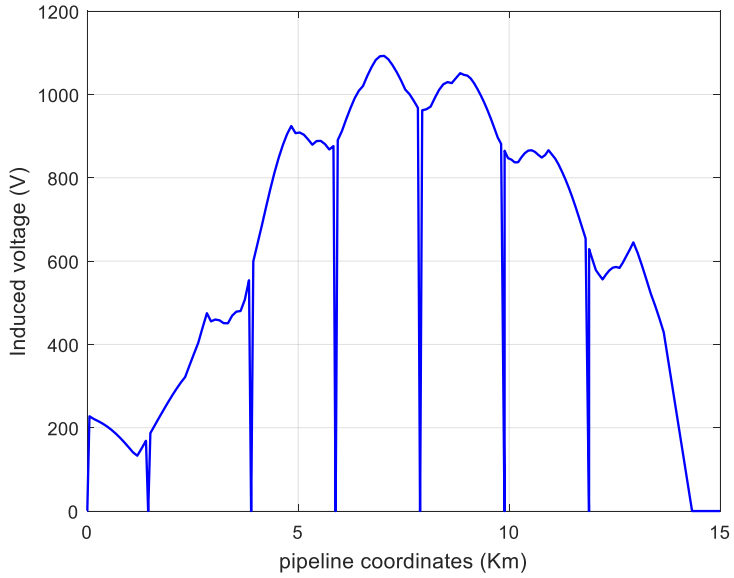


Figure 4- 14: Effect of pipeline diameter

From figure 4-1, voltage induced on the pipeline once a single phase to ground fault appears on each phase of the power line are shown. Since the level of fault current differs with the faulted phase, mitigation system is applied the worst-case scenario which appears when a fault occurs on phase C. Figure 32 shows induced voltage profile after the gradient control wire were installed. It can be observed form the same figure that the maximum voltage reaches 1111V which is in safe limit values as mentioned in ITU-T DL/T 5033-2006. Therefore, this method accomplished its purpose of protecting the personnel and the pipeline.

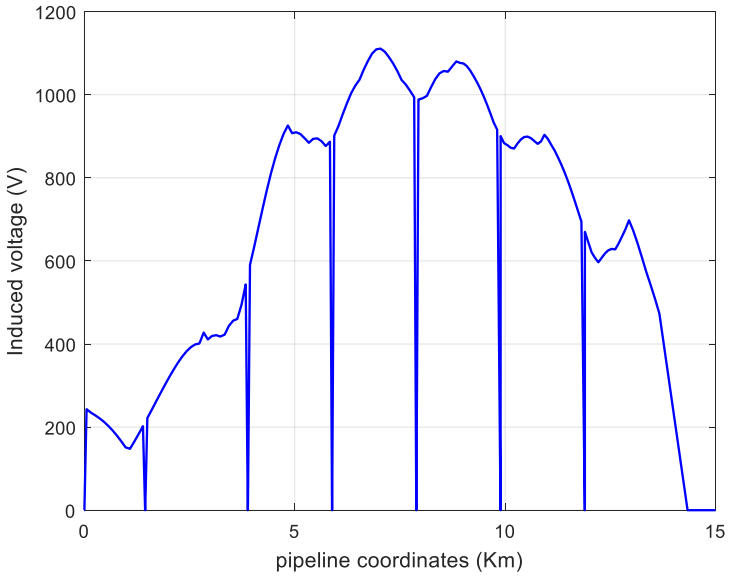


Figure 4- 15: Effect of short circuit fault on different phases

4.4 Summary of this Chapter

This chapter examined numerous parameters (e.g. earth resistivity, pipeline diameter, resistivity of ant-corrosion layer, distance between phase conductors, length of parallelism) that affect pipeline close to power line under single phase to ground fault. The results reveal that under this case voltage induced on the pipeline reach high values able to destroy the pipeline coating and present danger to the personnel that might be in contact with the pipeline at the time fault. It is in that case that, two types of mitigation systems were proposed, evaluated and applied to the worst-case scenario obtained in this section. Gradient control wire method is found to be more efficient than the earthing electrode. Therefore, gradient control wire method was applied to other cases to meet the standard limits.

Chapter 5: Project Application

5.1 Method of analysis of cases containing oblique proximity

In real engineering application, the AC transmission lines are commonly in oblique proximity to the pipeline rather than being parallel. Conferring to ITU directives, an equivalent parallel exposure can be computed if the analysis of a parallel exposure is not valid. The equivalent parallel distance of proximity computed in this case induces voltage on the pipeline as the same as the oblique situation [55], [50]. The zone of influence commonly contains a sequence of parallelisms and crossings. To determine the induced voltage along the zone of influence demands the division of the underground pipeline into segments which are after converted to parallelism according to the law defined in (5-1). Thereafter, each subdivision is reduced to a π-network exposed to the electromagnetic field as shown in figure 2-6 and the computation is carried out on different cells by solving the system of equations (2-3) and (2-4) [3]. Referring to figure 5-1 (a), the equivalent distance as:

$$d = \sqrt{d_1 d_2} \tag{5-1}$$

This formula remains valid as long as $d_2/d_1<3$, when the ratio is higher than 3 the pipeline has to be divided into sections as shown in figure: 5-1 (b) so that $d_3/d_1<3$ and $d_2/d_3<3$.

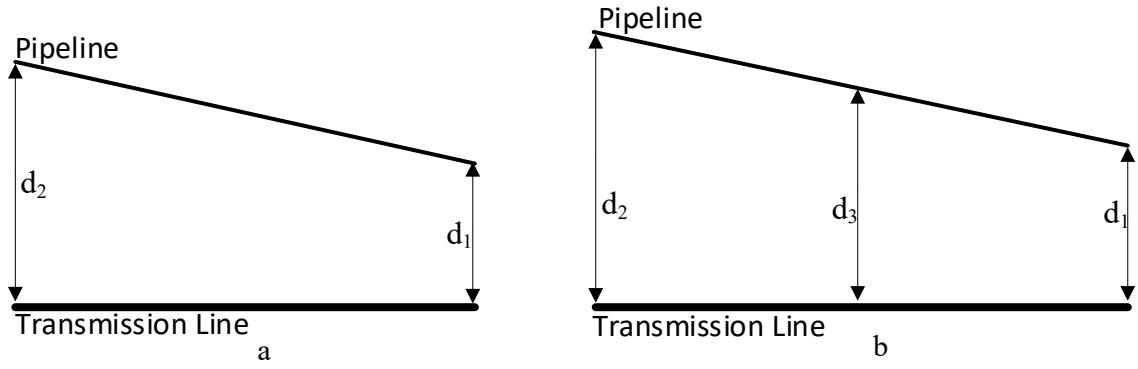


Figure 5- 1: Example of an oblique exposure

5.2 Description of the model Case Study

To study this case, a model having parallelism, approaches and crossings as shown in Figure 5-2 is evaluated. A layout illustrating a 50 Hz, 500 kV AC double vertical circuit line sharing common corridor with an underground metal pipeline for a distance of 15 Km is modelled and analyzed under steady state and fault operating conditions. In the calculation, the double vertical circuit line is configurated in reverse phase sequence (ABC-CBA) to analyze the effect of the generated electromagnetic field on the pipeline. The phase conductors of the double vertical circuit are configured with 4-bundle conductors per phase with bundle spacing of 400 mm. They are fixed in vertical arrangement on a steel tower structure with the span of 500 m.

The equivalent radius of the phase conductor is 188 mm, relative resistivity ρ=9.67 S/m and relative permeability ε_r=1. The two overhead earth conductors are at 65m above ground with an equivalent radius of 5.7 mm, relative resistivity ρ=9.67 S/m and relative permeability 636. In this analysis, it is assumed that the earth conductor is continuously and periodically grounded.

The underground metallic pipeline is buried at 1.6 m below the ground, with inner radius of 485 mm and outer radius of 505 mm. The thickness of the anti-corrosive layer is 3 mm with a resistivity of the anti-corrosion layer of $3*10^4$ Ωm^2. The relative resistivity ρ=9.67 Ωm and the relative permeability ε_r=300, with a relative dielectric constant of 2.3. The soil is assumed to be homogenous with a resistivity of 100 Ωm. The tower is practically formed by 4 vertical thin conductors each with the resistivity of 1.66×10^{-7} Ωm, equivalent radius of 6 mm and relatively magnetic permeability of 636. The conductors made of steel are buried at the depth of 0.6 m, with a radius of 6 mm, resistivity of 1.66×10^{-7} Ωm, and a magnetic permeability of 636.

In this case, the pipeline is split into different segments to get the equivalent parallel distance. For the non-parallelism situation, formula (5-1) is applied to get the equivalent parallel length between the power line and the pipeline.

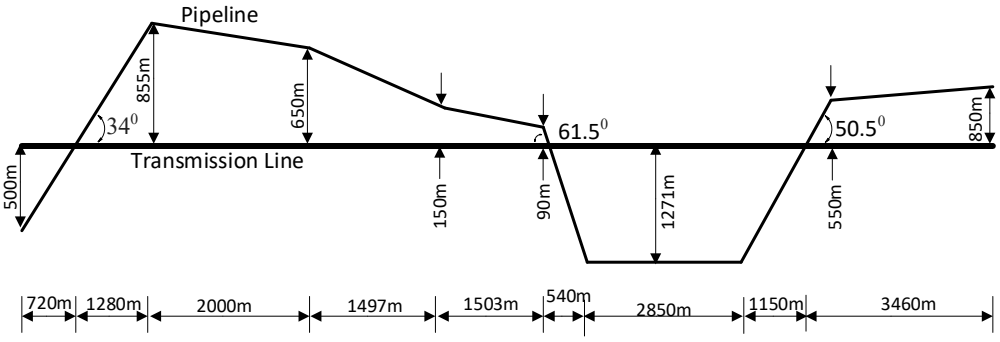


Figure 5- 2: layout of the transmission line and pipeline

5.2.1 Analysis under Normal Condition

Figure 5-3 shows induced voltage on the length of the pipeline under normal condition for the model described in figure 5-2. From the figure it is noticeable that under steady state condition induced voltages are within correct values for the safety of personnel. Therefore, no mitigation systems required to be installed.

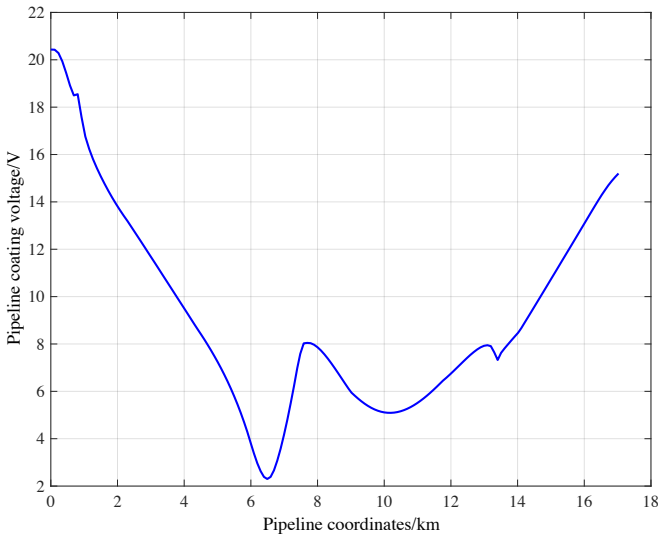


Figure 5- 3: Induced voltage along the pipeline under normal condition

The effect of ground resistivity is observed in figure 5-4, and the induced voltage due to changes in earth resistivity is much larger than other parameters. These induced voltages are proportional to the Earth's resistivity. The higher the resistivity of the earth, the greater the induced voltage on the pipe, resulting in high stress on the pipeline.

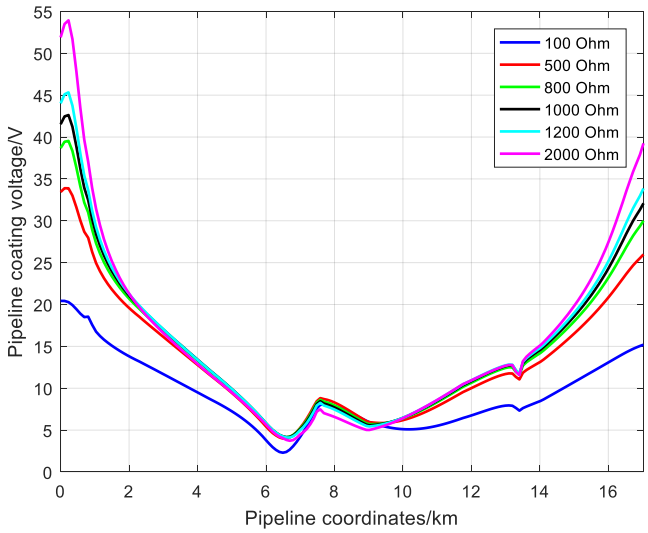


Figure 5- 4: Effect of earth resistivity

Figure 5-5 shows the effect of a constant current on the induced voltage. As can be observed in the figure, the induced voltage increases as the load current increases, which is caused by a high magnetic field formed close the conductor of the power line as the load current rises, resulting in large induced voltage on the pipeline.

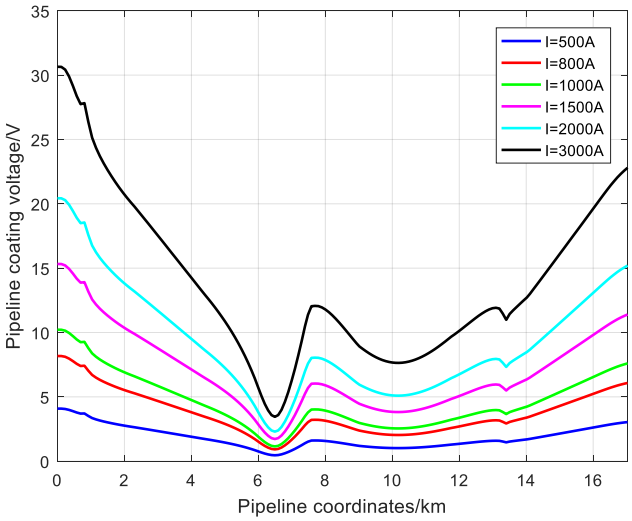


Figure 5- 5: Effect of load current

Figure 5-6 shows the influence of the overhead ground conductor on induced voltage on the pipeline under steady state operating conditions when considering the influence of the overhead ground conductor and not considering the influence of the overhead ground conductor. From the figure, it is observed that the voltage on the pipeline coating with the presence of ground conductor is higher than the induced voltage without the ground conductor.

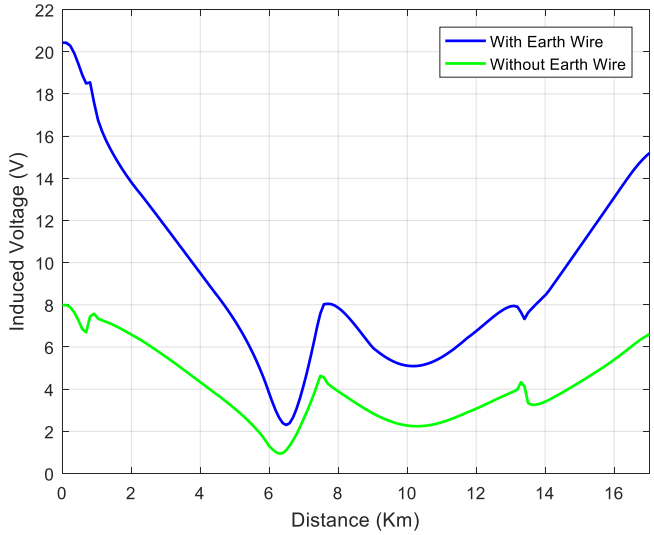


Figure 5- 6: Effect of overhead ground conductor

5.2.2 Analysis under Single Phase to Ground fault Condition

Figure 5-7 demonstrates induced voltage along the length of the pipeline under single phase to ground fault condition. From the figure it is noticeable that the induced voltage reaches levels capable of destroying pipeline coating. Therefore, in the next section mitigation systems are applied to the model to decrease these values to minimum acceptable levels.

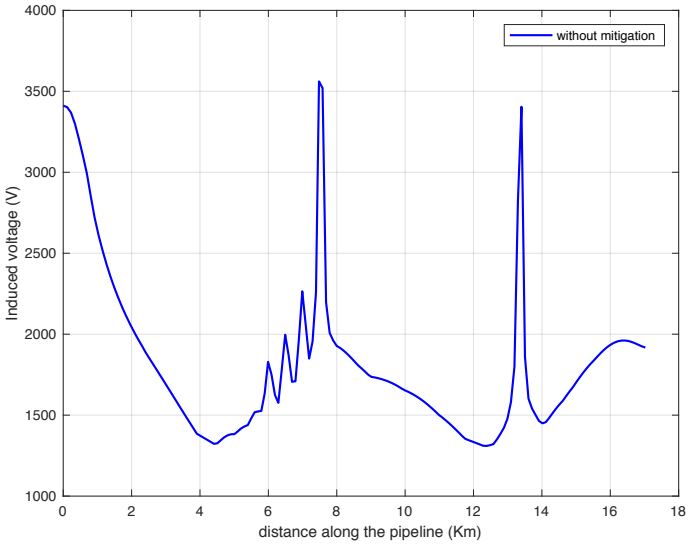


Figure 5- 7: Induced voltage along the pipeline under single phase to ground fault

5.2.3 Application of Mitigation Systems

As mentioned from the last two chapters, mitigation systems are intended to drop induced voltage on the pipeline to acceptable limit values. In this chapter gradient control wire method found to be more efficient than earth electrode method is applied to the case of fault condition where the induced voltages are found to be out of limits.

Figure 5-8 shows the comparison of two different mitigation systems for the engineering application model. Peak voltage with order of 3561V is observed at the faulted tower where the pipeline intersects the power line. By earthing both terminations of the pipeline with a 10Ω bare copper electrode the voltage rises to 3709V at the faulted point which coincides with the crossing of the power line and the pipeline. This is because under fault conditions, copper electrodes as they are bare metal installed closer to the power line structure; they offer a low resistance path to fault currents, thus higher currents are transmitted along the pipeline from the point of fault therefore, increasing induced voltage on the pipeline than it could induce without earthing electrodes [56], this could increase the risk of arc on the pipeline.

The second proposed mitigation method is the use of gradient control wires. A pair of bare copper wires with resistivity $\rho=1.68\times10^{-8}$ Ωm and relative permeability $\mu_r=1$ placed at 1 m from the pipeline at the depth of 1.6 m are running parallel to it and connected at both terminations of the pipeline. From the same figure, it is observed that the highest voltage reaches 2657V equaling to 74.6% of the peak voltage without application of mitigation. Research in [57] indicated 3kV as a conventional coating stress voltage limit for FBE and PE pipeline coatings, and that due to the development in pipeline coatings currently, pipeline coating able to withstand voltage ranging between 3kV and 5kV are in use. The same research also stated that for optimum designed mitigations, the highest coating stress voltage on the pipeline to be slightly below 3 kV.

Therefore, gradient control wires mitigation system is suggested to be applied under single phase to ground fault condition to decrease the likelihood of pipeline coating damage.

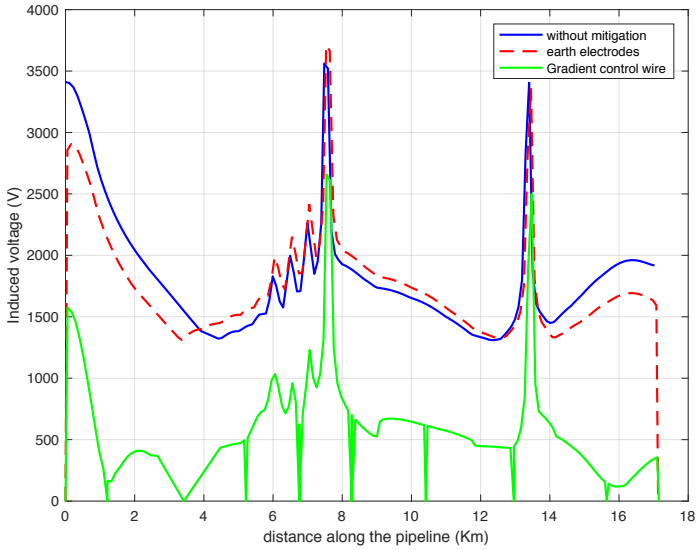


Figure 5- 8: Induced voltage along the pipeline under fault condition: different mitigation methods

5.3 Summary of this Chapter

This chapter described the analysis of EMI on an engineering application model which includes oblique proximity and crossings. The case study was analyzed under steady state and fault conditions. The results reveal that under normal operation, the induced voltage on the pipeline depends mostly on the power line and pipeline parameters and configuration.

It is found that under normal operating conditions induced voltage on the pipeline don't go beyond the value of 60 V which is the limit value for personnel safety as stated in GB 6830-1986. Therefore, under normal condition both the pipeline and people are not affected by these voltages.

However, high currents generated during single phase to ground fault condition lead to the rise in the voltage reaching the pipeline, thus rising induced voltage on the pipeline compared to the case of steady state condition. Therefore, two types of mitigation systems are analyzed and applied to the case study. From the results it is found that gradient control wire method reduces voltage induced on the pipeline at a higher degree than earthing electrode method.

Chapter 6: Conclusion and Future Research

Being a threat not only to pipelines but also to personnel, electromagnetic field interference from power lines neighboring metal pipelines has become a main concern for engineers over the last few decades. Research scholars starting with Carson, formulated mathematical models to analyze this problem resulting in many publications, national and international standards aiming to limit their effect to safe values for personnel and pipelines.

In this research the theory of electromagnetic field was described, and demonstrated a complete case study model using CDGS software package which assisted in the simulation and analysis of EMI issues. Furthermore, the study procedures of the proposed models were defined including all data required for the analysis. Thereafter, computation of electromagnetic interference from power close to underground pipeline under normal and single phase to ground fault condition was carried out.

To examine the effect of these interferences two case studies were chosen: first, where the underground pipeline is running parallel to the power line and second for an engineering application which includes parallel, approaches and crossings. A 50Hz, 500kV AC double vertical circuit for both case studies were modelled and analyzed under different parameters to study their degree of effect on neighboring underground metal pipeline using the above-mentioned software. The results of the induced voltage computed were checked if they are in compliance within international standards GB 6830-1986 for normal operating conditions and ITU-T DL/T 5033-2006 for single phase to ground fault conditions. Mitigation systems were applied where these voltages exceeded the limit values.

The study indicated that most of parameters analyzed, the peak induced voltage on underground pipeline under normal condition was in agreement with the standard, except for pipeline with FBE anti-corrosion coating layer, horizontal circuit tower type, triangular tower type and phase wire spacing. However, during single phase to ground short circuit, generated high currents flow to ground through the tower structure rising the potential of neighboring soil including the underground pipeline thus, increasing the induced voltages on these materials. Under this condition, induced voltages were found to be beyond the standard limits with peak voltages appearing on both ends for parallel case whereas for engineering application, these voltages were found to be induced on point of crossings.

Furthermore, two types of mitigation systems: the gradient control wire and earth electrode mitigation systems were proposed and analyzed for both cases. The proposed mitigation systems considerably reduced the induced voltages on the two studied cases during single phase to ground fault condition. The main contribution of the research shown that gradient control wire reduced these voltages to much lower voltages than grounding electrodes, also these voltages reduce with the increase in the number of welding connections between the pipeline and the gradient control wire.

Numerous researches focused on EMI effect from power lines to neighboring metal pipelines under normal and fault condition. However, most of these power lines are also strike by lightning and this results in higher currents which affect the pipeline at a factor higher than the two former cases described above. Therefore, this research suggests the study of lightning and mitigations under this condition including their economic considerations as future research direction.

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