



Addis Ababa University
Addis Ababa Institute of Technology
School of Electrical and Computer Engineering

***Analysis of Electromagnetic Emission from Contact lines of Light
Rail Transit System***

A Thesis Submitted to Addis Ababa University
Addis Ababa Institute of Technology

In Partial Fulfillment of the Requirement for the Degree of Master's
Of
Science in Electrical Engineering
(Railway Engineering)

By: - **Tsegu Worku**

Advisor: - **Dr. Ing: - Getahun Mekuria**

July, 2014



Addis Ababa University

Addis Ababa Institute of Technology

School of Electrical and Computer Engineering

*Analysis of Electromagnetic Emission from Contact Lines of Light Rail
Transit System*

By: - Tsegu Worku

APPROVED BY BOARD OF EXAMINERS

Chairman, Department of Graduate
Committee

Dr.Ing:- Getahun Mekuria

Advisor

Internal Examiner

External Examiner

Signature

Signature

Signature

Signature

Declaration

I, the undersigned declare that this thesis is my original work, and has not been presented for a degree in this or any other university, and all sources of materials used for the thesis have been fully acknowledged.

Tsegu Worku

Name

Signature

Addis Ababa, Ethiopia

Place

August, 2014

Date of submission

This thesis has been submitted with my approval as a university advisor.

Dr.Ing: Getahun Mekuria

Advisor's Name

Signature

Abstract

The implementation of Light Rail Transit System (LRTS) as an integrated form of public transportation, with the rail corridor running through city centers and connecting major commercial centers, presents a unique electromagnetic coupling scenario between sensitive installations and the dc magnetic field propagated from the LRTS. Magnetic fields created by a dc-electrified railway are a nuisance to the operation of a geomagnetic observatory and also disturb other electromagnetic studies and some researches were done using real operation measurements. Theoretical formulas and simulations that enable quantitative estimates of the magnetic effect of Addis Ababa LRT contact line including leakage currents in the ground are presented in this paper.

The sliding contact between catenary and pantograph has to transfer a large amount of current and power to the locomotive reliably. Sometimes detachment and attachment occur between the contact wire and the pantograph. Arcing from the pantograph, a commonly observed phenomenon is known to be a major source of wideband electromagnetic emission which is more pronounced during the winter.

Experience within the railway industry has shown that this source of Electromagnetic interference (EMI) and its characteristics need to be understood thoroughly for solving the associated EMI issues in the desired fashion. This thesis analyzes EMI generation from pantograph arcing, which is pantograph contact wire interaction, full loop of feeding line, which is substation, feeder line, train, return current and leakage current into the environment and ground. The methodology of the paper uses modeling of the system using mathematical modeling and simulates with MATLAB software. The result of this analysis is compared with the railway Electromagnetic Compatibility (EMC) standards and results with at 40m distance from center of track line out of the limit standard.

Keywords: - Electromagnetic field, Electromagnetic compatibility, Pantograph arcing, leakage current, feeder current.

Acknowledgements

I want to thank Dr. Ing. Getahun Mekuria, my advisor at AAiT for his friendship and the perfect collaboration on this thesis. He has been available to answer my questions and to help me to reach the objectives. The discussions and thoughts we shared have benefited me enormously.

I would like to express my special thanks to Ethiopian Railway Corporation for helping me to get the available documents from project office of Addis Ababa LRT.

I also thank Balcha Aba Nebso Hospital and other organization for their giving me information and support for my thesis.

I would also like to thank Mr. Abebe Tekelu, Demisu Legese and other my friends for their encouragement and interest in my work and also for giving me advice and idea.

Lastly, deepest appreciation to my sisters and my family, from Bishoftu for the wonderful time spent together.

Table of Contents

| | |
|--|----------|
| Declaration | i |
| Abstract | ii |
| Acknowledgements | iii |
| Table of Contents | iv |
| List of Figures | viii |
| List of Tables..... | x |
| List of Abbreviation and Symbols | xi |
| Chapter One..... | 1 |
| 1 Introduction | 1 |
| 1.1 Statement of the Problem | 1 |
| 1.2 Aim & Objectives | 2 |
| 1.3 Scope of the Study..... | 3 |
| 1.3 Methodology..... | 3 |
| 1.4 Thesis Structure | 4 |
| Chapter Two | 5 |
| 2 Backgrounds | 5 |
| 2.1 Railway Electric Power Feeding Systems | 5 |
| 2.1.1 Direct Current Feeding System..... | 5 |
| 2.1.2 Alternative Current Feeding System:- | 6 |
| 2.1.3 Autotransformer Feeding System | 7 |
| 2.1.4 Booster Transformer Feeding System..... | 7 |
| 2.1.5 Coaxial Cable Feeding System | 8 |

| | |
|---|-----------|
| 2.2 Railway Power Collecting System | 9 |
| 2.2.1 Third Rail System | 9 |
| 2.2.2 Overhead Contact Line System: - | 9 |
| 2.3 Introduction to Electromagnetic Compatibility and Electromagnetic Fields | 12 |
| 2.4 Source of Electromagnetic Field in Railway Electrification | 14 |
| 2.5 Electromagnetic Interference Sources, Victims and the Coupling Mechanisms..... | 16 |
| 2.6 Electromagnetic Field..... | 18 |
| 2.6.1 Sources | 19 |
| 2.6.2 Human Exposure..... | 20 |
| 2.7 Electromagnetic Interference..... | 22 |
| 2.7.1 Impact of Electrified Railway on Equipment | 23 |
| 2.8 Why EMC in Railway is so challenging?..... | 25 |
| 2.9 Cost of EMC during Design Life Cycle | 28 |
| 2.10 Electromagnetic Compatibility Regulation and Standards..... | 28 |
| 2.11 Description of Standards EMI Measurement Methods | 30 |
| Chapter Three | 31 |
| 3 Literature Review..... | 31 |
| 3.1 Impact of the Infrastructure on the Electromagnetic Emissions Radiated | 31 |
| 3.2 DC Railways and the Magnetic Fields they produce | 33 |
| 3.2.1 DC-Powered Railways | 33 |
| 3.2.2 The Power-Supply System..... | 33 |
| 3.2.3 The Train..... | 34 |
| 3.2.4 Division of Current Between Substations..... | 35 |
| 3.2.5 Earth-Leakage Currents | 36 |
| 3.2.6 Railway Ear thing Policy | 36 |
| 3.3 Measurement and Analysis of Electromagnetic Fields from Trams, Trains | 37 |
| 3.4 Optimization of Magnetic Field Propagated from DC Light Rail Transit System.... | 38 |

| | |
|---|-----------|
| 3.4.1 Compensation conductor optimization | 39 |
| 3.5 Assessment of Infrastructure Impact in Radiated Emission Tests of Rolling Stock | 40 |
| Chapter Four | 41 |
| 4 Design of System Component..... | 41 |
| 4.1 Assessment Scope..... | 41 |
| 4.2 Addis Ababa LRT Power Distribution System | 42 |
| 4.3 Overhead Contact System of Addis Ababa Light Rail Transit | 44 |
| 4.3.2 Material Perspective..... | 44 |
| 4.4 Specification of Rolling Stock..... | 45 |
| 4.4.1 Vehicle Fleet Characteristics | 45 |
| 4.5 Magnetic Field Disturbance Produced by Electric Railway..... | 46 |
| 4.6 Modeling of the System..... | 46 |
| 4.7 Electromagnetic Radiation Caused by Pantograph Disconnection | 52 |
| 4.7.1 Gas Discharge Process | 52 |
| 4.7.2 Field Strength Calculation of Electromagnetic Waves Spreading from Pantograp | 53 |
| Chapter Five | 54 |
| 5 MATLAB Simulation and Analysis..... | 54 |
| 5.1 Full Loop of Magnetic Field Simulations for Different Trains | 54 |
| 5.2 Leakage Current Magnetic Field Simulation..... | 60 |
| 5.3 3D Magnetic Field Simulations..... | 62 |
| 5.4 Pantograph Arcing Magnetic Field Simulation. | 62 |
| Chapter Six | 64 |
| 6 Results and Discussion | 64 |
| 6.1 Electromagnetic Site Survey | 64 |

| | |
|--|-----------|
| 6.2 Impact Assessment Methodology..... | 65 |
| 6.3 Impact Mitigation Measures | 66 |
| Chapter Seven..... | 68 |
| 7 Conclusion and Recommendation | 68 |
| 7.1 Conclusion..... | 68 |
| 7.2 Recommendation | 68 |
| Appendix A | 69 |
| References | 84 |

List of Figures

| | |
|---|----|
| Figure 2.1 Structure of DC feeding system | 6 |
| Figure 2.2 Structure of AC feeding system | 6 |
| Figure 2.3 Structure of AT feeding system | 7 |
| Figure 2.4 Structure of Negative Feeding- based BT feeding system | 8 |
| Figure 2.5 Coaxial cable feeding system | 8 |
| Figure 2.6 Third rail | 9 |
| Figure 2.7 Overhead contact line system..... | 10 |
| Figure 2.8 (a) Simple catenary (b) Stitched catenary (c) Compound catenary | 11 |
| Figure 2.9 Common pantograph types | 11 |
| Figure 2.10 The basic decomposition of the EMC coupling problems | 13 |
| Figure 2.11 The main interference phenomena generated from railway | 15 |
| Figure 2.12 Radiation of interference from the pantograph arcing catenary wires | 17 |
| Figure 3.1 Railway Electromagnetic Field Sources | 19 |
| Figure 2.13 Cost of EMC solution during the design lifecycle | 28 |
| Figure 2.14 Field of EMC | 29 |
| Figure 2.15 On site measurement of the electromagnetic radiation of the train..... | 30 |
| Figure 3.2 Rectifier substation feeds train via overhead and rail | 34 |
| Figure 4.1 The general topology of Addis Ababa LRT..... | 43 |
| Figure 4.2 Topology of the studies..... | 43 |
| Figure 4.4 Addis Ababa LRT railway line | 44 |
| Figure 4.5 Rectangular train-substation feeding loop..... | 46 |
| Figure 4.6 Rectangular full loop..... | 47 |
| Figure 4.7 Rectangular “leakage” loops with the current $j dx$ | 48 |
| Figure 4.8 Catenaries system model..... | 52 |
| Figure 5.1 One train modelling system | 55 |
| Figure 5.2 Simulation of one train result | 55 |
| Figure 5.3 Two train modelling system..... | 56 |
| Figure 5.4 Simulation of two trains result | 56 |
| Figure 5.5 Three train modelling system..... | 57 |
| Figure 5.6 Simulation of three trains result | 57 |

| | |
|---|----|
| Figure 5.7 Four train modeling system..... | 58 |
| Figure5.8 Simulation of four train’s results..... | 58 |
| Figure 5.9 Five train modelling system | 59 |
| Figure 5.10 Simulation of five train’s results | 59 |
| Figure 5.11Simulation of leakage current | 60 |
| Figure 5.12 Simulation result of full loop and leakage current loop | 61 |
| Figure 5.13 Simulation of 3D magnetic field result | 62 |
| Figure 5.14 Pantograph arcing model..... | 63 |
| Figure 5.15 Electric field of pantograph arcing..... | 63 |
| Figure 5.16 Magnetic field of pantograph arcing | 63 |
| Figure 6.1 EMI Investigation Zones & Applicable Standards | 64 |

List of Tables

| | |
|--|----|
| Table2. 1 Exposure Limits for Fundamental Frequency Electric Field..... | 21 |
| Table2. 2 Exposure Limits for Fundamental Frequency Magnetic Field | 21 |
| Table2. 3 Exposure limits for DC magnetic field..... | 22 |
| Table6. 4 Criteria for assessment of impact magnitude | 65 |
| Table6. 5 The impact assessment for the Addis Ababa LRT is shown below | 65 |

List of Abbreviation and Symbols

| | |
|---------------------------------|--|
| ACGIH | American conference of Government Industrial Hygienists |
| AT | Autotransformer |
| BT | Booster transformer |
| CC | compensation conductor |
| CU | Copper |
| d | Distance |
| dB | Decibels |
| dB μ v/m | Decibel microvolt per meter |
| E-W | East West |
| EMF | Electromagnetic Field |
| EMI | Electromagnetic Interference |
| EMC | Electromagnetic Compatibility |
| EN50121 | Electromagnetic Compatibility Railway Standards |
| ELF | Extremely Low Frequency |
| EN45502-2-1 | Active implantable medical devices |
| EMU | Electric Multiple Unit |
| EMDFX | Electromagnetic measuring device(dosimeter) |
| EPCO | Ethiopian Electric power corporation Authority |
| ERC | Ethiopian Railway Corporation |
| E _o , H _o | Electric and magnetic field strength |
| FCC | Federal Communication Commission |
| GSM-R | Global system for Mobile Communication-Railway |
| GTO | Transistor Gate Oxide |
| G | Gauss |
| IEMI | International created EMI |
| IGBT | Insulated Gate Bipolar Transistor |
| IEC | International Electro-Technical Commission |
| ICNIRP | International Commission on Non-Ionize Radiation Protection |
| IEEE | Institute of Electrical and Electronics Engineering |
| IEEE C95-1 | Standard for safety level with respect to human exposure |
| IEEE802.11 | Standard committee for Wireless local area network |
| IEEE241 | Recommended practical for electrical system in commercial building |
| J1 | Feeder current |
| LRTS | Light Rail Transit System |
| N-S | North South |
| NF | Negative feeding |
| Na | Not applicable |
| nT | nano Tesla |
| MRI | Magnetic Resonance Interference |
| MTL | Multi conductor Transmission line |
| mG | miliGauss |

Chapter One

1 Introduction

Railway has been playing significant social role in significant ground mass-public transportation. In spite of the discussion regarding its social role in the era of motorization in the latter half of the 20th century, electric railway systems are of growing importance again in recent arguments on energy saving and environmentally friendly sustainable civilization.

A substantial advantage of electrical railway compared to other transportation is the usage of electric energy, which allows variety of primary energy sources. That is also the reason for recent intensive technical development of electric traction in automobile industries including hybrid and fuel-cell electric vehicle technologies. The enhancement of the ratio of electric traction to mechanical/petroleum traction is expected to contribute to the reduction of carbon dioxide emission due to transportation and consequent sustainable growth of mobility. But in contrary of reducing carbon dioxide there is an emission of EMF from electric traction. Electromagnetic fields produced by dc railways can disturb operations at geomagnetic observatories and underground pipe lines. These magnetic fields consist of three parts: the ideal “full-loop” field due to the traction current in an overhead wire, pantograph arcing and in the rails, and the “leakage” field due to currents leaking from the track into the ground [1].

1.1 Statement of the Problem

Now a day a lot of attention is given to the EM field emissions generated in electric power facilities. In railway electrification the EM field emissions needs high attention. So that the nearby environment of this railway line has to be protected and reliable from the EM field emitted by the contact line of the Addis Ababa LRT railway system. The thesis will thoroughly deal with the following:

- ✓ Electrical devices found in commercial centers and residential along the route
- ✓ High sensitive electrical devices found in Hospital and Educational research centers near to the line

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

- ✓ Wayside signaling equipment's
- ✓ Distribution of power line near to the contact line
- ✓ Transmission of telecommunication line along the route
- ✓ Industries along the route
- ✓ Radio frequencies and mobile communication etc.

Especially medical equipment, mobile communication and radio frequencies need critical compatibility. All are considered from the railway EMC rules and standards set in international regulations.

1. 2 Aim & Objectives

The purpose of the study presented in this paper is to investigate the effect of EMI from Addis Ababa LRT on electrical/electronic devices and human being which are nearby to the route of LRT railway system. And also to suggest mitigation method to the problem that arise due to EMF emission from the LRT electrification system. The Addis Ababa LRT railway system was selected as a study route, because the project is currently on going on.

The Study Specific Objectives are:

1. Identify EMC Issues that arise within the railway environment, or may arise as a consequence of railway;
2. Perform a critical appraisal of the railway EMC standards, focusing on EN50121:2000 and EN61000-6-(1-2). In addition identify and propose suggestion for improving the measurement techniques and limits used for protecting the nearby environment included in these standards.
3. Perform theoretical analysis of the likelihood of interference to nearby environment caused by emissions from the railway.
4. Identify mitigations techniques that could be employed within the railway to reduce EMF emissions.

All these criteria were evaluated against the present project of Addis Ababa LRTS from N-S & E-W line routes.

1.3 Scope of the Study

The scope of the study is focus on the Addis Ababa LRT railway systems. The length of the route it covers is 34.25km, which is 17.4km E-W & 16.7km N-S of the city. The systems that have been evaluated as part of the research project include:

- DC electrification equipment (e.g. return rail, feeder and contact wire).
- Overhead contact system of LRTS and pantograph arcing
- The assessment of the nearby environment of the routes

A combination of modeling, calculation and simulation has been used to assess the configurations of these systems that have been the greatest potential to exceed the international standards electric and magnetic field limits.

1.3 Methodology

The study employed several strategies to investigate the analysis of electromagnetic emission from contact lines of LRTS. A brief review of the railway electrification, the associated impact of railway electrification, and EMC standard and regulations have been conducted and this part of the study was primarily based on the new project of Addis Ababa LRTS. Software simulation and mathematical modeling has been carried out for the study of the Addis Ababa LRTS project. The simulation and mathematical modeling is described in more detail later in this document. Throughout the study the researcher had conversations with advisors and experts of Addis Ababa LRTS project contractors. Also the assessment of the site has been done through:

- Data gathering on organization and their devices near the route
- Interviewing and site observation
- Literature review on the assessment of the environment near the route and

Taking sample organizations most nearest to the line and identifying the high sensitive electrical devices. All the collected information and the results from the simulation were incorporated in this study.

1.4 Thesis Structure

In the introduction the paper states the aims and objectives of the study, describes the scope, outlines the methods employed, and describes the structure of the thesis. In chapter two, background information about railway electrification, electromagnetic field, source of electromagnetic field in railway electrification, and impacts of EMF from LRT nearby to the environment. In chapter three, a literature review is about the history of railway electrification, Electromagnetic field emission from DC railway electrification, and different review of related studies. In chapter four the Addis Ababa LRT system modeled scenarios and mathematical modeling's is described. The detailed simulation is shown in chapter five. The paper presents the results and the discussion in chapter six, and concludes and presents recommendations in chapter seven.

Chapter Two

2 Backgrounds

The global supply chain and the movement of people depends on efficient transportation systems and some production efficiencies achieved through dependable transport, e.g., Just-In-Time, and outsourcing of production to distant parts of the world, e.g., from Ethiopia to China, would not be possible without modern transportation. In many ways it has not been possible for man to increase the standard of living without in turn increasing transportation capacity and improving the transportation systems [1]. Recent communication systems, such as the internet, did not change this century old trend. Railway transportation system is one of the vital transport systems in recent technologies which are propelled by electricity.

2.1 Railway Electric Power Feeding Systems

Electric power technology in the railway industry refers to the means of supplying good-quality electric power to the electric motors. It primarily consists of power conversion technology at substation feeding circuits for DC and AC feeding system and the structure, materials, measurement and maintenance of the electric over headlines.

The electric power generated by power station is carried to electric railway substation by transmission line or distribution line. The Addis Ababa LRT railway system is to be supplied from a 15kv utility power supply distribution system.

2.1.1 Direct Current Feeding System: - A direct current feeding system features a three-phase bridge silicon rectifier for conversion from alternating current to direct current. Since the three-phase rectifier uses a 6-pulse system, it causes lower harmonics in the AC side and distortion in the voltage waveforms, lowering the power quality. To reduce the harmonics, a more modern rectifier design using 12-pulse system featuring two sets of 6-pulse rectifying circuits, with AC inputs voltage phase 30° apart connected in series or parallel is used.

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

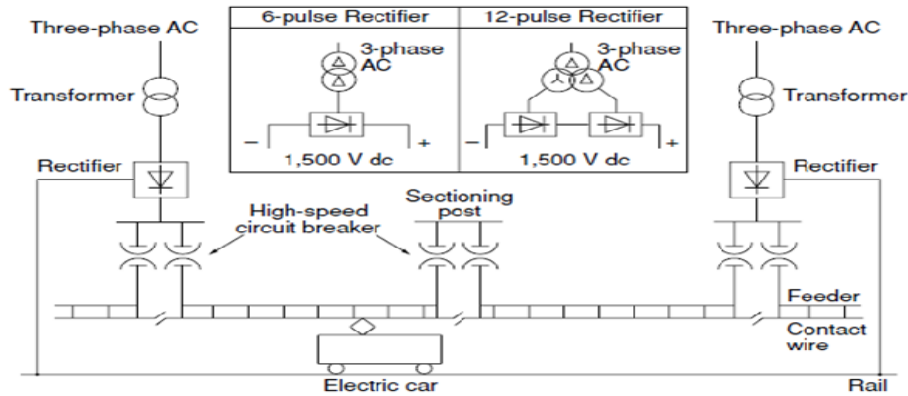


Figure 2.1 Structure of DC feeding system [2]

The above figure is an example showing the structure of DC feeding circuit connected to the nearest substation. Section and tie post sometimes used to prevent voltage drops on double tracks where substations are located far apart. In the above case, the UP and DOWN tracks are connected by a high speed circuit breaker [2].

2.1.2 Alternative Current Feeding System:- Since three-phase power from the power utility is converted to two single phase, to ensure that the current is as close as possible the three lines of the three-phase side, one separate phase is feed to each of the overhead up down tracks. Various methods can be used to connect the feeding transformer. Today the Scott connected transformer is used to receive extra high-tension and the modified wood-bridge connecting transformer is used to receive extra high voltage with the neutral point directly grounded.

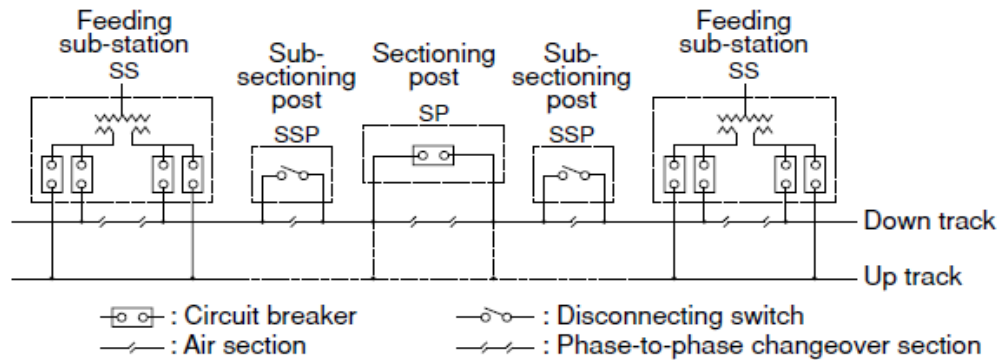


Figure 2.2 Structure of AC feeding system [2]

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

The above figure shows the composition of an AC feeding circuit. It includes feeding AC substation, sectioning post for feed section, and sub sectioning post for limited sectioning. The feeding substation feed the two single phase converted from the three phase source by feeding transformer in the opposite track direction with a 90° phase offset.

2.1.3 Autotransformer Feeding System: - In the AT feeding system, the feeding voltage of the substation is twice the voltage supplied to the electric car. An AT, at every 10km along the track, cuts the voltage to the overhead line voltage as necessary. This is very effective in reducing inductive interference in telecommunication lines.

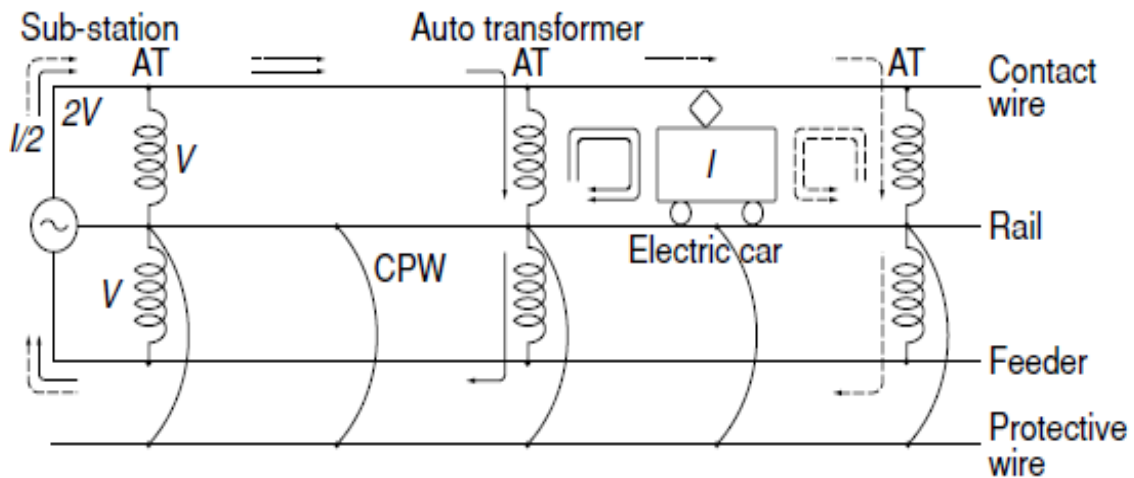


Figure 2.3 Structure of AT feeding system [2]

The AT is designed with a turn ratio of 1:1 and the substation feeding voltage is two times the overhead line voltage. This system deals with high speed and large capacity electric cars, because there is no large voltage drop or arcing section [2].

2.1.4 Booster Transformer Feeding System: - A BT is installed every 4km on the contact wire to boost the return circuit current on the negative line. This design minimizes the inductive interference in telecommunication lines because the current flows to the rail only in limited sections.

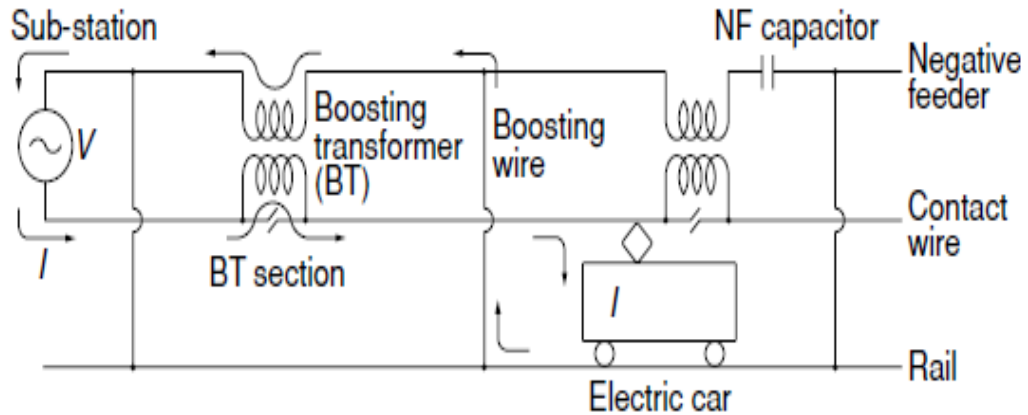


Figure 2.4 Structure of Negative Feeding- based BT feeding system [2]

In particular, when an electric car passes a BT section, a large arc is generated in the section and a large load current can cause a very large arc that can damage the overhead line. Consequently, capacitors are often inserted serially in the negative feeder to compensate for the reactance and reduce the amount of current intercepted by the pantograph, thereby reducing arcing and also helping to prevent voltage drops [2].

2.1.5 Coaxial Cable Feeding System: - The coaxial cable feeding system features a coaxial cable laid along the track. Every several kilometers, the inner conductor is connected to the contact wire and the outer conductor is connected to the rail. The cable itself is very expensive but the conductor layout is simple, making it ideal for use where space is limited.

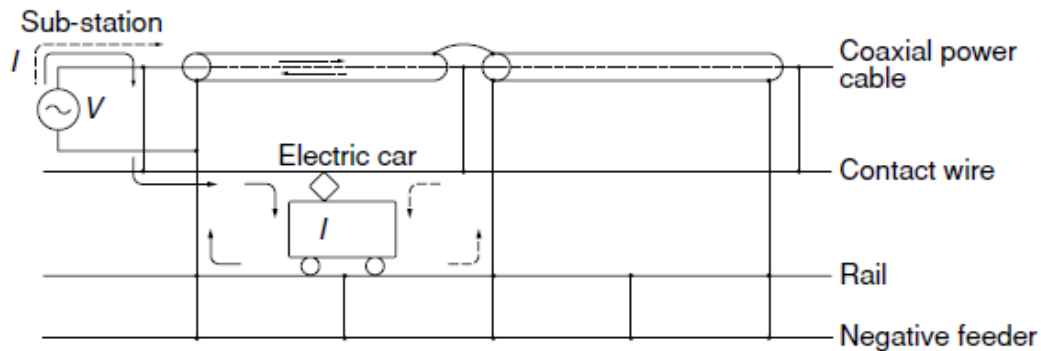


Figure 2.5 Coaxial cable feeding system [2]

In comparison to the overhead line, the coaxial power cable has extremely small round trip impedance. Therefore, the load current is boosted in the coaxial power cable from the

connection with the overhead line. This result in a rail current distribution similar to that of the AT feeding system significantly reducing the inductive interference in telecommunication lines.

2.2 Railway Power Collecting System

Traction power for train operation can be either generated on board or collected from overhead wire or third rail. For collecting power from overhead wire (third rail) we must have an appropriate power collecting mechanism.

2.2.1 Third Rail System: - A third rail is a method of providing electric power to a railway train, through a semi-continuous rigid conductor placed alongside or between the rails of a railway track.

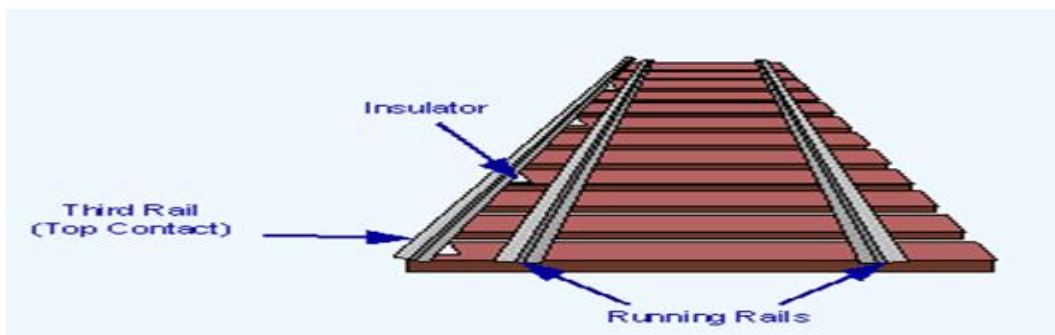


Figure 2.6 Third rail [45]

2.2.2 Overhead Contact Line System: - An electric train collects its traction power from the overhead contact wire running above the roof using pantograph. The overhead contact line through pantograph provides uninterrupted and qualified electric power at all time. For meeting the actual requirement, overhead equipment must be designed in such a way that:-

- Must have characteristic of meeting train current and speed requirement
- Must have uniform spring constant and bending rigidity
- Must have minimum vibration and motion to ensure smooth pantograph passage during high speed operation or strong wind
- Must with stand vibration, heat, corrosion

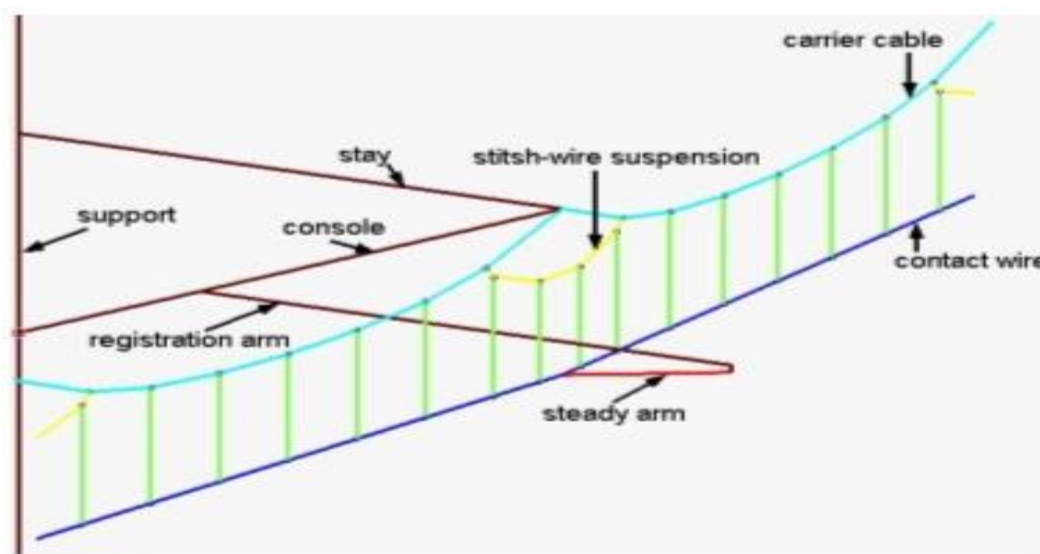


Figure 2.7 Overhead contact line system [45]

Overhead line is designed on the principle of one or more overhead wires (or rails, particularly in tunnels) situated over rail tracks, raised to a high electrical potential by connection to feeder stations at regular intervals. The feeder stations are usually fed from a high-voltage electrical grid.

2.2.2.1 Catenary: - The catenary is one of the important parts of railway electrification system where the catenary incidents stand for one of the principal causes of interruption of railway traffic.

The pantograph and the catenary together form a dynamically coupled vibrating system affecting each other through the contact force. The contact loss rate may be used as a criterion for current collection quality assessment through current or contact force measurements.

In general three types of catenary are under focus, the simple catenary (Fig.2.8 a), stitched catenary (Fig 2.8b) and compound catenary (Fig2. 8c). The compound catenary has a smaller static stiffness variation in comparison with simple catenary which allows a higher train speed.

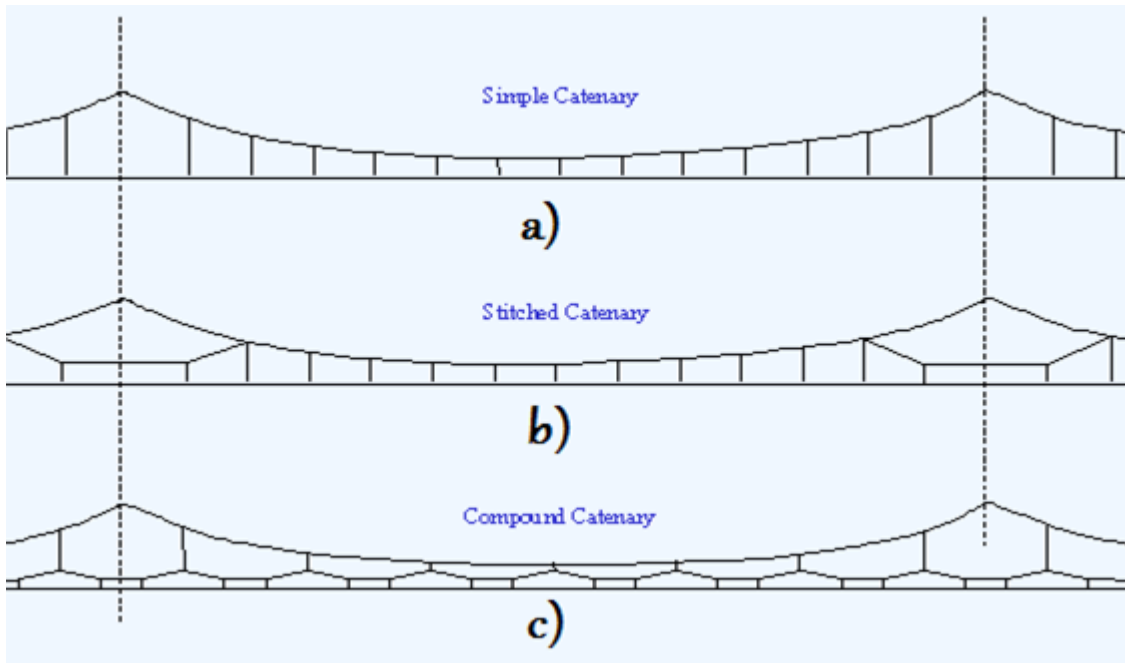


Figure 2.8 (a) Simple catenary (b) Stitched catenary (c) Compound catenary [45]

2.2.2.2 Pantograph: - There are many different pantograph design evolved through time. Some of the pantograph designs are:-

- **Single Stage:** - consists of four-bar linkage (frame) which is designed to move the contacting shoe vertically. The mass of large frame necessary to span a broad range of operating height can cause the single stage pantograph response slow.
- **Dual Stage:** - includes frame linkage and a relatively light and stiff head link designed to respond to the high frequency component of catenary shape. This pantograph is used for high speed, long distance train.

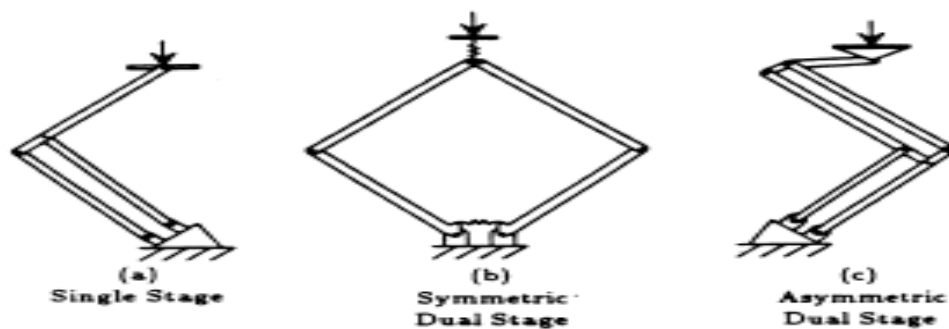


Figure 2.9 Common pantograph types [5]

2.3 Introduction to Electromagnetic Compatibility and Electromagnetic Fields

Electro Magnetic Compatibility (EMC) is the ability of equipment to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbance to other equipment in that environment.

Electric and magnetic fields are produced wherever electricity is used. The electric field is produced by voltage and the magnetic field by current. Electromagnetic fields (EMF) cause two types of effect:

- **Interference to electric and electronic equipment.** This is called electromagnetic interference (EMI) and is the disturbance that affects an electrical system due to magnetic and electric fields, electromagnetic induction or electromagnetic radiation emitted from an external source; and
- **The potential to cause harmful effects in the human body through EMF** [3].

The principle of electromagnetic compatibility (EMC) is to allow a correct and optimum functioning of any electrical or electronic devices in the presence of each other. In other words, it is the right of electrical/electronic equipment to co-exist in an electromagnetic environment without disturbing each other. This definition draws three poles of interest: **the study of sources of interference, the study of the coupling paths** and, finally, **the study of the impact of disturbances on the "victim" circuit, susceptibility**. The absence of one of these conditions will breach the EMI manifestation. In this research work, we apply this principle in the field of railway system, specifically in the field of traction substation, rectification substation, pantograph arcing and DC overhead contact lines of LRT. These DC overhead contact lines referred to as the catenary –pantograph arcing system during train movement start. The train movement has different track profile, in which the current drawn by train also differs. Irrespective of those the electric field and magnetic field emission from traction and rectification substation and the contact lines varies with track profile and line

capacity.

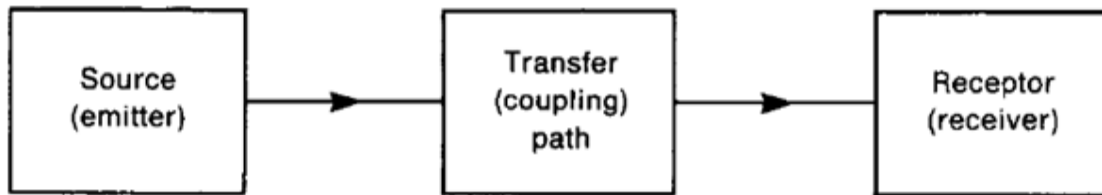


Figure 2.10 The basic decomposition of the EMC coupling problems [4]

A magnetic field will cause a changing current in a conductor to induce a voltage in another according to:

$E = M \cdot di/dt$ Where, M is the mutual inductance between the source and the victim circuit. Similarly, an electric field will cause a changing voltage on a surface to induce a current to flow in another conductor according to:

$I = C \cdot dv/dt$ Where, C is the capacitance coupling the source to the victim.

A source (also referred to as an emitter) produces the emission, and a transfer or coupling path transfers the emission energy to a receptor (receiver), where it is processed, resulting in either desired or undesired behavior. Interference occurs if the received energy causes the receptor to behave in an undesired manner. Transfer of electromagnetic energy occurs frequently via unintended coupling modes.

Unintentional transmission or reception of electromagnetic energy is not necessarily detrimental; undesired behavior of the receptor constitutes interference. So the processing of the received energy by the receptor is an important part of the question of whether interference will occur.

This suggests that there are three ways to prevent interference:

- Suppress the emission at its source.
- Make the coupling path as efficient as possible.
- Make the receptor less susceptible to the emission.

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

We may further break the transfer of electromagnetic energy (with regard to the prevention of interference) into four subgroups: *radiated emissions*, *radiated susceptibility*, *conducted emissions*, and *conducted susceptibility* [4].

- *Radiated Emission*: It refers to the unintentional release of electromagnetic energy from an electronic device or apparatus. Any electronic device may generate Electromagnetic fields that unintentionally propagate away from the device's structure.
- *Radiated Susceptibility*: is concerned with the ability of an electronic circuit, a piece of equipment, or a subsystem or system to operate acceptably when subjected to an externally generated electromagnetic field.
- *Conducted Emission*: is a term for radio frequency current that flows on one or more conductors connected to an electric circuit, or alternatively, radio frequency voltage between conductors connected to an electric circuit.
- *Conducted susceptibility*: is concerned with the ability of an electronic circuit, a piece of equipment, or a subsystem or system to operate acceptably when subjected to radio frequency voltage or current on interconnecting conductors [4].

2.4 Source of Electromagnetic Field in Railway Electrification

A railway system might pollute, in an electromagnetic sense, the surrounding environment, disturbing radio and communication systems which are not related to the railway itself. In this case the whole railway can be considered as a source of Electromagnetic Interference (EMI). In order to avoid the disruption of the electronic equipment's near to the railway, the overall field generated by railway system must be kept below certain safety values given by standards. Obviously, there are many sources of the electromagnetic field and their contributions can come from: [26]

- **Each part of the railway**: for example, a locomotive or the power supply substation can induce EMI that exceed the EMC standards limits set for the electromagnetic field, because of power circuits that might become a source of emissions.

- **The whole system**: the power supply line (cable) can behave as an antenna, which radiates an electromagnetic field proportional to the current. The spectrum and the intensity of

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

the current depend not only on the power absorbed by a train, but also from the structure (geometrical dimensions ...) of the line, that may cause resonances.

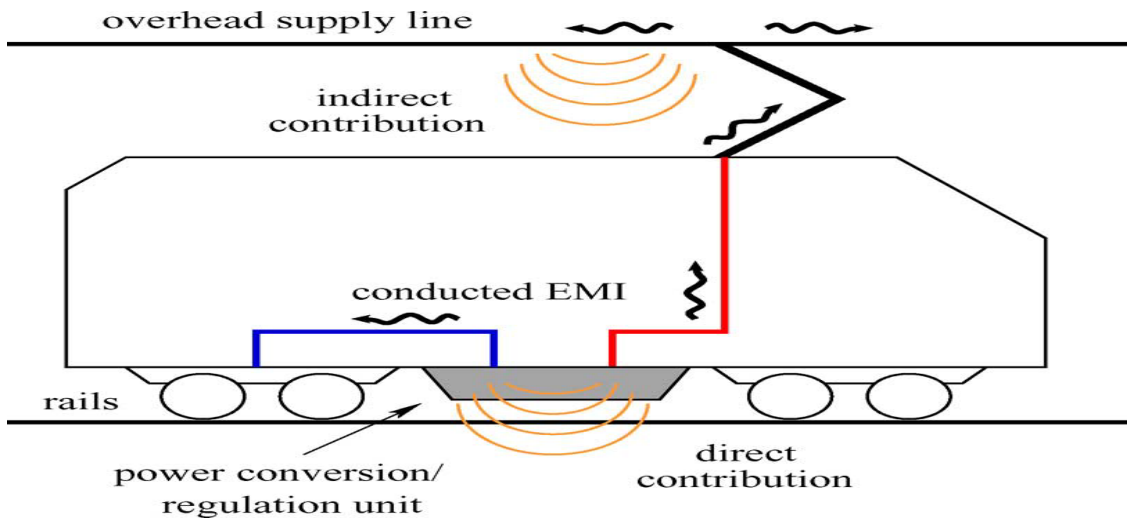


Figure 2.11 The main interference phenomena generated from railway [26]

However, a train might be or be not compliant to field standards depending on the line characteristics and on its position on the railway. Nowadays, trains are designed to meet EMC rules, but the non-compliances can be remedied thanks to identification of the different resonances frequency, which can occur mainly in a frequency range from some kilohertz up to one gigahertz.

So that Electromagnetic compatibility (EMC) is a large area of concern with in the railway industries. Interruption to service due to Unreliability is clearly unwanted for operators and passengers alike. In addition incidents that may compromise the safety of passenger and staff are also undesirable and the railway industry strives to reduce the risk of such incidents occurring through process of hazard identification and risk mitigation. It also concerns about the nearby environments, such as radio frequency, telecommunications, industry's and medical equipment's [7].

2.5 Electromagnetic Interference Sources, Victims and the Coupling Mechanisms

IEC defines EMC as "**The ability of an equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment**". In general the interference phenomena is composed of sources, coupling paths and victims and in some cases a victim of one system could be a source of interference to other systems' as well [22].

Electrified railways not only generate high electromagnetic pollution but are also often victimized because of the same. This also affects the use of sensitive equipment's both within the railways and in the neighboring world. The major EMI sources can be classified as:

- **On board Sources:** Pantograph arcing, fast switching of the power electronics and drives of the propulsion systems, switching of the onboard power circuit, emission from discharges in the power, display units and rotating machineries etc.
- **Track side power feeding system:** Switching and transients from the power system
- **Environmental sources:** Lightning, geomagnetic storms
- **Neighboring sources:** High power radio transmitters, nearby industries (e.g., blast furnaces of steel plants etc.)
- **Intentionally created EMI (IEMI)**
- **Electrostatic discharges:** A charged body is discharged to a victim circuit

The following Fig2.12, shows different sources and victims of radiated and conducted interference within the train and its vicinity. Most of the interference problems studied here is conned to the feeding and signaling systems. But it is important to mention that in some cases like transients, geomagnetic induced current etc. the entire grid, including the traction power supply may be affected [5].

There could be three modes of interference-:

- **Conducted interference:** Generally caused by harmonics from power semiconductor devices of traction power feeding system, propulsion system etc., pantograph arcing, return current, track circuit

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

- **Inductive interference:** Caused by power circuits of either the traction power system or the vehicle and
- **Radiated interference:** Caused by the high frequency components of the pantograph arcing and the high switching frequencies of semiconductor devices of the drives systems

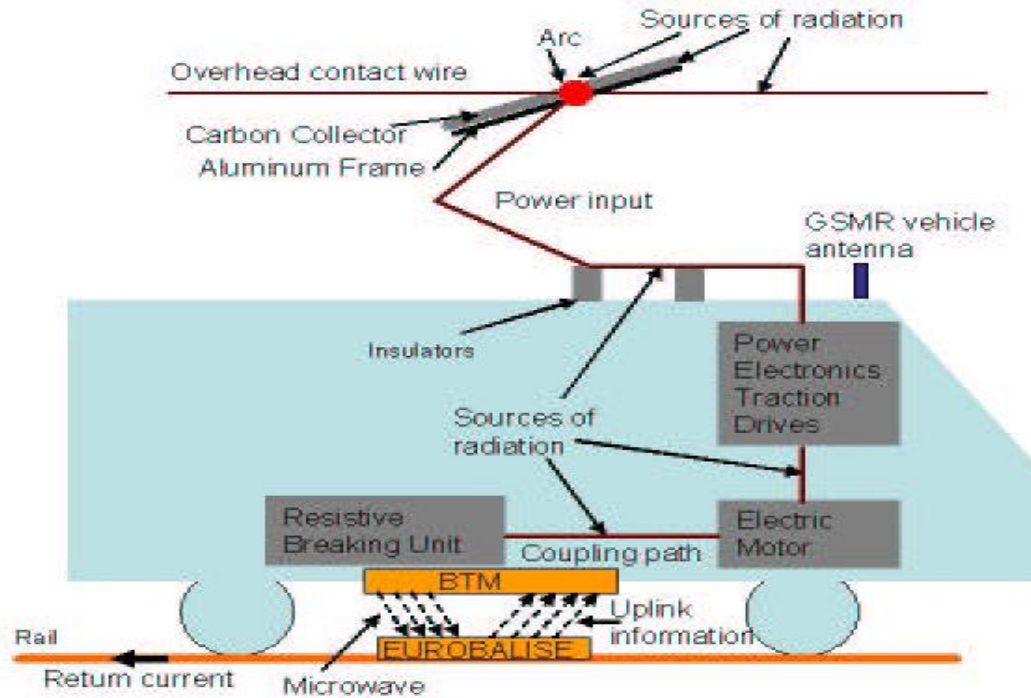


Figure 2.12 Radiation of interference from the pantograph arcing catenary wires [5]

The possible coupling mechanisms within the same railway, with other railways and non-railway systems could be as follows:-

- **Conduction coupling:** Through a common conducting path between the source and victim
- **Inductive coupling:** Time varying magnetic field produced by current in one circuit induces a voltage in the victim circuit via mutual inductance
- **Capacitive coupling:** Time varying electric field in one circuit creates voltage changes in the victim circuit via mutual capacitance

- **Electric (E) and magnetic (H) radiation:** Source and receivers are separated by a distance of more than a wavelength and circuit structures act as transmitting and receiving antennas [5].

2.6 Electromagnetic Field

Electric and magnetic fields are invisible lines of force that surround any electrical device. Power lines, electrical wiring, communication broadcasting antennas and electrical equipment all produce EMF. Electric fields are produced by voltage and increase in strength as the voltage increases. The electric field strength is measured in units of volts per meter (V/m).

Electric fields have the following characteristics:

- Metal conduits and encasements effectively attenuate electric fields
- The strength of the electric field decreases as the distance from the source increases
- Ground and buildings could significantly attenuate electric fields
- When the intensity of electric field changes, it induces magnetic field in a zone of the electric field influence.

Magnetic fields result from the flow of current through wires or electrical devices and increase in strength as the current increases. Magnetic fields are measured in units of gauss (G) or Tesla (T).

Magnetic fields have the following characteristics:

- Metal conduits and encasements of electric current sources effectively attenuate magnetic fields
- The strength of the magnetic field decreases as the distance from the source increases
- Ground and buildings do not significantly attenuate magnetic fields
- When the intensity of magnetic field changes, it induces electric current in a metallic loop located in a zone of the magnetic field influence [13].

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

2.6.1 Sources: - Radiofrequency (RF) and extremely low frequency (ELF) are the two main forms of EMFs. Figure 3.1 illustrates the main railway system EMFs and the following subsections describe these EMFs.

2.6.1.1 Radio Frequency Electromagnetic Field: - RF fields (approximately 3 kHz to 300 GHz in frequency range) result predominantly from the train and overhead contact system (OCS) interaction. Sources of RF noise include micro-arcing associated with the OCS/pantograph interaction, corona discharges from the surface of OCS insulators, and the railway system non-linear, harmonic producing loads. These fields are not permanent, are localized, transient in nature, and only occur for the duration of a train's passage.

There are also RF emissions from railway-licensed radio sources that will have emission levels regulated by FCC, Health Canada (*Safety Code 6*) and Industry Canada.

2.6.1.2 Extremely Low Frequency Electromagnetic Field: - The frequency range of ELF EMF is from dc to approximately 400 Hz, and in North America is predominately associated with the generation, distribution, transmission, and use of 60 Hz electricity. As such, the predominantly 60 Hz frequencies are called the 'fundamental frequency'. Many man-made sources of ELF EMF exist, including power lines, substations, appliances, electric motors and generators. The most significant source of EMF at the railway system environment is the OCS, emanating 50Hz or 60 Hz electric and magnetic fields [13].

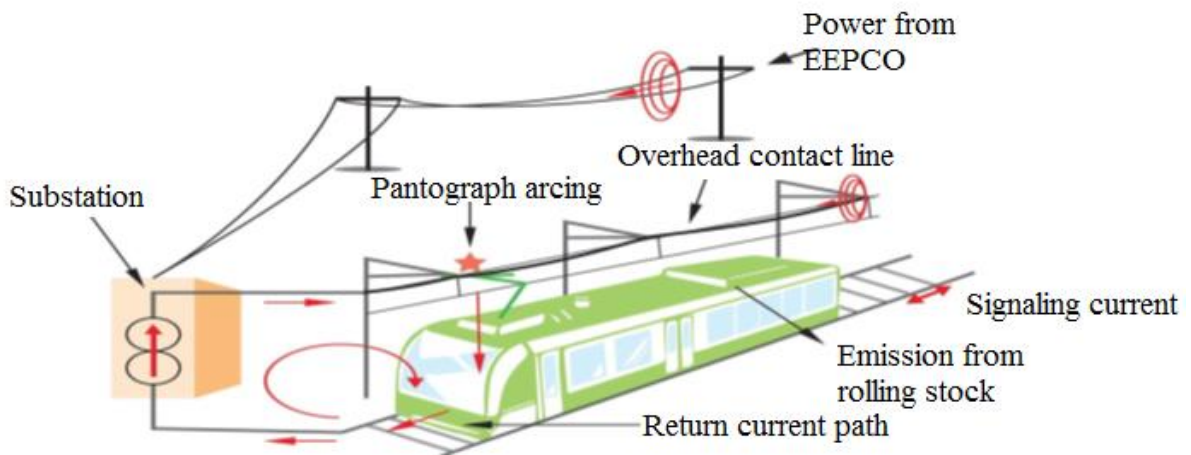


Figure 3.13 Railway Electromagnetic Field Sources

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

60 Hz or 50Hz magnetic fields can be illustrated using the right hand rule. If an electric current passes through a straight wire (i.e., overhead line), and the thumb points are in the direction of the conventional current (from positive to negative), the fingers point in the direction of the magnetic field. Electric fields for wires, on the other hand, radiate perpendicular to the line. Lateral decrease of the electric and magnetic fields may be assumed to attenuate linearly with distance [13].

2.6.2 Human Exposure: - Human exposure to electromagnetic fields can be divided into exposure to RF and ELF.

2.6.2.1 Radio Frequency Electromagnetic Field:-Licensed radio sources for the railway system will have radio frequency (RF) emission limits as per Industry Canada and Health Canada's *Safety Code 6: Limits of Human Exposure to Radiofrequency Electromagnetic Energy in the Frequency Range from 3 kHz to 300 GHz*. The limits will ensure human exposure to these fields does not pose a threat to human health.

Microwave radiation is in the range from 300 MHz to 3 GHz. Electrified railways are not considered to be a source of microwave radiations and therefore microwave radiations are not discussed in this report.

The railway transient RF EMF emanation occurring for the duration of train passage does not pose a human health risk since it is not a permanent field (I e, the field only occupies the electromagnetic environment for the duration of the train passage). Non-permanent fields do not cause significant thermal effects on human body tissue [13].

2.6.2.2 Extremely Low Frequency Electromagnetic Field:-The railway ELF EMF will be permanent since the OCS will always be energized under normal operating conditions. There are currently no Canadian-specific standards that regulate power line frequency EMF limits. However, there are three main organizations in North America that have introduced standards that limit power line frequency electromagnetic field exposures from a human health risk perspective:

- The International Commission on Non-Ionizing Radiation Protection (ICNIRP) through their *Guidelines for limiting exposure to time-varying electric and magnetic fields, 1 Hz to 100 kHz*

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

- The Institute of Electrical and Electronics Engineers (IEEE) through *IEEE C95.1 Standard for Safety Levels with Respect to Human Exposure to Electromagnetic Fields 0 to 3 kHz*
- The American Conference of Governmental Industrial Hygienists (ACGIH).

In combination, these standards set limits for occupational and public settings as well as for workers who have pacemakers. From a health risk perspective, the 60 Hz fundamental frequency electric and magnetic field exposure limits are per the tables below [13]

Table2. 1 Exposure Limits for Fundamental Frequency Electric Field

| | ICNIRP(kV/m) | IEEE(kV/m) | ACGIH(kV/m) |
|-----------------------------|--------------|------------|-------------|
| Occupational | 8.3 | 20 | 25 |
| Public | 4.2 | 51 | n/a |
| Worker with Medical implant | n/a | n/a | 1 |

Table2. 2 Exposure Limits for Fundamental Frequency Magnetic Field

| | ICNIRP(mG) | IEEE(mG) | ACGIH(mG) |
|-----------------------------|------------|----------|-----------|
| Occupational | 10,000 | 27,100 | 10,000 |
| Public | 2,000 | 9,040 | n/a |
| Worker with Medical implant | n/a | n/a | 1,000 |

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

Table 2.3 Exposure limits for DC magnetic field

| Criteria | | Impact magnitude | | |
|------------|---------------|-----------------------|--------------------|-------------------------------------|
| Field Type | Limit | Industrial/Commercial | Residential/School | Sensitive research centers/Hospital |
| DC Field | >1mT(1,000μT) | Very high | Very high | Very high |
| | >50 μT | High | Medium | High |
| | >10 μT | Medium | Low | Medium |
| | >1 μT | Low | Very low | Low |
| | >0.1 μT | Very low | Very low | Very low |

The above table 3.3 exposure limits is at the impact distance of 100m based on implantable medical devices standard EN 45502-2-1 [44].

2.7 Electromagnetic Interference

Electromagnetic interference is defined as the degradation of performance of a device, equipment or system caused by an electromagnetic disturbance.

Sources of electromagnetic interference include –

- The propulsion system’s high voltage and high current operational mode emissions
- Train signaling systems and their associated computer operating codes
- Train control system emissions
- Track to train control circuits
- Right-of-way electromagnetic field emission sources.

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

Electromagnetic interference involves three elements:

- **Sources** generate electromagnetic fields or energy such as the overhead contact system and the Electric Multiple Unit (EMU)
- These sources may interfere with electrical **receptors** such as railway and substation electrical components or third party devices such as electron microscopes, magnetic resonant imaging devices or antennas
- Potential interference is transmitted through a **coupling path** through a conductor such as an electric power line or ground wire, or through the air by induction or radiation (often referred to simply as radiation). Coupling paths can be complex, involving both conducted and radiated elements.

These disturbances can be mitigated through various technical measures to achieve electromagnetic compatibility to ensure that all electrical and electronic devices can co-exist and function satisfactorily. [13]

2.7.1 Impact of Electrified Railway on Equipment: - ELF and RF EMF emanating from the railway system may interfere with the proper operation of third party and Metrolinx (An agency of the Government of Ontario) equipment. EMC is mainly a concern for EMI sensitive sites as discussed below.

2.7.1.1 Electromagnetic Interference Sensitive Sites: - EMI sensitive sites are often equipped with electrical devices susceptible to EMI, for example:

- Airport navigational aid and communication systems
- Radars
- Medical imaging equipment
- MRIs
- Scientific instruments that utilize charged beams or high precision magnet systems
- Electron microscopes
- Electron beam lithography systems

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

- Focusses ion beams
- Systems requiring a very stable magnetic field, such as magnetic field imaging devices and nuclear magnetic resonance spectrometers.

Per *IEEE 241*, the following facilities are considered to be EMI sensitive sites and may require a degree of control of electromagnetic energy:

- Research and development laboratories for low-noise circuitry work
- Research and development laboratories using high-energy radio-frequency devices
- Special computer facilities
- Test and measurement laboratories
- Hospital and other biomedical research and treatment rooms
- Railway signaling and communication systems
- Airport navigational aid and communication equipment.

2.7.1.2 Extremely Low Frequency Electromagnetic Interference: - The alternating currents and voltages associated with the traction power supply and OCS of an electrified railway system may interfere with nearby communications systems, Wi-Fi networks, including railway communication and signaling systems. ELF EMF is normally the predominant source of interference in the form of magnetic induction. Specifically, alternating current flowing in the OCS, including its harmonics, generates a magnetic field that induces a voltage in nearby communication conductors and equipment in EMI sensitive sites.

For inductive coordination between the OCS and communication conductors, the clearance requirement between the OCS and communication conductors will be as per the Ontario Electrical Safety Code requirement, which will ensure that the inductive interference from the OCS to nearby communication lines is minimized.

Electromagnetic compatibility between the UP Express electrification systems and the current and future Wi-Fi networks in close proximity of the railway would be ensured during the detailed design to prevent any interference. To ensure compatibility, Wi-Fi networks compliance to *IEEE 802.11* for the specific Wi-Fi frequency bands would be mandatory. [13]

2.7.1.3 Radio Frequency Electromagnetic Interference: - Intentional radiators (licensed radio sources) pertaining to Metrolinx and third parties may cause interference with each other due to frequency overlap between radio applications. RF noise from the OCS/pantograph interaction may cause interference with nearby RF receivers. It should be noted that the RF noise from the OCS/pantograph interaction will be limited as per *EN 50121* via field verification and interference with nearby RF receptors will be minimized.

As well, the nonlinear loads in the rolling stock produce harmonic voltages and currents which will introduce harmonic EMFs in the RF range. These harmonics are normally limited to values set forth in industry standards and are not significant.

2.7.1.4 Equipment Impact on Electrified Railway: - The frequency management plan that will be executed by Metrolinx during the detailed design stage will identify and avoid any frequency overlaps between the railway RF receivers and third party RF intentional radiators. The radios pertaining to the railway system will use the frequency allocated to railway radio devices by Industry Canada. Other third party radio devices in the vicinity of the railway system have different frequencies of operation assigned to them by Industry Canada and normally do not interfere with railway radios and vice versa.

Furthermore, since railway equipment will be immunized per *EN 50121* and no significant background electromagnetic radiation at the UP Express corridor has been measured and estimated during the site survey, it is not expected that nearby third party equipment will interfere with the proper operation of the railway equipment [13].

2.8 Why EMC in Railway is so challenging?

Compared to large power systems, the electrified railway systems provide different yet challenging Electromagnetic Interference and Compatibility (EMC) issues mainly due to the system topology, configurations, and equipment. All the modern developments within the railways have indeed led to a faster, smoother, reliable and efficient operation of the railway industry. However, they bring new challenges for engineers and researchers as well. A review of some of those challenges can be found in:

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

1. Usage of sliding contact to draw high power to the rolling stock through a contact area of few square mm, which causes:[5]
 - Distorted supply voltage and current waveforms
 - Generation of a net DC components, harmonics, including even harmonics, and Inter-harmonics
 - Wideband electromagnetic noise emissions
 - Transients and surges
2. Wide variations in the power supply configurations, layout and system topologies between different trains and at different sections of the railway infrastructure
3. Trains are bulk dynamic loads (consume power between 1-12 MW, sometimes even more) and their speeds, electrical loads, currents etc. vary in a wide range.
4. Usage of the rail for both current return and signaling (same conductor for high voltage and low voltage applications)
5. Depending on soil characteristics for long track sections the return currents could find its path either through the rail or through the soil.

These inherent and other additional features in a railway system may introduce several challenges:

- All these DC components and harmonics propagates in the entire traction power and signaling system causing EMI issues:
 - Saturation of different Transformers used, i.e., booster transformers, auto transformers, substation transformers, vehicle transformers etc.
 - Saturated transformers are a source of even harmonics and inter-harmonics
 - Radiated EM fields cause interference to wireless services, like GSM-R communication, other radio and wireless based services
 - DC components cause corrosion of bearings
 - Even harmonics and inter-harmonics affect the control systems of the drives and power electronics
- Different levels of inrush current, wide band frequency content of transients and surges due to switching in the traction power system, raising and lowering the

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

pantograph UP and DOWN etc. With the recent development trends in the propulsion system, where Insulated Gate Bipolar Transistor (IGBT) based drive system are prevailing over Transistor Gate Oxide (GTO) based systems. On the other hand more and more sensitive equipment's and sensors are being used for control and signaling purposes. This leads to:

- Higher frequency switching and sometimes presence of higher order harmonics
- It is difficult to estimate the electromagnetic environment because:
 - Difficulties in simulating the high frequency behavior of the power electronic devices and the complete drive systems
 - Schematic details and layout of the complete system is difficult to achieve and vary widely between different train models, and depends on customer requirements
 - Difficulties in performing experiments due to cost, inaccessibility of the system
 - System topologies vary widely and changes often happen in the middle of a project
 - Most importantly, because of the involved high complexity as well as high sensitivity makes it difficult to predict the associated EM environment and performance after the full system is assembled [5].

In many cases, EMI issues appear after the completion of the project, owing to the incomplete knowledge of the overall system configurations, types of EMI sources, relevant mediums and environmental factors. Also, investigations with regard to the above specific cases helped to develop the required experience and expertise in improving the standards, design and planning of railway networks and its efficient operations from an EMC perspective. Such an approach could be used as a benchmark in other similar applications.

With further advancements in the application of more electromagnetically sensitive devices, sensors and wireless technology for both rail control and signaling and the outside non railway world, the specified emission limits in the standards are becoming stricter by the day. At the same time the drives and propulsion systems started using semiconductor devices with higher switching frequencies. In EMC terminologies this translates to the sources becoming worse

and the victims more sensitive, making the job of EMC engineers more interesting challenging! [5]

2.9 Cost of EMC during Design Life Cycle

EMI should be considered early in design cycle of a product, in order to decrease expensive post-development modifications for EMI compliance. On the other hands shown in Fig 2.13. The more the EMI problems are left at the end of the design cycle of the product, the more the cost and time to market increases. Hence, it is necessary to resolve all the issues pertaining to EMI at the design stage of the product or the system [6].

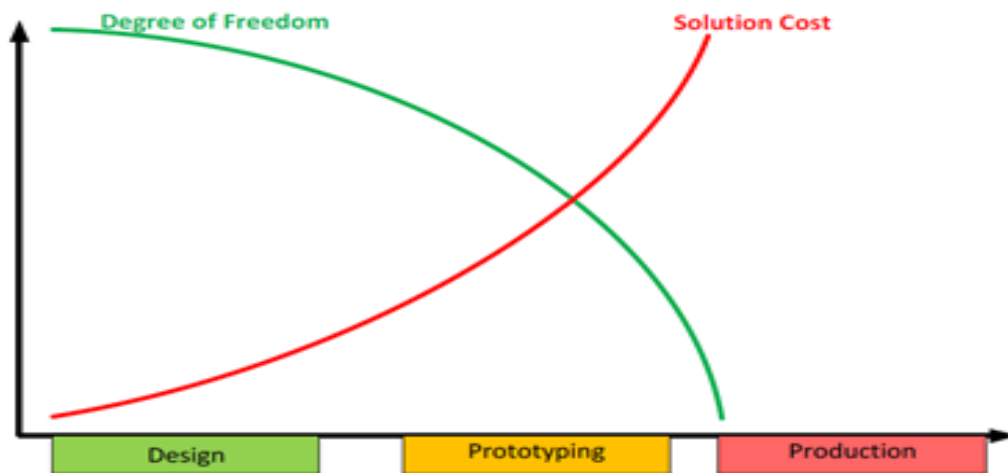


Figure 2.14 Cost of EMC solution during the design lifecycle

2.10 Electromagnetic Compatibility Regulation and Standards

Interference problems are not new. Since the beginning, radio engineers have perceived the difficulties encountered when trying to make ground connections to the chassis of different systems. All these are manifestations of EMI and demonstrate the need to design systems which are compatible with their electromagnetic environment. There are two aspects to EMC. First, systems must be designed so that they do not emit significant amounts of unintended electromagnetic (EM) radiation into their environment. This aspect is described as emission and may be divided in turn into conducted and radiated emission. Second, systems must be capable of operating without malfunction in their intended environment. This aspect is described as immunity, or alternatively, as susceptibility. Hence, all EMC analyses and design

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

techniques aim to address these two aspects using circuit-based and field-based experimental, analytical, and numerical techniques.

EMC is defined as the study and analysis to resolve electromagnetic interaction problems in the field of electrical engineering. EMC is branched into two distinct categories: EM emissions and EM susceptibility with alternating medium of propagation. The two categories are fundamentally reciprocal. Fig.2.14 illustrates the areas of EMC fields. [6]

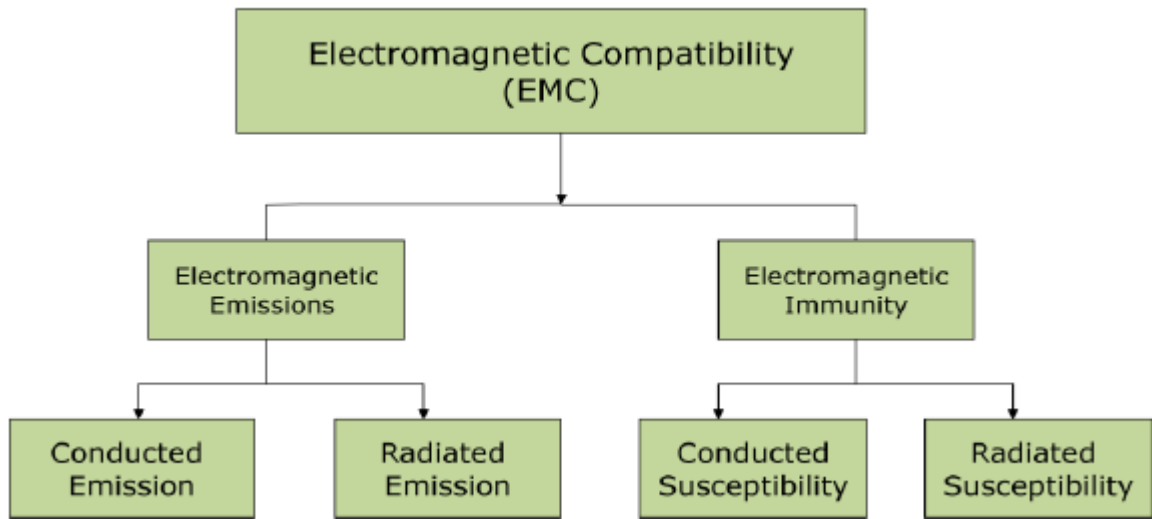


Figure 2.15 Field of EMC [6]

International standardization bodies have recognized for many years the need to define standards and procedures for the certification of systems meeting EMC requirements. These are the responsibility of various national standard bodies and are overseen by the International Electro-technical Commission (IEC).

Furthermore, various regulations have been imposed by government authorities to limit the level of the EMI emissions. These regulations have been developed as EMC standards and are a condition to product marketing and circulation [6].

2.11 Description of Standards EMI Measurement Methods

The EMC standard EN 50121 [1] is used to characterize the EM environment, in the railway systems; it notably aim to limit the EMI levels from the railway infrastructures to the external environment. This standard EN 50121 describes the methodologies and the limits to apply, relating to the EM radiations and immunity of railway equipment's, vehicles and infrastructures. The objective of the tests specified in this standard is to verify that the EM emissions produced by the whole railway systems do not disturb the neighboring equipment's and systems.

The methodology then consists in measuring the radiated EM emissions at a distance of 10m from the middle of the tracks and at about 1.5 m from the floor (Fig2.15) and in comparing them with the maximum levels. The measurements protocol and the limits are specified for the frequencies varying from 9 kHz to 1 GHz.

During measurements of the electromagnetic field radiated at 10 m from the railway track, we can observe that, sometimes, for some frequency, the standards limit can be exceeded.



Figure 2.16 On site measurement of the electromagnetic radiation of the train [13]

Chapter Three

3 Literature Review

In this chapter the paper describes the history of railway electrification, Electromagnetic field emission from railway electrification, and different review of related studies.

The development of railway has been substantial since the beginning of 20th century. Railway transportation is playing a significant role not only in peoples' daily life but also in global economic growth. In 1897, Siemens displayed the first electrically powered locomotive at the Berlin Commerce Fair. Since then, electrified railways have been improved dramatically due to the rapid development of power electronics, electric motors, and manufacturing techniques [6].

3.1 Impact of the Infrastructure on the Electromagnetic Emissions Radiated by a Railway System

The EMC level of a railway system to the outside world is determined by the combined effect of the EM emission sources of the rolling stock and the infrastructure. On the other side, the EM interaction between different parts of a railway system determines the internal EMC level of that system. As regards emissions of the whole system toward the outside world, in addition to emissions directly radiated from on-board power electronic systems (primary radiation phenomenon), another phenomenon which plays an important role is conduction of noise currents (generated by the power electronic systems as well), which are placed onto the power supply line (i.e., the overhead wire) and radiated by the infrastructure (secondary radiation phenomenon). Indeed, further contributions to EM emissions that should be considered are, for example, those related to the noise-current distribution along the supply line and due to:

- a) The non-ideal behavior of substations connected to the end-points of the portion of the infrastructure where the rail vehicle under test is operated;
- b) The conducted emissions due to other rail vehicles operated in proximity of the site where radiated emissions are measured. Also these contributions are to be ascribed to the infrastructure rather than to the rail vehicle under test [11].

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

On the other side, it should be noticed that the infrastructure behaves essentially as a very large horizontally-shaped antenna, whose radiation properties strongly depend on a number of parameters, such as the length of the segment used for test execution, the termination loads, discontinuities along the conductors, geometrical asymmetries, etc. As a consequence, the radiation phenomenon associated with the functional behavior of the on-board power systems is substantially influenced by the architecture and the electrical configuration of the infrastructure over which rolling stock is operated.

All the considerations discussed above are the motivations for this work, which represents an attempt to model and interpret the dominant phenomena involved in the generation of the emissions radiated by a railway system. In particular, the main scope of this theoretical analysis is to understand the impact of the electrical and geometrical features of the infrastructure on the radiated emissions. In line with this objective, a circuit model based on multi conductor transmission lines (MTL) theory is developed and validated versus full-wave EM simulation of a suitable stretch of a 2x25kV AT railway system. Unlike the modeling procedure introduced in, which is limited to the analysis of functional aspects (50 Hz), the MTL model proposed here is aimed at analyzing the main properties of the distribution of the noise currents along the line conductors. That is, the conducted disturbances along the railway line wires and the rails (for frequencies extending up to a few megahertz) to which the radiation properties of the infrastructure are directly related. Development of a simplified distributed-parameter model is of paramount importance in order to overcome the huge computational cost required by direct three-dimensional EM modeling of a stretch of a railway line (extending for several kilometers), in a wide frequency range. This is a crucial point also because large uncertainties related to several parameters of a railway system may require estimations based on repeated-run analyses.

Throughout the paper EM modeling is applied to a simplified version of a High-Speed 2x25kV AT railway system in order to assess the validity and accuracy of the distributed-parameter (MTL) model which, subsequently, will be used to characterize more complex and electrically large portions of the railway system under analysis. Since MTL theory has an inherent frequency limitation, the modeling tool developed in this paper is limited to frequencies below 1-5 MHz that is to the frequency range in which radiation is dominated by the magnetic field.

The computational efficiency of MTL modeling combined with the possibility to obtain approximate radiated field estimates from the current distributions allows for effective investigation of the impact of the various subsystems (and their parameters). Accordingly, the tool developed in this work can be used to get an insight into the role played by the infrastructure on the radiated emissions of the whole railway system to the outside world. [11]

3.2 DC Railways and the Magnetic Fields they produce

DC electric railways produce magnetic fields, not only from the intended traction currents, but also from unintended earth-leakage currents; these fields, particularly those from the leakage currents, are becoming an increasing problem for geomagneticians. Currents leaking to the ground from the systems produce direct effects over tens of kilometers on telluric measurements, and have been used as a telluric source to monitor ground resistivity.

Close to the railway the magnetic field produced by the traction current flowing to and from the train is significant, but at larger distances the dominant field is that produced by currents leaking from the railway track into the ground; it is these two sources of field that will be considered. [8]

3.2.1 DC-Powered Railways: - DC powered rail vehicles are used on both long-distance and commuter railways; in the latter case they are sometimes called Light Rapid Transits (LRTs) or Metros, or Trams when street running,

3.2.2 The Power-Supply System: - The railway traction current will be supplied by rectifiers at DC substations. Each substation will usually have two or more rectifiers, normally working in parallel. To carry the current from the substation to and from the train, two conductors are needed and these conductors is an overhead copper wire with the height of the wire above the ground is typically in the range 4.5–5.5 m. With very rare exceptions, this overhead conductor is the positive conductor; it is convenient to think of the overhead as ‘feeding’ current to the train. In the vast majority of systems the current is returned to the substation through one or both of the running rails, using some of the train wheels as a rolling contact.

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

Current International Standards specify nominal DC supply voltages of 750, 1500 and 3000 V. As typical loads are now of the order of 1 MW or more, this means that the traction currents are of the order of 1000 A or more. In heavily trafficked urban areas the rectifier substation spacing might be 2 km or less, but in single-track rural systems the spacing might be 20 km or more.

A typical single overhead contact wire has a resistance of $0.17\Omega/\text{km}$ when it is new. In areas of high demand this contact wire is doubled up, connected to extra wires in the catenary support system, or connected to a parallel underground ‘reinforcing feeder’ cable. Even so, there are large Ohmic drops in the overhead wire, and the voltage seen by the train can vary over a wide range.

International Standards allow this voltage to vary between -33% and $+20\%$ (e.g. for a 750 V system, the allowable range is 500 V to 900 V). In normal running conditions the overhead wire is electrically continuous, so that there will be current sharing between adjacent substations. In double-track situations there might also be bonding between the two overheads. [8]

3.2.3 The Train: - Because of the wide voltage variation seen by the train, most train traction-motor control systems are designed to provide the current programmed for that particular situation, regardless of the overhead-to-rail voltage difference at that point provided it is within the system’s working range.

So when considering the traction current in the rail, at any one time we can replace the rectifier at the substation, and the motors etc. of the train, by a ‘constant-current generator’, whose output current does not depend on the voltage at its terminals [8][9].



Figure 3.1 Rectifier substation feeds train via overhead and rail [8]

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

A train travelling at a fixed speed on a level track would be working at a constant power, just sufficient to overcome rail friction and air drag. But trains need to accelerate from rest, and climb hills, and the power can be higher in these situations. The traction control system on passenger trains is often programmed to give a prescribed acceleration/time behavior, with the driver essentially just selecting a particular program. And on an urban passenger system having frequent stops, trains often accelerate away from a station, and then coast un-powered before braking for the next stop. So the overall traction-power/time curve will be different for different systems.

3.2.4 Division of Current Between Substations: - As argued above, if there is only one substation, and only one train on the track, to a good approximation the train can be considered to act as a high-internal-impedance current generator; this generator replaces the actual rectifiers, control system, and motors, and it does not matter if we think of it as being in the train or at the substation.

If we add more substations, then to the same approximation the train still draws the same current. If the train is between two substations, this current is divided between the two, the ratio of the currents being the inverse of the ratio of the resistances (overhead + substation + rail) of the two current paths; in practice this ratio is dominated by the resistance of the overhead wire. Therefore, assuming uniform overhead, to a good approximation this ratio is a linear function of the along-track train position, and is very little affected by whatever might be happening in the rails. (If there are also other, more remote, substations, then because of the finite internal resistance of the rectifiers, a small fixed fraction of the current from each direction will be supplied by the remote substations.) We can think of the train pushing its total traction current into the rail, with the relevant fraction of this current having no option but to get back to its 'own' substation. It is important to note that this division of current between the substations is determined almost entirely by the resistance of the overhead, and is hardly affected by whether or not there is earth leakage.

However this division does vary as the train moves along the track. To the good approximation that the substation/overhead/rail resistance network is linear, removing the rectifiers, and inserting a current generator between the overhead and rails at a given position will give the

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

same distribution of *its* current between substations whether or not there are any other current generators (trains) elsewhere on the network. So, each train on the system will behave as an *independent* current generator, with the division of *its* current between the substations determined by *its* position on the track, independent of the presence of other trains. [8][10].

Then the overall current distribution in the overhead and rails is given by the algebraic sum of the current distributions for each train. Of course this can involve considerable cancellation of individual current contributions at some locations, but this approach does allow using a set of very simple separate calculations, rather than having to solve a set of simultaneous equations.

3.2.5 Earth-Leakage Currents: - Clearly the magnetic field produced by the traction current in the loop substation-overhead-train-rails-substation will produce a significant magnetic field; this is the dominant field near the track. But at larger distances what dominates is the magnetic field due to currents that have leaked from the track into the ground, returning to the track and/or substation elsewhere. (Leakage from the overhead wire, or third or fourth rail, is usually insignificant, as they are much easier to insulate.)

The running rails are close to the ground, so unless precautions are taken it is very easy for them to have significant electrical contact with the ground. As a result, a proportion, sometimes quite large, of the return traction current in the rails will leak into, and elsewhere return from, the ground.

3.2.6 Railway Ear thing Policy:- Some older railways tried to keep their track very close to earth potential; for example, Iliceto and Santarato (1999) said that some DC railways in Italy are “carefully earthed at discrete points about 100 m apart”; however such deliberate ear thing is no longer common practice. Modern practice is to use nominally insulated track. For example the UK Railway Group Standard GL/RT1254 (Rail track, 2000) says that DC systems “shall be designed, installed and maintained so as to ensure that there are no deliberate low resistance points of contact between the traction return circuit and the general mass of the earth”.

All current International, European and National Standards follow the joint principles of a nominally insulated track, and a low along-track resistance. And new railways might be compelled by their planning consent to comply with some numerical specification. For

example, the European Standard EN 50122-2:1998 (European Standard, 1998) recommends maintaining a track-to-ground conductance of not more than 0.5 S/km for single track on surface track, and not more than 0.1 S/km in tunnel; however, particularly in urban areas, it is now common to specify the smaller figure (or less) for all track. (Note that this figure of 0.1 S/km is a *distributed linear* conductance; the actual total conductance in Siemens between the rail and the body of the earth is this figure multiplied by the length of track in km. Some texts use the equivalent linear resistance value of (10 Ω /km.)

The aim of reducing earth leakage is not out of consideration for geomagneticians, but because of the need to reduce electrolytic corrosion of the infrastructure of other utilities.

The problem is that if there are DC currents flowing in the ground, these will tend to be collected and concentrated into any metal pipelines, metal-armoring of cables, etc. that happen to be around. Nothing much happens where the (positive) current enters the metal, but where it leaves the metal there is electrolytic corrosion. A rough figure is that 1 A flowing for one year results in a loss of 10 kg of iron. [8][9][10].

3.3 Measurement and Analysis of Electromagnetic Fields from Trams, Trains and hybrid Cars.

Electricity is used substantially and sources of electric and magnetic fields are, unavoidably, everywhere. The transportation system is a source of these fields, to which a large proportion of the population is exposed. Hence, investigation of the effects of long-term exposure of the general public to low-frequency electromagnetic fields caused by the transportation system is critically important. Measurements of electric and magnetic fields emitted from Australian trams, trains and hybrid cars were investigated [9]. These measurements were carried out under different conditions, locations, and are summarized in this article.

This study analyses the weak magnetic field strength from transportation systems. The findings can be used:

- (1) To reduce the magnetic fields from transportation system and
- (2) To set-up new laboratory experiments to observe the possible biological effects.

Those replicated biological studies can contribute to future recommendations for exposure

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

limits, such as those published by the World Health Organization and the International Commission on Non-Ionizing Radiation Protection (ICNIRP).

The studies of EMF exposure levels for several types of trains, such as DC underground, AC rains and Maglev, have been taken. The measurements were carried out using various types of magnetic field measuring instruments that are operated in various frequency bands. The static and alternating magnetic flux densities in the electric trains and trams were seen. The recording device was an EMDEX II logging magnetic field dosimeter. The measurements were taken for the London underground 600 V DC system, the suburban railways at 750 V DC, and mainline railways at 25 kV and 50 Hz. The maximum alternating flux density was at 100 Hz, and the typical static magnetic flux densities to which passengers might be exposed were less than 300 mG.

The results seem to be compatible with the evidence of the laboratory studies on the biological effects that are found in the literature; nonetheless, the results are far lower than those levels recommended by the ICNIRP. [9][10].

3.4 Optimization of Magnetic Field Propagated from DC Light Rail Transit System.

Electrified traction systems are a source of electromagnetic field emissions; this is particularly true for large power systems but also for modern light rail, trolley bus and street car systems, that are embedded into cities, and thus closer to potential victims. The location of the alignment presents a unique scenario where the railway is in close proximity to sensitive installation. The low frequency magnetic field may be computed easily by applying Biot-Savart's law to the whole set of the currents circulating in a given transversal section of the traction system, comprising the OCW, or third rail, and the return circuit, which for simply traction system comprises the RR only. Waki et al, [33] investigated the use of magnetic shields, installed along the alignment, to attenuate the magnetic field propagated by the railway; this solution is feasible where the railway does not share the right of way with an existing road network. Schepper and Rabl, analyzed a Compensation Conductor (CC) arrangement using a resistance network approach and reported a 42% improvement in the magnetic field due to the CC. Mariscotti and Ogunsola in, investigated the effectiveness of a

mitigating technique based on the installation of CCs that can either be installed to be at the same potential of either the OCW or RR; the authors were able to demonstrate a 10 dB attenuation of the propagating magnetic field. In this paper, the work of Mariscotti and Ogunsola is furthered by optimizing the CCs arrangement with a view of maximizing the attenuation of the propagated magnetic field. [12]

3.4.1 Compensation conductor optimization: The problem of external magnetic field minimization with respect to the geometry of Compensating Conductors (CC) may be formalized following two approaches. The CC geometry consists of their position (x_i, y_i) and their cross section S_i with $i = 1 \dots N$. One approach builds an objective function J containing induction field values $B(x, y)$ for selected points computed with Biot-Savart's law and then numerically identifies the optimal solution (x_i, y_i, S_i) ; even if the calculation of B in the 2D surface containing the cross section is, in general, a valuable visualization tool for the expression of results, using it directly to drive the optimization poses the following additional issues: (1) the selection of points that correctly represent the problem and, (2) the possibility that closer locations with larger B values may bias" the solution. The other approach considers the problem reformulated in terms of impedance terms expressions and minimization of the so-called loop impedance; in this approach the solution doesn't depend on the selected points, but accounts for the whole set of points on the 2D surface.

Before describing the two approaches in detail, it is worth defining more accurately the target of the analysis. If a set of points $(x_k; y_k)$ with $k = 1 \dots K$ is considered, the requirement of minimization implies that each $B(x_k; y_k)$ value is minimized with respect to the $3NC$ degrees of freedom of the problem given by the independent setting of $(x_i; y_i; S_i)$ and to the fixed geometry of the existing traction line conductors $(x_i; y_i; S_i)$ with $i = N + 1 \dots N$. Yet, with a more practical approach, the problem would be better expressed by the fact that each $B(x_k; y_k)$ is lower than a predetermined limit value B_k^* (given for instance by equipment susceptibility or human exposure), that may vary with the location in real applications there are different limits for workers in technical rooms and along the line, separate limits for the general population at platforms, and separate limits for sensitive equipment in hospitals and laboratories. [12]

3.5 Assessment of Infrastructure Impact in Radiated Emission

Tests of Rolling Stock

The dramatic increase in the use of electronic devices in almost any domain has led to a substantial rise of the potential for interference between equipment working in the same environment. Because of the likely disruptions that may follow this scenario, electromagnetic compatibility (EMC) has established itself as the cornerstone for the proper working of any electronic equipment. The railway domain has been part of this trend since the early introduction of static conversion through power transistors acting as switches, through switched-mode conversion/regulation, that generates strong current/voltage gradients leading to interference phenomena that could jeopardize the proper working of electronic devices within the train itself and the correct interpretation of railway control signals propagating along the rails.

This is a major issue because of the inherent security hazards involved: the failing of security and control devices could have dire consequences. This was a major point for the introduction of EMC testing of rolling stock. Moreover, electromagnetic interference (EMI) can affect, through radiation and propagation, other systems not directly related to the railway domain, such as telecommunications lines and wireless systems.

Chapter Four

4 Design of System Component

The main focus of this thesis is the detailed analysis of one of the major EMI sources, namely contact lines(feeder line) with return current and pantograph arcing, and their possible victims within the railways in specific and the outside world in general. Any system has its own components that comprise different things. Addis Ababa light rail transit system component has been described as follows:

4.1 Assessment Scope

A survey of the route was undertaken to identify any potentially sensitive sites within a 100m corridor either side of the center of the nearest Addis Ababa LRT track, or from the proposed power equipment, e.g. overhead lines and traction substations (EN50121 and EN61000-6-(1-4). The primary causes of EMI and EMF will come from the traction power distribution and overhead line electrification. The level of EMF diminishes rapidly with distance from the source, so the extent of any interference or harmful effects will be limited to only a short distance from the railway boundary or the boundary of any traction power substation or switching station. A 100m corridor was selected to identify all potential receptors within that area to demonstrate that the level of risk will be limited to a much shorter distance from the railway. Any receptor outside of the 100m corridor may not be affected.

Addis Ababa LRTs data for levels of traction current is based on estimated maximum power usage at typical locations along the route and has generated estimated EMF contour plots that show worst case levels of EMF.

Modeling traction power at this early stage is a complex process, which will undergo much iteration throughout the design of the Proposed Scheme, right up to the detailed design stage. Actual levels of EMF emitted cannot be confirmed until the Proposed Scheme is operational; however levels of emitted EMF should not exceed those used for this assessment. Possible third party receptors to EMI and EMF were identified by mapping and analyzing the route. From this information, third party receptors that fall within the 100m corridor either side of the

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

center line of the nearest track and also the proposed power equipment, e.g. overhead lines and traction substations, were identified.

Typical receptors identified by the study includes; residential zones, schools, hospitals, emergency services, military establishments, radio transmitters, mobile phone masts, and commercial zones.

Using the methodology detailed above the baseline data was tabulated. Once each potential receptor had been identified, an assessment was undertaken for compliance with the ICNIRP Guidelines and applicable harmonized EMC standards and to identify the level of risk and, if required, potential mitigation for each site [3].

Infrastructure running parallel to Addis Ababa LRTs for any significant distance that may be susceptible to the effects of induced voltages was also identified. This included power lines and other aerial cable routes, metal fences, pipe lines and motorway telecommunication cables.

4.2 Addis Ababa LRT Power Distribution System

In the power distribution system of Addis Ababa LRT system, a 15kV AC voltage is received from the EEPCO (Ethiopian Electric power corporation Authority) power system and transformed down to the appropriate AC voltage 0.59kV in the substation transformer for LRT system, and it is converted to DC voltage 750V by rectification equipment. Thus, Each substation will be fed from two separate incoming lines in order to avoid any failures in one line from disrupting the operation of a system. The DC voltage is distributed to the overhead contact system, and LRT vehicles are operated. The DC power distribution system of Addis Ababa LRT system rectifies AC power to DC power using power diodes. The provided DC voltages and currents are obtained, and the harmonic components which are generated in the rectification process are separated and used with electromagnetic interference source for the electromagnetic wave analysis of the LRT system.

The length of the LRT system is 17.4km E-W & 16.7km N-S of the city. A 15KV incoming line is used as an external power supply system and fed to 20 different substations out of which 19 are a combined step down and rectifier substation, whereas the remained one is step down substation for the traction power supply system, DC750V overhead contact system

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

(OCS) and running rail return mode are installed. Each rectifier substation, Fig4.1, is equipped with rectifier/transformers to convert the power to DC750V [20].

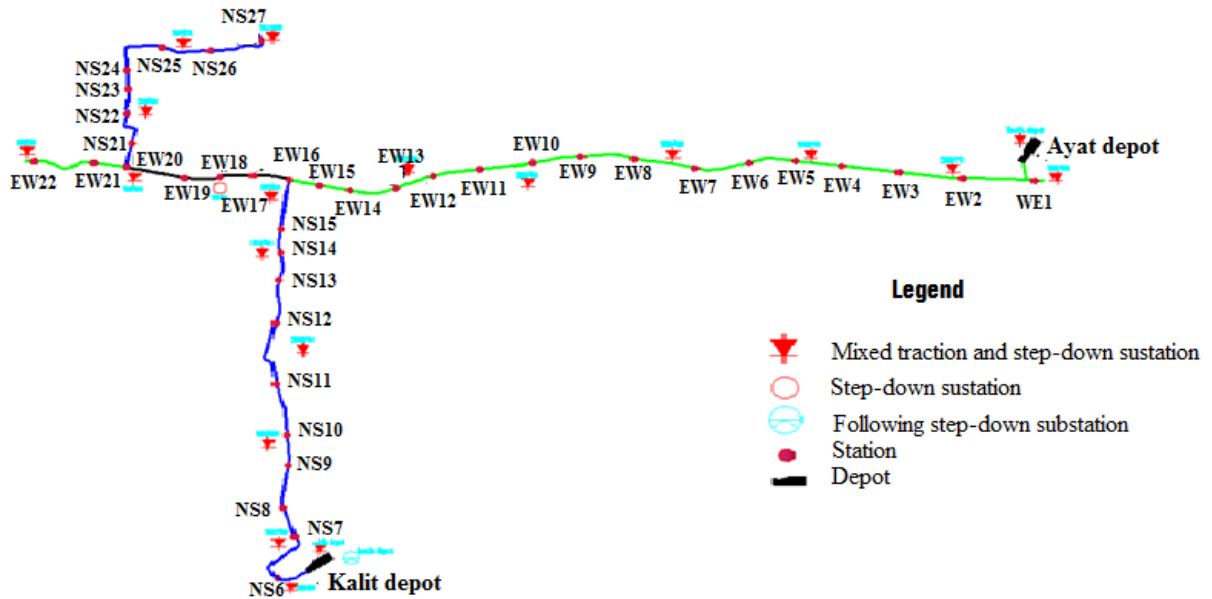


Figure 4.1 The general topology of Addis Ababa LRT route [20]

The section from EW9 up to EW 22(Megenanga to Tor- hayiloch), Fig4.2, is the closer to the nearby environment and taken for electromagnetic analysis in this paper. This section is chosen because of that; relatively high traffic section, closer to the nearby environment, large spacing between feeder substations and highly loaded sections. But the analysis is used for all the route and in the future expansion.

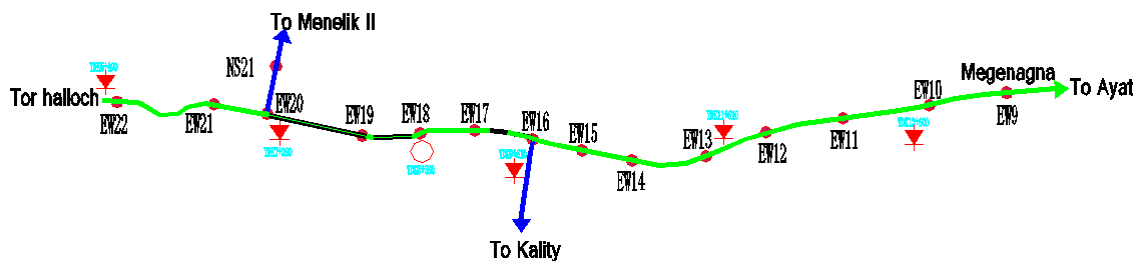


Figure 4.2 Topology of the study route

The configuration of the traction substation consists, basically, power transformation equipment's for traction units which convert AC electricity to DC. Rectification is made through three phase diode rectifiers connected to the secondary winding of the power

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

transformers. DC terminals of the rectifiers are connected in parallel to a positive and a negative DC bus, respectively. The positive bus is connected to the line and the negative to the rail.

4.3 Overhead Contact System of Addis Ababa Light Rail Transit

Traction power for train operation can be either generated on board or collected from overhead wire or third rail. For collecting power from overhead wire or third rail we must have an appropriate power collecting mechanism. The Addis Ababa LRT railway system uses the overhead contact wire; power collection mechanism.



Figure 4.3 Addis Ababa LRT railway line

The Addis Ababa LRTs catenary power collecting system has the following dimensions:

- Track gauge 1435mm
- Mainline between section 50m
- Yard line 30m
- Maximum gradient 55%
- Height of contact line for ground section from top of rail is generally 4500mm to 5400mm
- Height of contact line for underground section from top of rail is generally 4040mm

4.3.2 Material Perspective: - Carbon, Sn-Sb alloy impregnated carbon, Cu or Cu alloy impregnated carbon is the most widely used material for sliding contact. While pure carbon is still being used in many rail ways, Cu or Cu alloy impregnated carbon is most popular. Since

only one blade is used in most of the high speed railways (not for LRT), the current density is very high in the contact region. This can cause increased wear of the overhead contact wire as well as contact strip surface, where metal migration occurs during arcing. Another issue is the increase in temperature when the train is at standstill and still drawing current. This is due to increased resistivity of the contact surface by metal migration.

The Addis Ababa LRT system used the silver-copper alloy contact wire with cross-sectional area of 150mm^2 for main line and access line and 120mm^2 for rolling stock depot and other yards. [20]

4.4 Specification of Rolling Stock

The vehicles shall be 70% low-floor articulated 6-axle modern trams, consisting of three modules, bi-directional driving. Two tramcars shall be able to operate with double heading.

- Train formation: $-Mc + Tp + Mc-$, where Tp = Trailer pantograph and Mc = Motor car
- Mc module: motor car with driver's cab
- Tp module: trailer without driver's cab and with pantograph

4.4.1 Vehicle Fleet Characteristics: The following are the proposed parameters of specifications:

- Number of coaches per train: 3
- Car capacity: 286 passengers or 306 passengers
- Car weight at full load 63.02 tone
- Operational speed: 21.6 km/h to 30Km/h
- Maximum speed 70Km/h
- Trains in operation: 41
- Train Spacing: 2.16 km
- Headway: 6 min

4.5 Magnetic Field Disturbance Produced by Electric Railway

It is known that the leakage current from a DC electric railcar forms magnetic fields in the surrounding environment. Unwanted noises occur from these magnetic fields, causing interference to the observation of natural magnetic fields. Because the noises spread three-dimensionally, they travel over a long distance without decaying and cause interference at remote locations. They have complex waveforms and it is technically impossible to remove them under the circumstances. If the railway track could be completely insulated from the ground and if the current supplied to drive the electric railcar could be made to flow only in a closed circuit from a power substation to a feeder line to an electric railcar, and then to a railway track, the noises would not propagate so long a distance even if a DC electric railcar is used. Because the railway track and the feeder line are installed close to one another, the effect of the same amount of current flowing in them cancels each other. Therefore, at a remote location the circuit is regarded as if it carried no currents. In reality, however, a considerable amount of leakage current flows into the ground, because the railway track is not completely insulated from the ground [8].

4.6 Modeling of the System.

We consider a rectangular train-feeding substation loop of length L and height h shown in Fig4.5 the current injected by the substation via the feeding line into the train is J_1 . Let us use a right-handed Cartesian xyz coordinate system in which the x axis is parallel to the loop with the substation and the train located at $x = 0$ and $x = L$, respectively, and the z axis points downwards. The bottom of the loop lies at the xy plane (the earth's surface). It is thus assumed in the model that the feeding line and the rails between the substation and the train are straight.

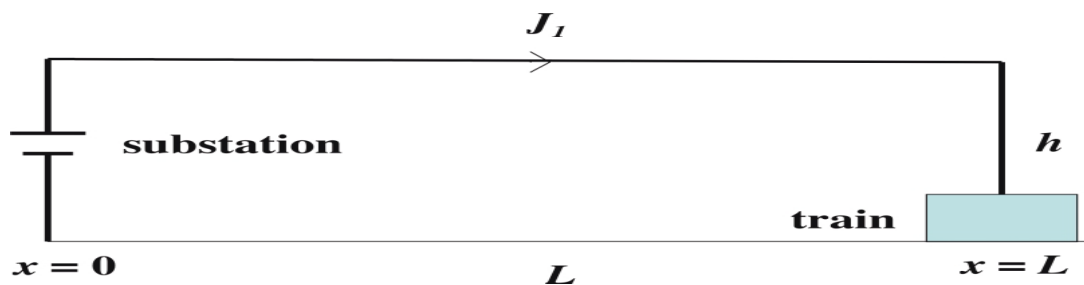


Figure 4.4 Rectangular train-substation feeding loop

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

The feeding current is J_1 . The x axis is assumed to be parallel to the loop so that the feeder and the train are located at $x = 0$ and $x = L$, respectively. The above modeling of the train-substation feeding is assumed to be as a rectangular current loop system. But in practical the substation and the train has a different components that makes the system more complex. The feeder line and the return rail current is just take as a line current.

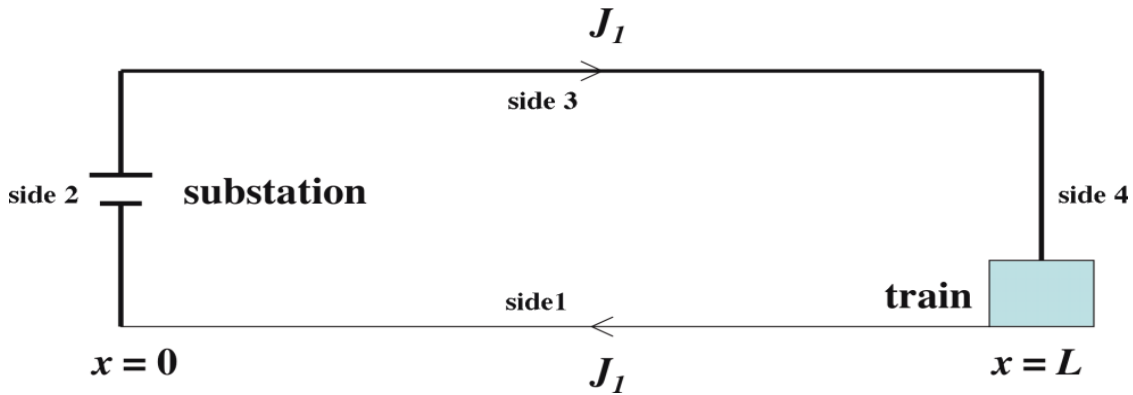


Figure 4.5 Rectangular full loop

The sides of the loop are numbered: 1 = rails, 2 = substation, 3 = feeding line, 4 = train. In the ideal case, the feeding current should return from the train to the substation along the rails, i.e. from $x = L$ to $x = 0$ at $z = 0$, so that a “full” rectangular J_1 loop depicted in Fig4. 6 are considered. In practice, however, the rails are not insulated from the ground, and so there is a significant current leakage from the rails into the ground. We assume that the leakage current returns to the system at the substation, which is justified by the low grounding resistance of the station.

The earth’s conductivity is assumed to be uniform, so that the leakage currents flow radially symmetrically from the point of injection to all directions in the ground. This means that when considering the magnetic field at the earth’s surface we may replace the symmetrically-flowing current by a single semi-infinite downward vertical line current. Replacing a radial distribution by a single vertical current is actually a modification of the well-known “Fukushima theorem” widely used when studying magnetic fields on the ground due to magnetospheric-ionospheric currents [24]. Its validity can be easily proved by applying Amperes’ law, which states that, when neglecting the displacement currents, the line integral of the magnetic field around any closed loop equals the total current through the loop multiplied by the permeability.

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

The equivalence between a radially symmetric current distribution and a semi-infinite vertical current also holds true for a time-dependent situation provided the displacement currents can still be neglected. This corresponds to the real situation in which the feeding current varies following the acceleration and deceleration activities of the train.

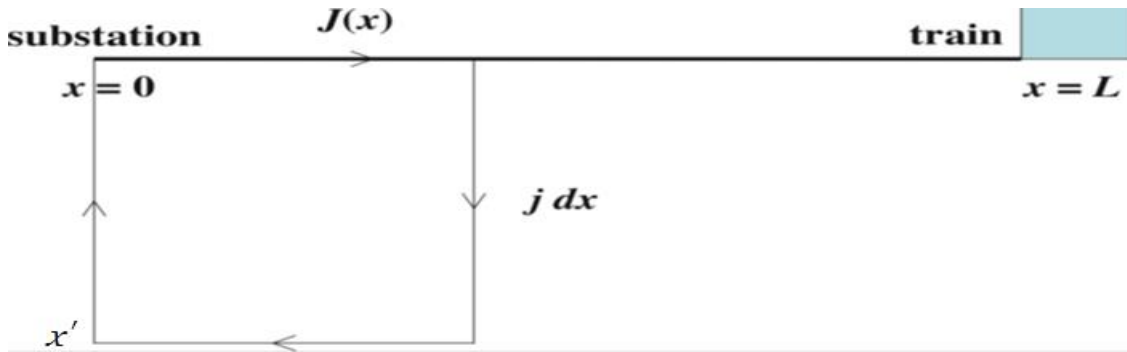


Figure 4.6 Rectangular “leakage” loops with the current $j dx$

The amount of the “leakage” current at the point x , which decreases the “full-loop” current (J_1 in Fig4. 5), is $J(x) = j(L - x)$. The bottom horizontal part of the loop lies at infinity. We assume that the leakage is constant ($j dx$) along the rails, i.e. the leakage current density per unit length ($= j$) is the same at each infinitesimal section $[x, x + dx]$ between $x = L$ and $x = 0$. Thus, in addition to the ideal “full” loop depicted in Fig4. 6, we also have a set of “leakage” loops (Fig4. 7). Consequently, the current that actually flows along the rails at a point x towards the substation is

$$J_{rail}(x) = J_1 - \int_x^L j dx = J_1 - j(L - x) \quad (1)$$

The latter term $j(L - x)$ represents the decrease of J_1 due to the leakage and can be described as an opposite “leakage” current as indicated by $J(x)$ in Fig4. 7. The total “leakage” current between $x = L$ and $x = 0$, denoted by J_0 , equals $J_{(0)} = jL$, and so $j = J_0/L$.

To calculate the magnetic field at a point (x, y) at the earth’s surface ($z = 0$), we thus have to add the contributions from the “leakage” loops $j dx = J_0 dx/L$ to the magnetic field produced by the “full” loop. The magnetic field element dB caused by any (vector) current element $Id\mathbf{s}$ is obtained from the Biot-Savart’s law:

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

$$dB = \frac{\mu_0 I ds \times r}{4\pi r^3} \quad (2)$$

Where μ_0 is the (vacuum) permeability and r is the vector from the current element to the point of observation ($r = |r|$). All currents included in the present problem and shown in (Fig4. 6 and Fig4.7) are straight and have a finite or semi-infinite length. Application of Eq. (2) to a straight current line I easily leads to the magnetic field expression.

$$B = \frac{\mu_0 I}{4\pi R} (\cos\theta_1 - \cos\theta_2) e_\phi \quad (3)$$

Where R is the perpendicular distance of the point of observation from the line determined by the current, e_ϕ is a unit vector around the line in a cylindrical coordinate system, and θ_1 and θ_2 are the angles between the line and the vectors from the ends of the current to the point of observation.

(For an infinitely long line current, θ_1 and θ_2 are 0° and 180° , so that Eq. (3) reduces to the well-known for $B = \frac{\mu_0 I}{2\pi R} e_\phi$

Equation (3) and somewhat tedious geometrical considerations enable the calculation of the magnetic point ($x, y, z = 0$) due to the different currents shown in (Fig4. 6 and Fig4.7). The contribution from the “full” loop is

$$B_x^F = -B_2 \frac{y}{\sqrt{y^2+x^2}} - B_4 \frac{y}{\sqrt{y^2+(L-x)^2}} \quad (4)$$

$$B_y^F = -B_2 \frac{x}{\sqrt{y^2+x^2}} - B_3 \frac{h}{\sqrt{y^2+h^2}} - B_4 \frac{L-x}{\sqrt{y^2+(L-x)^2}} \quad (5)$$

$$B_z^F = -B_1 + B_3 \frac{y}{\sqrt{x^2+h^2}} \quad (6)$$

Where the B_k ($k = 1, 2, 3, 4$) quantities are the fields created by the four sides of the “full” loop. As shown in Fig4. 6, the side numbers are 1 for the bottom (rails), 2 for the left hand (substation), 3 for the top (feeding line) and 4 for the right-hand side (train). The expressions of the B_k quantities are

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

$$B_1 = \frac{\mu_0 J l}{4\pi y} \left(\frac{L-x}{\sqrt{y^2 + (L-x)^2}} + \frac{x}{\sqrt{y^2 + x^2}} \right) \quad (7)$$

$$B_2 = \frac{\mu_0 J l}{4\pi \sqrt{y^2 + x^2}} \frac{h}{\sqrt{x^2 + y^2 + h^2}} \quad (8)$$

$$B_3 = \frac{\mu_0 J l}{4\pi \sqrt{y^2 + h^2}} \left(\frac{x}{\sqrt{x^2 + y^2 + h^2}} + \frac{L-x}{\sqrt{y^2 + (L-x)^2 + h^2}} \right) \quad (9)$$

$$B_4 = \frac{\mu_0 J l}{4\pi \sqrt{y^2 + (L-x)^2}} \frac{h}{\sqrt{y^2 + (L-x)^2 + h^2}} \quad (10)$$

We now apply Eq. (3) to the sides of a single elementary “leakage” loop carrying the current $j dx'$, which has the upward and downward vertical parts at $x = 0$ and at $x = x'$ (see Fig4. 7). The vertical sides of the loop only contribute to the magnetic x and y components at the point of observation ($x, y, z = 0$) whereas the upper horizontal part only creates a z -directed field. The lower horizontal part lying at an infinite distance does not contribute to the field at the earth’s surface. Consequently and after some geometrical considerations, we obtain the following expressions for the magnetic field due to the elementary “leakage” loop $j dx'$:

$$dB_x = \frac{-\mu_0 j dx'}{4\pi} \left(\frac{y}{y^2 + (x' - x)^2} - \frac{y}{y^2 + x^2} \right) \quad (11)$$

$$dB_y = \frac{-\mu_0 j dx'}{4\pi} \left(\frac{x' - x}{y^2 + (x' - x)^2} + \frac{x}{y^2 + x^2} \right) \quad (12)$$

$$dB_z = \frac{\mu_0 j dx'}{4\pi y} \left(\frac{x' - x}{y^2 + (x' - x)^2} + \frac{x}{\sqrt{y^2 + x^2}} \right) \quad (13)$$

To obtain the total magnetic field, the contributions from all “leakage” loops $j dx'$ have to be summed. In the other words, Eq. (11) – (13) are integrated over x' from $x' = 0$ to $x' = L$. The integral functions of all terms are elementary functions, and the final result of the magnetic contribution from the “leakage” loops is:

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

$$B_x^L = \frac{-\mu_0 J_0}{4\pi L} \left(\arctan\left(\frac{L-x}{y}\right) + \arctan\frac{x}{y} - \frac{yL}{y^2+x^2} \right) \quad (14)$$

$$B_y^L = \frac{-\mu_0 J_0}{4\pi L} \left(\ln\left(\frac{\sqrt{y^2+(L-x)^2}}{\sqrt{y^2+x^2}}\right) + \frac{xL}{y^2+x^2} \right) \quad (15)$$

$$B_z^L = \frac{\mu_0 J_0}{4\pi y L} \left(\frac{xL}{y^2+x^2} + \sqrt{y^2+(L-x)^2} - \sqrt{y^2+x^2} \right) \quad (16)$$

(Note that $j = J_0/L$.) Finally, the contributions from the “full” loop and from the “leakage” loops have to be added together:

$$B_u^{Total} = B_u^F + B_u^L \quad (17)$$

Where, the subscript u refers to x, y or z.

$$B_x^{Total} = B_x^F + B_x^L$$

$$B_y^{Total} = B_y^F + B_y^L$$

$$B_z^{Total} = B_z^F + B_z^L$$

To calculate the total contribution of full loop and leakage loop of magnetic field, we use

$$B_{sum} = \sqrt{(B_x^{Total})^2 + (B_y^{Total})^2 + (B_z^{Total})^2} \quad (18)$$

Note that the xy coordinate system at the earth’s surface was defined by the train-feeding substation system, so when considering the magnetic field produced by several trains simultaneously we have many different xy systems. Naturally, the final result, i.e. the magnetic field components at the point of observation, should be obtained in a fixed coordinate system.

4.7 Electromagnetic Radiation Caused by Pantograph

Disconnection

4.7.1 Gas Discharge Process

The basic process of gas discharge is: excitation, ionization, deionization, migration, and proliferation. The mutual constraints of basic process determine the specific form and character of the discharge. Under normal circumstances, the pantograph have a good contact with contact line, locomotives thereby obtain energy from the grid so that EMU get high-speed, while the pantograph detachment of occurs, due to the voltage increases rapidly, reaching the gas breakdown point, start spark discharge, temperature rise sharply, releasing energy in the form of arc, and constitutes a complex electromagnetic environment generated by arc high-frequency electromagnetic radiation, affecting factors involves the amount of energy ,the generation and extinguish mechanism of arc, temporal and spatial distribution, energy transmission characteristics and other aspects. Therefore, it is necessary to study their theoretical analysis and experimental simulation method. The spectrum of electromagnetic pulses noise generated by pantograph system covers from tens kHz to GHz. [41]

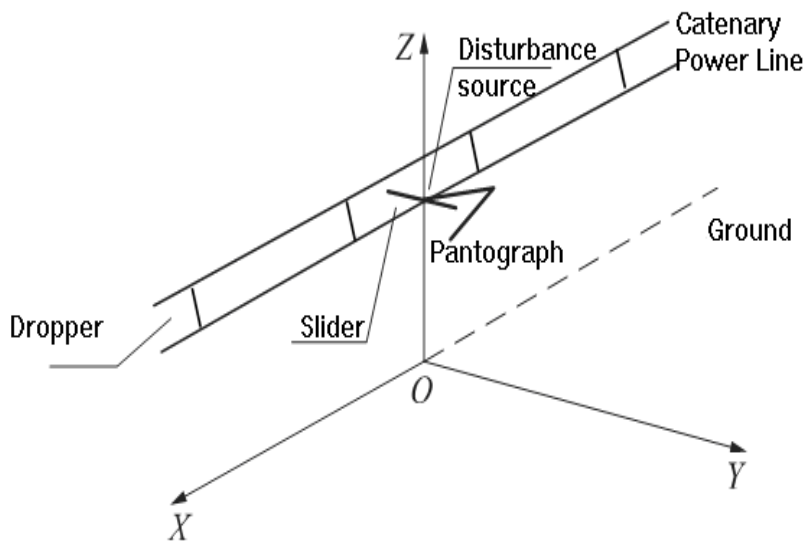


Figure 4.7 Catenaries system model

4.7.2 Field Strength Calculation of Electromagnetic Waves Spreading from Pantograph Arcing

Assuming wave source at point O, and wave source radiate energy uniformly, radiated power is P_{Σ} , the energy density at distance d from the wave source is:

$$S = \frac{P_{\Sigma}}{4\pi d^2} \quad (1)$$

When distance d meets far field conditions.

The electromagnetic wave can be considered as a uniform plane wave, such that the phase angle of electric and magnetic fields are all the same, but the ratio of electric field strength (E_0) and magnetic field strength (H_0) $E_0 / H_0 = 120\pi\Omega(\text{Ohm})$, thus the average power per unit area is: [41]

$$S = E_0 H_0 = \frac{E_0^2}{120\pi\Omega} \quad (2)$$

By formula (1) (2), we can obtain,

$$E_0 = \frac{\sqrt{30P_{\Sigma}}}{d} \quad (3)$$

And by formula (2) (3), we can obtain,

$$H_0 = \frac{\sqrt{30P_{\Sigma}}}{120\pi d} \quad (4)$$

Electric field strength in units of $\text{dB}\mu\text{V}/\text{m}$, expressed in dB

$$E_0 = 74.77 + 10\log P_{\Sigma} - 20\log d \quad (5)$$

Magnetic field strength in units of $\text{dB}\mu\text{A}/\text{m}$, expressed in dB

$$H_0 = 74.77 + 10\log P_{\Sigma} - 7536\log d \quad (6)$$

Chapter Five

5 MATLAB Simulation and Analysis

The equations presented in the previous section and the MATLAB programs now enable calculations of the magnetic fields created by different train-feeding substation configurations at any point of observation from the track line.

Let us first consider a straight line East-West railway of 10km in length. This route covers from Megenanga to Tor-hiloch railway line. Along this route there are five substations which are found at Tor-hiloch, Ledeta, Debr-werk tower, St.yoseph school, Urael church and Legese Feleke hotel.

5.1 Full Loop of Magnetic Field Simulations for Different Trains

Assuming from the LRT data the average distance of substation is 2.5km and trains spacing 2.16km intervals. The maximum current drawn by one train is 1400A, which is the average feeder line current (J_1) and average leakage current is 5A for all trains along the route [15]. Also the length of the loop depends on the feeder line length. The height of the contact line from the return current (rail) is 5.4m from the ground.

Now consider the following figure, which is one train simulation. Using a right-handed Cartesian xyz coordinate system in which the x axis is parallel to the loop with the substation and the train located at $x = 0$ and $x = L$, respectively, and the z axis points downwards. The bottom of the loop lies at the xy plane (= the earth's surface). The x axis is assumed to be parallel to the loop so that the feeder and the train are located at $x = 0$ and $x = L$, respectively.

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

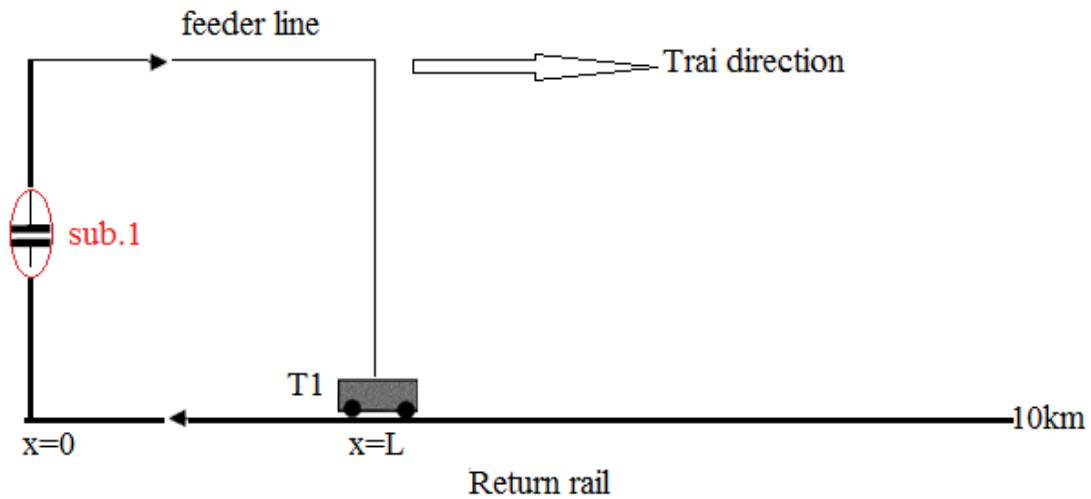


Figure 5.1 One train modelling system

The total magnetic field is simulated based on the previous mathematical modeling using the Bio-savar's law and the simulation of **one train** is shown in the following graph.

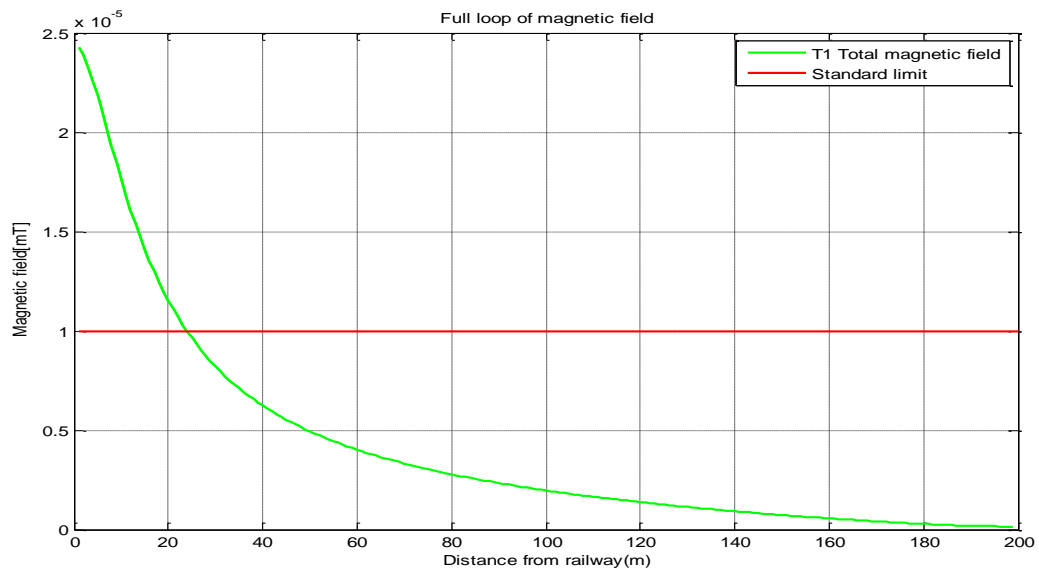


Figure 5.2 Simulation of one train result

The above simulation result shows the resultant magnetic field of **one train**. The horizontal graph shows the maximum allowable magnetic field (10nT) which is standard. But from the graph we see that up to **24m** the magnetic field graph is above the standard.

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

Let us consider for **two** train simulations with 2.16km train spacing and **two** substations with interval between 2.5km.

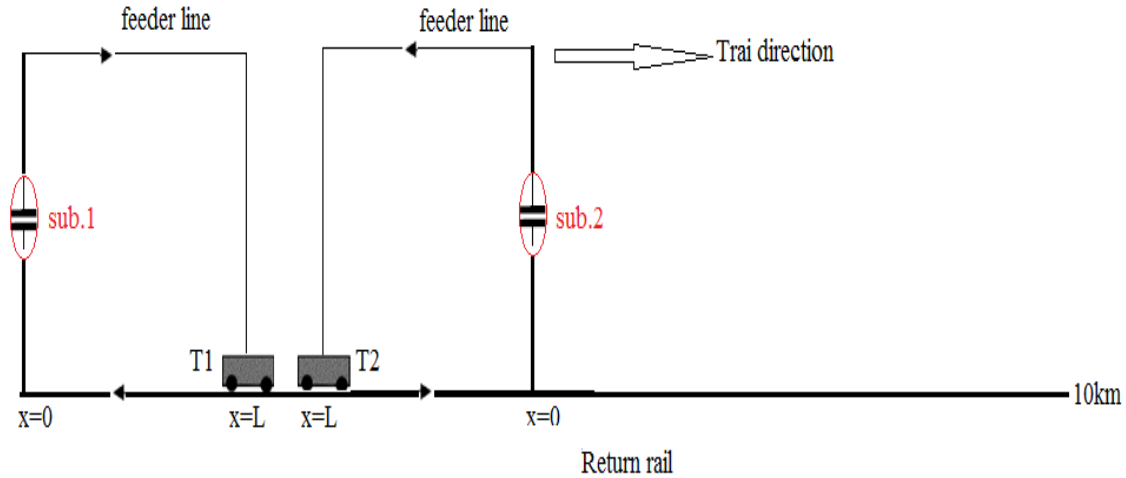


Figure 5.3 Two train modelling system

The simulation result of **two** trains and **two** substations is shown below.

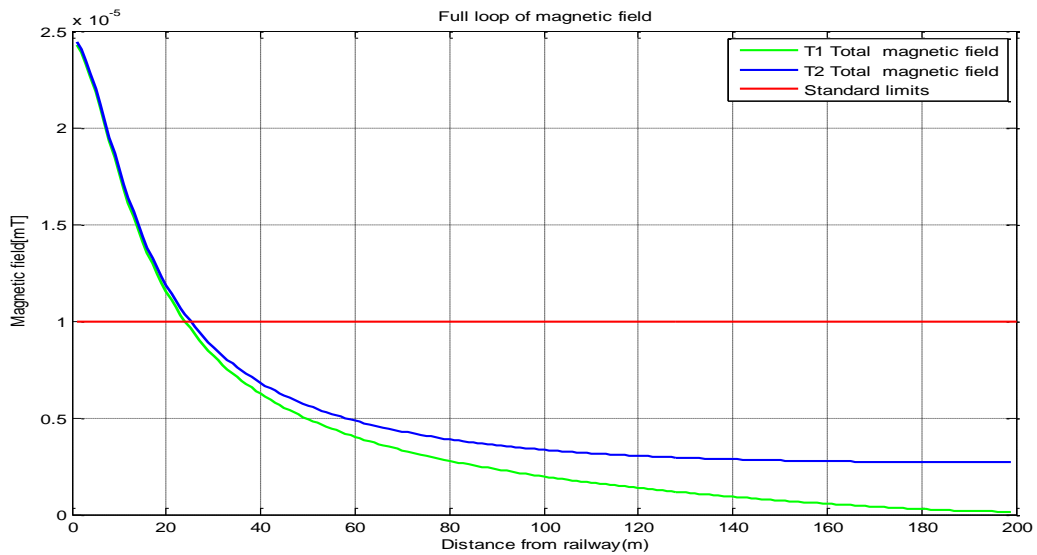


Figure 5.4 Simulation of two trains result

The above simulation result shows the resultant magnetic field of each **two** trains. The horizontal graph shows the maximum allowable magnetic field (10nT). As we can see from

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

graph the magnetic field is increased and from the graph we see that up to **25m** the magnetic field graph is above the standard.

Let us consider for **three** train simulations with 2.16km train spacing and **two** substations with interval between of 2.5km and total of 5km. The figure shows as below.

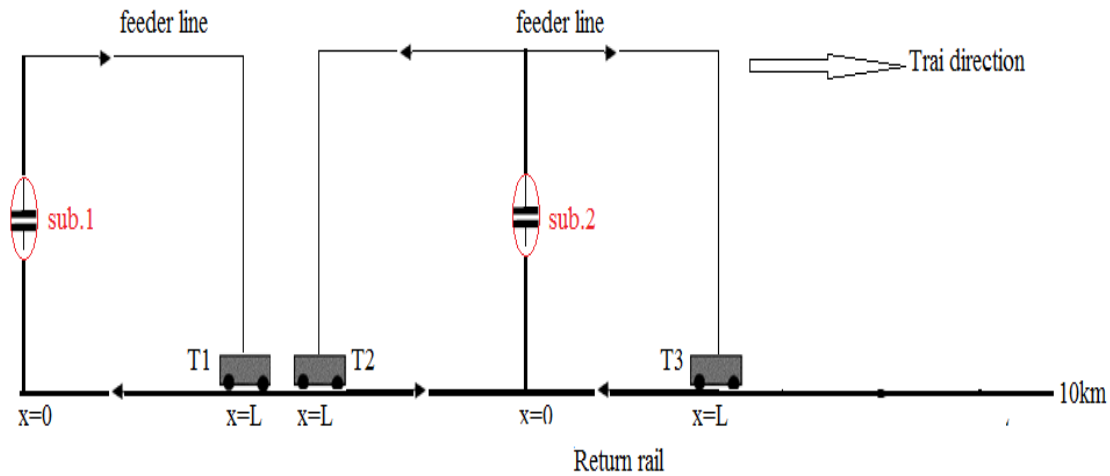


Figure 5.5 Three train modelling system

The simulation result of **three** trains and **two** substations is shown below

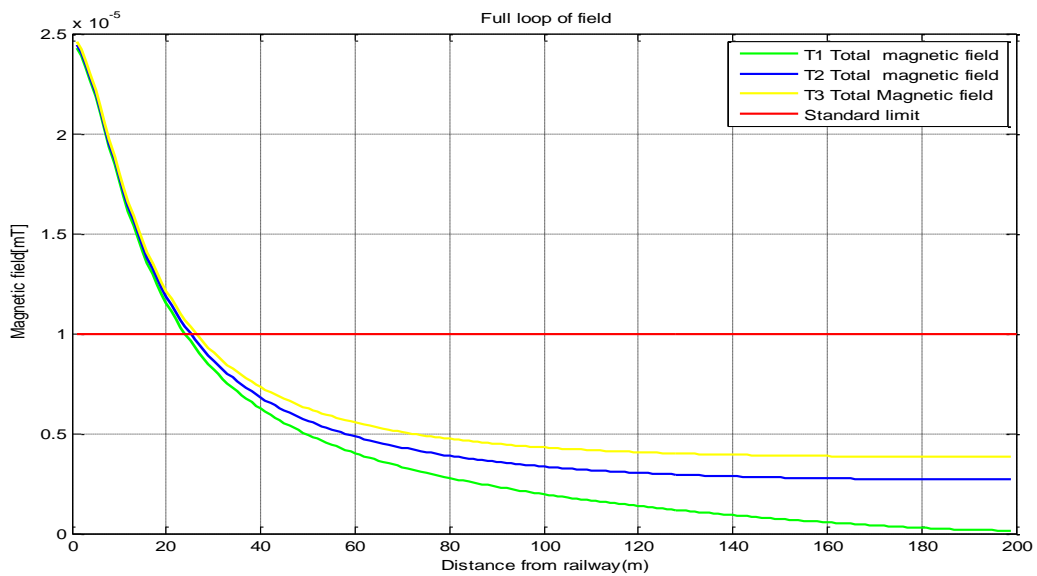


Figure 5.6 Simulation of three trains result

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

The above simulation result shows the resultant magnetic field of each **three** trains. The horizontal graph shows the maximum allowable magnetic field (10nT). As we can see from graph the magnetic field is increased and from the graph we see that up to **26m** the magnetic field graph is above the standard.

Let us consider for **four** train simulations with 2.16km train spacing and **three** substations with interval between 2.5km and total of 7.5km.

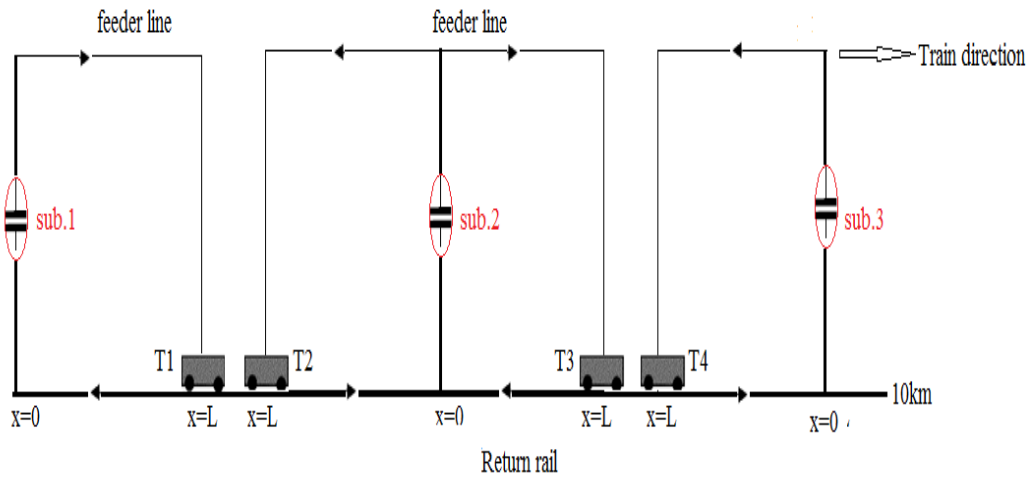


Figure 5.7 Four train modeling system

The simulation result of **four** trains and **three** substations is shown below

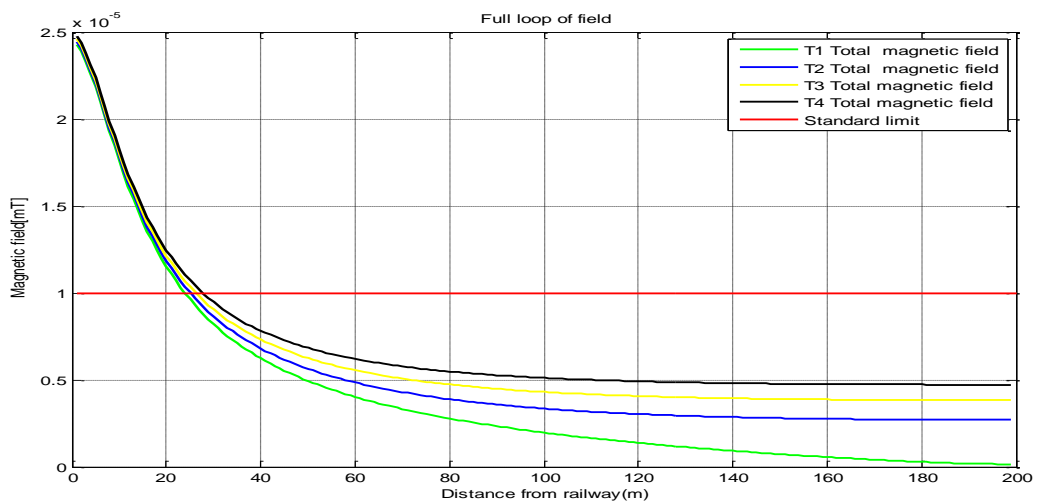


Figure5.8 Simulation of four train's results

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

The above simulation result shows the resultant magnetic field of each **four** trains. The horizontal graph shows the maximum allowable magnetic field (10nT). As we can see from graph the magnetic field is also increased and from the graph we see that up to **28m** the magnetic field graph is above the standard.

Let us consider for **five** train simulations with 2.16km train spacing and **three** substations with interval between 2.5km and total of 10km.

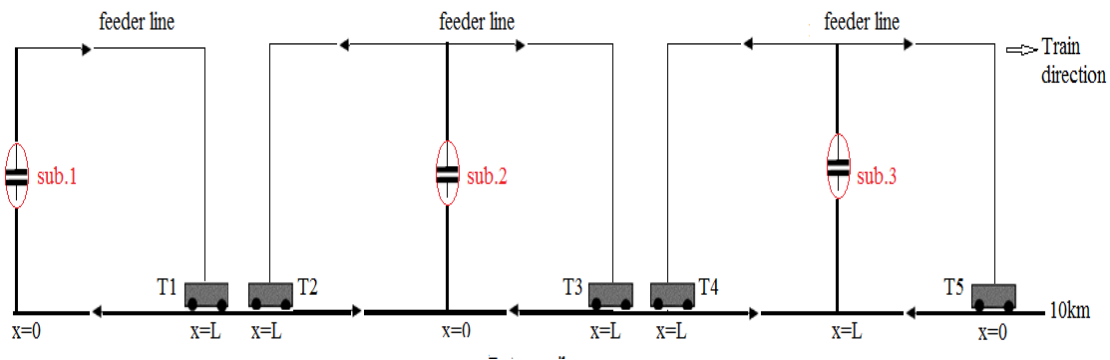


Figure 5.9 Five train modelling system

The simulation result of **five** trains and **three** substations is shown below

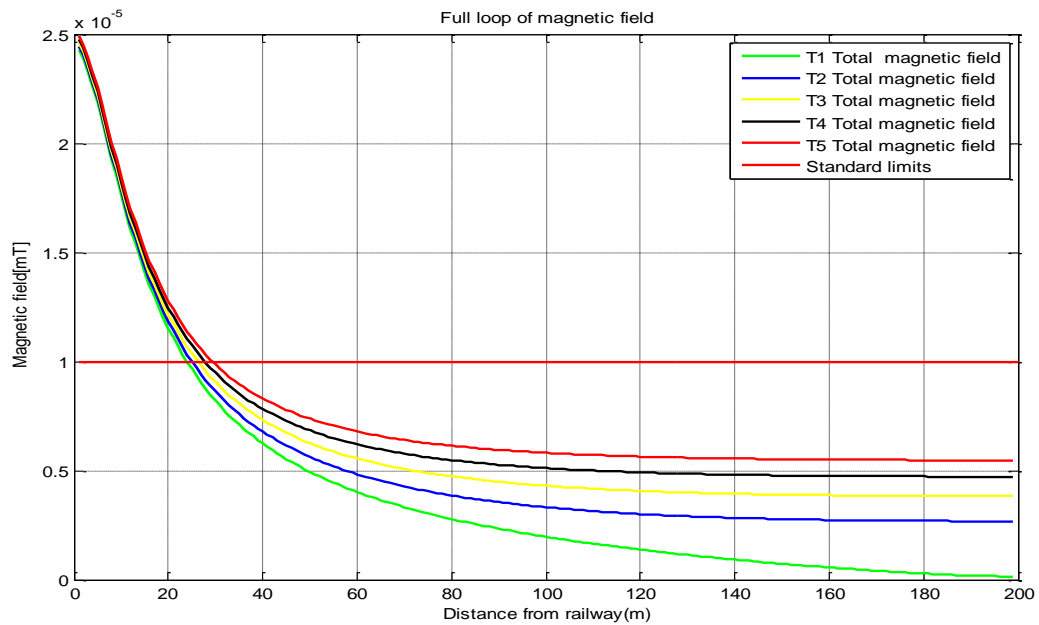


Figure 5.10 Simulation of five train's results

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

The above simulation result shows the resultant magnetic field of each **five** trains. The horizontal graph shows the maximum allowable magnetic field (10nT). As we can see from graph the magnetic field is also increased and from the graph we see that up to **30m** the magnetic field graph is above the standard.

In general, as the number of train is increase the magnetic field is also increased. From the rectangular full loop magnetic field emission; we have seen that up to 30m length from the center of track line is out of the limit standards.

5.2 Leakage Current Magnetic Field Simulation

Leakage current is an inherent flow of current from the live electrical parts of an appliance or instrument to the accessible metal casing or parts.

From the given route of line length and number of train we assume a total leakage current of 5A from LRT data. The simulation of this leakage current shown as follows.

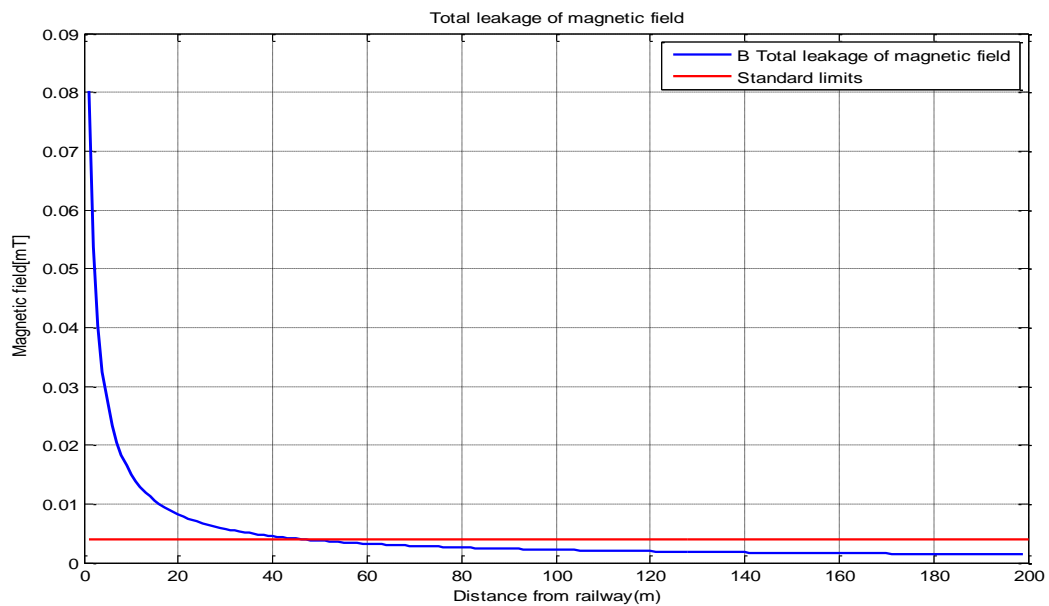


Figure 5.11 Simulation of leakage current

The horizontal graph shows the maximum allowable magnetic field (0.005mT). Here the standard limit for “full loop” and “leakage loop” is not the same, since leakage current

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

resistance is very low. As we can see from graph the leakage magnetic field up to 40m, the result is above the standard limits.

If we sum up the magnetic field of ‘full loop’ and ‘leakage loop’ the result is swallowed by the leakage current. Because the leakage current is propagate, without decaying for a long distance. The simulation of the sum of full loop and leakage current loop is shown below.

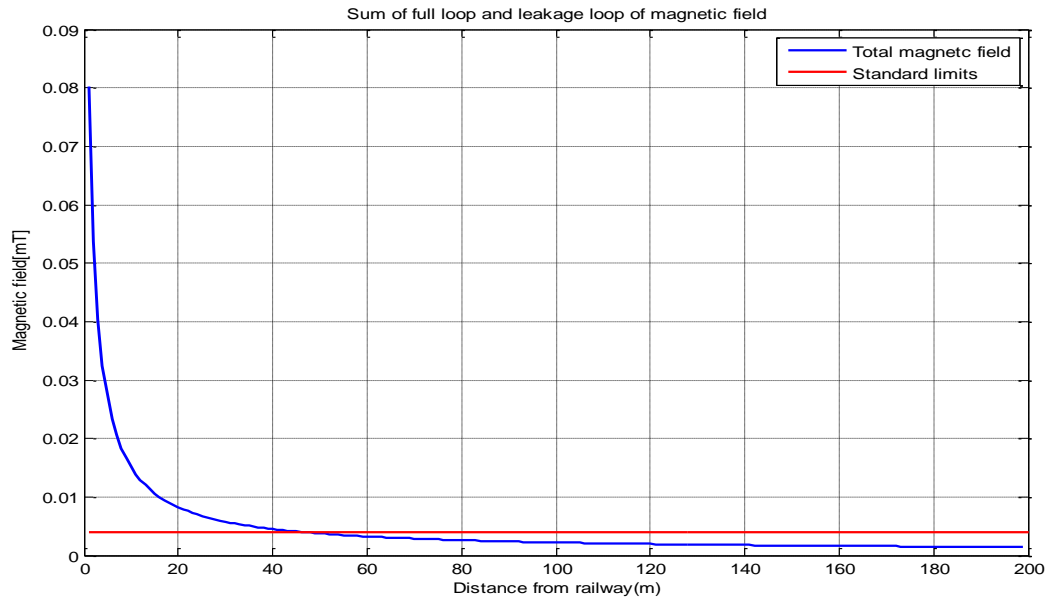


Figure 5.12 Simulation result of full loop and leakage current loop

5.3 3D Magnetic Field Simulations

Since the magnetic field can be visualized in three dimensions, the simulation result of all the trains is seen in 3D below.

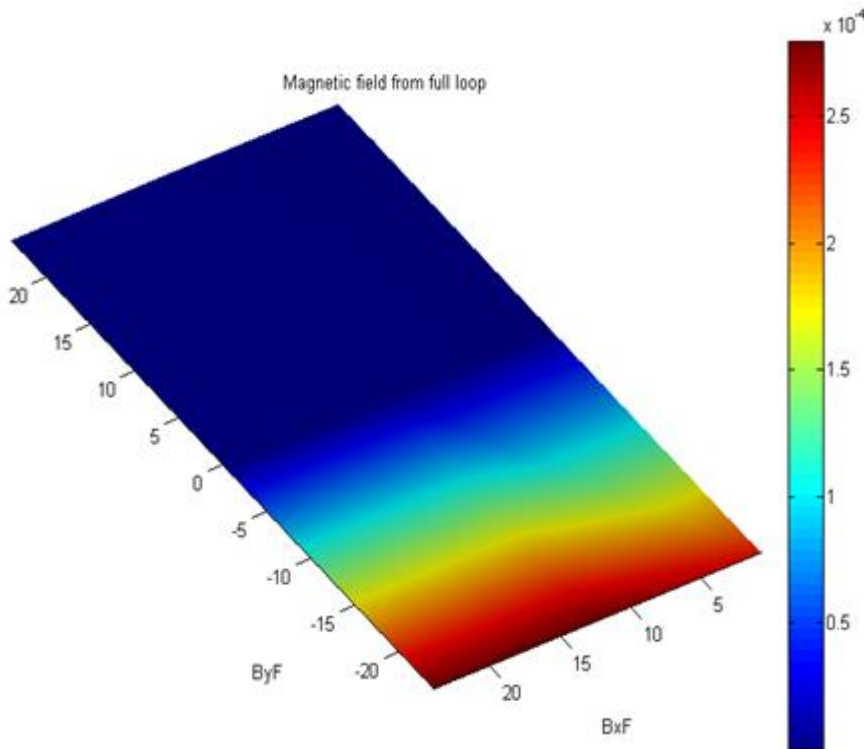


Figure 5.13 Simulation of 3D magnetic field result

The 3D simulation figure indicates that the more red color is the more the magnetic fields are there.

5.4 Pantograph Arcing Magnetic Field Simulation.

The pantograph-catenary arcing model and simulation result is seen below. It was taking the power density of the pantograph arcing from different research method of measurement analysis and LRT data. From LRT data the maximum power density during arcing is assumed to be 6.8kw.

Because there is no formulas to calculate the arc power density, since it is random phenomena.

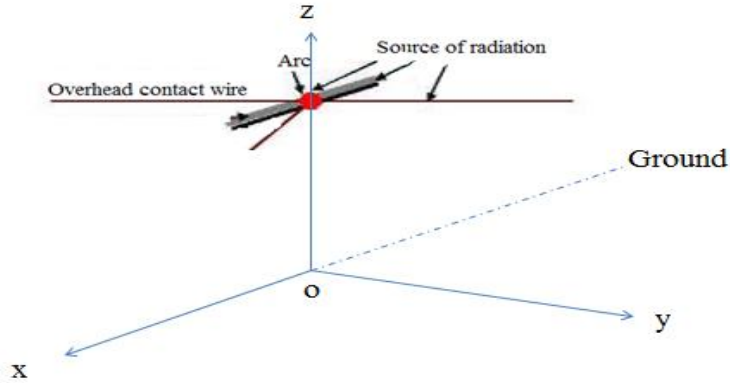


Figure 5.14 Pantograph arcing model

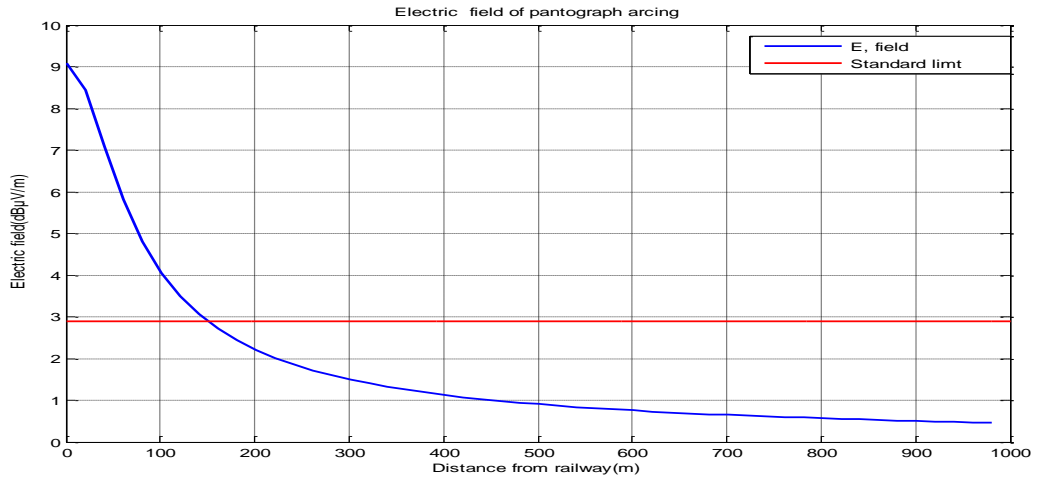


Figure 5.15 Electric field of pantograph arcing

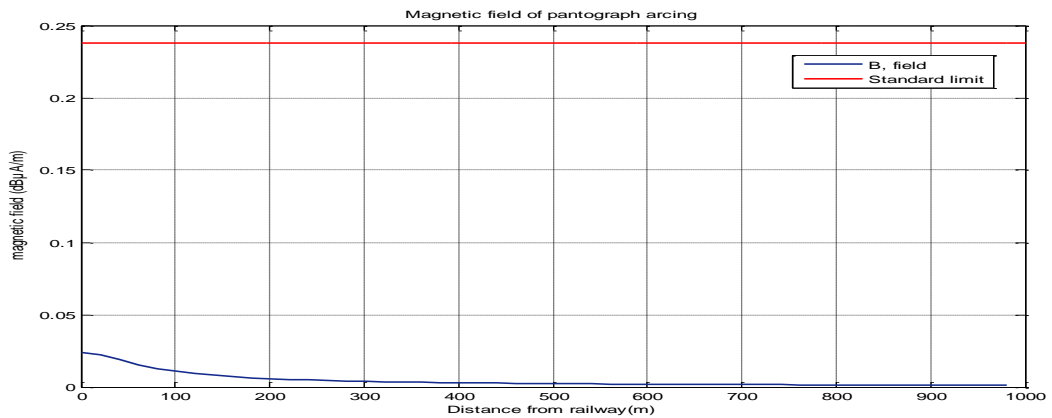


Figure 5.16 Magnetic field of pantograph arcing

Chapter Six

6 Results and Discussion

The simulation results of the trains modelled for pantograph arcing, Rectangular full loop and leakage loop model of magnetic field over the MATLAB from Megenanga to Tor-Hayiloch was shown in chapter five. As per the standard we have to see the zones of the susceptible to electromagnetic radiation from an electrified railway. The discussion below indicates briefly which type of standards is applicable in the classified zones.

6.1 Electromagnetic Site Survey

There were three investigation zones in the site survey:

1. **Zone one:** The LRT right-of-way railway signaling system and equipment up to 3m (10') from the centerline of the outmost track.
2. **Zone two:** The external third party systems and equipment, located on the right-of-way and outside the right-of-way but in close proximity to the track up to 10m (33') from the center line of outermost track.
3. **Zone three:** External third party EMI- sensitive sites(such as laboratories, hospitals and airports) located between 10m and 100m(33'' and 330'' respectively) from the outer most track

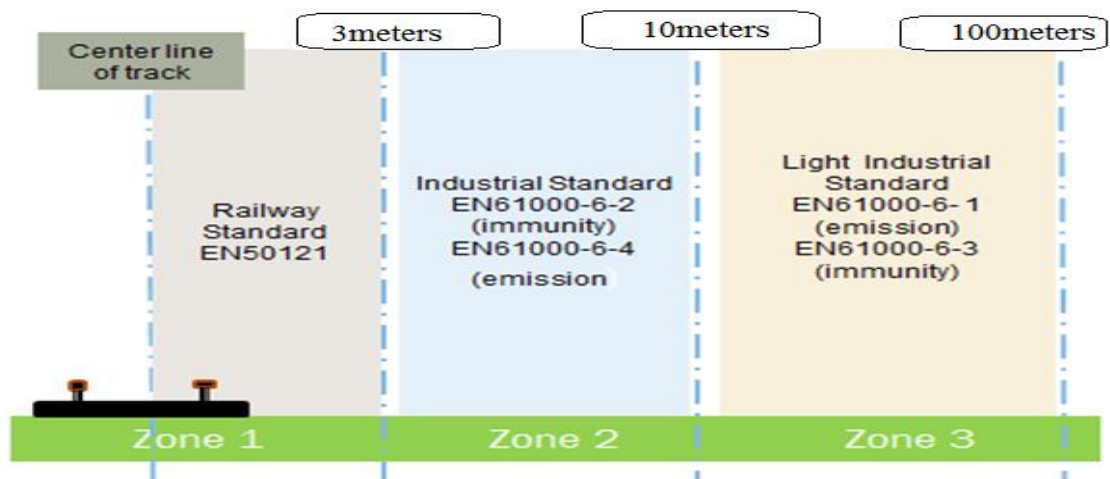


Figure 6.1 EMI Investigation Zones & Applicable Standards

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

6.2 Impact Assessment Methodology

As part of the assessment of the baseline environment, potential sensitive receptors were identified. The baseline electromagnetic (EM) field levels were also measured as part of this assessment and documented in the Human Beings: Radiation and Leakage Current baseline.

Table6. 4 Criteria for assessment of impact magnitude

| Criteria | | Impact magnitude | | |
|------------|---------------|-----------------------|--------------------|--------------------------------------|
| Field Type | Limit | Industrial/Commercial | Residential/School | Sensitive research centers/Hospitals |
| DC Field | >1mT(1,000μT) | Very high | Very high | Very high |
| | >50 μT | High | Medium | High |
| | >10 μT | Medium | Low | Medium |
| | >1 μT | Low | Very low | Low |
| | >0.1 μT | Very low | Very low | Very low |

Table6. 5 The impact assessment for the Addis Ababa LRT is shown below

| Criteria | | Impact magnitude | | |
|------------|-------|-----------------------|--------------------|-------------------------------------|
| Field Type | Limit | Industrial/commercial | Residential/school | Sensitive research centers/Hospital |
| Dc field | ≥50μT | High | Medium | High |

6.3 Impact Mitigation Measures

There are a range of methods which are available to mitigate impacts on the baseline radiation and leakage current environment. This section describes the measures to mitigate the significant adverse impacts at the operational phase of the proposed scheme. Measures to minimize leakage current have been incorporated into the design specifications and will be implemented during the construction and operation of the proposed scheme by the paper and standards. These measures include:

- Maximizing the rail to earth resistance
- Reducing the rail to earth potential (the so-called touch voltage)
- Reducing the traction return resistance between the rails and the substation
- Using a stray current collector system
- Monitoring the levels of stray current during the operation of the system

The following tests and maintenance procedures are recommended to mitigate EMI to track circuits and increase personnel safety due to EMI induced common mode voltage:

1. Common mode voltage control for personnel safety as follows:

- Maximum rail to ground voltages should be measured periodically. Excessive values per each section of the track (between insulated joints) should be investigated and mitigated as needed.

2. Differential mode voltage control to reduce interference to track circuits as follows –

- Rail to rail voltages should be measured periodically. Values are not to exceed track circuit manufacturer recommended maximum voltage level per each section of the track (between insulated joints). Deviations should be investigated and corrective measures undertaken as needed.
- Insulated joints to be tested as per product manufacturer recommendations. Defective insulated joints to be replaced or repaired.
- Surge (lightning) arresters to be tested as per product manufacturer recommendations. Defective arresters to be replaced or repaired.

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

- Proper ballast maintenance to be performed per the supplier's recommendation.

To protect the nearby environment from pantograph arcing and full loop of the magnetic interference, we need to use;

- As installed and used, medical systems and cabling should be shielded against the electric field and magnetic field generated by the railway systems.
- Measuring equipment should comply with the EMC Directive 2004/108/EC.
- All electrical construction equipment and tools will comply with the EMC Directive 2004/108/EC or the Machinery Directive 2006/42/EC.
- Increasing of the distance from the center of the track line for the high sensitive electrical devices.

Chapter Seven

7 Conclusion and Recommendation

Most of the DC traction systems have positive contact wire. The reason for this selection was to avoid vagabonding return current and hence reduce galvanic corrosion across trackside metal structures. Railways operating by dc currents create magnetic fields that can cause problems to geomagnetic observatories. These magnetic disturbances are mostly due to return currents leaking into the ground, rectangular loop of feeding line and pantograph arcing.

7.1 Conclusion

In this paper, it was presented a theoretical model and formulas for calculating the magnetic field at any point of observation due to contact lines and pantograph arcing of dc railway occupied by one or several trains.

Computer programs written in the MAT LAB, languages are emphasis the mathematical modeling of the pantograph arcing, rectangular full loop of train feeding and leakage current. Numerical simulations presented in this paper indicate that magnetic fields larger than the standard to be considered as the maximum allowable noise level at today's high precision observatories extend to distances of even tens of meters from a railway line.

7.2 Recommendation

In this paper analysis of electromagnetic emission from contact lines of LRT for Addis Ababa city was performed based on review of different research papers and interprets using mathematical modeling and simulation to compare with railway EMC standards. But the paper recommends measurement of electromagnetic emission on site has to be recommended during the operation of the Addis Ababa Light Rail Transits.

It also recommends analyzing of electromagnetic emission from the rectifier substation and the rolling stock of the railway system.

The paper recommends to the nearby environment, all the sensitive and research center electrical devise has to be 30m to 40m away from the center of track line.

Appendix A

1. For Five Trains MATLAB code

```
%initialization of variables;
muo = 4*pi*1e-7;
I_current = 1400;
Il_current = 5;
h = 5.4;
L = 10000;
H = 0.00001;
x = 1:0.5:10000;
y = 1:0.5:100;
%@ Loop over the segments in the current loop in xy plane
NSegments =length(x);
NSegments =length(y);
for k=1:NSegments;
for n=1:NSegments;
B1(k)=muo*I_current*(L-x(k))/(4*pi*y(n)*sqrt(y(n)^2+(L-x(k))^2))+
muo*I_current*x(k)/(4*pi*y(n)*sqrt(y(n)^2+x(k)^2));
B2(k)=muo*I_current*h/(4*pi*sqrt(y(n)^2+x(k)^2)*sqrt(y(n)^2+x(k)^2+h^2));
B3(k)=muo*I_current*x(k)/(4*pi*sqrt(y(n)^2+h^2)*sqrt(y(n)^2+x(k)^2+h^2))+muo*I_current*(L-
x(k))/(4*pi*sqrt(y(n)^2+h^2)*sqrt(y(n)^2+(L-x(k))^2+h^2));
B4(k)=muo*I_current*h/(4*pi*sqrt(y(n)^2+(L-x(k))^2)*y(n)^2+h.^2+(L-x(k))^2);
%For train two and substation two
B12(k)=muo*I_current*(L-(x(k)+2160))/(4*pi*y(n)*sqrt(y(n)^2+(L-(x(k)+2160))^2))+
muo*I_current*(x(k)+2160)/(4*pi*y(n)*sqrt(y(n)^2+(x(k)+2160)^2));
B22(k)=muo*I_current*h/(4*pi*sqrt(y(n)^2+(x(k)+2160)^2)*sqrt(y(n)^2+(x(k)+2160)^2+h^2));
B32(k)=muo*I_current*(x(k)+2160)/(4*pi*sqrt(y(n)^2+h^2)*sqrt(y(n)^2+(x(k)+2160)^2+h^2))+muo*
I_current*(L-(x(k)+2160))/(4*pi*sqrt(y(n)^2+h^2)*sqrt(y(n)^2+(L-(x(k)+2160))^2+h^2));
B42(k)=muo*I_current*h/(4*pi*sqrt(y(n)^2+(L-(x(k)+2160))^2)*y(n)^2+h.^2+(L-(x(k)+2160))^2);
%For train three and substation two
B13(k)=muo*I_current*(L-(x(k)+4320))/(4*pi*y(n)*sqrt(y(n)^2+(L-(x(k)+4320))^2))+
muo*I_current*(x(k)+4320)/(4*pi*y(n)*sqrt(y(n)^2+(x(k)+4320)^2));
```

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

```

B23(k)=muo*I_current*h/(4*pi*sqrt(y(n)^2+(x(k)+4320)^2)*sqrt(y(n)^2+(x(k)+4320)^2+h^2);
B33(k)=muo*I_current*(x(k)+4320)/(4*pi*sqrt(y(n)^2+h^2)*sqrt(y(n)^2+(x(k)+4320)^2+h^2))+muo*
I_current*(L-(x(k)+4320))/(4*pi*sqrt(y(n)^2+h^2)*sqrt(y(n)^2+(L-(x(k)+4320))^2+h^2));
B43(k)=muo*I_current*h/(4*pi*sqrt(y(n)^2+(L-(x(k)+4320))^2)*y(n)^2+h.^2+(L-(x(k)+4320))^2);
%For train four and substation three
B14(k)=muo*I_current*(L-(x(k)+6480))/(4*pi*y(n)*sqrt(y(n)^2+(L-(x(k)+6480))^2))+
muo*I_current*(x(k)+6480)/(4*pi*y(n)*sqrt(y(n)^2+(x(k)+6480)^2));
B24(k)=muo*I_current*h/(4*pi*sqrt(y(n)^2+(x(k)+6480)^2)*sqrt(y(n)^2+(x(k)+6480)^2+h^2);
B34(k)=muo*I_current*(x(k)+6480)/(4*pi*sqrt(y(n)^2+h^2)*sqrt(y(n)^2+(x(k)+6480)^2+h^2))+muo*
I_current*(L-(x(k)+6480))/(4*pi*sqrt(y(n)^2+h^2)*sqrt(y(n)^2+(L-(x(k)+6480))^2+h^2));
B44(k)=muo*I_current*h/(4*pi*sqrt(y(n)^2+(L-(x(k)+6480))^2)*y(n)^2+h.^2+(L-(x(k)+6480))^2);
%For train five and three substations
B15(k)=muo*I_current*(L-(x(k)+8640))/(4*pi*y(n)*sqrt(y(n)^2+(L-(x(k)+8640))^2))+
muo*I_current*(x(k)+8640)/(4*pi*y(n)*sqrt(y(n)^2+(x(k)+8640)^2));
B25(k)=muo*I_current*h/(4*pi*sqrt(y(n)^2+(x(k)+8640)^2)*sqrt(y(n)^2+(x(k)+8640)^2+h^2);
B35(k)=muo*I_current*(x(k)+8640)/(4*pi*sqrt(y(n)^2+h^2)*sqrt(y(n)^2+(x(k)+8640)^2+h^2))+muo*
I_current*(L-(x(k)+8640))/(4*pi*sqrt(y(n)^2+h^2)*sqrt(y(n)^2+(L-(x(k)+8640))^2+h^2));
B45(k)=muo*I_current*h/(4*pi*sqrt(y(n)^2+(L-(x(k)+8640))^2)*y(n)^2+h.^2+(L-(x(k)+8640))^2);
% Full loop of magnetic field in xy plane
BxF1(k)= B2(k)*y(n)/sqrt(y(n)^2+x(k)^2)-B4(k)*y(n)/sqrt(y(n)^2+(L-x(k))^2);
ByF1(k)= -B2(k)*x(k)/sqrt(y(n)^2+x(k)^2)-B3(k)*h/sqrt(y(n)^2+h^2)-B4(k)*(L-x(k))/sqrt(y(n)^2+(L-
x(k))^2);
BzF1(k)= -B1(k)+B3(k)*y(n)/sqrt(x(k)^2+h^2);
%For train two and substation two
BxF2(k)= B22(k)*y(n)/sqrt(y(n)^2+(x(k)+2160)^2)-B42(k)*y(n)/sqrt(y(n)^2+(L-(x(k)+2160))^2);
ByF2(k)= -B22(k)*(x(k)+2160)/sqrt(y(n)^2+(x(k)+2160)^2)-B32(k)*h/sqrt(y(n)^2+h^2)-B42(k)*(L-
(x(k)+2160))/sqrt(y(n)^2+(L-(x(k)+2160))^2);
BzF2(k)= -B12(k)+B32(k)*y(n)/sqrt((x(k)+2160)^2+h^2);
%For train three and substation two
BxF3(k)= B23(k)*y(n)/sqrt(y(n)^2+(x(k)+4320)^2)-B43(k)*y(n)/sqrt(y(n)^2+(L-(x(k)+4320))^2);
ByF3(k)= -B23(k)*(x(k)+4320)/sqrt(y(n)^2+(x(k)+4320)^2)-B33(k)*h/sqrt(y(n)^2+h^2)-B43(k)*(L-
(x(k)+4320))/sqrt(y(n)^2+(L-(x(k)+4320))^2);
BzF3(k)= -B13(k)+B33(k)*y(n)/sqrt((x(k)+4320)^2+h^2);

```

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

%For train four and substation three

$B_{xF4}(k) = B_{24}(k) * y(n) / \sqrt{y(n)^2 + (x(k) + 6480)^2} - B_{44}(k) * y(n) / \sqrt{y(n)^2 + (L - (x(k) + 6480))^2};$

$B_{yF4}(k) = -B_{24}(k) * (x(k) + 6480) / \sqrt{y(n)^2 + (x(k) + 6480)^2} - B_{34}(k) * h / \sqrt{y(n)^2 + h^2} - B_{44}(k) * (L - (x(k) + 6480)) / \sqrt{y(n)^2 + (L - (x(k) + 6480))^2};$

$B_{zF4}(k) = -B_{14}(k) + B_{34}(k) * y(n) / \sqrt{(x(k) + 6480)^2 + h^2};$

%For train five and substation tree

$B_{xF5}(k) = B_{25}(k) * y(n) / \sqrt{y(n)^2 + (x(k) + 8640)^2} - B_{45}(k) * y(n) / \sqrt{y(n)^2 + (L - (x(k) + 8640))^2};$

$B_{yF5}(k) = -B_{25}(k) * (x(k) + 8640) / \sqrt{y(n)^2 + (x(k) + 8640)^2} - B_{35}(k) * h / \sqrt{y(n)^2 + h^2} - B_{45}(k) * (L - (x(k) + 8640)) / \sqrt{y(n)^2 + (L - (x(k) + 8640))^2};$

$B_{zF5}(k) = -B_{15}(k) + B_{35}(k) * y(n) / \sqrt{(x(k) + 8640)^2 + h^2};$

%leakage loop

$B_{xL}(k) = -\mu_0 * I_{l_current} * \text{atan}(((L - x(k)) / y(n))) / (4 * \pi * L) - \mu_0 * I_{l_current} * \text{atan}((x(k) / y(n))) / (4 * \pi * L) + \mu_0 * I_{l_current} * y(k) * L / (4 * \pi * L * \sqrt{y(n)^2 + x(k)^2});$

$B_{yL}(k) = -\mu_0 * I_{l_current} * \log((\sqrt{y(n)^2 + (L - x(k))^2}) / (\sqrt{y(n)^2 + x(k)^2})) / (4 * \pi * L) - \mu_0 * I_{l_current} * x(k) * L / (\sqrt{y(n)^2 + x(k)^2} * (4 * \pi * L));$

$B_{zL}(k) = \mu_0 * I_{l_current} * x(k) * L / (4 * \pi * y(n) * L * \sqrt{y(n)^2 + x(k)^2}) + \mu_0 * I_{l_current} * \sqrt{y(n)^2 + (L - x(k))} / (4 * \pi * y(k) * L) - \mu_0 * I_{l_current} * \sqrt{y(n)^2 + x(k)^2} / (4 * \pi * y(n) * L);$

end

end

%subplot(2,1,1)

figure(1)

$B_{xF} = \sqrt{B_{xF1}.^2 + B_{xF2}.^2 + B_{xF3}.^2 + B_{xF4}.^2 + B_{xF5}.^2};$

$B_{yF} = \sqrt{B_{yF1}.^2 + B_{yF2}.^2 + B_{yF3}.^2 + B_{yF4}.^2 + B_{yF5}.^2};$

$B_{zF} = \sqrt{B_{zF1}.^2 + B_{zF2}.^2 + B_{zF3}.^2 + B_{zF4}.^2 + B_{zF5}.^2};$

plot(B_xF,'r')

hold on

plot(B_zF,'b')

hold on

plot(B_yF,'g')

hold on

*plot(H*ones(200,1),'r');*

hold on

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

```
legend('X com. magnetic field', 'Y com. magnetic field', 'Z com. magnetic field')
xlabel(' Distance from railway(m)')
ylabel(' Magnetic field[mT]')
title(' Full loop of field')
hold on
grid on
%subplot(2,1,2)
figure(2)
B = sqrt(BxF.^2+ByF.^2+BzF.^2);
plot(B,'r')
hold on
plot(H*ones(200,1),'r');
hold on
legend('T5 Total magnetic field')
xlabel(' Distance from railway(m)')
ylabel(' Magnetic field[mT]')
title(' Full loop of field')
grid on
```

2. For Leakage loop MATLAB code

```
%initialization of variables;
muo = 4*pi*1e-7;
I_current = 1400;
II_current = 2;
h = 5.4;
L = 10000;
Hl = 0.01;
Hf = 0.00001;
x = 1:0.5:10000;
y = 1:0.5:100;
%@ Loop over the segments in the current loop in xy plane
NSegments =length(x);
NSegments =length(y);
for k=1:NSegments;
```

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

```

for n=1:NSegments;
%leakage loop
BxL(k)          =          -muo*IL_current*atan(((L-x(k))/y(n)))/(4*pi*L)          -
muo*IL_current*atan((x(k)/y(n)))/(4*pi*L)+muo*IL_current*y(k)*L/(4*pi*L*sqrt(y(n)^2+x(k)^2));
ByL(k)  =  -muo*IL_current*log((sqrt(y(n)^2+(L-x(k))^2))/(sqrt(y(n)^2+x(k)^2)))/(4*pi*L  )  -
muo*IL_current*x(k)*L/(sqrt(y(n)^2+x(k)^2)*(4*pi*L));
BzL(k)          =          muo*IL_current*x(k)*L/(4*pi*y(n)*L*sqrt(y(n)^2+x(k)^2))+
muo*IL_current*sqrt(y(n)^2+(L-x(k)))/(4*pi*y(k)*L)-
muo*IL_current*sqrt(y(n)^2+x(k)^2)/(4*pi*y(n)*L);
end
end
% subplot(2,1,1)
figure(3)
title(' leakage loop of field')
hold on
plot(BxL,'r')
hold on
plot(BzL,'b')
hold on
plot(ByL,'g')
hold on
plot(HI*ones(200,1),'r');
legend('X com. leakage magnetic field', 'Y com. leakage magnetic field', 'Z com. leakage magnetic
field')
xlabel(' Distance from railway(m)')
ylabel(' Magnetic field[mT]')
grid on
% subplot(2,1,2)
figure(4)
Bl = sqrt(BxL.^2+ByL.^2+BzL.^2);
plot(Bl)
hold on
plot(HI*ones(200,1),'r');

```

```
hold on
legend('B Total leakage magnetic field')
xlabel(' Distance from railway(m)')
ylabel(' Magnetic field[mT]')
title(' Total leakage magnetic field')
grid on
```

3. For Sum of Full Loop and Leakage Loop MATLAB code

```
%initialization of variables;
muo = 4*pi*1e-7;
I_current = 1400;
II_current = 2;
h = 5.4;
L = 10000;
HI = 0.01;
Hf = 0.00001;
x = 1:0.5:10000;
y = 1:0.5:100;
%@ Loop over the segments in the current loop in xy plane
NSegments =length(x);
NSegments =length(y);
for k=1:NSegments;
for n=1:NSegments;
B1(k)=muo*I_current*(L-x(k))/(4*pi*y(n)*sqrt(y(n)^2+(L-x(k))^2))+
muo*I_current*x(k)/(4*pi*y(n)*sqrt(y(n)^2+x(k)^2));
B2(k)=muo*I_current*h/(4*pi*sqrt(y(n)^2+x(k)^2)*sqrt(y(n)^2+x(k)^2+h^2));
B3(k)=muo*I_current*x(k)/(4*pi*sqrt(y(n)^2+h^2)*sqrt(y(n)^2+x(k)^2+h^2))+muo*I_current*(L-
x(k))/(4*pi*sqrt(y(n)^2+h^2)*sqrt(y(n)^2+(L-x(k))^2+h^2));
B4(k)=muo*I_current*h/(4*pi*sqrt(y(n)^2+(L-x(k))^2)*y(n)^2+h.^2+(L-x(k))^2);
%For train two and substation two
B12(k)=muo*I_current*(L-(x(k)+2160))/(4*pi*y(n)*sqrt(y(n)^2+(L-(x(k)+2160))^2))+
muo*I_current*(x(k)+2160)/(4*pi*y(n)*sqrt(y(n)^2+(x(k)+2160)^2));
B22(k)=muo*I_current*h/(4*pi*sqrt(y(n)^2+(x(k)+2160)^2)*sqrt(y(n)^2+(x(k)+2160)^2+h^2));
```

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

$$B_{32}(k) = \mu_0 * I_{\text{current}} * (x(k) + 2160) / (4 * \pi * \sqrt{y(n)^2 + h^2}) * \sqrt{y(n)^2 + (x(k) + 2160)^2 + h^2}) + \mu_0 * I_{\text{current}} * (L - (x(k) + 2160)) / (4 * \pi * \sqrt{y(n)^2 + h^2}) * \sqrt{y(n)^2 + (L - (x(k) + 2160))^2 + h^2});$$

$$B_{42}(k) = \mu_0 * I_{\text{current}} * h / (4 * \pi * \sqrt{y(n)^2 + (L - (x(k) + 2160))^2}) * y(n)^2 + h.^2 + (L - (x(k) + 2160))^2);$$

%For train three and substation two

$$B_{13}(k) = \mu_0 * I_{\text{current}} * (L - (x(k) + 4320)) / (4 * \pi * y(n) * \sqrt{y(n)^2 + (L - (x(k) + 4320))^2}) + \mu_0 * I_{\text{current}} * (x(k) + 4320) / (4 * \pi * y(n) * \sqrt{y(n)^2 + (x(k) + 4320)^2});$$

$$B_{23}(k) = \mu_0 * I_{\text{current}} * h / (4 * \pi * \sqrt{y(n)^2 + (x(k) + 4320)^2}) * \sqrt{y(n)^2 + (x(k) + 4320)^2 + h^2};$$

$$B_{33}(k) = \mu_0 * I_{\text{current}} * (x(k) + 4320) / (4 * \pi * \sqrt{y(n)^2 + h^2}) * \sqrt{y(n)^2 + (x(k) + 4320)^2 + h^2}) + \mu_0 * I_{\text{current}} * (L - (x(k) + 4320)) / (4 * \pi * \sqrt{y(n)^2 + h^2}) * \sqrt{y(n)^2 + (L - (x(k) + 4320))^2 + h^2});$$

$$B_{43}(k) = \mu_0 * I_{\text{current}} * h / (4 * \pi * \sqrt{y(n)^2 + (L - (x(k) + 4320))^2}) * y(n)^2 + h.^2 + (L - (x(k) + 4320))^2);$$

%For train four and substation three

$$B_{14}(k) = \mu_0 * I_{\text{current}} * (L - (x(k) + 6480)) / (4 * \pi * y(n) * \sqrt{y(n)^2 + (L - (x(k) + 6480))^2}) + \mu_0 * I_{\text{current}} * (x(k) + 6480) / (4 * \pi * y(n) * \sqrt{y(n)^2 + (x(k) + 6480)^2});$$

$$B_{24}(k) = \mu_0 * I_{\text{current}} * h / (4 * \pi * \sqrt{y(n)^2 + (x(k) + 6480)^2}) * \sqrt{y(n)^2 + (x(k) + 6480)^2 + h^2};$$

$$B_{34}(k) = \mu_0 * I_{\text{current}} * (x(k) + 6480) / (4 * \pi * \sqrt{y(n)^2 + h^2}) * \sqrt{y(n)^2 + (x(k) + 6480)^2 + h^2}) + \mu_0 * I_{\text{current}} * (L - (x(k) + 6480)) / (4 * \pi * \sqrt{y(n)^2 + h^2}) * \sqrt{y(n)^2 + (L - (x(k) + 6480))^2 + h^2});$$

$$B_{44}(k) = \mu_0 * I_{\text{current}} * h / (4 * \pi * \sqrt{y(n)^2 + (L - (x(k) + 6480))^2}) * y(n)^2 + h.^2 + (L - (x(k) + 6480))^2);$$

%For train five and three substations

$$B_{15}(k) = \mu_0 * I_{\text{current}} * (L - (x(k) + 8640)) / (4 * \pi * y(n) * \sqrt{y(n)^2 + (L - (x(k) + 8640))^2}) + \mu_0 * I_{\text{current}} * (x(k) + 8640) / (4 * \pi * y(n) * \sqrt{y(n)^2 + (x(k) + 8640)^2});$$

$$B_{25}(k) = \mu_0 * I_{\text{current}} * h / (4 * \pi * \sqrt{y(n)^2 + (x(k) + 8640)^2}) * \sqrt{y(n)^2 + (x(k) + 8640)^2 + h^2};$$

$$B_{35}(k) = \mu_0 * I_{\text{current}} * (x(k) + 8640) / (4 * \pi * \sqrt{y(n)^2 + h^2}) * \sqrt{y(n)^2 + (x(k) + 8640)^2 + h^2}) + \mu_0 * I_{\text{current}} * (L - (x(k) + 8640)) / (4 * \pi * \sqrt{y(n)^2 + h^2}) * \sqrt{y(n)^2 + (L - (x(k) + 8640))^2 + h^2});$$

$$B_{45}(k) = \mu_0 * I_{\text{current}} * h / (4 * \pi * \sqrt{y(n)^2 + (L - (x(k) + 8640))^2}) * y(n)^2 + h.^2 + (L - (x(k) + 8640))^2);$$

% Full loop of magnetic field in xy plane

$$B_{xF1}(k) = B_2(k) * y(n) / \sqrt{y(n)^2 + x(k)^2} - B_4(k) * y(n) / \sqrt{y(n)^2 + (L - x(k))^2};$$

$$B_{yF1}(k) = -B_2(k) * x(k) / \sqrt{y(n)^2 + x(k)^2} - B_3(k) * h / \sqrt{y(n)^2 + h^2} - B_4(k) * (L - x(k)) / \sqrt{y(n)^2 + (L - x(k))^2};$$

$$B_{zF1}(k) = -B_1(k) + B_3(k) * y(n) / \sqrt{x(k)^2 + h^2};$$

%For train two and substation two

$$B_{xF2}(k) = B_{22}(k) * y(n) / \sqrt{y(n)^2 + (x(k) + 2160)^2} - B_{42}(k) * y(n) / \sqrt{y(n)^2 + (L - (x(k) + 2160))^2};$$

$$B_{yF2}(k) = -B_{22}(k) * (x(k) + 2160) / \sqrt{y(n)^2 + (x(k) + 2160)^2} - B_{32}(k) * h / \sqrt{y(n)^2 + h^2} - B_{42}(k) * (L - (x(k) + 2160)) / \sqrt{y(n)^2 + (L - (x(k) + 2160))^2};$$

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

```

BzF2(k)= -B12(k)+B32(k)*y(n)/sqrt((x(k)+2160)^2+h^2);
%For train three and substation two
BxF3(k)= B23(k)*y(n)/sqrt(y(n)^2+(x(k)+4320)^2)-B43(k)*y(n)/sqrt(y(n)^2+(L-(x(k)+4320))^2);
ByF3(k)= -B23(k)*(x(k)+4320)/sqrt(y(n)^2+(x(k)+4320)^2)-B33(k)*h/sqrt(y(n)^2+h^2)-B43(k)*(L-(x(k)+4320))/sqrt(y(n)^2+(L-(x(k)+4320))^2);
BzF3(k)= -B13(k)+B33(k)*y(n)/sqrt((x(k)+4320)^2+h^2);
%For train four and substation three
BxF4(k)= B24(k)*y(n)/sqrt(y(n)^2+(x(k)+6480)^2)-B44(k)*y(n)/sqrt(y(n)^2+(L-(x(k)+6480))^2);
ByF4(k)= -B24(k)*(x(k)+6480)/sqrt(y(n)^2+(x(k)+6480)^2)-B34(k)*h/sqrt(y(n)^2+h^2)-B44(k)*(L-(x(k)+6480))/sqrt(y(n)^2+(L-(x(k)+6480))^2);
BzF4(k)= -B14(k)+B34(k)*y(n)/sqrt((x(k)+6480)^2+h^2);
%For train five and substation tree
BxF5(k)= B25(k)*y(n)/sqrt(y(n)^2+(x(k)+8640)^2)-B45(k)*y(n)/sqrt(y(n)^2+(L-(x(k)+8640))^2);
ByF5(k)= -B25(k)*(x(k)+8640)/sqrt(y(n)^2+(x(k)+8640)^2)-B35(k)*h/sqrt(y(n)^2+h^2)-B45(k)*(L-(x(k)+8640))/sqrt(y(n)^2+(L-(x(k)+8640))^2);
BzF5(k)= -B15(k)+B35(k)*y(n)/sqrt((x(k)+8640)^2+h^2);
%leakage loop
BxL(k)          =          -muo*Il_current*atan(((L-x(k))/y(n)))/(4*pi*L)          -
muo*Il_current*atan((x(k)/y(n)))/(4*pi*L)+muo*Il_current*y(k)*L/(4*pi*L*sqrt(y(n)^2+x(k)^2));
ByL(k)   =   -muo*Il_current*log((sqrt(y(n)^2+(L-x(k))^2))/(sqrt(y(n)^2+x(k)^2)))/(4*pi*L   )   -
muo*Il_current*x(k)*L/(sqrt(y(n)^2+x(k)^2)*(4*pi*L));
BzL(k)          =          muo*Il_current*x(k)*L/(4*pi*y(n)*L*sqrt(y(n)^2+x(k)^2))+
muo*Il_current*sqrt(y(n)^2+(L-x(k)))/(4*pi*y(k)*L)-
muo*Il_current*sqrt(y(n)^2+x(k)^2)/(4*pi*y(n)*L);
end
end
%subplot(2,1,1)
figure(1)
BxF = sqrt(BxF1.^2+BxF2.^2+BxF3.^2+BxF4.^2+BxF5.^2);
ByF = sqrt(ByF1.^2+ByF2.^2+ByF3.^2+ByF4.^2+ByF5.^2);
BzF = sqrt(BzF1.^2+BzF2.^2+BzF3.^2+BzF4.^2+BzF5.^2);
plot(BxF,'r')
hold on

```

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

```
plot(BzF,'b')
hold on
plot(ByF,'g')
hold on
plot(Hf*ones(200,1),'r');
hold on
legend('X com. magnetic field', 'Y com. magnetic field', 'Z com. magnetic field')
xlabel(' Distance from railway(m)')
ylabel(' Magnetic field[mT]')
title('com. Full loop of magnetic field')
hold on
grid on
%subplot(2,1,2)
figure(2)
Bf = sqrt(BxF.^2+ByF.^2+BzF.^2);
plot(Bf)
hold on
plot(Hf*ones(200,1),'r');
hold on
legend('B Total magnetic field')
xlabel(' Distance from railway(m)')
ylabel(' Magnetic field[mT]')
title(' Tota Full loop of magnetic field')
grid on
% subplot(2,1,1)
figure(3)
title(' leakage loop of field')
hold on
plot(BxL,'r')
hold on
plot(BzL,'b')
hold on
plot(ByL,'g')
```

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

```
hold on
plot(HI*ones(200,1),'r');
legend('X com. leakage magnetic field', 'Y com. leakage magnetic field', 'Z com. leakage magnetic field')
xlabel(' Distance from railway(m)')
ylabel(' Magnetic field[mT]')
grid on
% subplot(2,1,2)
figure(4)
Bl = sqrt(BxL.^2+ByL.^2+BzL.^2);
plot(Bl)
hold on
plot(HI*ones(200,1),'r');
hold on
legend('B Total leakage magnetic field')
xlabel(' Distance from railway(m)')
ylabel(' Magnetic field[mT]')
title(' Total leakage magnetic field')
grid on
figure(5)
BxF = sqrt(BxF1.^2+BxF2.^2+BxF3.^2+BxF4.^2+BxF5.^2);
ByF = sqrt(ByF1.^2+ByF2.^2+ByF3.^2+ByF4.^2+ByF5.^2);
BzF = sqrt(BzF1.^2+BzF2.^2+BzF3.^2+BzF4.^2+BzF5.^2);
BxT = BxF + BxL;
ByT = ByF + ByL;
BzT = BzF + BzL;
HT = sqrt(BxT.^2 + ByT.^2 + BzT.^2);
plot(HT,'b')
grid on
hold on
plot(HI*ones(200,1),'r');
hold on
legend('Total magnetic field')
xlabel(' Distance from railway(m)')
ylabel(' Magnetic field[mT]')
```

```
title(' Sum of full loop and leakage loop of magnetic field')
```

```
grid on
```

4. For 3D Simulation MATLAB code

```
% Initialization of variables
muo = 4*pi*1e-7;
I_current = 1400;
Il_current = 10;
h = 5.4;
L = 10000;
% H = 0.00001;
x = 1:4000:10000;
y = 1:4000:10000;
NSegment =length(x);
NSegmen =length(y);
% % @ Loop over the segments in the current loop in xy plane
for k=1:NSegment;
for n=1:NSegmen;
B(k,n)=muo*I_current*(L-x(k))/(4*pi*y(n)*sqrt(y(n)^2+(L-x(k))^2))+
muo*I_current*x(k)/(4*pi*y(n)*sqrt(y(n)^2+x(k)^2));
B2(k,n)=muo*I_current*h/(4*pi*sqrt(y(n)^2+x(k)^2)*sqrt(y(n)^2+x(k)^2+h^2));
B3(k,n)=muo*I_current*x(k)/(4*pi*sqrt(y(n)^2+h^2)*sqrt(y(n)^2+x(k)^2+h^2))+muo*I_current*(L-
x(k))/(4*pi*sqrt(y(n)^2+h^2)*sqrt(y(n)^2+(L-x(k))^2+h^2));
B4(k,n)=muo*I_current*h/(4*pi*sqrt(y(n)^2+(L-x(k))^2)*y(n)^2+h.^2+(L-x(k))^2);
%For train two and substation two
B12(k,n)=muo*I_current*(L-(x(k)+2160))/(4*pi*y(n)*sqrt(y(n)^2+(L-(x(k)+2160))^2))+
muo*I_current*(x(k)+2160)/(4*pi*y(n)*sqrt(y(n)^2+(x(k)+2160)^2));
B22(k,n)=muo*I_current*h/(4*pi*sqrt(y(n)^2+(x(k)+2160)^2)*sqrt(y(n)^2+(x(k)+2160)^2+h^2));
B32(k,n)=muo*I_current*(x(k)+2160)/(4*pi*sqrt(y(n)^2+h^2)*sqrt(y(n)^2+(x(k)+2160)^2+h^2))+mu
o*I_current*(L-(x(k)+2160))/(4*pi*sqrt(y(n)^2+h^2)*sqrt(y(n)^2+(L-(x(k)+2160))^2+h^2));
B42(k,n)=muo*I_current*h/(4*pi*sqrt(y(n)^2+(L-(x(k)+2160))^2)*y(n)^2+h.^2+(L-
(x(k)+2160))^2);
%For train three and substation two
```

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

$$B13(k,n)=\mu_0 I_{current} (L-(x(k)+4320))/(4\pi y(n) \sqrt{y(n)^2+(L-(x(k)+4320))^2}) + \mu_0 I_{current} (x(k)+4320)/(4\pi y(n) \sqrt{y(n)^2+(x(k)+4320)^2});$$

$$B23(k,n)=\mu_0 I_{current} h/(4\pi \sqrt{y(n)^2+(x(k)+4320)^2}) \sqrt{y(n)^2+(x(k)+4320)^2+h^2};$$

$$B33(k,n)=\mu_0 I_{current} (x(k)+4320)/(4\pi \sqrt{y(n)^2+h^2}) \sqrt{y(n)^2+(x(k)+4320)^2+h^2}) + \mu_0 I_{current} (L-(x(k)+4320))/(4\pi \sqrt{y(n)^2+h^2}) \sqrt{y(n)^2+(L-(x(k)+4320))^2+h^2});$$

$$B43(k,n)=\mu_0 I_{current} h/(4\pi \sqrt{y(n)^2+(L-(x(k)+4320))^2}) y(n)^2+h.^2+(L-(x(k)+4320))^2);$$

% For train four and substation three

$$B14(k,n)=\mu_0 I_{current} (L-(x(k)+6480))/(4\pi y(n) \sqrt{y(n)^2+(L-(x(k)+6480))^2}) + \mu_0 I_{current} (x(k)+6480)/(4\pi y(n) \sqrt{y(n)^2+(x(k)+6480)^2});$$

$$B24(k,n)=\mu_0 I_{current} h/(4\pi \sqrt{y(n)^2+(x(k)+6480)^2}) \sqrt{y(n)^2+(x(k)+6480)^2+h^2};$$

$$B34(k,n)=\mu_0 I_{current} (x(k)+6480)/(4\pi \sqrt{y(n)^2+h^2}) \sqrt{y(n)^2+(x(k)+6480)^2+h^2}) + \mu_0 I_{current} (L-(x(k)+6480))/(4\pi \sqrt{y(n)^2+h^2}) \sqrt{y(n)^2+(L-(x(k)+6480))^2+h^2});$$

$$B44(k,n)=\mu_0 I_{current} h/(4\pi \sqrt{y(n)^2+(L-(x(k)+6480))^2}) y(n)^2+h.^2+(L-(x(k)+6480))^2);$$

% For train five and three substations

$$B15(k,n)=\mu_0 I_{current} (L-(x(k)+8640))/(4\pi y(n) \sqrt{y(n)^2+(L-(x(k)+8640))^2}) + \mu_0 I_{current} (x(k)+8640)/(4\pi y(n) \sqrt{y(n)^2+(x(k)+8640)^2});$$

$$B25(k,n)=\mu_0 I_{current} h/(4\pi \sqrt{y(n)^2+(x(k)+8640)^2}) \sqrt{y(n)^2+(x(k)+8640)^2+h^2};$$

$$B35(k,n)=\mu_0 I_{current} (x(k)+8640)/(4\pi \sqrt{y(n)^2+h^2}) \sqrt{y(n)^2+(x(k)+8640)^2+h^2}) + \mu_0 I_{current} (L-(x(k)+8640))/(4\pi \sqrt{y(n)^2+h^2}) \sqrt{y(n)^2+(L-(x(k)+8640))^2+h^2});$$

$$B45(k,n)=\mu_0 I_{current} h/(4\pi \sqrt{y(n)^2+(L-(x(k)+8640))^2}) y(n)^2+h.^2+(L-(x(k)+8640))^2);$$

% Full loop of magnetic field in xy plane

$$BxF1(k,n)= -B2(k) y(n)/\sqrt{y(n)^2+x(k)^2}-B4(k) y(n)/\sqrt{y(n)^2+(L-x(k))^2};$$

$$ByF1(k,n)= -B2(k) x(k)/\sqrt{y(n)^2+x(k)^2}-B3(k) h/\sqrt{y(n)^2+h^2}-B4(k) (L-x(k))/\sqrt{y(n)^2+(L-x(k))^2};$$

$$BzF1(k,n)= -B(k)+B3(k) y(n)/\sqrt{x(k)^2+h^2};$$

% For train two and substation two

$$BxF2(k,n)= -B22(k) y(n)/\sqrt{y(n)^2+(x(k)+2160)^2}-B42(k) y(n)/\sqrt{y(n)^2+(L-(x(k)+2160))^2};$$

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

```

ByF2(k,n)=          -B22(k)*(x(k)+2160)/sqrt(y(n)^2+(x(k)+2160)^2)-B32(k)*h/sqrt(y(n)^2+h^2)-
B42(k)*(L-(x(k)+2160))/sqrt(y(n)^2+(L-(x(k)+2160))^2);
BzF2(k,n)= -B12(k)+B32(k)*y(n)/sqrt((x(k)+2160)^2+h^2);
%For train three and substation two
BxF3(k,n)= -B23(k)*y(n)/sqrt(y(n)^2+(x(k)+4320)^2)-B43(k)*y(n)/sqrt(y(n)^2+(L-(x(k)+4320))^2);
ByF3(k,n)=          -B23(k)*(x(k)+4320)/sqrt(y(n)^2+(x(k)+4320)^2)-B33(k)*h/sqrt(y(n)^2+h^2)-
B43(k)*(L-(x(k)+4320))/sqrt(y(n)^2+(L-(x(k)+4320))^2);
BzF3(k,n)= -B13(k)+B33(k)*y(n)/sqrt((x(k)+4320)^2+h^2);
%For train four and substation three
BxF4(k,n)= -B24(k)*y(n)/sqrt(y(n)^2+(x(k)+6480)^2)-B44(k)*y(n)/sqrt(y(n)^2+(L-(x(k)+6480))^2);
ByF4(k,n)=          -B24(k)*(x(k)+6480)/sqrt(y(n)^2+(x(k)+6480)^2)-B34(k)*h/sqrt(y(n)^2+h^2)-
B44(k)*(L-(x(k)+6480))/sqrt(y(n)^2+(L-(x(k)+6480))^2);
BzF4(k,n)= -B14(k)+B34(k)*y(n)/sqrt((x(k)+6480)^2+h^2);
%For train five and substation tree
BxF5(k,n)=          -B25(k)*y(n)/sqrt(y(n)^2+(x(k)+8640)^2)-B45(k)*y(n)/sqrt(y(n)^2+(L-
(x(k)+8640))^2);
ByF5(k,n)=          -B25(k)*(x(k)+8640)/sqrt(y(n)^2+(x(k)+8640)^2)-B35(k)*h/sqrt(y(n)^2+h^2)-
B45(k)*(L-(x(k)+8640))/sqrt(y(n)^2+(L-(x(k)+8640))^2);
BzF5(k,n)= -B15(k)+B35(k)*y(n)/sqrt((x(k)+8640)^2+h^2);
%leakage loop
BxL(k,n)           =          -muo*Ii_current*atan(((L-x(k))/y(n)))/(4*pi*L)          -
muo*Ii_current*atan((x(k)/y(n)))/(4*pi*L)+muo*Ii_current*y(k)*L/(4*pi*L*sqrt(y(n)^2+x(k)^2));
ByL(k,n)  =  -muo*Ii_current*log((sqrt(y(n)^2+(L-x(k))^2))/(sqrt(y(n)^2+x(k)^2)))/(4*pi*L  )  -
muo*Ii_current*x(k)*L/(sqrt(y(n)^2+x(k)^2)*(4*pi*L));
BzL(k,n)           =          muo*Ii_current*x(k)*L/(4*pi*y(n)*L*sqrt(y(n)^2+x(k)^2))+
muo*Ii_current*sqrt(y(n)^2+(L-x(k)))/(4*pi*y(k)*L)-
muo*Ii_current*sqrt(y(n)^2+x(k)^2)/(4*pi*y(n)*L);
end
end
BxF = sqrt(BxF1.^2+BxF2.^2+BxF3.^2+BxF4.^2+BxF5.^2+BxL.^2);
ByF = sqrt(ByF1.^2+ByF2.^2+ByF3.^2+ByF4.^2+ByF5.^2+ByL.^2);
BzF = sqrt(BzF1.^2+BzF2.^2+BzF3.^2+BzF4.^2+BzF5.^2+BzL.^2);
% B = sqrt(BxF.^2+ByF.^2+BzF.^2);

```

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

```
% B = B./max(max(B));
BxFmax = 8*NSegmen;           % Dimensions of detector space
ByFmin = 1*NSegmen/4;
ByFmax = 8*NSegmen;
BxF = linspace(-BxFmax,BxFmax,NSegmen);
ByF = linspace(ByFmin,ByFmax,NSegmen);
[xBxF, yByF] = meshgrid(BxF,ByF);
figure(5);
surf(xBxF,yByF,B,'FaceColor','interp',...
     'EdgeColor','none',...
     'FaceLighting','phong')
daspect([4 4 4])
axis tight
view(-122,36)
camlight left
colormap(jet)
xlabel('ByF');ylabel('BxF');
grid on
axis on
colorbar
title('Magnetic field from full loop')
```

5. For pantograph arcing MATLAB code

```
% initialization of variables
p = 6880;
x = 1:20:1000;
y = 50:10:1000;
NSegment = length(x);
dis=zeros(NSegment,1);
dis(1)=50;
for n = 2:NSegment
dis(n) = sqrt(dis(1)^2+(x(n)-x(1))^2);
end
```

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

```
for n=1:NSegment
s(n) = p/(4*pi*dis(n).^2);
Eo(n) = sqrt(30*p)/dis(n);
Ho(n) = sqrt(30*p)/(dis(n)*120*pi);
end
figure(1)
H = 0.238;
plot(H*ones(1000,1),'r');
grid on
hold on
plot(x,Ho,'g')
hold on
grid on
hold on
title('Magnetic field of pantograph arcing')
xlabel('Distance from railway(m)')
ylabel(' magnetic field (dBμA/m)')
figure(2)
E = 2.895;
plot(E*ones(1000,1),'r');
grid on
hold on
plot(x,Eo,'g')
grid on
hold on
title('Electric field of pantograph arcing')
xlabel('Distance from railway(m)')
ylabel(' Electric field(dBμV/m)')
```

References

- [1]. Kelin Jia, "High Frequency Model of Electrified Railway Propulsion System for EMC Analysis", Division of Electromagnetic Engineering, KTH School of Electrical Engineering SE 100-44, Stockholm, Sweden, 2012
- [2]. Y.yashifumi mahinga, and H. Nagaswa, "Railway electric power feeding systems", *Railway Technology today* 3(Edited by konji wako)
- [3]. Leeds New Generation Transport Environmental Statement," *Electromagnetic Compatibility (EMC) Technical Appendix E*" Metro and Leeds City Council, volume II, September 2013
- [4]. CLAYTON R.PAUL, 2006, "Introduction to Electromagnetic Compatibility" second Edition, published by John Wiley & Sons, Inc., Hoboken, New Jersey
- [5]. S. Midya," *Conducted and Radiated Electromagnetic Interference in Modern Electrified Railways with Emphasis on Pantograph Arcing*" *Electromagnetic Engineering, KTH Electrical Engineering, SE-100 44 Stockholm, Sweden, 2009*, <http://www.etk.ee.kth.se>
- [6]. Djilali Hamza," *Electromagnetic Interference Mitigation in Switched Mode Power Converters Using Digital Sampling Techniques*" Queen's University, Kingston, Ontario, Canada, (November, 2011)
- [7]. M. Mandić, I. Uglešić, V. Milardić, "Study of Electromagnetic Fields from AC 25KV/50 Hz Contact Line System"
- [8]. F. J. Lowes, *DC railways and the magnetic fields they produce—the geomagnetic Context, School Of Chemistry, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK* Received January 20, 2009; Revised April 23, 2009; Accepted April 24, 2009; Online published October 19, 2009)
- [9]. Malka N. Halgamuge*, Chathurika D. Abeyrathne and Priyan Mendis, *Measurement and analysis of electromagnetic fields from trams, trains and Hybrid cars*" Civil and Environmental Engineering, School of Engineering, the University of Melbourne, Parkville, VIC3010, Melbourne, Australia

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

- [10]. J. Ben Hadj Slama, D.Chariag, 2008, “*Measurement and Analysis of Magnetic field Radiated from D.C. Tramway*” case study for Tunisi’o metro, journal of Electrical System, 4-2-7, 1-12.
- [11]. S. A. Pignari and D. Bellan,”*Impact of the Infrastructure on the Electromagnetic Emissions Radiated by a Railway System*”, Polytechnic of Milan, Milan, Italy
- [12]. A. Ogunsola^{1; 2} and A. Mariscotti³,”*Design Optimization to Reduce the Magnetic Fields Propagated from DC Light Rail Transit Systems*, ¹Department of Electrical and Electronics Engineering, Faculty of Engineering, University of Lagos, Lagos, Nigeria, ²Rail Transit Division, Parsons Group International, London, United Kingdom; ³Naval and Electrical Engineering Department, University of Genoa, Via All' Opera Pia 11A, 16145 Genoa, Italy
- [13] .S. Baranowski¹, H. Ouaddi¹, L. Kone¹ and N. Idir²,”*EMC Analysis of Railway Power Substation Modeling and Measurements Aspects*”, ¹Université Lille 1 Science ET Technologies, USTL, IEMN/TELICE Laboratory, ²Université Lille 1 Sciences ET Technologies, USTL, L2EP Laboratory, F-59650 Villeneuve d’Ascq,
- [14]. T Kontel, D a J.pears, C a Marshman, L M McCormack” *Potential electromagnetic Interference to radio services from railways* , AY4110, York EMC service Ltd, 9.
- [15]. China Railway Group Limited, 2009, “*Addis Ababa LRT project east-west line Project Study Report*”, 05
- [16]. S. Baranowski¹, H. Ouaddi¹, L. Kone¹ and N. Idir² “*EMC Analysis of Railway Power Substation Modeling and Measurements Aspects*”¹Université Lille 1 Sciences ET Technologies, USTL, IEMN/TELICE Laboratory, ² University Lille 1 Sciences ET Technologies, USTL, L2EP Laboratory, F-59650 Villeneuve d’Ascq,
- [17]. LUAS LINE A1 EIS, ELECTROMAGNETIC INTERFERENCE, Section 39 (ii) Of the Transport (Railway Infrastructure), Act 2001, 2-4.
- [18]. S. Niska, 2008, “*Measurements and Analysis of Electromagnetic Interferences in the Swedish Railway Systems*”, Lulea University of Technology, Division of Operation and Maintenance, Lulea Railway Research Center.

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

- [19]. RSSB, November 2009, “*Investigation into the effect of the Physical Agents (Electromagnetic Fields) Directive on railway operations*”, T5
- [20]. Ethiopian Railways Corporation (ERC)
- [21]. European Standards: EN50121, *Railway applications-Electromagnetic Compatibility*; part1-5, CENELEC, 2006
- [22]. CLAYTON R.PAUL, 2006, “*Introduction to Electromagnetic Compatibility*” Second Edition, Published by John Wiley & Sons, Inc., Hoboken, New Jersey.
- [23]. Andrea Cozza, 2005, “*Railways EMC: Assessment of Infrastructure Impact*”, Dottorato in Ingegneria Elettronica e delle Communication XVII ciclo.
- [24] .Tetsuo TOKUMOTO and Satoru TSUNOMURA, *Calculation of Magnetic Field Disturbance Produced by Electric Railway*, Translated to English from paper in Japanese originally Published in: *Memoirs of the Kakioka Magnetic Observatory*, Vol.20, No.2, 33-44, 1984 with Permission of the authors.
- [25]. Mott MacDonald Internal Ref. 312694/RPT011, *Electromagnetic Compatibility Environmental Statement* volume II, September 2013
- [26] .Andrea Cozza, Member, IEEE, and Bernard D’emoulin, “*On the Modeling of Electric Railway Lines for the Assessment of Infrastructure Impact in Radiated Emission Tests of Rolling Stock*” IEEE, TRANSACTIONS ON ELECTROMAGNETIC COMPATIBILITY, VOL. 50, NO. 3, AUGUST 2008 1
- [27].S. A. Pignari and D. Bellan, “*Impact of the Infrastructure on the Electromagnetic Emissions Radiated by a Railway System*”, Polytechnic of Milan, Milan, Italy
- [28] .A. Hoffrichter, “*The Feasibility of Discontinuous Electrification: Case Study of the Great Western Main Line*”
- [29]. JOHN O. ATTIA, “*ELECTRONICS and CIRCUIT ANALYSIS using MATLAB*”, Department of Electrical Engineering, Prairie View A&M University, Boca Raton London New York Washington, D.C.

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

- [30] .St. Stephen's Green to Broombridge, Luas Broombridge (Line BXD), Part 2 - Chapters 6-7
- [31]. Z. Mazloom," *Multi-conductor transmission line model for electrified railways: A method for including responses of lumped devices*", Doctoral thesis in Electrical Systems Stockholm, Sweden 201
- [32]. Hong-Shik Cho, Rag-Gyo Jeong, Sang-Gi Chung, Myung-Kon Song*1, Sang-Jin Lee*2, and Jung-Do Park*2, "*Magnetic Fields Shielding Analysis of Light Rail Transit System*, Korea Railroad Research Institute, Uiwang-Si, 437-050, Korea,*1 VFK Inc., Korea *2 Department of Electrical Engineering, Uiduk University, Korea
- [33]. A. Ogunsola¹; ² and A. Mariscotti³, "*Design Optimization to Reduce the Magnetic Fields Propagated from DC Light Rail Transit Systems*", ¹Department of Electrical and Electronics Engineering, Faculty of Engineering, University of Lagos, Lagos, Nigeria, ²Rail Transit Division, Parsons Group International, London, United Kingdom, ³Naval and Electrical Engineering Department, University of Genoa, via all' Opera Pia 11A, 16145 Genoa, Italy
- [34]. A. Ogunsola and Andrea Mariscotti, "*Electromagnetic Compatibility in Railways Analysis and Management*
- [25]. CALIFORNIA HIGH-SPEED TRAIN PROJECT EIR/EIS, *electromagnetic fields and Merced to Fresno section electromagnetic interference*
- [36]. KINH D. PHAM, RALPH S. THOMAS, WALTER E. STINGER, JR,"Operational and Safety Considerations for Light Rail DC Traction Electrification System Design", *Elcon Associates, Inc., Engineers & Consultants LTK Engineering Services*
- [37]. Frans Schoren ,"*Transients in railway environments; Measurements & Modelling*", BIT TIPS,Singapore Erwin Smulders, Holland Rail consult, The Netherlands, Gert-Jan van Alphen, Holland rail consult, The Netherlands,Kees Post, Lambda Engineering BV, The Netherlands Contact address: Holland rail consult, PO Box 2855, 3500 GW Utrecht, The Netherlands

Analysis of Electromagnetic Emission from Contact lines of Light Rail Transit System

[38]. P. Imbesi, “*Limiting of Electromagnetic Field inside Rolling Stock with Reference to Human Body Exposure, Test Measurement and Shielding Impact*”, Bombardier Transportation, Locomotive Division, Vado Figure, Italy

[39]. [http:// www.tuv.com](http://www.tuv.com) online

[40]. <http://www.kth.se/en/ees/omskolan/organisation/avdelningar/etk/research/emc/>

[41]. Liu Jin-Jiang, Cheng Qiang, Cheng Ning,” *Study on Electromagnetic Interference of High-Speed Railway EMU*”, TELKOMNIKA Indonesian Journal of Electrical Engineering, Received June 15, 2013; Revised August 22, 2013; Accept September 22, 2013 Nanyang Normal University, Nanyang 473061, China, Vol.12, No.1, January 2014, pp. 141 ~ 148

[42]. PANTOGRAPH ARC DETECTION INSPIRED SYSTEMS

[43]. PIERRE-VINCENT VERSCHRAEGE,”*A Model of the Pantograph Arc Impedance for 50 Hz Catenary Voltage*,” NExamensarbete, KTH Skolan for Elektro- och systemteknik, Electromagnetic Engineering Lab, March 2010, XR-EE-ETK 2010:002

[44]. Luas Broom bridge, “*Environmental impact assessment*” Area 29, St. Stephen’s Green to former Broad stone railway cutting, part-2, chapter 6-7

[45]. <https://www.google.com/search?q=railway+power+collecting+system&newwindow>