ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING

Harmonic Analysis in 25kV AC Railway Electrification system: The case of the proposed Ethiopian Railway System

A thesis submitted to the School of Electrical and Computer Engineering, Addis Ababa University in partial fulfillment for the Degree of Master of Science in Electrical Railway Engineering

By

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Declaration

I declare that this thesis represents my own work, except where due acknowledgement is made, and that it has not been previously submitted to this university or to any other institution for a degree or other qualification.

Signed…………………………………………………….

Henok Million

Abstract

Electrical locomotives generate harmonic currents in railway power-supply system. Which in turn produce continuous distortion of current and voltage waveform in the supply network. This distortion gives adverse effect in traction power-supply system such as overheating, vibration and torque reduction of rotating machines, additional losses of lines and transformers, interference with communication systems, malfunctions of protection relays, measuring instrument error, etc. Therefore, the distortion in voltage and current waveform at various points in the traction system should be quantified and analyzed according to international standards such as IEEE 519-1999.

This thesis focuses on studying voltage and current distortion in the supply system due to harmonics injected by locomotive with diode rectifier. The system considered under study for harmonics analysis is a proposed Ethiopian single-phase 25KV AC electrification system. Major components of the electric traction system are modeled for harmonic study using MATLAB/SIMPOWER system. Added to this, mathematical model of supply network to quantify voltage distortion at different bus analytically is developed. The systems without harmonic filter have been simulated to investigate the harmonic levels for different operating conditions. Accordingly, the simulation result at PCC for train at full load reveals that a THD of 11.26% for voltage and a THD of 37.15% for current in worst scenario. This is large as compere to the limit set by IEEE 519-1999.Therefore, a passive harmonic LC filter is designed to filter out the noticeable harmonics in the system. As the result, it was found that THD of 3.13% for voltage and THD of 3.15% for current waveform, which are below IEEE 519 standard, limits. This shows power quality and EMC improvement of the traction power supply system.

Keywords: Electric Traction System, Power Quality, modeling, harmonic distortion, harmonic mitigation, passive filter.

Acknowledgement

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List of Abbreviations and Symbols

Abbreviations

AC	Alternate Current
AT	Autotransformer
BT	Booster Transformer
D	Distortion Power
DC	Direct Current
DF	Direct Feeding
EMC	Electromagnetic Compatibility
EN	European Norms
ETS	Electric Traction System
FD	Frequency Domain
FFT	Fast Fourier Transforms
FS	Feeder Section
HPFA	Harmonic Power Flow Analysis
HV	High Voltage
IEC	International Electro-technical Committee
IEEE	Institute of Electrical & Electronics Engineers
IHA	Iterative Harmonic Analysis
IHD	Individual Harmonic Distortion

NO	Normally Open
NCCB	Normally Closed Circuit Breaker
ITSC	Intermediate Track Section Cabin
kVA	Kilo Volt Ampere
LV	Low Voltage
MPTSC	Mid-point Track Section Cabin
PQ	Power Quality
MVA	Mega Voltage Ampere
OCS	Overhead Contact System/line
PCC	Point of Common Coupling
PF	Total Power factor
PU	Per Unit
RMS	Root Mean Square
RPSS	Railway Power Supply System
TD	Time Domain
THD	Total Harmonic Distortion
V	Volt
kV	Kilo Volt
TSS	Traction Substation
CF	Crest Factor

Symbols

V_{rms}	Root Mean Square Voltage
I_{rms}	Root Mean Square Current
V_h	Harmonic Voltage
I_h	Harmonic Current
V_1	Fundamental Voltage
V_n	Nominal Voltage
I_1	Fundamental Current
P_{Loss}	Power Loss
ϕ	Power Factor Angle
q	Pulse Number
R	Resistance
L	Inductance
C	Capacitance
Z	Impedance
Z_h	Harmonic Impedance
Y_h	Harmonic Admittance

Z_{sub}	Thevenin Impedance of Substation
Z_{grid}	Short-Circuit Impedance of the Utility Supply Grid
p	Real Power
S	Apparent Power
Q/Q_c	Reactive Power
ω	Angular Frequency
π	Pi
μ	Micro
V_{dc}	Average DC Link Voltage
V_r	Ripple Voltage
L	Length
γ	Propagation Constant
Z_o	Characteristics Impedance
R	Resistance
Ω	Ohm
I_{sc}	Short Circuit Current

CHAPTER ONE

1 INTRODUCTION

1.1 Overview of Electric Railway Systems

The development of railway has been significant 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. The maximum speed of this train was 13-kilo meter per hour, and the output energy came to about 2.2 kilowatt. Since then, electrified railways have been improved dramatically due to the rapid development of power electronics and manufacturing industries. Nowadays, the transportation capability of a single locomotive has been increased to thousands of tons [3].

The main advantage of electric traction is a higher power-to-weight ratio than forms of traction such as diesel or steam that generate power onboard. Electricity enables faster acceleration and higher tractive effort on steep gradients. On locomotives equipped with regenerative brakes, descending gradients require very little use of air brakes, as the locomotive's traction motors become generators sending current back into the supply system and/or on-board resistors, which convert the excess energy to heat. Other advantages include the lack of exhaust fumes at point of use, less noise and lower maintenance requirements of the traction units. Given sufficient traffic density, electric trains produce fewer carbon emissions than diesel trains, especially in countries where electricity comes primarily from non-fossil sources [3]

The evolution in electrical traction systems has produced a variety of electrification systems inspired to very different principles. Now several kinds of Railway Power supply system's (RPSS) exist in Europe: such as

- Direct current (DC) systems (750/1500/3000 V)
- Medium voltage alternate current (AC) systems (15/25 kV, 50/60 Hz)
- High voltage AC systems (50/2x25 kV, 50 Hz)
- Low frequency systems (15 kV, 15-$16^{2/3}$ Hz)

The low voltage DC system is used for light rails usually supplied at 750 Volts (metro transit) and for commuter and intercity trains usually supplied at 3000 Volts, which is the case of the traditional Italian traction system [12].

The medium voltage AC system was adopted in order to reduce voltage losses. The 25 kV systems was practically born in France and had great development in USA, UK, Russia and several other countries thanks to the various advantages it offered such as the simplicity of substations and of single contact wires. It is typically used for commuter trains or freight trains.

The high voltage AC systems are the 50-kilovolt and 2x25 kV (or ±25kV) ones. The 50 kV systems, adopted in USA and in South Africa, exalt the economic advantages of the medium voltage systems. The system has been used where the traction load is high and the traction distances are large. Typically, it can be used for traction in rural areas and may be difficult in urban areas for the insulation requirements. Generally, RPSS are, for practical reasons, single phase AC or DC systems. The AC systems may be operated either at the same frequency as the public power grid or at a different frequency, normally a lower frequency [12].

Electricity is delivered to the trains in different ways often through an overhead contact system/line (OCS) normally called the catenary. The physical catenary goes somewhat above the actual OCS. It is however normal to denote the entire system of conductors hanging from the poles alongside the railway line as the catenary system. For subways, it is common with conductors on ground level, similar to the third-rail system common mainly in Great Britain [12].

1.2 Power Quality Issues in Electric Railway System

Both AC and DC electrified systems have been employed to operate for railway traction application based on different engineering and financial considerations as mentioned before. With development of technology over the years, especially the progress of power electronics applications has brought about many technical conveniences and economical profits, but it has simultaneously created new challenges in power system operation. One of the major concerns in this aspect is quality of power for both AC and DC electrified RPSS [4].

Power Quality (PQ) is generally used to express the quality of the voltage. This quality signifies the deviation of the voltage magnitude and frequency from the rated values and the deviation of the waveform from a pure sinusoid. That is, disturbance, unbalance, distortion and Voltage Fluctuations and Flicker can be defined as PQ problems [9]. With the wide use of power electronics and non-linear loads, harmonics in traction currents are the most important aspects of PQ. This is because harmonics are steady state, periodic phenomena that produce continuous distortion of voltage and current waveforms unlike transient events that last from a few milliseconds to several cycles. Beside, distortion gives adverse effects to a high-power electrical system such as

- Overheating, vibration and torque reduction of rotating machines
- additional losses of lines and transformers
- interference with communication systems
- malfunctions of protection relays, measuring instrument error
- Resonance effect with overvoltage and overcurrent consequences

In addition, the traffic increase of urban railways has made the harmonic pollution aspect of PQ more significant [4].The adverse effects of harmonics in the railway system and power supply system call for serious concern to both the train operation and power utility companies.

Though to alleviate the problems of harmonic disturbances, special equipment, such as passive filter and active filters are available, the cost of installation and maintenance for such equipment is expensive. Beside, oversize design of filters may results in high cost and should be avoided .The determination of installation as well as the design of the rating and the performance of the equipment requires knowledge about the level of harmonic disturbance. This knowledge is important to both management in decision-making and engineers in technical assessment. Therefore, Harmonic current flow through the contact line system has to be accurately modeled to analyze and assess the harmonic effect on the transmission system [4]

1.3 Overview of AC Electrified Traction Systems under Study

The system considered under study for harmonics analysis is the proposed Ethiopian single-phase 25KV AC electrified system. In this system, the traction transformers are supplied from state grid, normally at 132 kV voltage levels. **This voltage is further step down to 25kV nominal voltage at traction substation of using 132/27.5kV (no load voltage) transformers**. Each traction substation has two 132kV independent power lines. Branch connection is used at 132kV side and single bus bar section is applied at 25kV bus bar. Permanent spare system is used. Figure 1.1 shows the single line diagram of the traction substation (TSS) under study [24].

In this research, the span of the AC electric railway being studied is only 13.521km, which is double track normal feeding section supplied from sebeta traction substation. This substation is equipped with a single-phase 132/27.5kV transformer. Power supply mode for traction system is direct power with return line mode as shown in Fig.1.3 Section post is set between two adjacent traction substations. Circuit breaker (parallel interrupter) is also installed between up direction feeder and down direction feeder to implement parallel-connected power supply and independent power supply at double track. Operation mode for traction network is unilateral power supply at single rail track in which traction substations work independently as shown in figure 1.2. Usually, phase split insulator is installed at the exit of the substation and section post. If one of the substation faults, switches at the both ends section post will close to support over-zone feeding. Figure.1.3 illustrates the substation to be studied with its normal feeding section.

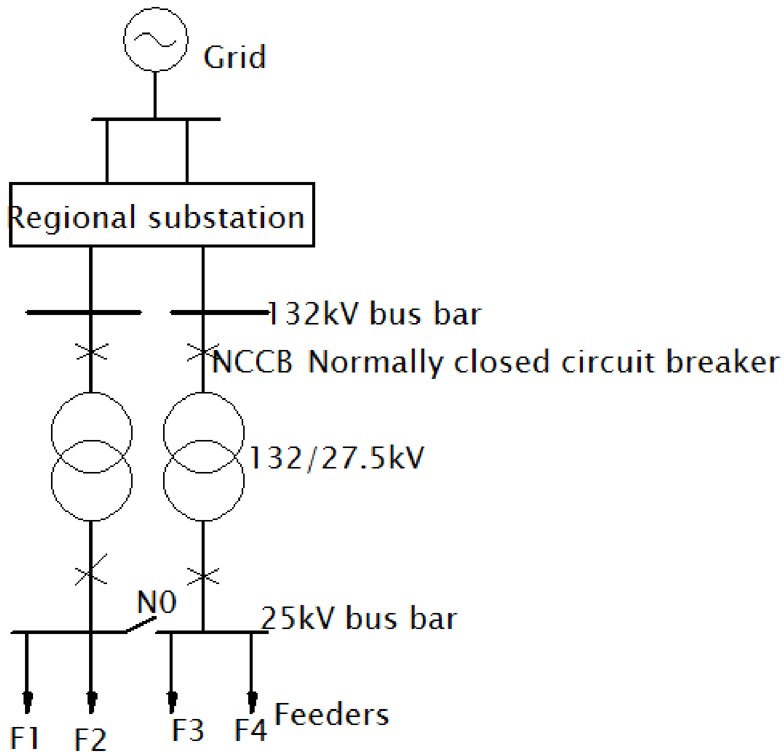

Figure 1.1: Single line diagram of the main 132/25kV traction substation (author)

The proposed traction load in this system is AC-DC-AC locomotive with six axle (co-co type) and rated power of 7200KW [24]. Due to operation of power electronics used for train control and drive systems electric locomotive causes current waveform distortion and consequently voltage distortion in transmission power system. Therefore, performing harmonic analysis to identify the voltage and current harmonic distortion levels to provide a concrete mitigation techeniqu is mandatory. Hence, **in this research, the effort is focused on the study of impact of the traction load on harmonic distortion due to its line side converter in 25kV AC electrified railway.**

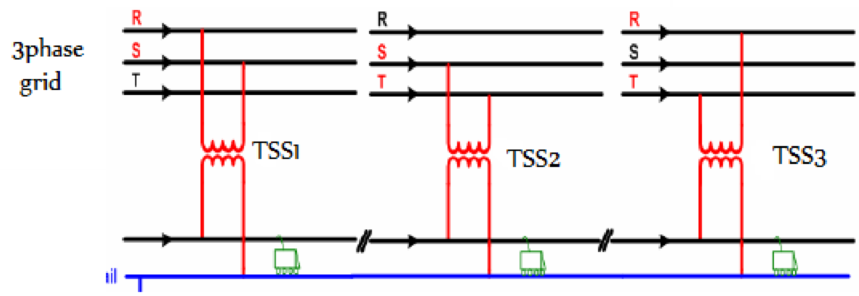

Figure 1.2 : Traction electrification system with single phase transformer arrangement [37]

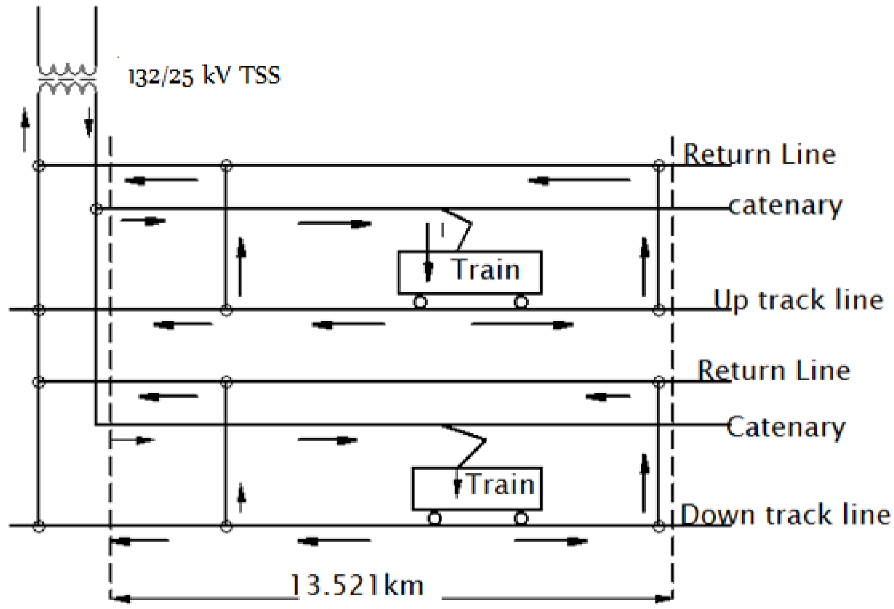

Figure 1.3: Arrangement of direct power with return line power supply mode of the TSS under study with it normal feeding section (author)

1.4 Objectives of This Thesis

This research concerns mainly in performing study and analysis on the impact of the traction load on harmonic distortion due to its line side converter in 25kV traction power supply of AC electric railways and to provide a concrete mitigation technique.

Thus, the following are the specific objective of this research:

- To develop models for AC electric traction systems and do harmonic analysis

- To quantify the distortion in voltage and current wave form at various points in the electric traction supply network
- To investigate and evaluate voltage distortion using harmonic Power flow analysis method (HPFA)
- To introduce corrective solution to mitigate the harmonic level

1.5 Scope of Thesis

The power quality analysis in this work was based on the electrical parameters obtained from the proposed Ethiopian single-phase 25kV AC Electrified system. Even though a power quality problem encompasses a wide range of problems, this paper focuses on studying voltage and current distortion in the supply system due to harmonics injected by the traction load. The characteristics of harmonics will be identified for different operation conditions and a range of solutions based on analyses procedures will be examined. Finally, proposing an optimal solution to reduce the power quality problems is the scope of this paper.

1.6 Organization of the Thesis

Brief introductions of RPSS together with standard electrification systems have been seen. A discussion on PQ issues in electric railway system also presented in consolidated manner. This has been followed by the description of the objectives and scope of the research. The rest of this thesis is outline as follows:

Chapter 2 presents a literature review of various other works that has been done on harmonic analysis for both general power system and electric traction system. The theory and study strategies of these methods are summarized. A brief discussion on harmonic sources, their impact on the railway power system along with basic concepts of harmonics are presented, and tools for analysis of harmonic waveforms are also provided. This chapter also aimed to present various modeling approaches to railway system.

Chapter 3 provides the proposed research strategy for the problem in hand. In account of this, it presents the proposed computer aided modeling in terms of literature for the electrified railway system that involves model of the three-phase supply grid with traction substation, model of traction feeder section and load modeling. In addition to this, analytical approach to model the traction power-supply network for harmonic characterization of the supply network with suitable adoption of HPFA also presented in this chapter.

Chapter 4 this chapter provides the simulation results and discussions of harmonic analysis of the system for different scenarios. In addition, resonance phenomena of the system and sensitivity of voltage distortion at PCC for change in feeding length and TSS impedance are examined through computer simulation result.

Chapter 5 presents the design of the proposed harmonic filter to eliminate the dominant harmonic component and resonance problems in the system in hand along with simulation results for verification.

Chapter 6 presents the conclusions of this thesis and states the specific contributions of this research along with recommendations and future work.

CHAPTER TWO

2 LITERATURE REVIEW

2.1 Overview of 25kV AC Electrification System

2.1.1 Power Supply

Referring to British railway system a 25 kV, AC 50 Hz single-phase power supply for electric traction is derived from the grid of State Electricity Boards through traction sub-stations located along the route of the electrified sections at distance of 35 to 50 km apart. The distance between adjacent substations may however be even less depending on intensity of traffic and load of train [15].

The security of the incoming supply is of paramount importance to the reliability of the traction distribution system and normally the incoming feeder circuits from the 132 kV supply network to the 25 kV feeder station are duplicated at each supply point. Both incoming circuits are capable individually of carrying the total load at the incoming supply point for normal traffic operating conditions

Where practicable the high voltage (HV) feeders from the supply system to the 132/25 kV transformers are derived from a source which has itself a level of security at least equivalent to that afforded by the provision of independent, duplicate, fully rated, incoming feeders to the 25 kV railway distribution system. Such levels of security at the supply point may be provided by an HV bus bar, sectionalized by a circuit breaker. With each section of bus bar being fed via an independent circuit from an independent part of the HV network, or by a duplicate HV bus bar with the two bus bars being similarly independently fed, such that failure of supplies to one section of the bus bar does not interrupt supplies to the other. In such a case the two "railway" feeders would be connected one on each section of the HV bus bar but may be "banked" with 132/33 kV or 132/11 kV transformers feeding local distribution networks or other consumers to economize on 132 kV switchgear. The bank being controlled by a single 132 kV circuit breaker. Figure 2.1 shows diagram of a typical **132** kV supply arrangement [15].

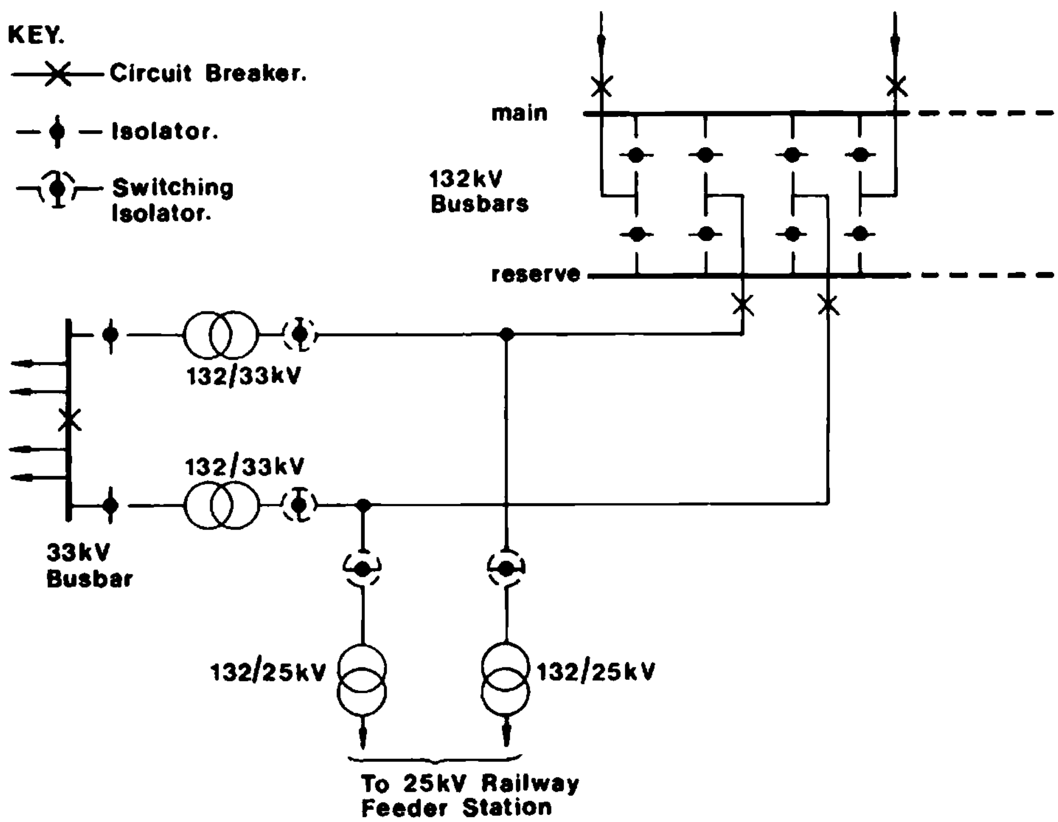

Figure 2.1: Diagram of a typical 132 kV power supply arrangement of British Railway [15]

2.1.2 AC Railway Overhead Catenary Feeding System Component

The feeding arrangement of the single-phase AC railway power supply requires neutral sections to separate two adjacent feeding networks at the feeder substation, and the Mid-point track-sectioning cabin (MPTSC) under normal operation. The MPTSC is located approximately mid-way between feeder substations. Furthermore, there may be other sub-sectioning cabins on the trackside such as an Intermediate track-sectioning cabin (ITSC). When either a temporary fault or a permanent fault occurs on any feeding section, the corresponding sub-sectioning must isolate the fault instantly while other feeding sections continue to operate without any interruption. The ITSC is located between feeder substations and MPTSC. In addition, to provide some conventional equipment (e.g. SVC and/or power factor correction or power filter) there needs to be space at sub-sectioning cabins for installation. A typical feeding arrangement is shown in figure [2].

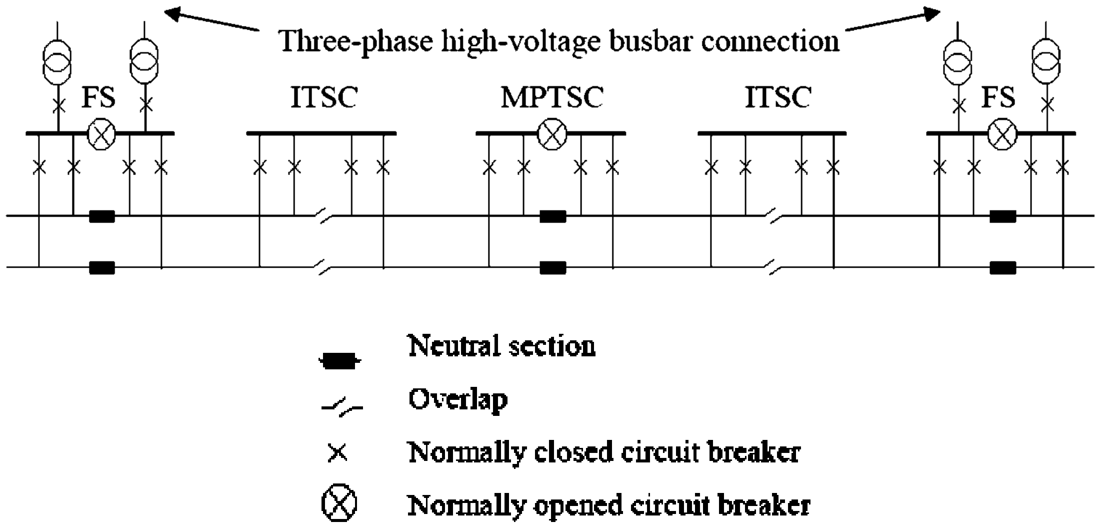

Figure 2.2: Typical feeding diagram of a double-track 25 kV railway in UK [2]

2.1.3 Power Supply Mode for Traction System

Some basic feeding configurations are widely used for feeding electric energy to electric trains in mainline AC railways. These are:

a) Direct Feeding Configuration

Direct connection of the feeding transformer to the overhead catenary and the rails at each substation, namely direct feeding configuration is quite simple and cheap. However, there are some disadvantages to this scheme (high impedance of feeders with large losses, high rail-to-earth voltage and the interference to neighboring communication circuits). To reduce those effects, the addition of an extra conductor

(Return Conductor) paralleled and tied to the rails at typically 5 or 6 km is needed and this can reduce electromagnetic interference in parallel communication lines by 30%. Figure 2.3 shows the diagrams of the direct feeding configuration [2].

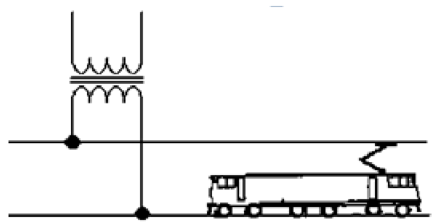

Figure 2.3 :Typical diagrams of the direct feeding configuration [2]

b) Booster Transformer Feeding Configuration

This method employs booster transformers (BT) added along the catenary at every 3-4 km. To force the return current to flow in the return conductor rather than in the rails to suppress the magneto-motive force resulting from the catenary current, the turn ratio needs to be unity. Although this feeding reduces electromagnetic interference with about 0.025 screening factor, the leakage inductance of BTs with a return conductor increases the total feeding impedance by approximately 50% compared with the direct feeding. Thus, the distance of two adjacent feeder substations is reduced because of the voltage drop along the contact wire. Figure 2.4 shows the configuration of the BT feeding system [2].

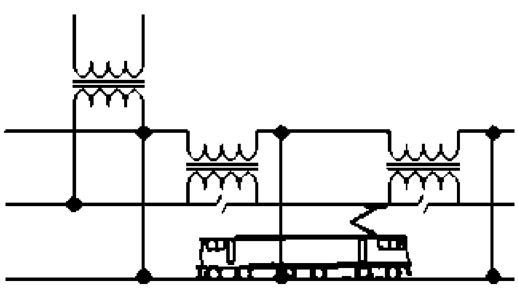

Figure 2.4 : Typical diagram of the BT feeding configuration [2]

c) Autotransformer Feeding Configuration

Adding autotransformer (AT) at every 8-15 km intervals can increase substation distance up to 50-100 km. The AT has two equal-turn windings, whose middle tap is connected to the rails to provide earth potential for balancing a voltage between the contact wire and the return conductor. The electromagnetic interference in an AT system is normally lower than that in the BT system. However, the size and MVA rating of the AT are much larger and more expensive than the BT. In addition, its protection equipment is more complicated and it needs more installation space. Figure 2.5 shows the configuration of the AT feeding system [2]

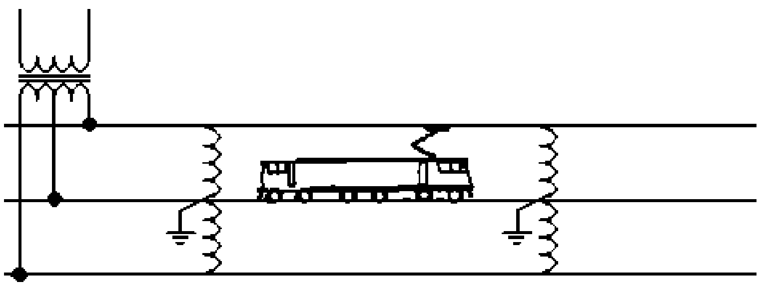

Figure 2.5: Typical diagram of AT transformer feeding configuration [2]

2.2 Basics of Harmonics

Harmonics are applied to describe the distortion of voltages or currents. Harmonics components are used to express the deviation from a pure sinusoidal wave called fundamental component. Harmonics in general are not like transient events such as lightning that only lasts a few seconds rather harmonics is a steady state periodic phenomenon that produces continuous distortion of the waveform. Harmonics in power systems are considered as being current and voltage waveforms that consist of a fundamental frequency and multiples of the fundamental frequency. For a 50HZ fundamental frequency the harmonics generated are multiples of the 50 HZ.

In order to analyze distorted waveform a number of mathematical methods can be used, of which the most popular method is the Fourier Transformation. The Fourier transformation is used to analyze periodic waveforms, where the source of harmonics does not change over time to ensure that enough data is sampled, and the harmonic frequency band must be half the sampling frequency. This sampling criterion is referred to as the Nyquist sampling criteria [9]

The study of harmonics consists of the periodic steady state distortion of voltage and current waveforms. One of the methods of analyzing harmonics is by doing a Fourier analysis on the distorted waveform. The Fourier representation for a periodic function f (t) with a period of T seconds and a fundamental frequency of f_1 can be written as

$$f(t) = C_O + \sum_{h=1}^{\infty} C_h \cos(h\omega t + \theta_h) \qquad (2.1)$$

Where C_O the DC value of the function; C_h is the peak value of the h^{th} harmonic component; ω is angular frequency and θ_h is its phase angle. A plot of normalized harmonic amplitudes C_h/C_1 is called the harmonic magnitude spectrum, as illustrated in Figure 2.6. The superposition of harmonic components to create the original waveform is shown in Figure 2.7 [26].

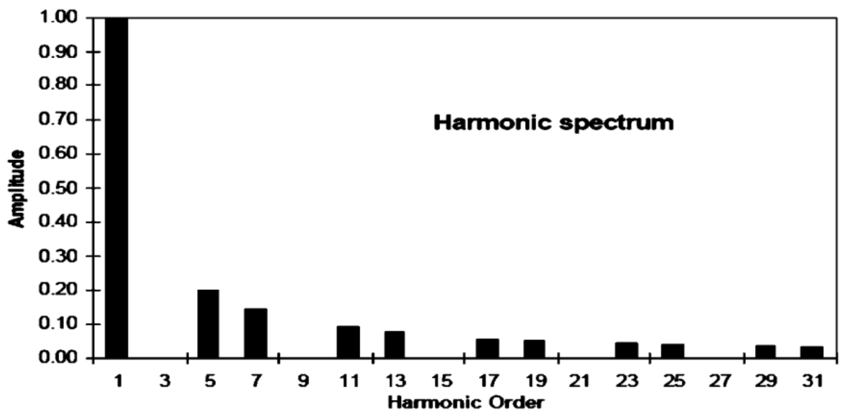

Figure 2.6 : Harmonic magnitude spectrum of six-pulse rectifier [26]

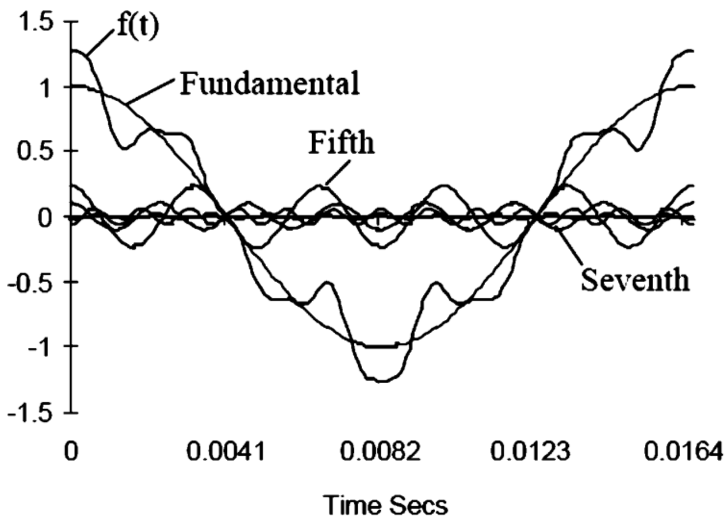

Figure 2.7 : Superposition of harmonic components to create the original waveform [26]

Nonlinear and switch loads generate a lot of harmonic distortion to the voltage and current. It is essential to determine the level of harmonics. In an electrical system, individual and total harmonic distortion can be used to indicate harmonic level.

Individual harmonic distortion (IHD) is the ratio between the root mean square (RMS) value of the individual harmonic and the RMS value of the fundamental

$$IHD_h = \frac{X_h}{X_1} \tag{2.2}$$

Where X_h the RMS value of harmonic order h; X_1 is the RMS value of the fundamental Total harmonic distortion (THD) is the ratio between the RMS value of the harmonics and the RMS value of the fundamental. For example, if a nonlinear current/voltage has a fundamental component of $X_1$and harmonic components $X_h$then:

The RMS value of the Harmonics

$$X_H = \sqrt{\sum_{h=2}^{h=\max} X_h^2} \tag{2.3}$$

Total harmonic distortion

$$THD = X_H / X_1 \tag{2.4}$$

The individual harmonic distortion indicates the contribution of each harmonic frequency to the distorted waveform, and the total harmonic distortion describes the net deviation due to all the harmonics. These are both important parameters. In order to solve harmonic problems, we require information on the composition of the individual distortions so that any treatment may be tailored to suit the problem. The total harmonic distortion, while conveying no information on the harmonic makeup, is used to describe the degree of pollution of the power system as far as harmonics are concerned. Defining the individual and total harmonic distortions will be helpful as we look at some typical nonlinear waveforms and their harmonic frequency characteristics [9].

The significant harmonic frequency currents generated in power conversion equipment can be stated as:

$$h = kq \pm 1 \tag{2.5}$$

Where h is the significant harmonic frequency, k is any positive integer (1, 2, 3, etc.), and q is the pulse number of the power conversion equipment which is the number of power pulses that are in one complete sequence of power conversion. For instance, for single phase full bridge rectifier the value of q is two therefore the characteristics harmonics are 3^{rd},5^{th},7^{th} ,…….which are odd harmonics [9].

Ref. [4] highlights that the representations of harmonics in power calculations and power factor evaluations are essential. However, upon the presence of harmonics, the calculations of power and power factor become complicated. The real power (P) represents the average rate of energy delivered to the load. The reactive power (Q) is the portion of the apparent power (S) that is out-of-phase with the real power. The conventional definition of Q in power engineering is based on the case of pure sinusoidal voltage and current. Common definitions of power including harmonic distortion are given by

Active power, mean instantaneous power (total active power)

$$P = \frac{1}{T}\int_0^T p(t)dt = \sum_{h=1}^{\infty} V_h I_h \cos\phi_h \quad (2.6)$$

Reactive power

$$Q = \sum_{h=1}^{\infty} V_h I_h \sin\phi_h \quad (2.7)$$

Apparent power

$$S = V_{rms} I_{rms} \quad (2.8)$$

Distortion power

$$D = \sqrt{S^2 - P^2 - Q^2} \quad (2.9)$$

Total power factor

$$PF = P/S \quad (2.10)$$

2.3 Power Electronics in Railway

Ref. [6] states that in railway traction application, the high-power diode and thyristor are widely used. Gate-Tum-Off thyristor (GTO) has become popular in electric traction as the power limit of GTO is improved recently. The high-power PWM converters in traction application also become feasible. However, even if problems will tend to be alleviated because of the advancement of power electronics devices, the lifetime of the trains and locomotives is about 30-40 years. Such trains are still on duty for a long time. Traction drives utilize the technology of power electronics. Concerning harmonic disturbance, the traction drives act as harmonic current sources to the system. Added to this, the use of power electronics spreads to the non-traction equipment in rolling stock such as air conditioners, compressors and auxiliary.

2.4 Power System Harmonic Sources and Impacts of Harmonics

2.4.1 Power System Harmonic Sources

Ref. [6] underline that the dominating distortion-producing group, globally, are the loads. The characteristic behavior of non-linear loads is that they draw a distorted current waveform even though the supply voltage is sinusoidal. Most equipment only produces odd harmonics but some devices have a fluctuating power consumption, from half cycle to half cycle or shorter, which then generates odd, even and inter harmonic currents. The current distortion, for each device, changes due to the consumption of active power, background voltage distortion and changes in the source impedance.

Ref. [5] shows a simple network structure consisting of a nonlinear load and some other loads, all connected to the point of common coupling (PCC). The PCC is typically a point of metering. There is some flexibility in determining the PCC, but in most instances, it is the point at which the high voltage side of a customer transformer is connected to the distribution network. Figure 2.8 illustrates a simple power network

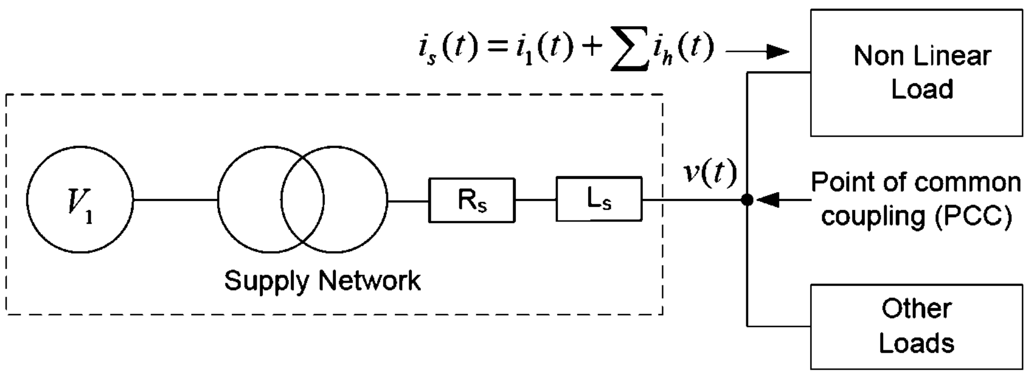

Figure 2.8 : Schematic of a simple power distribution network [5]

The nonlinear load current $i_s(t)$ consists of a fundamental component and harmonics. When such loads are supplied from a sinusoidal voltage source, their injected harmonic currents are referred to as contributions from the load, or load harmonics.

The nonlinear load produces harmonic current flow in the supply network, which reacts with the network impedance (R_S, L_S) to create voltage drops along this impedance.

Hence, the voltage at the PCC is therefore distorted and no longer sinusoidal even if V_1 is sinusoidal. Any other loads, even linear loads, connected to the PCC therefore have harmonic currents injected into them by the distorted PCC voltage. Such currents are referred to as contributions from the power system, or supply harmonics.

In Ref. [9], the cause of voltage and current harmonics are explained in details. According to this paper, the voltage waveform, even at the point of generation, contains a small amount of distortion due to no uniformity in the excitation magnetic field and discrete spatial distribution of coils around the generator stator slots. The distortion at the point of generation is usually very low, typically less than 1.0%. The generated voltage is transmitted many hundreds of miles, transformed to several levels, and ultimately distributed to the power user. The user equipment generates currents that are rich in harmonic frequency components, especially in large commercial or industrial installations. As harmonic currents travel to the power source, the current distortion results in additional voltage distortion due to impedance voltages associated with the various power distribution equipment's, such as transmission and distribution lines, transformers, cables, buses and so on. Figure 4.9 illustrates how current distortion is transformed into voltage distortion.

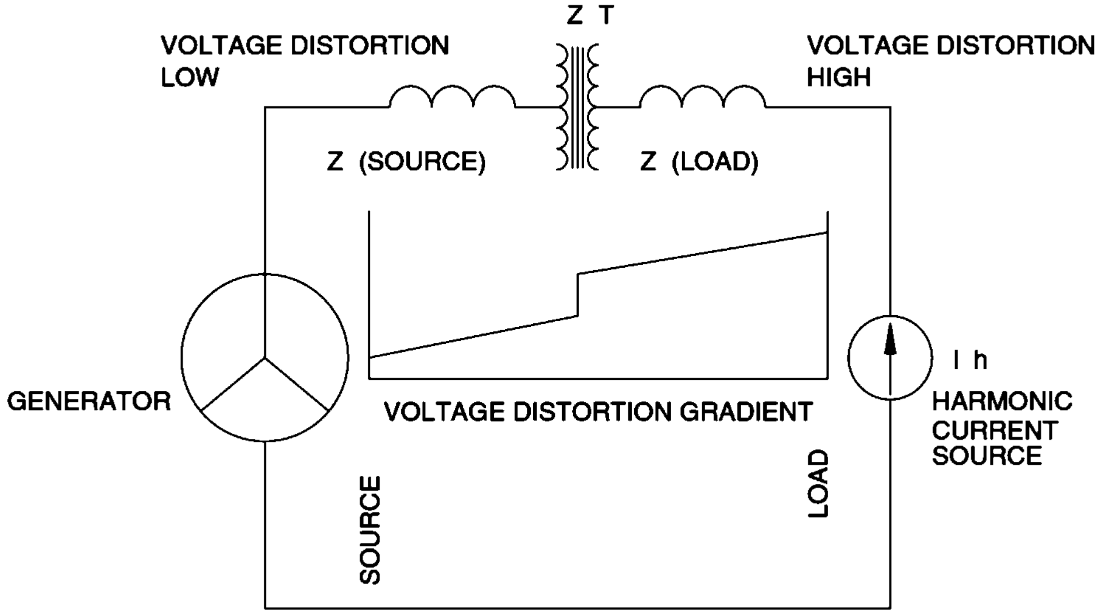

Figure 2.9 : Voltage distortion due to current distortion, the gradient graph indicates how distortion changes from source to load [9].

2.4.2 Impacts of Harmonics

Ref.[5] emphasize that as far as the impact of harmonics on power system equipment is concerned, it can be generally stated that harmonics are causing equipment (both in networks and in user's installations) to be subjected to voltages and currents at frequencies for which it was not designed. The effects of such exposure are usually not instantly visible, but can have serious consequences in the medium and long term. Practically speaking, utilities frequently encounter the following harmonic related problems:

- Voltage distortion in distribution feeders;
- Increased RMS currents, heating and line losses;
- Overheating of power transformers, which require higher K-factor transformers
- Derating of distribution equipment;

- Overloading of phase and neutral conductors - neutral currents in a typical commercial office building may carry more than phase RMS currents;
- Amplification of harmonic currents in the utility system due to series and parallel resonances between the utility system and nonlinear loads;
- Overloading and fuse blowing of power factor correction capacitors;
- Tripping of voltage harmonic sensitive equipment;
- Failure of control electronics, microprocessors;
- Reduced accuracy of measuring instruments (such as watt-hour meters);
- Malfunction of solid-state fuses, breakers and relays;
- High failure rate of filter capacitor banks;
- Reactive power and resonance problems;
- Reduced system stability and safe operating margins

In particular the detrimental effect of certain harmonics like even harmonics, triplens etc. are also explained in the paper.

Ref. [18] indicates that resonances between line and transformer reactance, and capacitors in the system can result in amplification of voltage and / or current harmonics. As a result, even small harmonic sources can cause high levels of harmonic current flow between the utility and a customer, and can cause unexpected problems in locations far removed and unconnected with the harmonic source. Further, as utilities and customers change their connected loads, system impedance changes, which can cause resonances and harmonic problems where none existed before. Such problems are not easily identified without a detailed system analysis.

Ref. [8] provides a discussion on influence of harmonics on power factor and network losses. In this paper, Results show that the harmonic current, increase distribution network losses up to 6.8 percent. Transmission capacity is a function of the harmonic current, and if the harmonic is more in standard level, transmission lines capacity is more occupied. According to this paper, the active power loss of transmission lines for each harmonic order are calculated by equation (2.11).

$$P_{LOSS} = RI_{rms}^2 = R\sum_{h=1}^{\infty} I_h^2 = RI^2 + R\sum_{h=2}^{\infty} I_h^2 \tag{2.11}$$

Where RI^2 is related to the main frequency.

Ref. [7] presents the effects of harmonic distortion of load current and voltage on single-phase transformer losses utilizing the on-line measurements (monitoring) method of the primary side. From experimental results of this paper, it is observed that input power factor is significantly dependent on the harmonic content of the system. The power factor decreases with the increasing of total harmonic distortion. The total harmonic distortion and crest factor are higher at low input voltage compared to higher input voltage. The paper also presents the mathematical definition of the crest factor and power factor as shown below:

$$\text{Crest factor (CF)} = \frac{peak\ waveform}{rms\ waveform} \tag{2.12}$$

By definition, a perfect sine wave current or voltage will have a crest factor of 2 or 1.414 and any deviation of this value represents a distorted waveform.

$$\text{The total power factor (PF)} = \frac{1}{\sqrt{1+THD^2}} DPF \tag{2.13}$$

Where DPF is the displacement power factor, assuming that for non-inductive or non-capacitive loads, the value can be considered as one [7].

2.5 Harmonic Studies of Power System

Ref. [16] provides a concise review on the main developments and conclusions in the area of power system harmonic analysis. In the first part of the paper, modeling of power system components for harmonic analysis is described as follows: Overhead lines and underground cables can be modeled with a multiphase-coupled equivalent pi-circuit. For balanced harmonic analysis, the model can be further simplified into a single-phase pi-circuit determined from the positive sequence impedance data of the component. Transformers and rotating machines can be modeled using its short circuit impedance for most harmonic studies. According to this paper, power electronics devise (loads/ a compensator) which are harmonic sources are commonly modeled as the current source model. However, the paper suggests that assessment of cases involving non-typical operating conditions becomes difficult using the current source model.

In the second part of the paper, network solution techniques for harmonic analysis are described. In this section, two most common and useful harmonic analysis techniques, frequency scan analysis and harmonic power flow analysis, are presented and discussed briefly. Furthermore, the paper provides future directions of harmonic analysis. Generally, it can be regarded as a basic guideline to deal with harmonic analysis.

2.6 Harmonic Studies of Traction Systems

In order to study harmonics in the electric network of a railway system, model of the load, model of three phase supply grid with substations and model of supply network(catenary system) are required. Hence, literatures are reviewed in the following categories

2.6.1 Locomotive Modeling

In Ref [10], electric locomotive consists of an autotransformer, diode rectifiers and four DC motors is modeled using a circuit model.

In Ref [1], a locomotive consists of four wagons, two with cabin and two intermediates are considered. Each wagon leans over two bogies with two motors each, this is, each convoy has 16 induction motors of 180 kW supplied by a PWM inverter connected directly to DC line voltage. The model that has been used in the convoy simulation, has been developed by means of only one inverter and only one 2.880 kW equivalent motor.

In Ref [12], a simplified and complete model scheme of AC-DC-AC locomotives is compared. According to this reference, the complete model allows accounting for all the interactions between the line side four-quadrant rectifiers and the inverter operation in case of AC Traction systems. In particular, the inter-harmonic components of the pantograph current can be ascertained and quantified.

In the simplified model, the value of each resistance is chosen as the one that guarantees the same active power absorbed at the fundamental power frequency by the corresponding group of inverter and AC motors. The simplified model only allows evaluating the harmonic components of the pantograph current but with greatly reduced computational efforts. This paper suggests that also the harmonic components obtained with the simplified model practically coincide with those obtained with the complete model.

Ref. [13] compares three different type of traction load modeling which are constant current, constant power and constant resistance model. It is suggested that the constant resistance load model has the best result of all the three loads in terms of amplitude of overshoot and settling time. Figure 2.10 illustrates the three types traction load modeling, which are compered in this reference.

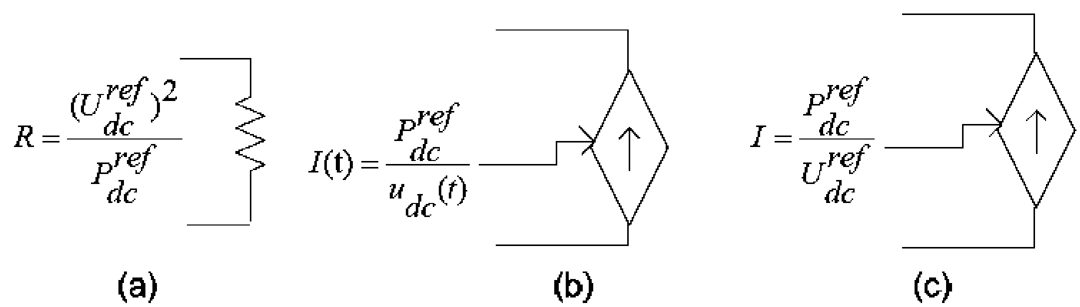

Figure 2.10: Schematic representation of three different load models (a) constant resistance (b) constant power (c) constant current [13]

2.6.2 Three Phase Supply Grid with Substation Modeling

In Ref [11], the traction substation is represented by its equivalent inductance, which account for short circuit inductance of substation transformer and high voltage supply network and by voltage source.

Ref. [14] [2], emphasizes that a typical AC railway power feeding system receives the electric energy at the substation. Conventionally, the power substation is modeled by a combination of an infinite bus bar (ideal voltage source) in series with equivalent high-voltage grid impedance connected to a feeder transformer with on-load tap changer as shown in Fig. 2.11a. This circuit is then simplified to either Thevenin or Norton equivalent circuits as shown in Figs.2.11b and Fig.2.11c, respectively.

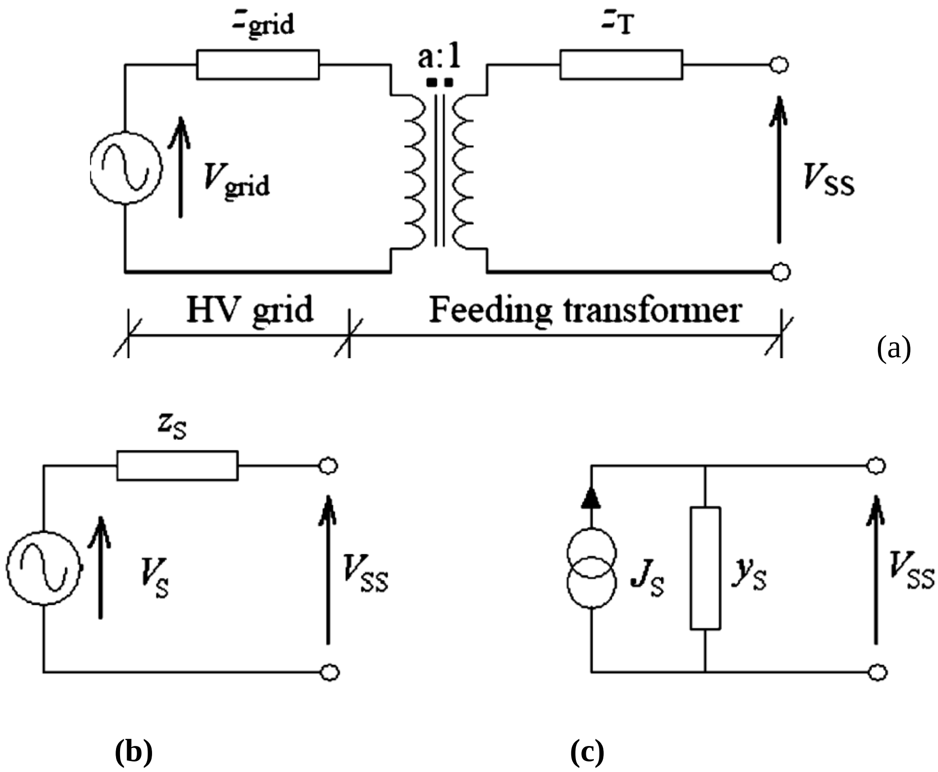

Figure 2.11: Power substation model a) simplified substation model b) Thevenin equivalent circuit c) Norton equivalent circuit [2]

2.6.3 Feeding Section Modeling

In Ref [10] [1], the normal feeding section of the catenary system is modeled as series of lumped pi section with line parameter of R, L and C.

In Ref [11], the catenary system is modeled as n-port model. The characterization of a railway supply network means to model the impedance seen by the rolling stock (by its pantograph) anywhere in the network, commonly named pantograph impedance. Catenaries (transmission lines) are seen as n-port network, expressed in matrix form. This transmission matrix relates voltages and currents in the emission point and the receptor point. The two-port network model expressed in matrix form is given in as shown in equation (2.14).

$$\begin{bmatrix} V_e \\ I_e \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_r \\ I_r \end{bmatrix} \qquad (2.14)$$

$$\Rightarrow V_e = AV_r + BI_r \quad ; \; I_e = CV_r + BI_r$$

Where V_e *and* I_e respectively are voltage and current at the emission; V_r & I_r respectively are voltage and current at receptor point. The matrix elements are given by

$$A = D = \cosh \gamma L \qquad (2.15)$$

$$B = Z_O \sinh \gamma L \qquad (2.16)$$

$$C = \frac{\sinh \gamma L}{Z_O} \qquad (2.17)$$

Z_O, γ *and* L are characteristics impedance of the line, propagation constant and length of the line respectively. Where

$$Z_O = \sqrt{\frac{R + j\omega L}{G + j\omega L}} \quad (\Omega) \qquad (2.18)$$

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega L)} \quad \text{(Rad/m)} \qquad (2.19)$$

Ref [19] [20] established a simplified model for traction network using T-type distributed model to analyze the amplification phenomenon of harmonic currents by the traction network in an electric railway. Furthermore, the conductors of the traction network were represented by a delicate multi-port model, which has been reduced in ends. Figure 2.12 illustrates the T-type distributed model presented in this paper.

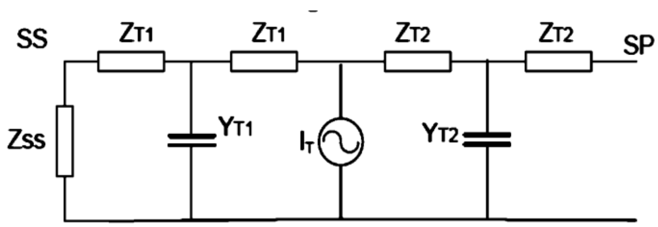

Figure 2.12: Equivalent circuit of traction network [19]

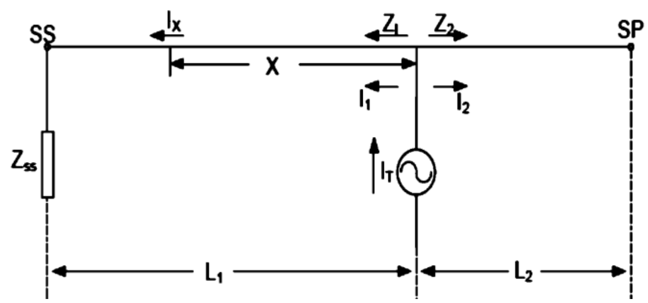

Figure 2.13: Simplified model of traction network [19]

Accordingly, after certain mathematical simplification,

$$Z_1 = Z_0 \left[\frac{Z_{sub} \cosh \gamma L_1 + Z_0 \sinh \gamma L_2}{Z_{sub} \sinh \gamma L_1 + Z_0 \cosh \gamma L_2} \right] (\Omega) \quad (2.20)$$

$$Z_1 = Z_O \left[\frac{\cosh \gamma L_2}{\sinh \gamma L_2} \right] (\Omega) \quad (2.21)$$

Where Z_1 is contact line input impedance toward the substation and seen from the electric train;

Z_2 is contact line input impedance toward the end of the supply section and seen from the electric Train;

L_1 is distance between the electric train and the substation;

L_2 is distance between the electric train and the end of the feeder section;

Z_{sub} is resultant impedance of the feeder substation;

Z_0 is characteristic impedance of the contact line;

γ is unit-length propagation constant of the contact line

These reference suggests that the network impedance as seen from the locomotive loading point can be found as a parallel combination of Z_1 and Z_2.

2.7 Techniques for Harmonic Analysis of Power Supply System

Ref. [21] states that Conventional methods for PQ analysis in literatures in general can be classified into two main categories: frequency and time domains. These methods vary in terms of data requirements, modeling complexity, problem formulation and solution algorithms. Available techniques in frequency-domain (FD) can broadly be classified into direct solution (non-iterative), iterative harmonic analysis and harmonic power flow.

In practice, the periodic electric response of a power network can be acquired directly in time-domain by obtaining solutions of the differential equations or state-space matrices that describe the dynamics of the system. The periodic steady-state solutions can be obtained once the transient response has decayed. A common brute-force approach for harmonic analysis in time-domain is to run the simulation over considerable periods until the transient vanishes and a steady state is reached. Then the fast Fourier transfer (FFT) is performed on the voltage and current waveforms for collecting harmonic spectra of interest. Any of highly developed commercial simulation packages, such as EMTP/ATP, PSCAD/EMTDC and MATLAB/SIMULINK, are capable of performing such purpose. However, such solution process may potentially presents ineffective for some limitations.

Ref. [21] states that frequency scan (FS) is the simplest and most commonly used technique for harmonic analysis. The input data requirement is minimal. It calculates the frequency response of a network seen at a particular bus or node. Typically, a one per unit sinusoidal current is injected into the bus of interest and the voltage response is calculated. This calculation is repeated using discrete frequency steps throughout the range of interest. Mathematically, the process is to solve the following network equation

$$[Y_h][V_h]=[I_h] \qquad (2.22)$$

Where $[I_h]$the known is current vector and $[V_h]$is the nodal vector voltage to be calculated.

If a harmonic source is connected to the bus of interest, the harmonic voltage at the bus is given by the harmonic current multiplied by the harmonic impedance. The frequency scan thus gives a visual picture of impedance levels and potential voltage distortion. It is a very effective tool to detect resonances that appear as peaks (parallel resonance) and valleys (series resonance) in the plot of impedance magnitude vs. frequency. The limitations of FS method is that in the presence of multiple harmonic sources a fundamental frequency load flow is necessary to determine the magnitudes and phase angles of the injected currents accurately. Another disadvantage of FS is its reliance on typical harmonic spectra to describe nonlinear devices.

If one needs to find the harmonic distortion levels in different operating conditions, a network harmonic power flow analysis (HPFA) should be conducted. Several harmonic power flow techniques have been proposed in the past. Many years of application experiences have shown that a non-iterative technique that represents harmonic sources as current sources is sufficient for many common harmonic analysis tasks. This technique is summarized as follows:

Step 1: Compute the fundamental frequency power flow of the network. The results define the operating scenario for harmonic analysis. In this step, the harmonic producing loads are modeled as constant power loads.

Step 2: Determine the harmonic current source models for the harmonic producing loads.The model consists of the magnitudes and phase angles of current source at various harmonic frequencies.

Step 3: Calculate the network harmonic voltages and currents by solving the following network nodal equation, which is described in equation (2.22) for harmonic number h of interest:

Step 4: The results of Steps 1 and 3 jointly define the harmonic power flow conditions of the study system.

Harmonic indices such as total harmonic distortions and transformer k factors can be calculated from the results. The main disadvantage of the above method is the use of typical harmonic spectra to represent harmonic-producing devices. It prevents an adequate assessment of cases involving non-typical operating conditions. Such conditions include, for example, partial loading of harmonic-producing devices, excessive harmonic voltage distortions and unbalanced network conditions. The applications of HPFA include:

- network harmonic distortion assessment,
- harmonic limit compliance verification,
- filter performance evaluation, and
- equipment de-rating

Iterative harmonic analysis (IHA) often presents the harmonic producing device as a supply voltage-dependent current source, which represented by a fixed harmonic current source at each iteration

$$\text{In} = \text{F}\ (V_1, V_2, \dots \dots., V_h, c) \qquad (2.23)$$

Where $(V_1, V_2, \dots \dots., V_h)$the harmonic components of the supply voltage, and care are is a set of control variables such as converter firing angle or output power. An estimated supply voltage first solves the harmonic currents. The results are then used as the current sources to obtain harmonic voltages of bus of interest.

These harmonic voltages in turn allow the computation of more accurate harmonic current sources form. The iterative solution process stops once the convergence is achieved. One of the main advantages of this “decoupled” approach is that the power network components can be modeled in a closed form, with a time-domain simulation or any other forms. However, the restricted stability margin and slow convergence characteristic of IHA has limited its application to the solution of practical problem in power systems.

2.8 Power Quality Monitoring and Harmonic Suppression

2.8.1 Harmonic Suppression

Ref. [9] emphasize that one means of ensuring harmonic currents produced by a nonlinear current source will not interfere with the rest of the power system is to filter out the harmonics with the application of harmonic filters. Harmonic filters are broadly classified into passive and active filters. This reference underlines the importance of computer simulation of the power system before and after the application of filters together with steps to be followed during simulation.

Ref. [17] compares passive and active filters in the following manner, various methods exist to reduce harmonics and their energy content: duly

1. Passive filters tuned for specific harmonics: these filters are used to clamp specific harmonics, thus periodic harmonics.

2. Active filters: these filters are used to firstly measure harmonics and on the next cycle

produce currents to reduce the energy content.

The advantage of passive filters over active filters is the price of the passive components used. The advantage of the active filter is that it can “track” specific harmonic frequencies and adapt accordingly, thus the active filter is more dynamic and efficient. In some cases, hybrid filters are employed to save money and to have an active nature for some frequency bands, thus combining the advantages of both filter topologies.

Ref. [23] emphasize that passive filters are tuned harmonic filters consist of the combination of an inductor, resistor and capacitor elements. It is sometimes desirable to have circuits capable of selectively filtering one frequency or range of frequencies out of a mix of different frequencies in a circuit. Passive filter provide a low impedance path for harmonic current. These currents are then "sucked off" and the network is cleaned of damaging harmonic currents.

The different types of filters are Band-pass filters and High-pass (damped) filters. Band-pass filters, which are used to filter lowest order harmonics, it can be tuned at a single frequency called single-tuned filter or at two frequencies called double-tuned filter. High-pass filters are used to filter high-order harmonics. One type of high-pass filters are the C-type high-pass filter, is used to filter low order harmonics and provide reactive power. C type filter avoids parallel resonance. Figure 2.14 shows types of passive filters.

In Ref. [27], the design procedures of passive filters are described. Design steps of single-tuned series filter are as follows

Step 1: Determine the value of the capacitance, QC to improve the power factor and to eliminate any penalty by the electric power company

Step 2: Evaluate the capacitor reactance at fundamental frequency, $X_C = \frac{kV^2}{Q_C}$ (2.24)

Step 3: Calculate the reactor size providing the resonance, $X_L = \frac{X_C}{h^2}$ (2.25)

Step 4: Calculate the characteristic reactance is , $X_n = \sqrt{\frac{L}{C}}$ (2.26)

Step 5: Calculate the reactor resistance for a specified quality factor, Q, $R = \frac{X_n}{Q}$ (2.27)

Design steps of damped filters follows the same steps of 1-4 that are described above but the reactor resistance value is calculated with the following equation

$$R = X_n Q \quad (2.28)$$

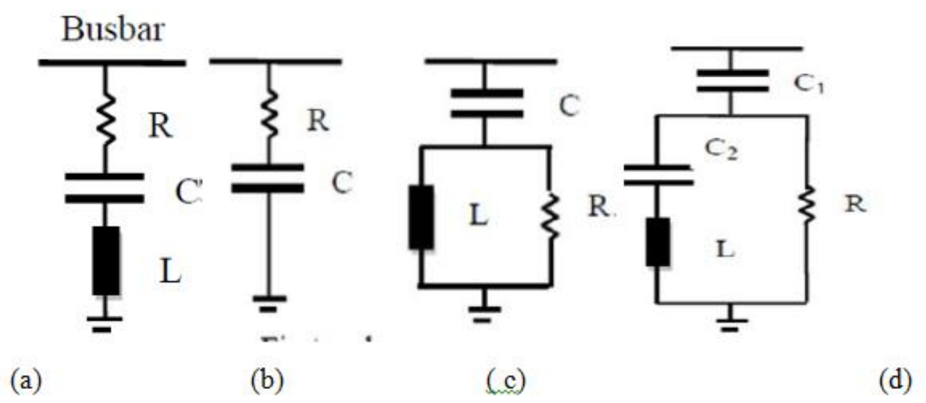

Figure 2.14: Passive filters a) single tuned filter b) first order damped filter c) second order damped filter d) third order (C-type) damped filter [23]

2.8.2 Power Quality Monitoring

Ref. [5] briefly states that an important aspect of power quality monitoring is the collection of information regarding the performance of the system in terms of voltage and current harmonics. For voltage and current harmonics, the obtained information (magnitude and phase) are usually compared with standards like IEEE 519 to evaluate the influence of these events.

In 1981, the IEEE 519 harmonic standard was issued for harmonic related issues; it was revised in 1992. IEEE 519 attempts to establish reasonable harmonic goals for electrical systems that contain nonlinear loads. The objective is to propose steady state harmonic limits that are considered reasonable by both electric utilities and their customers. The underlying philosophy is that:

- Customers should limit harmonic currents;
- Electric utilities should limit harmonic voltages;

- Both parties share the responsibility for holding harmonic levels in check.

IEEE 519 applies to all voltage levels, including 120V single-phase residential services. While it does not specifically state the highest-order harmonic to limit, the generally accepted range of application is through the 50th harmonic. Direct current, which is not a harmonic, is also addressed and is prohibited. Since no differentiation is made between single-phase and three-phase systems, the recommended limits apply to both. A brief outline of the IEEE 519 standard is given in appendix A.

Harmonic analysis in general can benefit from monitoring. The collected waveforms of voltage and current are also used to test protection and control algorithms Power quality meters play an important role in the monitoring process.

CHAPTER THREE

3 METHODOLOGY

3.1 Overview of the Research Strategy

The goal of harmonic studies is to quantify the distortion in voltage and current waveforms at various points in a power system. The results are useful for evaluating corrective measures and troubleshooting harmonic caused problems. Harmonic studies can also determine the existence of dangerous resonant conditions and verify compliance with harmonic limits. The need for a harmonic study may be indicated by excessive measured distortion in existing systems or by installation of harmonic-producing equipment [16]

Similar to other power systems studies the harmonics study in this thesis consists of the following steps

- Definition of harmonic-producing equipment and determination of models for their representations
- Determination of the models to represent other components in the system including external networks
- Simulation of the system for various scenarios
- Identifying range of solutions
- Evaluation of solutions
- Introducing optimum solution

3.2 Computer Simulation Studies

Computer simulations are useful tools to analyze electrical conditions and help develop possible measures to deal with such problems. To conduct simulation for harmonic analysis, both TD and FD methods can be used. For TD analysis, a circuit model may represent trains. The current waveform absorbed by the train is simulated in time domain according to the operation conditions. **The simulation also includes the train circuit connected to the traction supply circuits. For each time step, the whole system would be simulated.**

For FD analysis, the simulation is performed at each frequency. The voltage and current in circuit are assumed pure sinusoidal components at fundamental and harmonic frequencies. The results would be represented in frequency domain. It is also possible to synthesize the time waveform by transforming the frequency components of the waveform.

A model of the trains is an essential part of computer simulation studies. It is necessary to model non-linear traction loads. A behavioral model to represent electric railway vehicle is used for our analysis because it is difficult to develop analytical model including many detail elements such as motor impedance and switching strategy. Models and methods used depend upon system complexity and data availability [4].

In this thesis, the RPSS and the traction load is modeled first and then TD analysis with deterministic approach is used in the computer simulation. Since it is possible to estimate the instant harmonic injected by a train as train speed, operation mode of the train and distance of the train from the traction substation are all known based on our scenarios. Consequently, a single-phase electrified system can be simulated in order to quantify the harmonic distortion at a point of interest. Furthermore, FFT that is automated in powergui block of SIMPOWERSYSTEM is used to analysis current and voltage waveform distortion in FD.

3.3 Computer Aided Modeling of Electric Railway System

In order to attain steady-state solution of the electrical circuit of the system, which include the sources, feeding networks and traction loads, must be properly modeled which is no simple task, given the varieties of supply systems and operation conditions.

3.3.1 Three Phase Supply Grid with Substation Model

The aim of the modeling of the substation is to get an understanding of the distorted voltages and currents caused by electric traction load at the PCC. To analyze this effect and to see the efficiency of the passive harmonic filters, a model for the AC supply grid transmitted to the load side is required.

In this work, the traction substation is represented by Thevenin equivalent that consists of an ideal source and its equivalent inductance, which account for short circuit inductance of substation transformer and high voltage supply network. The modeling approach is given below

- Available data: of considered substation (sebeta) [24]
  - ✓ 132/25kV, 21MVA single-phase transformer
  - ✓ Short circuit capacity of grid is 400MVA.
- Taking transformer percentage impedance 12% [33]
  - ✓ Three phase in feed of the 132kV system

$$I_{SC} = \frac{Fault\,MVA \times 10^3}{\sqrt{3}kV} \tag{3.1}$$

Where I_{SC} is three-phase fault current.

$$\therefore\ I_{SC} = \frac{400 \times 10^3\ MVA}{\sqrt{3}\left(132kV\right)} = 1.75kA$$

- ✓ Line to line (L-L) fault current (curve formula)

$$\Rightarrow\ I_{L-L} = I_{SC} \times \sqrt{3}/2 = 1.515\text{kA} \tag{3.2}$$

- ✓ Then for single phase AC traction, the system impedance

$$\Rightarrow\ Z_{grid} = \frac{V_{L-L}}{I_{L-L}} \tag{3.3}$$

$$Z_{grid} = \frac{132kV}{1.515kA} = 87.13\Omega$$

- ✓ Converting to 25kV side (27.5kV is the no load voltage)

$$Z_{grid} = a^2 \times Z_{grid} \tag{3.4}$$

Where a is transformer turns ratio

$$\Rightarrow Z_{grid} = \left(\frac{27.5}{132}\right)^2 \times 87.13 = 3.78\Omega$$

- ✓ Transformer impedance to LV side

$$Z_T = Z_{p.u} \times Z_{base} \tag{3.5}$$

Where, $$Z_{p.u} = \frac{Z\%}{100} = \frac{12}{100} = 0.12 \tag{3.6}$$

$$Z_{base} = \frac{(KV_{base})^2}{MVA_{base}} = \frac{25^2}{21} = 29.76\Omega \tag{3.7}$$

$$\Rightarrow Z_T = Z_{base} \times Z_{p.u} = 29.76 \times 0.12 = 3.57\Omega$$

- ✓ Assuming these two z's are purely inductive, the Thevenin equivalent impedance of the source reduced to load side is

$$Z_S = X_S = Z_{grid} + Z_T = j3.78 + j3.57 = j7.35\Omega \tag{3.8}$$

$$\Rightarrow \quad L_{sub} = \frac{1}{2\pi f X_s} = \frac{1}{2\pi(50)(7.35)} = 23.4mH \tag{3.9}$$

- ✓ Finally, the model can be simplified into Thevenin equivalent form as shown in figure 3.1 below

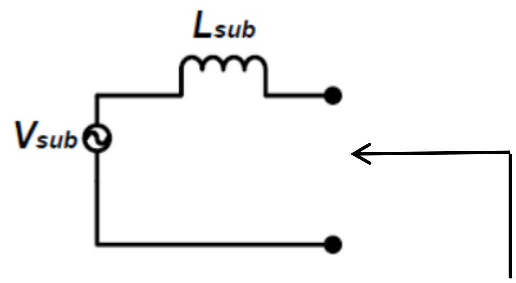

Figure 3.1: Thevenin equivalent of TSS

Modeling of the traction substation is done using MATLAB/ SIMPOWER Systems library. AC Voltage source block has a dialog box to enter the amplitude, phase, and frequency parameters. Note that the amplitude to be specified for a sinusoidal source during simulation is its peak value.

$$\Rightarrow \; V_{peak} = \sqrt{2} V_{sub} \tag{3.10}$$

Where V_{sub} is the source RMS voltage transformed to load side.

3.3.2 Traction Power Feeding Section Model

For the purpose of simulation in this thesis, the feeding section is modeled as series of lumped impedance networks, which is suitable for representing medium and low voltage distribution systems and for balanced harmonic analysis [26]. The average length of the catenary during normal feed conditions is 13.521 km. This feeder is modeled as four 3.38 km pi sections, each having a longitudinal impedance of 0.130081+j0.39238 Ω/km at 50 HZ and shunt capacitance of 0.011 μF/km [24].figure 3.4 shows the modeling of the feeder line.

In MATLAB/SIMPOWER system the feeding section model obtained by cascading the Pi Section Line block that is shown in figure 3.2 from the elements library since it purpose is to implement a single phase transmission line with lumped parameters and the line parameters are enters manually as illustrated in figure 3.3.

Figure: 3.2: Pi section line block

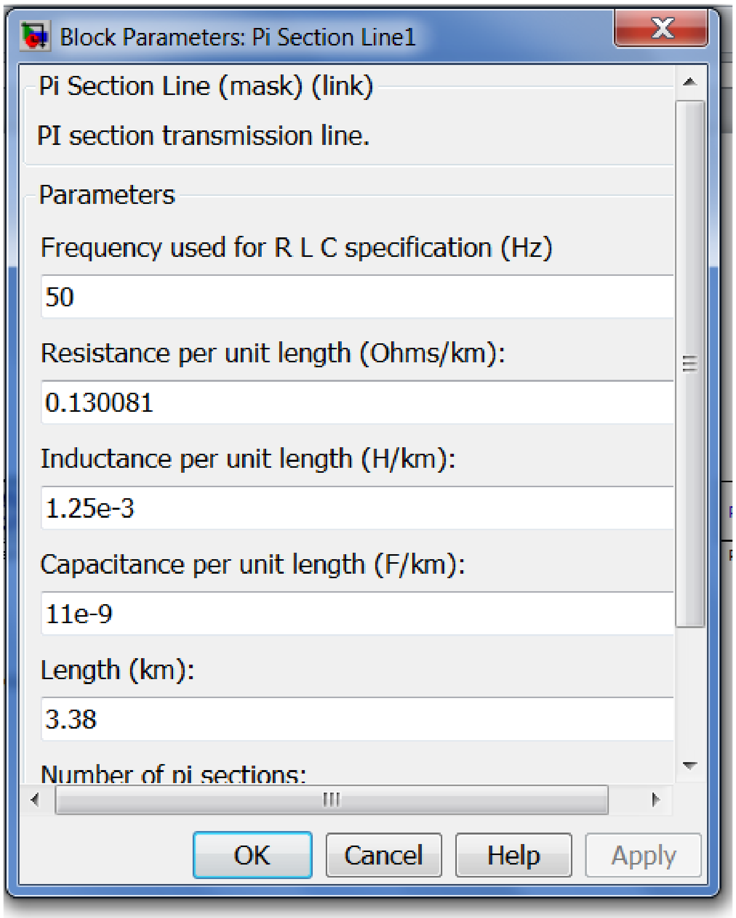

Figure 3.3: Block parameters of pi section line

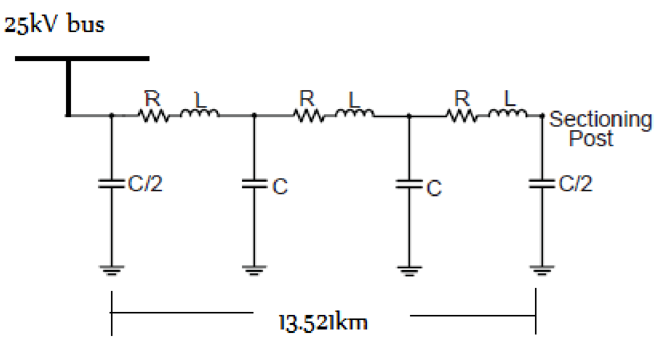

Figure 3.4: Modeling of the feeder line

3.3.3 Electric Locomotive Model

As mentioned in the introduction part the proposed traction load in this system is AC-DC-AC locomotive with power of 7200KW. Thus, the locomotive is equipped with main transformer, line side converter, DC-Link, motor side converter and six asynchronous squirrel cage motors. The model that has been used in simulation has been developed by means of only one line side converter and only one inverter-motor group like it is done in Ref [22].Figure C.1 shows the proposed model.

Since technical data of the traction control parameters and motor nominal parameters of the locomotive are not available while this research is conducted , the following assumptions are made while modeling the load that lead us to good representation of the nonlinear load for line side harmonic study with reduced computational time and model complexity.

- **Basic practical assumptions**
  - ✓ The locomotive main transformer includes one primary winding, six traction winding and one auxiliary winding
  - ✓ AC/DC Ideal general purpose diode rectifier with high smoothing capacitor for line side converter
  - ✓ In put ac power to the rectifier is equal to the output dc power
  - ✓ A constant resistance load (resistance) equivalent for cross pounding group of inverter and ac motor side is assumed in which the value of each resistance is chosen as the one that guarantees the same active power absorbed at the fundamental power frequency by the corresponding group of inverter and ac motor as mentioned in [12]
- **Modeling approach**
  - ✓ Main transformer rating at 25kV line voltage: [28]
    - Primary winding 25kV, 9300kVA
    - Traction winding 6*1650kV, 9300 kVA
  - ✓ Traction winding impedance at 25kV, 9.3MVA, 8.35% (IEC 76)

- Using equation (3.7) Primary winding

$$Z_{base} = \frac{kV^2}{MVA} = \frac{25^2}{9.3} = 67.2\Omega$$

- And from equation (3.5)

$$Z_T = Z_{base} \times Z_{p.u} = 67.2 \times 0.0835 = 5.61\Omega$$

- Assuming that $\frac{X}{R} = 10$ and knowing that

$$Z^2 = R^2 + X^2 \qquad (3.11)$$

- And together with equation (3.9) ,we can get

$$L = X/2\pi f = 0.017586H, R = 0.56\Omega$$

- Similarly, for traction winding of secondary side the value of R and L are found to be 0.08799Ω and 0.0028H respectively.

✓ **DC-Link capacitance** : [30]

- The DC-Link capacitance calculated in order to reduce the voltage ripple. It is calculated as follows

$$C \geq \frac{P_m}{12 * f * V_r * V_{dc}} \qquad (3.12)$$

- Where P_m is the nominal power of the motor drive in Watt

$$P_m = S\cos\phi = 9300KVA \times 0.95 = 8835KW \qquad (3.13)$$

- f is the frequency of AC source in Hertz (50HZ)

- The desired voltage peak to peak ripple in volt is

$$V_{p-p} = 5\%(V_{dc} peak) = 0.05 * \sqrt{2} * V_{rms} = 700V \quad (3.14)$$

- Then the cross pounding ripple is

$$V_r = \frac{V_{p-p}}{2} = 350V \quad (3.15)$$

- Average dc bus voltage

$$V_{dc} = \frac{2\sqrt{2}V_{rms}}{\pi} = 8.913KV \quad (3.15)$$

$$\Rightarrow C \geq \frac{P_m}{12 * f * V_r * V_{dc}} = 4.72mF$$

✓ **Load side (motor-inverter)**

- As it is mentioned before in assumption and with the assumption that the load will see the peak of the ac in put voltage to diode the load constant resistance is calculated as follows

$$R = \frac{V_{dc\,peak}{}^2}{P_{act}} = 22\Omega \quad (3.16)$$

- Where $P_{act} = P_m$ active power absorbed by load

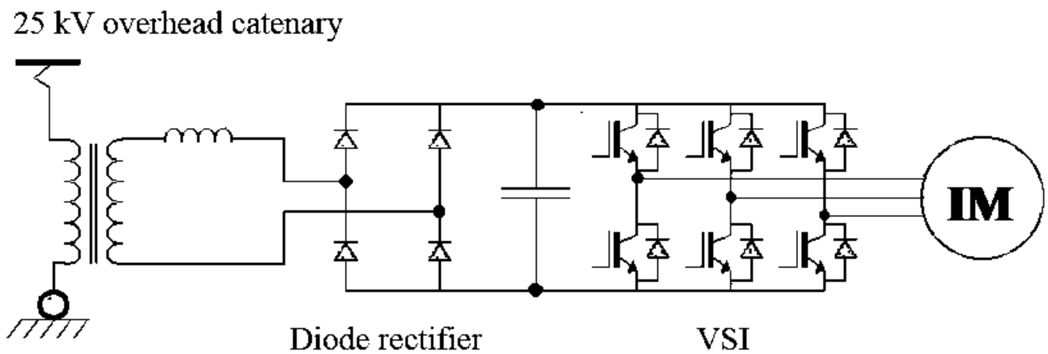

Figure 3.5: AC-DC-AC Diode locomotive schematic diagram [2]

The simplified computer model of the locomotive, which is done using MATLAB/SIMPOWER, is shown in appendix c.

3.3.4 Integration of Models

Harmonic analysis at substation and at loading point requires the integration of substation model, feeding section model and traction load model. Thus, a model of electric railway system connected to 132kV network was developed in order to determine the distortion level of voltage and current waveform. A model consists of electric railway substation and contact line feeding electric locomotives equipped with diode rectifiers. Figure shows the model in MATLAB software, which is used for analysis of harmonic distortion. The locomotives have been modeled as subsystem and a parallel interrupter modeled as switch.

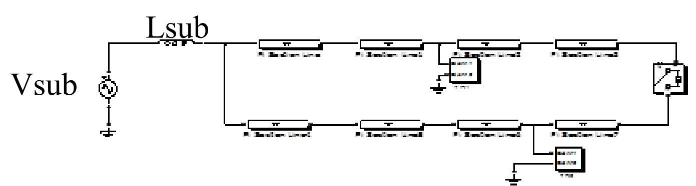

Figure 3.6: MATLAB/SIMPOWER Model of the traction system to be studied [author]

3.4 Analytical Approach for Harmonic Characterization of the Supply system

In this part, first supply network model is developed analytically. The characterization of a railway supply network means to model the impedance seen by the locomotive (by its pantograph) anywhere in the network, commonly named pantograph impedance. In our case, Catenaries (transmission lines) of each track are seen as a two-port network, expressed in matrix in equation (2.14).

Once the pantograph impedance is computed analytically the voltage distortion of the supply system is computed using HPFA concept that is described mathematically in equation (2.22) since if a harmonic source is connected to the bus of interest, the harmonic voltage at the bus is given by the harmonic current multiplied by the harmonic impedance. The HPFA thus gives us a visual picture of impedance levels and potential voltage distortions provide the electric locomotive similar to current generator of harmonic component.

This work assumes that this approach gives more flexibility as compere to what has been done in some previous works that uses the current source model to generate the current spectrum as it allows us to consider different operation condition of the train. Finally, compering between simulated and calculated result is presented to verify this approach

The aim of this section is to characterize the voltage distortion of supply network, commonly known as pantograph voltage distortion. In order to analysis the pantograph voltage distortion the following basic assumption are made.

- There is no background voltage distortion from the AC voltage source, only the fundamental voltage exists.
- The distorted load current will couse voltage distortion
- The electric locomotive similar to current generator of harmonic component
- Catenaries system considered as homogeneous electric line

With the above all assumptions, the analysis approach proceeds along the following series of steps to characterize voltage distortion of the railway supply network using HPFA method with some modification as the current source is represented by electric locomotive circuit model .

Step 1: compute the individual current harmonic injected by the locomotives to the Network using software program (MATLAB/SIMPOWER).

Step 2: model the impedance of the railway supply network as seen by the locomotive anywhere in the network while including the contribution of source (commonly named

-pantograph impedance).

Step 3: Apply HPFA to compute system voltage distortion for each frequency of interest at considered bus using the equation given in (2.22)

In this analysis, to model a single track feeding section the method described in chapter 2 from equation (2.14) to (2.21) of Ref. [11] is adopted in a manner to apply for double track section. In this work, the double track section is considered as two networks in parallel and the concept of two-port model that is defined in equation (2.14) is applied to formulate the pantograph impedance of the system. Traction substation is represented by equivalent impedance Z_{sub} .The catenary has a length $L = L_1 + L_2$ and it's terminated by impedance Z_{end} in the substation opposite end, which is considered to be very high, in other words, the right terminal is open Figure 3.6 illustrates this

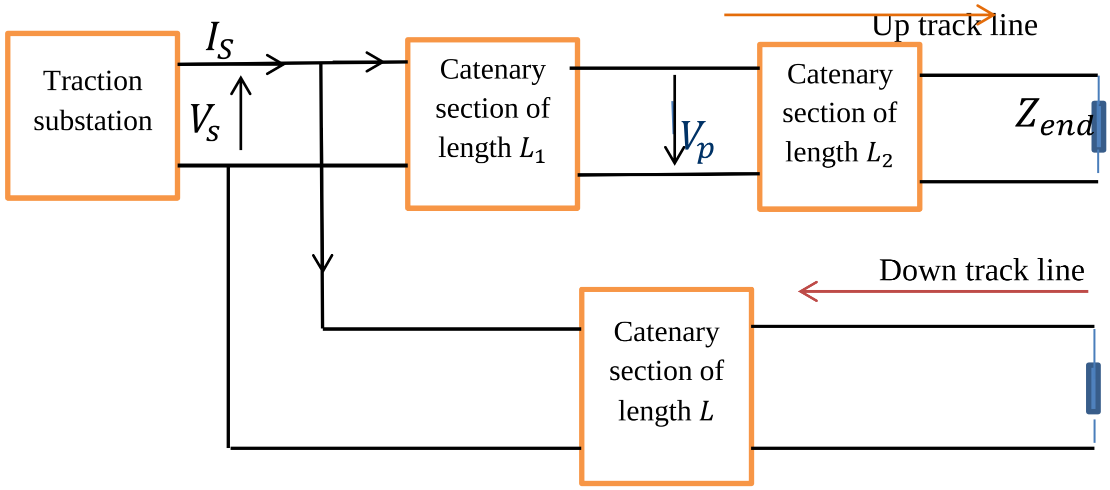

Figure 3.7: Configuration of the railway section in study [author]

The modeling is based on the following electrical parameter of the line per track

Table 3.1: Electrical parameter of the line

R(Ω/Km)	L(mH/Km)	C (nF/Km)	$Z_0(\Omega)$	$\gamma\left(\frac{rad}{Km}\right)$

0.130081	1.25	11	337.1	1.165×10^{-3}

Where in the above table the value of characteristics impedance (Z_0) and propagation constant (γ) are calculated respectively using equation (2.18) and (2.19) as follows with the assumption that the line is loss less

$$Z_O = \sqrt{\frac{L}{C}} = \sqrt{\frac{1.25*10^{-3}}{11*10^{-9}}} = 337.1\Omega$$

$$\gamma = \omega\sqrt{LC} = 2\pi f\sqrt{LC} = 1.165\times 10^{-3} \text{ Rad/km}$$

In the analysis only the worst-case scenario of railway supply network voltage distortion is considered. Thus, we have the following two conditions:

Condition 1: when only the up track section is loaded at the end of the feeding section

With this condition the configuration of the railway section in study, which is described in figure 3.6 will have the following form

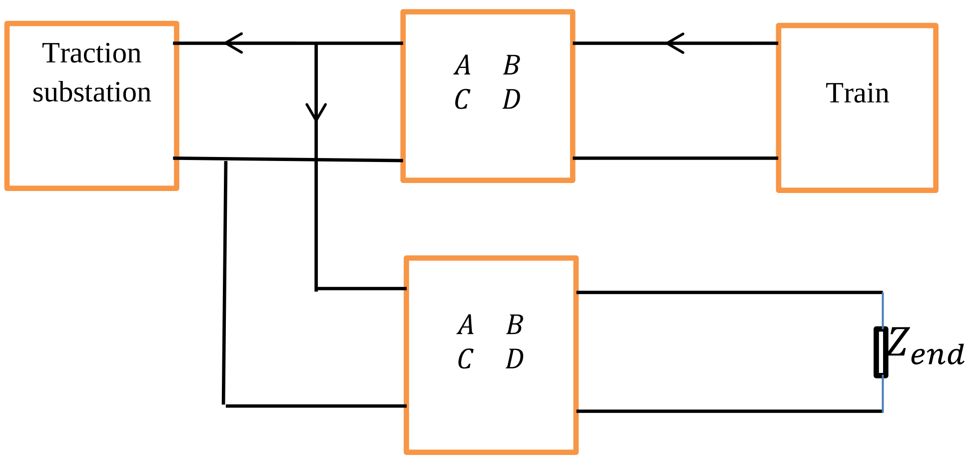

Figure 3.8: Configuration of the railway section in study [author]

Now considering the down track section, it is possible to have the following relations

$$\begin{bmatrix} V_p \\ I_2 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_{end} \\ I_{2end} \end{bmatrix} \tag{3.17}$$

$$\Rightarrow \quad V_p = AV_{end} + BI_{2end} \tag{3.18}$$

$$I_2 = CV_{end} + BI_{2end} \tag{3.19}$$

Where $I_2 \cong I_{2end}$ (3.20)

equating equation (3.18) and (3.19) it is possible to have the following expression for the unloaded section from the load terminal point of view

$$Z_2 = \frac{AZ_{end} + B}{CZ_{end} + D} \tag{3.21}$$

With the assumption that the end of the feeding section is open,

$$Z_2 = Z_0 \left[\frac{\cosh \gamma L}{\sinh \gamma L} \right] \tag{3.21}$$

This is connected in parallel to substation impedance. Thus, the left side of the upstream network as seen from the locomotive terminated at Z_{SS}.where

$$Z_{SS} = \frac{Z_{sub} Z_2}{Z_{sub} + Z_2} = \frac{Z_{sub} Z_0 \cosh \gamma L}{Z_0 \cosh \gamma L + Z_{sub} \sinh \gamma L} \tag{3.22}$$

Therefore considering the up track section the expression for pantograph impedance is obtained as follows

$$\begin{bmatrix} V_p \\ I_p \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_{ss} \\ I_{ss} \end{bmatrix} \tag{3.23}$$

$$V_p = AV_{ss} + BI_{ss} \tag{3.24}$$

$$I_p = CV_{ss} + BI_{ss} \tag{3.25}$$

Since there is no other train than the one we assumed at the end of the feeding section and assuming that the effect of shunt capacitor is not significant for such short distance (13.521km) between the terminals, it is practical to assume that $I_p \cong I_{ss}$

$$\Rightarrow \qquad Z_p = \frac{AZ_{ss} + B}{CZ_{ss} + D} \tag{3.26}$$

Substituting the values of A, B, C and D parameters in equation (3.26),

$$Z_p = Z_0\left[\frac{Z_{ss}\cosh\gamma L + Z_0\sinh\gamma L}{Z_{ss}\sinh\gamma L + Z_0\cosh\gamma L}\right] \tag{3.24}$$

Now let $x = \cosh\gamma L \; and \; y = \sinh\gamma L$ then substituting equation (3.22) in (3.24),

$$Z_P = Z_0\left[\frac{Z_{sub}Z_0x^2 + Z_0^2xy + Z_0Z_{sub}y^2}{Z_{sub}Z_0xy + x^2Z_0^2 + Z_0Z_{sub}xy}\right] \tag{3.25}$$

Dividing both the nominator and the dominator by 1/xy the above equation will be simplified into

$$Z_P = Z_0\left[\frac{Z_0 + Z_{sub}[\coth\gamma L + \tanh\gamma L]}{2Z_{sub} + Z_0\coth\gamma L}\right] \tag{3.26}$$

Now the pantograph impendence for particular harmonic order (h) can be found using the following equation

$$Z_P(h) = Z_0\left[\frac{Z_0 + hZ_{sub}[\coth\gamma hL + \tanh\gamma hL]}{2hZ_{sub} + Z_0\coth\gamma hL}\right] \tag{3.27}$$

Then , $for \; h = 3, \; Z_p(h) =$ 37.8Ω

$$h = 5, \; Z_p(h) = 62.5\Omega \tag{3.28}$$

$$h = 7, \; Z_p(h) = 86.26\Omega$$

In other hand if we approximate $Z_0\cosh\gamma L + Z_{sub}\sinh\gamma L \cong Z_0\cosh\gamma L$ in equation (3.22) which is practical from mathematical point of view then $Z_{ss} \cong Z_{sub}$ .This results,

$$Z_p(h) = Z_0 \left[\frac{Z_{sub} \cosh \gamma hL + Z_0 \sinh \gamma hL}{Z_{sub} \sinh \gamma hL + Z_0 \cosh \gamma hL} \right] \tag{3.29}$$

Then , $h = 3,\ Z_p(h) = 37.78\Omega$

$$h = 5,\ Z_p(h) = 62.8\Omega \tag{3.30}$$

$h = 7,\ Z_p(h) = 86.55\Omega$

This results shows that the unloaded network does not have influence on the system impedance from locomotive point of view. Analogues result can be obtained from electrical engineering point of view knowing that only very small capacitive current will flow to the unloaded section such that the parallel combination of Z_{sub} and Z_2 can be approximated to Z_{sub} .

Now relying on the results obtained above for the referred harmonic frequencies the cross pounding voltage distortion of the railway supply network at the considered bus (loading point) is calculated using HPFA. According to HPFA technic for harmonic analysis at a particular bus the voltage equation is given by:

$$V(h) = I(h)Z(h) \tag{3.31}$$

Thus, the percentage individual distortion of the voltage is calculated

$$\%V(h) = \frac{\%I(h)I_1Z(h)}{V_n} \tag{3.32}$$

Where I_1=272.7A is rms value of locomotive primary current at 50HZ (simulation result for the given condition)

V_n=25000V is the nominal voltage of the line

Condition 2: when both track is loaded at their feeding end with a locomotive at the same operating condition. In this case, the traction substation receives harmonic current injected from both locomotive and of course, it is the vector sum of each individual harmonic at PCC. On the top of this, it is logical to assume the current injected per train is the same since they are in identical operating condition. Consequently,

$$I_s = I_1 + I_2 \cong 2I_1 = 2I_2 \tag{3.33}$$

Then pantograph impedance from the reference locomotive is found as shown below taking up track section

$$\begin{bmatrix} V_p \\ I_p \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_{sub} \\ I_{sub} \end{bmatrix} \tag{3.34}$$

Applying the same procedure as what is done before we got the following expression for pantograph impedance

$$Z_p(h) = Z_0 \left[\frac{2Z_{sub} \cosh \gamma hL + Z_0 \sinh \gamma hL}{2Z_{sub} \sinh \gamma hL + Z_0 \cosh \gamma hL} \right] \tag{3.36}$$

$$Z_p(h) = Z_0 \left[\frac{2Z_{sub} \cosh \gamma hL + Z_0 \sinh \gamma hL}{2Z_{sub} \sinh \gamma hL + Z_0 \cosh \gamma hL} \right] \tag{3.37}$$

$$=> Z_p(3)=59.57\Omega$$

$$Z_p(5)=98.43\Omega \tag{3.38}$$

$$Z_p(7)=135.43\Omega$$

Applying similar procedure as it is done previously the voltage distortion is characterized at the bus of interest. During simulation of this scenario, it has been seen that the primary side of locomotive current at 50HZ is 256.3A

In the next chapter, Table 4.11 and Table 4.12 illustrates the result obtained from above two condition of this analytical approach and compares it with the result acquired from simulation.

CHAPTER FOUR

4 SIMULATION RESULTS AND DISCUSION

4.1 Simulations with Deterministic Approach for Harmonic Analysis

This section of the thesis work aims in studying and analyzing how different operating conditions of the locomotive will affect the harmonics of the railway system under the study. The model developed in this research has been used for this analysis purpose.

Harmonic analysis is performed by using computer simulations developed in time domain by means of MATLAB/SIMPOWER System block set, a tool with feasible and attractive characteristics, allowing to easily evaluating complex system behavior. Every power system component is represented by a block in which it is possible to vary the component characteristic parameters; furthermore, the interconnection among the various components is effected by reproducing the real ones. The toolbox is provided of suitable supports that result very useful for efficient time-domain simulations, allowing capturing the functional dependence of system characteristics of various interest parameters.

A train is regarded as a basic harmonic-producing component for harmonic analysis and evaluation in a traction power-supply system. **Simulations for analysis were taken from traction substation and train loading point for different scenarios with deterministic** approach. **In this study**, the simulations are performed by considering the following operation conditions of the train with the assumption that the sub-station under test is supplied from balanced three-phase system.

- **A single train simulation case**
    - ✓ With full load
    - ✓ With half load

- ✓ At different position from substation

- **Two train simulation case**
  - ✓ With full load
  - ✓ At the end of feeding section

The system parameters for the simulation are shown below in Table 4.1

Table 4.1: System parameters for simulation

Parameters	**values**
Source voltage	$\sqrt{2}(27.5KV), 50HZ$
Source inductance	23.4mH /km
Pi section line inductance	1.25mH /km
Pi section line resistance	0.130081Ω/km
Pi section line capacitance	11nF /km
nominal voltage of the contact line	25kV, 50HZ
On board transformer	25kV/6*1.65kV, 9.3MVA
Dc Link capacitance	5mF
Load	22Ω(full load), 44Ω (half load)

4.1.1 Simulation of Single Train Unit

Assumed that there is only one train in service along the feeding section, no harmonics are produced by other trains. In this situation, harmonics injected to the supply network from a single train unit can be analyzed for various operating conditions by using the train model proposed in the section 3.4.3.The simulation is performed in time domain initially a sinusoidal voltage is feeding the locomotive. A common brute-force approach for harmonic analysis in time-domain is followed .i.e. to run the simulation over considerable periods until the transient vanishes and a steady state is reached. Then the

FFT is performed on the voltage and current waveforms for collecting harmonic spectra of interest.

Case 1: when a locomotive with full load is located at different position along the up track feeding section

Table 4.1 and Table 4.2 show simulation result of current; Table 4.3 and Table 4.4 also present simulation result of voltage of this use case. Accordingly, discussion is made based on the results.

Table 4.2: **Simulation result of current waveform at traction substation**

Harmonic order	**IHD in %**	**IHD in %**	**IHD in %**	**IHD in %**
3	35.83	34.63	33.59	32.55
5	7.56	7.54	7.54	7.54
7	4.26	3.96	3.73	3.55
9	3.03	2.92	2.79	2.66
11	1.86	1.86	1.85	1.83
13	1.29	1.24	1.21	1.2
15	1.12	1.06	1.00	0.95
THD in %	**37.15**	**35.99**	**34.90**	**33.86**
Position	**3.38km**	**6.76km**	**10.14km**	**13.521km**

Table 4.3: Simulation result of current waveform at loading point

Harmonic order	IHD in %	IHD in %	IHD in %	IHD in %
3	35.59	34.39	33.25	32.16
5	7.45	7.41	7.38	7.35

7	4.13	3.84	3.60	3.39
9	2.91	2.78	2.63	2.48
11	1.75	1.73	1.69	1.64
13	1.19	1.12	1.07	1.03
15	1.01	0.93	0.85	0.77
THD	**36.82**	**35.60**	**34.44**	**33.34**
Position	**3.38km**	**6.67km**	**10.14km**	**13.521km**

Table 4.1 shows that the THD of substation current decreases as the train move away from traction substation. It can also be seen that THD of substation current of a single train varied from 33.86% to 37.15%. The highest peak value of IHD is seen for 3rd harmonic order this is because the individual harmonic distortions of current waveform become lower due to increasing impedance presented to higher frequency components by the overhead catenary system inductive reactance. In other word, the impedance presented to 3rd harmonic component is the smallest that in turn results the highest IHD.in addition to this, line side (AC side) harmonics produced by two pulse rectifier is inversely proportional to order of harmonics.

Table 4.2 shows the THD of train current decreases as the train move away from substation. It is found that the THD of the train current varies from 33.34 % to 36.82 % along the feeding section.

From **Table 4.1** and **Table 4.2** it is possible to conclude that the current harmonic distortion results obtained at substation and loading point for a given train position are almost the same, which reveals that the supply network impedance has low impact for such short distance(13.521km) feeding section.

Table 4.4: Simulated result of voltage at traction substation when a locomotive with full load situated at different distance

Harmonic order	**IHD in %**	**IHD in %**	**IHD in %**	**IHD in %**
3	8.55	8.14	7.75	7.39
5	3.00	2.95	2.9	2.85
7	2.36	2.17	2.01	1.88
9	2.17	2.05	1.93	1.81
11	1.62	1.6	1.57	1.52
13	1.34	1.26	1.21	1.18
15	1.34	1.25	1.00	1.07
THD	**11.26**	**10.69**	**10.19**	**9.74**
Position	**3.38km**	**6.67km**	**10.14km**	**13.521km**

Table 4.5: **Simulation result of voltage at loading point when a locomotive with full load situated at different distance**

Harmonic order	**IHD in %**	**IHD in %**	**IHD in %**	**IHD in %**
3	10.21	11.33	12.36	13.32
5	3.58	4.1	4.61	5.12
7	2.81	3.01	3.18	3.35
9	2.58	2.83	3.04	3.21
11	1.93	2.2	2.45	2.67
13	1.58	1.72	1.88	2.04
15	1.58	1.69	1.77	1.84
THD	**13.32**	**14.46**	**15.61**	**16.67**
Position	**3.38km**	**6.67km**	**10.14km**	**13.521km**

Table 4.4 shows that the THD of voltage at substation decreases with increase train position, which indicates that the voltage distortion at substation is affected by train current, which also decreases with position as seen in **Table 4.2** provide that substation impedance be not affected by train position. In addition, the THD of the voltage varies from 9.74% to 11.26% while the highest value crosses pounds to nearest position of the case that is 3.38km.

Table 4.4 also indicates that the IHD of voltage for 3rd harmonic order passes the recommended limits of IEEE 591-1992, for individual harmonic voltage distortion at PCC (3%), all position of the train.

Table 4.5 indicate that the THD of voltage at loading point increases with increase in position of the train, which reveals that the voltage distortion at pantograph is influenced by network impedance as the network impedance(the impedance between the source and load) seen from load point increases with position of the train.

Case 2: when a locomotive with half load is found at different position from the substation

Simulation results of this case are illustrated in Table 4.6, Table 4.7 and Table 4.8 followed by discussions.

Table 4.6: Simulation result of train current at substation when the train is half loaded

Harmonic order	IHD in %	IHD in %	IHD in %	IHD in %
3	43.43	42.39	41.41	40.48
5	9.49	8.9	8.42	8.01
7	6.61	6.4	6.19	5.96

9	3.07	3.03	3.01	3.00
11	2.58	2.38	2.23	2.1
13	1.79	1.78	1.77	1.73
15	1.31	1.25	1.20	1.18
THD	**45.27**	**44.11**	**43.01**	**41.99**
Position	**3.38km**	**6.67km**	**10.14km**	**13.521km**

Table 4.7: Simulation result of voltage at substation when the train is half loaded

Harmonic order	**IHD in %**	**IHD in %**	**IHD in %**	**IHD in %**
3	6.18	5.96	5.76	5.56
5	2.25	2.09	1.95	1.84
7	2.19	2.1	2.01	1.91
9	1.31	1.28	1.25	1.24
13	1.1	1.22	1.14	1.06
15	0.93	1.09	1.06	1.03
THD	**8.34**	**8.00**	**7.67**	**7.37**
Position	**3.38km**	**6.67km**	**10.14km**	**13.521km**

Table 4.8: Simulation result of voltage at loading point when the locomotive is half loaded

Harmonic order	**IHD in %**	**IHD in %**	**IHD in %**	**IHD in %**
3	7.33	8.21	9.04	9.83
5	2.67	2.87	3.05	3.23

7	2.6	2.88	3.13	3.34
9	1.55	1.75	1.95	2.15
11	1.55	1.66	1.75	1.82
13	1.3	1.47	1.62	1.76
15	1.09	1.18	1.27	1.36
THD	**9.97**	**10.69**	**11.55**	**12.35**
Position	**3.38km**	**6.67km**	**10.14km**	**13.521km**

Comparison of **Table 4.2** and **Table 4.6** show that at a given position of train the THD of current at traction substation increases with decrease in load. For instant, for a train with half load at 3.38km form traction substation the THD% of current at substation is larger by 8.17% than for a train at the same distance but with full load. This shows that a considerable load variation of the locomotive can introduce a significant change in current harmonics of the contact line.

In fact, locomotive with lower load will draw the smaller fundamental current at 50HZ.However, the current distortion is high this can be illustrated mathematically as follows

$$load \downarrow => I_1 \downarrow => \left(\frac{I_h}{I_1}\right) \uparrow$$

From **Table 4.4** and **Table 4.7**, it can be found that for a given position of the train the THD of voltage decreases with decrease in load. This is because the lower the load is the lower the harmonic current (I_h) , which in turn results low voltage distortion.

Taking the highest result of both tables, we can see that with full load case the THD in percentage is larger than with half load case by 2.91%.

Due to the same reason as it is mentioned for Table 4.4 and Table 4.7, the voltage distortion at loading point decreases with decrease in load for the same position of the train. This can be clearly seen by comparing the results of Table 4.5 and Table 4.8.

Figure 4.1, figure 4.2 and figure 4.3 summarize the most unaffordable condition of voltage and current waveform distortion that are observed during single train simulation scenario.

The voltage waveform at PCC as it is illustrated in Fig.4.2 has THD of 11.26 %, which is very high as compared to the standard limit THD (5 %) at PCC. In addition to the THD, 3rd harmonics also fail to satisfy the standard value set for IHD (3 %).

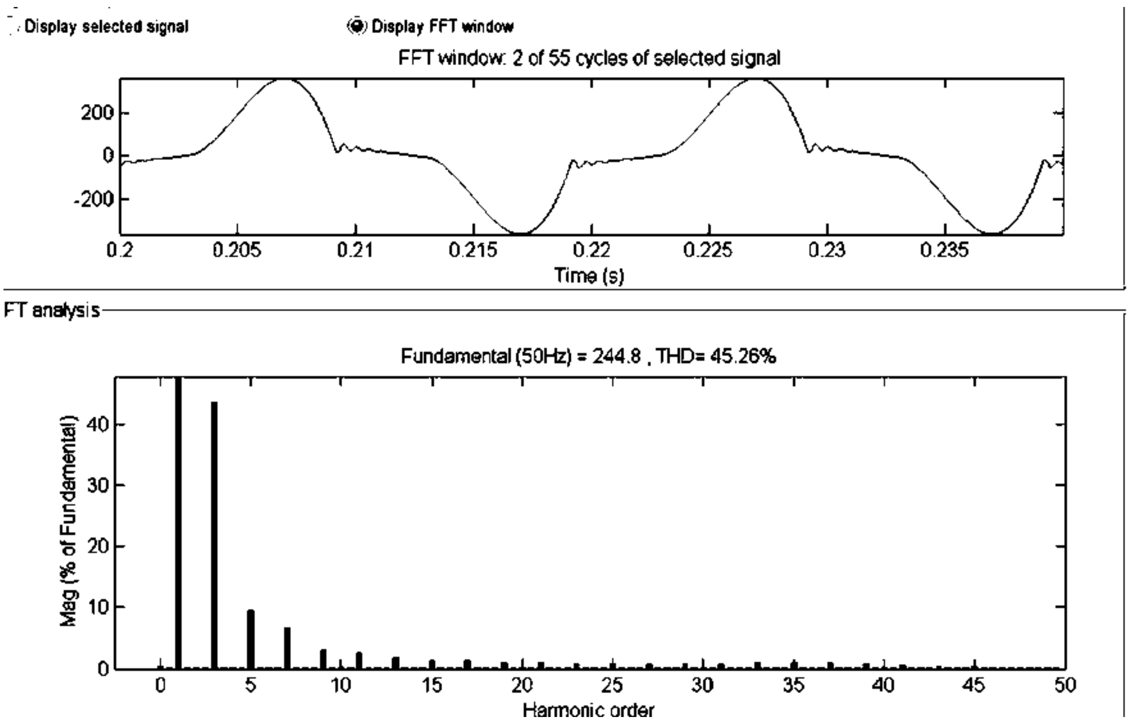

Figure 4.1: Current waveform and its harmonic spectrum simulated at PCC when a train with half load is located at 3.38km from TSS.

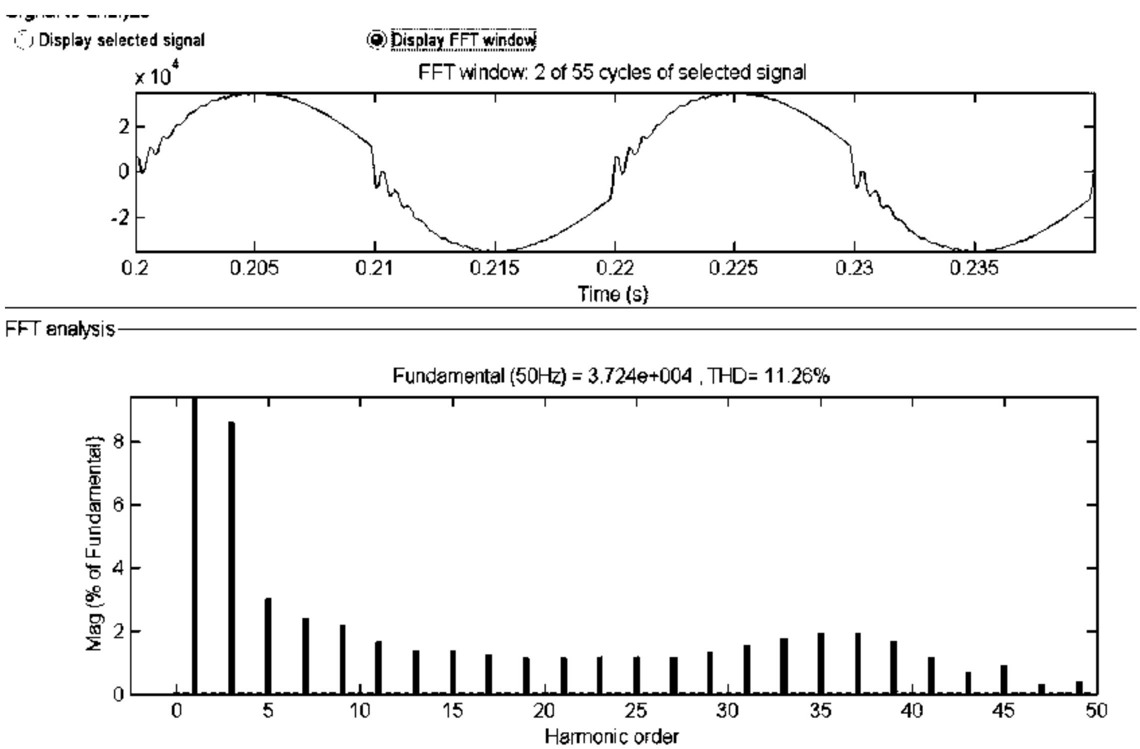

Figure 4.2 : Voltage waveform and its harmonic spectrum simulated at PCC while a train with full load is located at 3.38km from TSS.

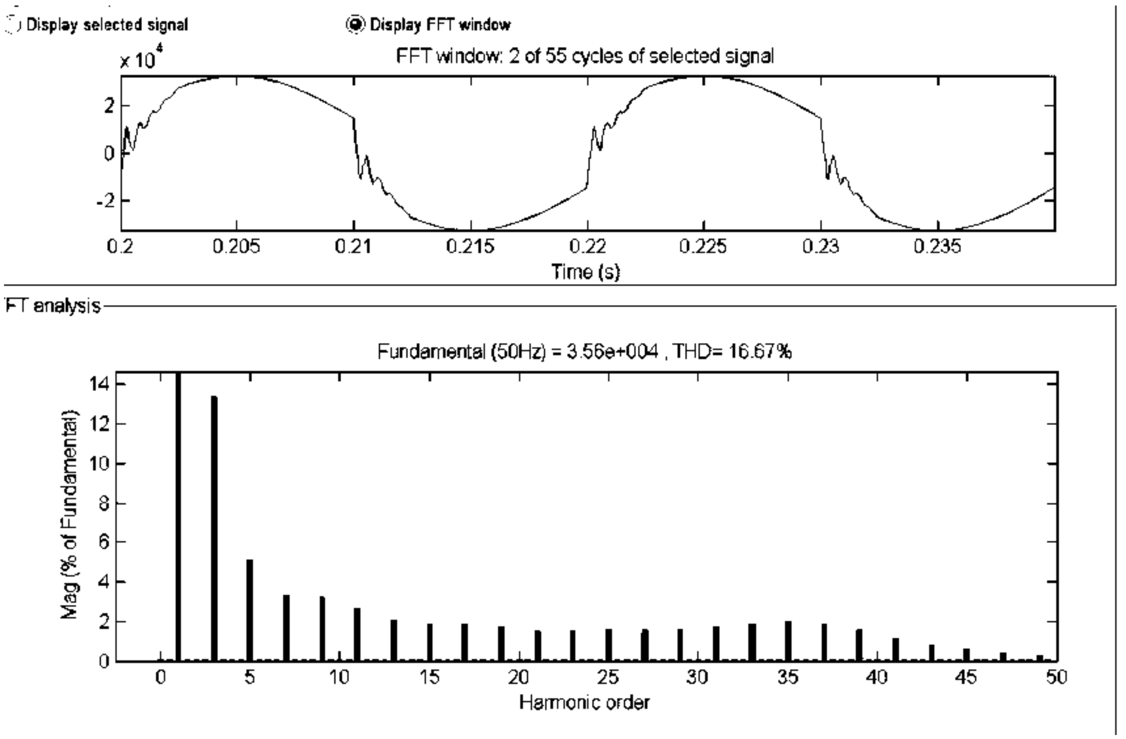

Figure 4.3: Voltage waveform and its harmonic spectrum simulated at loading point while a train with full load is located at the end of feeding section (13.521km)

4.1.2 Simulation of Two Train Units

In a practical railway system, there are a number of trains servicing simultaneously. Harmonic evaluation for the possible worst case becomes sophisticated. Multi-train situation requires the information of the speed and notch setting of each train in services at the same track section. Number of trains in the same section also varies drastically from time to time. Huge number of cases may occur accordingly [4]. Taking in account the proposed signaling system in our case, the maximum number of train per section is one for single track and two for double track line i.e. one per feeding section.

Use case: when two train with full load are found at the end of each feeding section of the double track line in the manner that one train is in the up track line and the other train is in down track line

Table 4.9: Simulation result of current at traction substation and loading point when both tracks are loaded at their feeding end

Harmonic order	IHD in % at PCC	IHD in % at LP
3	27.78	27.51
5	7.54	7.37
7	3.12	2.99
9	2.05	1.91
11	1.57	1.42
13	1.17	1.00
15	0.84	0.69
THD in %	**29.14**	**28.77**
Train Position	13.521km	

Table 4.10: Simulation result of voltage at traction substation and loading point when both tracks are loaded at their feeding end

Harmonic order	IHD in % at PCC	IHD in % at LP
3	12.40	17.64
5	5.61	7.97
7	3.25	4.60
9	2.74	3.87
11	2.58	3.62
13	2.25	3.15
15	1.88	2.16
THD in %	**15.79**	**22.18**
Train position	13.521km	

Results of Table 4.9 indicate that the presence of a train on the down track line in addition to the train at up track line brings decrease in THD of the current harmonics at substation. This shows that as the number of trains with the same operation condition distributes evenly on both section the chance for harmonic cancelation will increases. The fact is the harmonic current at PCC is the vector sum of harmonic currents injected from each train. It can be also seen that as the number of trains increases, the supply network voltage distortion increases.

Fig.4.4and Fig.4.5 shows that the most unaffordable condition of voltage and current waveform distortion that is observed during two-train simulation time.

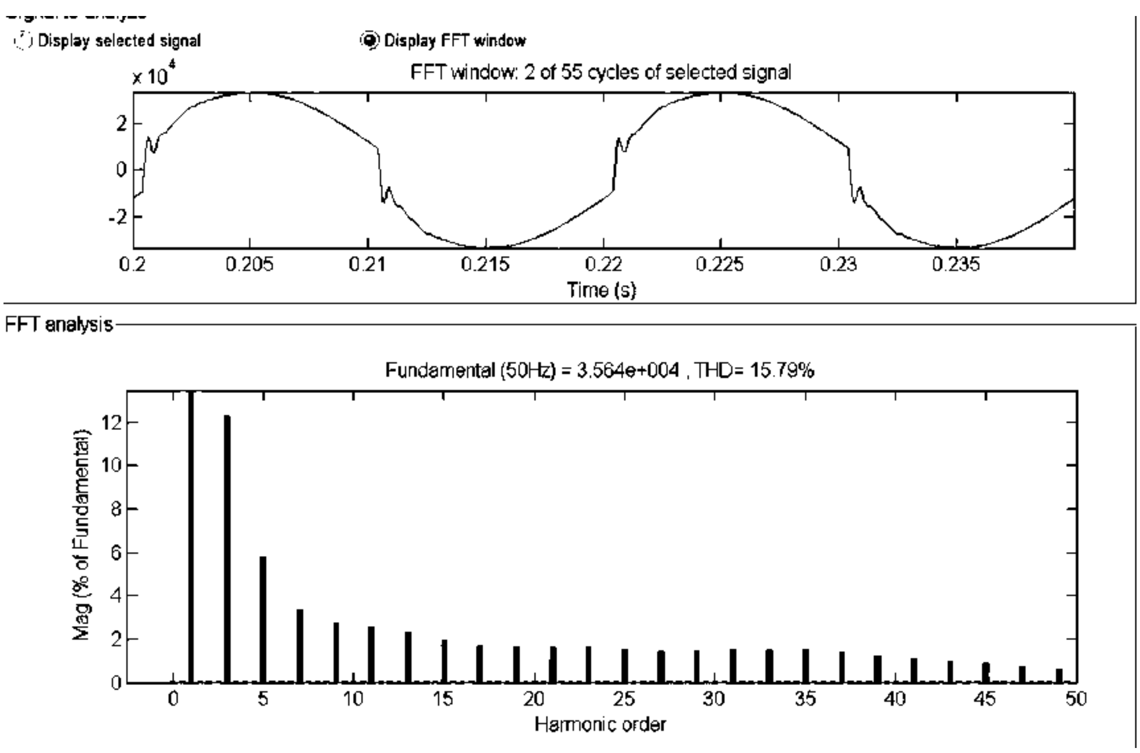

Figure 4.4: Voltage waveform and its harmonic spectrum at PCC when two train with full load is found at the end of feeding section (a train per track)

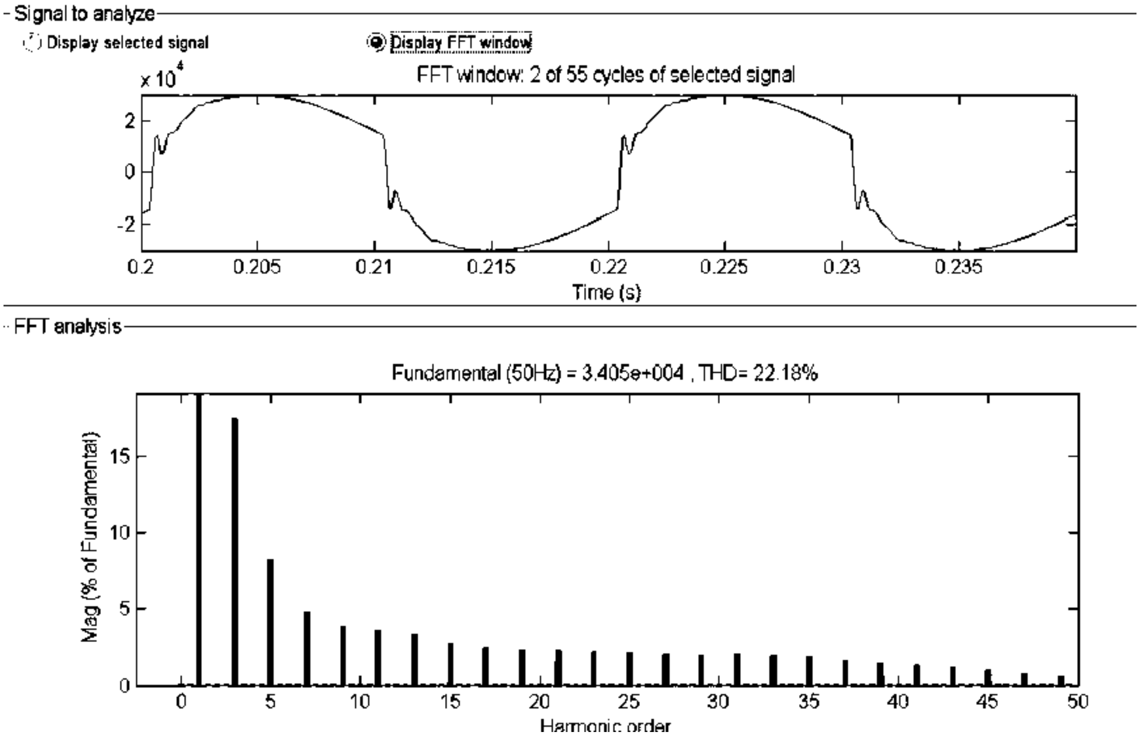

Figure 4.5: Voltage waveform and its harmonic spectrum simulated at loading point while Train with full load is positioned at feeding end.

The worst-case railway network supply voltage distortion obtained by both simulation and calculation (in chapter 3) for single train and two-train case are shown in Table 4.11 and Table 4.12 respectively.

Table 4.11: **Comparisons of the simulated and calculated values of individual voltage distortion**

Harmonic order	**Simulated** $\%\, I(h)$	**Simulated %** $V(h)$	**Calculated** $\%\, V(h)$	**% error**
3	32.16	13.32	13.25	0.52%
5	7.35	5.12	5.05	1.36%

7	3.39	3.35	3.2	4.15%

Table 4.12: **Comparisons of the simulated and calculated values of individual voltage distortion**

Harmonic order	Simulated% I(h)	Simulated% V(h)	Calculated % V(h)	% error
3	27.51	17.64	16.8	4.76%
5	7.37	7.97	7.44	6.65%
7	2.99	4.60	4.15	9.78%

From **Table 4.11** and **Table 4.12**, it is observed that the simulation results and the calculated results of the percentage individual voltage distortion for the most dominant harmonics (3^{rd} ,5^{th} and 7^{th}) component were almost the same. Moreover, looking to the percentage errors of each table it is possible to conclude that the percentage error will increase for higher harmonic orders. This verified that the proposed model of the railway supply network is reasonably accurate to characterize lower harmonic components.

Figure 4.6 and figure4.7 summarizes the variation of THD of voltage at PCC and loading point respectively. From figure 4.6 and Figure 4.7 it can be conclude that the voltage waveform distortion, for a given position of the locomotive depend on its load characteristics equivalently possible to say on the absorbed power .On other word, for a given load of locomotive, the distortion depend on the position of the locomotive in the traction feeding section.

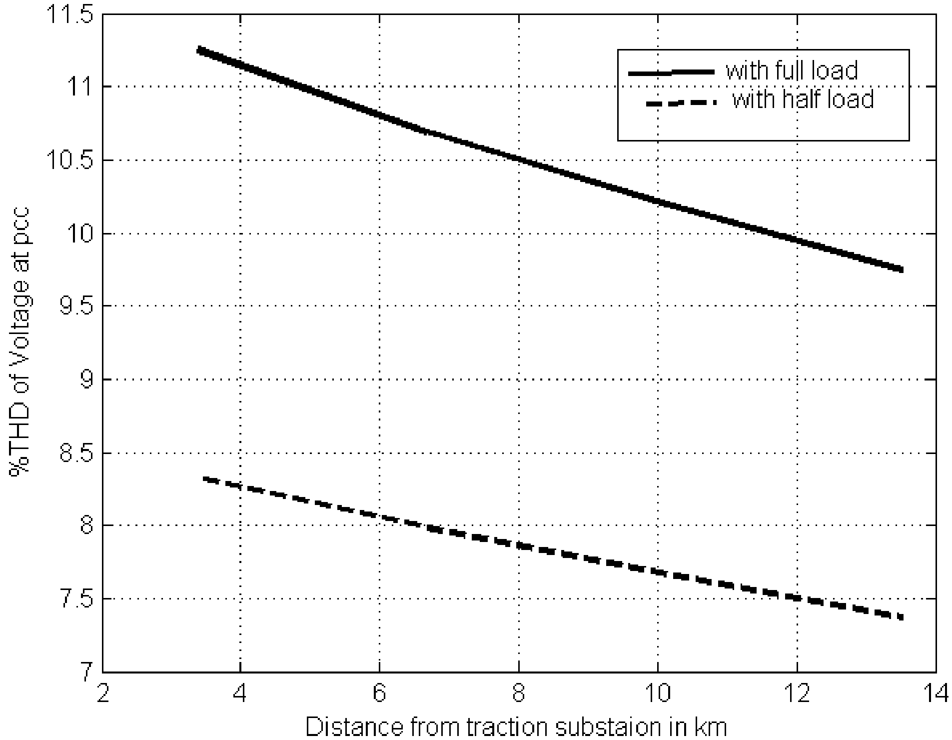

Figure 4.6 :The variation of THD of voltage at PCC with distance and load characteristics of the train

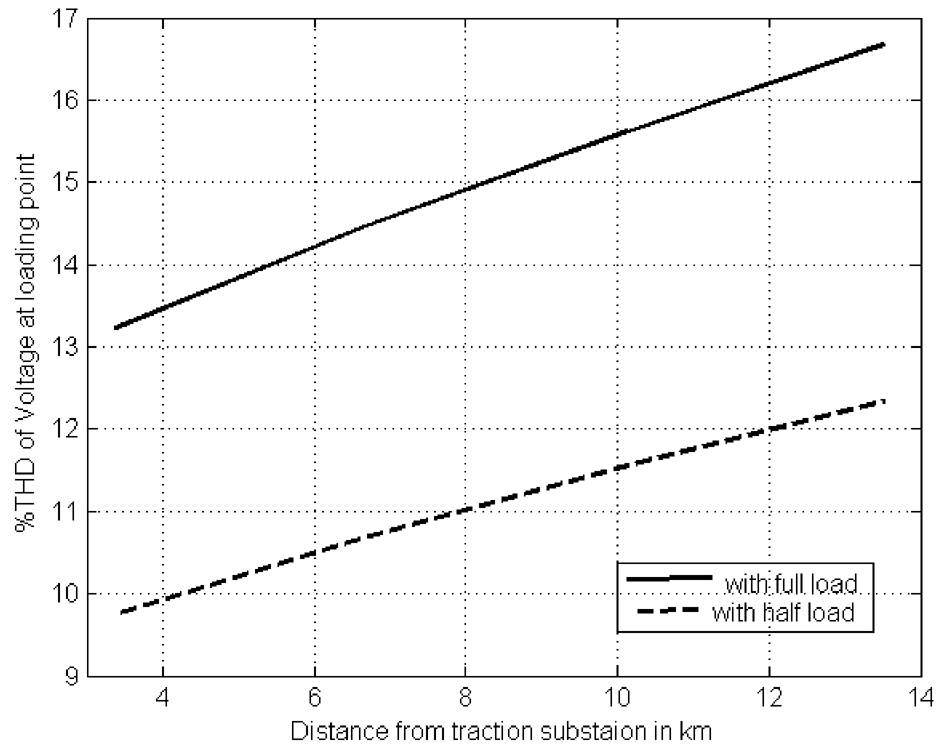

Figure 4.7: The variation of THD of voltage at point of loading with distance and load

4.2 Harmonic Evaluation

Development of flow chart for harmonic current evaluation

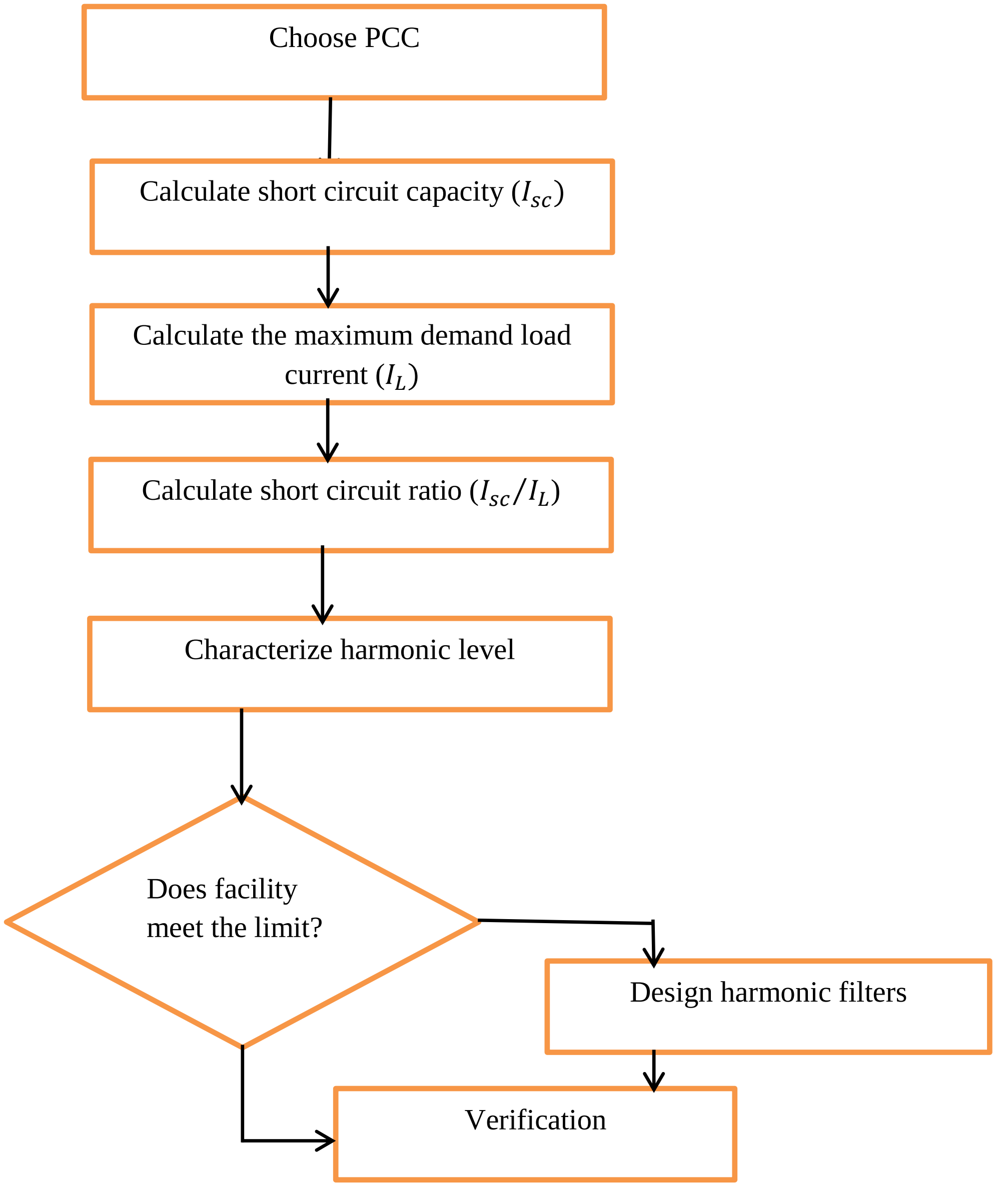

Figure 4.8 : **Flow chart for evaluating harmonics**

To evaluate harmonics at PCC only the most unfavorable condition is considered. For current wave distortion, the most unfavorable condition result when a locomotive is at 3.38km form traction substation.

In the case of locomotive with full load

- Step 1: the power outgoing point from TSS is taken at PCC

- Step 2: The short circuit current (I_{sc})

$$(I_{SC}) = \frac{V_s}{Z_{sub}}$$

$$I_{SC} = \frac{27500V}{7.35\Omega} = 3741.5A$$

Where V_s source voltage; Z_{sub} Traction substation impendence

- Step 3: The maximum load current RMS value (I_L) approximated by maximum fundamental RMS current (I_1) at PCC

$$I_L \cong I_1 = 284.8A$$

- Step 4: then the short circuit ratio

$$\frac{I_{SC}}{I_L} = \frac{3741.5}{284.8} = 13.14 \qquad (4.2)$$

Now applying IEEE 519-1992 recommended limit for current distortion with ($\frac{I_{sc}}{I_L}$) <20 the following result shown in Fig.4.9 in which the 3rd, 5th and 7th fail to satisfy the standard value set for IHD (4 %).

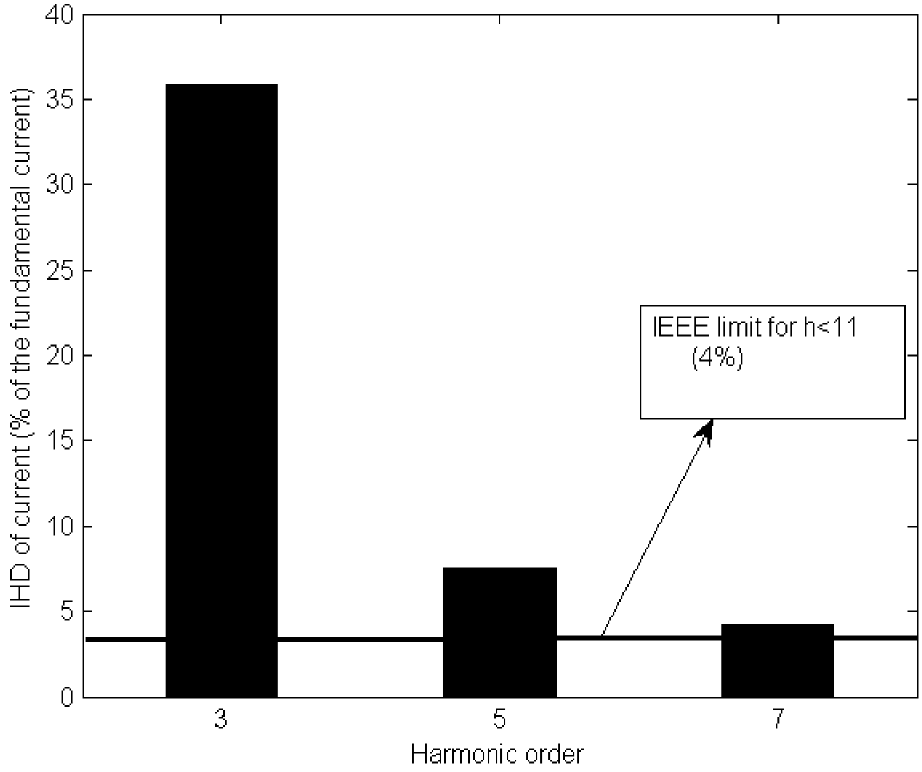

Figure 4.9 :Comperes current harmonic spectrum of 3rd,5th,and 7th component with IEEE 519-1992 standard for individual current distortion (limit compliance)

In the case of locomotive with half load,

- The maximum load current RMS value (simulation result): $I_L \cong I_1 = 173.1A$

- Then the short circuit ratio: $\frac{I_{SC}}{I_L} = \frac{3741.5}{173.1A} = 21.6$

This is greater than 20 and less than 50.

According to IEEE 519-1992 recommended limit for current distortion with ($\frac{I_{sc}}{I_L}$) between 20 and 50, the individual current harmonic distortion for h<11 should be maximum of 7 %.Having this one can see limit compliance is a problem for 3rd and 5th harmonic current of the considered case. Fig.4.10 Illustrates this

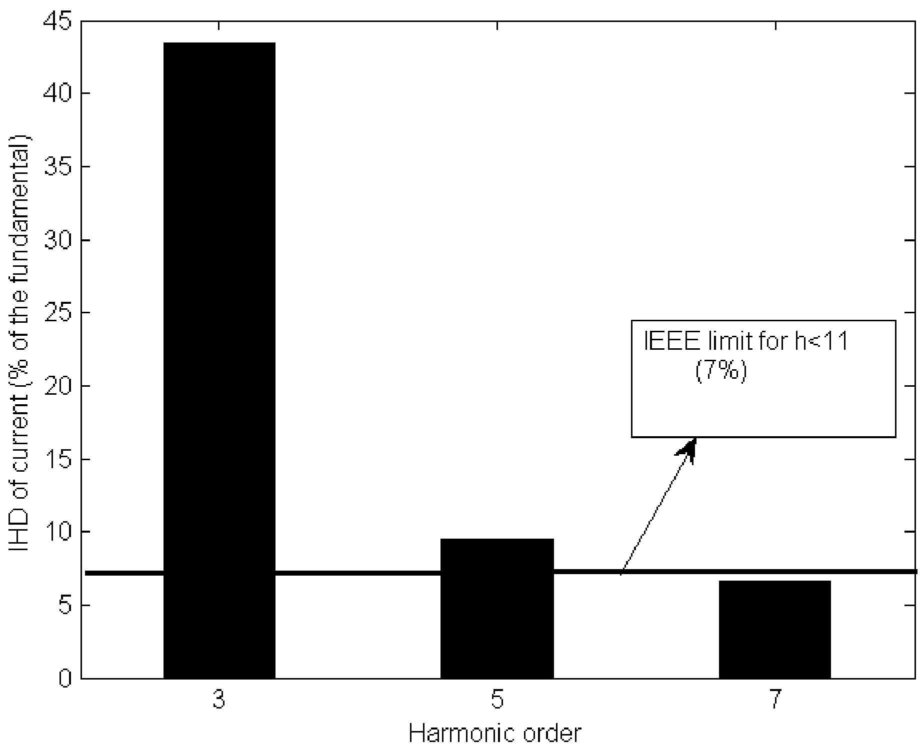

Figure 4.10: Comperes current harmonic spectrum of 3rd,5th,and 7th component with IEEE 519-1992 standard for individual current distortion (limit compliance)

In this case, the current waveform is highly distorted with a THD value of 45.26 %, which is very high as compare to the standard limit of THD (8%).

The individual harmonic distortion evaluation for voltage wave form can be performed with direct observation of the simulated results that is presented with Tables and making limit compliance test with the recommended IEEE 519 limits for individual voltage distortion that is shown in appendix Table A.1.

4.3 Sensitivity Analysis of Voltage Distortion

A**) Sensitivity to substation equivalent impedance**

This sensitivity analysis is made taking in to account that the supply grid capacity may change which in turn can affect the short circuit capacity of the substation so the equivalent impedance.

Table 4.12 shows % THD of voltage obtained from simulation for 50% decrease in substation equivalent impedance. Note that 50% decrease in equivalent impedance of traction substation results around 41.53% and 26.34% decrease in % THD of voltage at PCC and at loading point respectively. This reveals that the voltage distortion at traction substation is more sensitive than voltage distortion at loading point.

Table 4.13: **THD of voltage variation at PCC and loading point with variation of substation equivalent inductance**

Use case	A train with full load at end of each feeding section	
L_{sub}	23.4mH	11.7mH
THD_V at PCC	15.82%	9.25%
THD_V at LP	22.21%	16.36%

B) Sensitivity to over zone feeding

This sensitivity analysis is considered since there is a chance for a given traction substation to feed over its normal feeding section.

Table 4.13 shows % THD values obtained from simulation for 100% increase in feeding section. Note that the 100% increase in feeding section length results 8% decrease and 20.8% increase in THD of voltage at PCC and LP respectively. This indicates that the pantograph voltage distortion is more sensitive than voltage distortion at PCC.

Table 4.14: **THD of voltage variation at PCC and LP with variation of feeding section length**

Use case	A train with full load at feeding end	
Length	13.521Km	2*13.521km
THD_V at PCC	9.74%	8.94%
THD_V at LP	16.67%	20.14%

4.4 Resonance Frequency Analysis by Computer Simulation

Generation of correct impedance versus frequency plots for a feeder circuit to shows up any resonances present in the supply network is the key for the analysis

The analysis focuses on the first resonance peak cross ponding to the following issues

- Effect of position of analysis on resonance frequency initially determine by supply network topology only and
- pantograph impedance amplitude
- Effect of locomotive presence on the resonance frequency which is defined by the supply topology only

In this part first the resonance frequency set by the supply topology is examined at two different points along the feeding section this is to see if the resonance frequency shows variation with position of analysis and then the resonance phenomena of the system is analyzed again but with introduction of locomotive within the feeding section. Results of this analysis are shown in figure 4.11, figure 4.12 and figure 4.13.

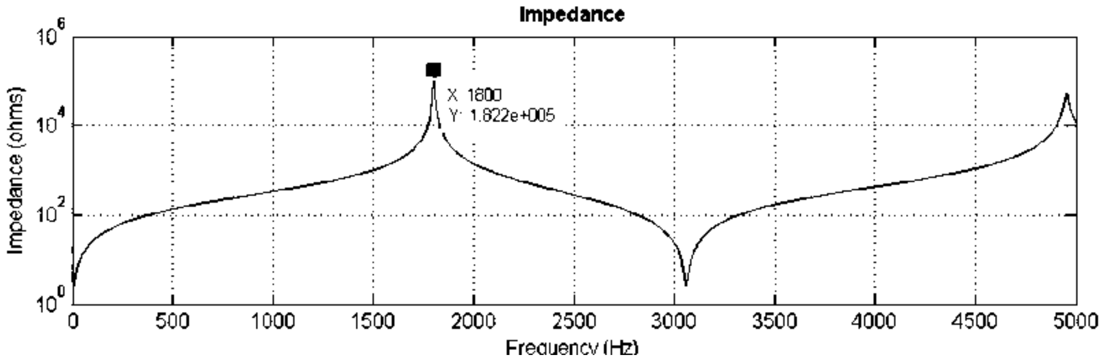

Figure 4.11: Frequency analysis of pantograph impedance at supply end without Locomotive

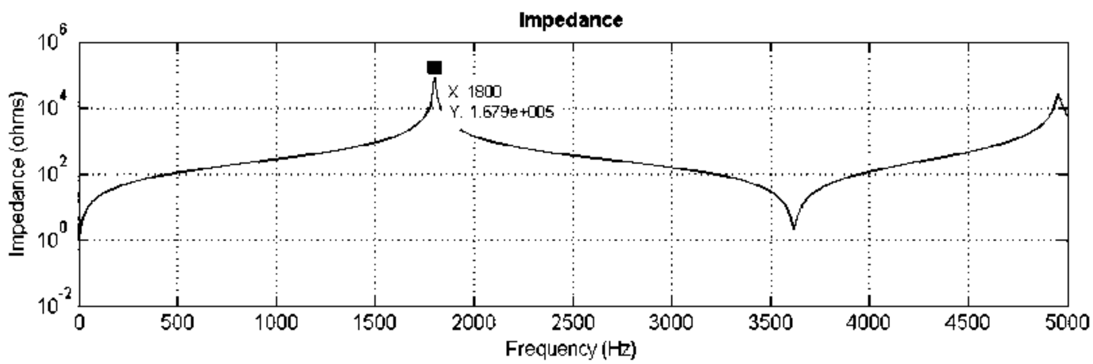

Figure 4.12 :Frequency analysis of pantograph impedance at middle of supply network

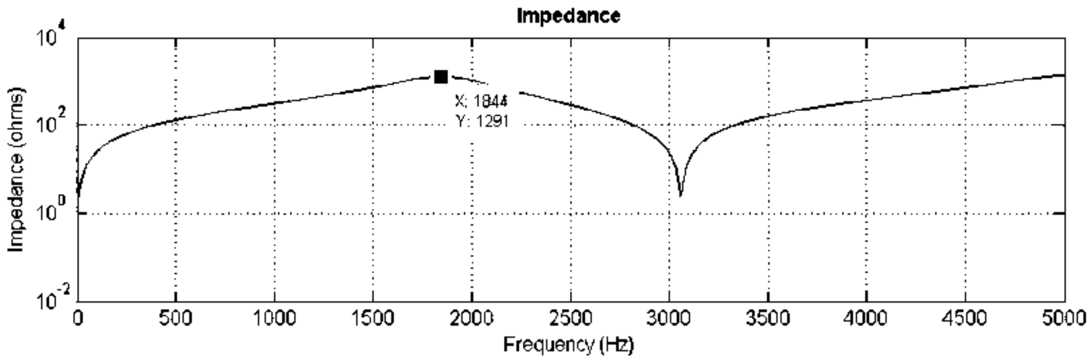

Figure 4.13: Frequency analysis of pantograph with locomotive at supply end

Figure 4.11 shows that the resonance frequency initially determines by the supply topology is independent of position of analysis and it occurs at h=36.

From figure 4.11 and figure 4.12, it can be seen that the amplitude of the pantograph impedance at the first resonance frequency increases with position from substation. Thus, the harmonic amplification is also high as it is mentioned in [20].

From figure 4.13, it is found that the resonance frequencies increase with the presence of locomotive in the supply network so the order of harmonics also shifted accordingly to 37, which indicates that from an electrical point of view, the locomotive represents the introduction of impedance in the network at the loading point. Thus, the topology of the network initially determined is no longer the same as what is before and this affects the position of the first resonance peak along the frequency axis.

CHAPTER FIVE

5 DESIGN OF PASSIVE FILTER AND SIMULATION RESULT

5.1 Passive Filter Design

This part deals with the investigation of current harmonics mitigation by using passive filters. Passive filters provide low impedance path to divert harmonic current to the ground and thus clears harmonics from the circuit. The design and simulation of passive filters for the double purpose of providing the filtering action and compensating power factor to the desired level is done. Simulation results of the system with the application of passive filter are presented to prove that THD is reduced within the recommended limits of IEEE 519-1999.

As most commonly recommended by other literatures passive filters in this work are designed based on rated kVA of the locomotive at full load because it can otherwise be exposed to overloading, which can rapidly develop into extreme overheating and thermal break down. The passive filters consisting of capacitors and inductors are connected in parallel with nonlinear load to provide low-impedance paths for specific harmonic frequencies, thus resulting in absorbing the dominant harmonic currents flowing out of the load.

A given L and a given C have equal absolute reactance at a well-defined frequency, the so-called resonant frequency

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{5.1}$$

For each frequency, there is an infinite multitude of LC pairs with the same resonance frequency but entirely different characteristics within the rest of the frequency range:

Big L and small C always provides the higher filtering quality, which is to say the impedance rises more steeply on either side, above and below the resonance frequency [25].

Since in the worst-case scenario 3rd, 5th and 7th harmonic currents generated by two pulse rectifier(line side converters) of the locomotive are dominant during simulation, single tuned passive filter is required to suppress each of this harmonic currents. Moreover, a high pass filter also included to address resonance problem at high frequency range. Therefore, Series RLC circuits were tuned to the 3rd , 5th and 7th harmonic orders, and a broadband filter was set to reduce all the harmonic order above as illustrated in figure 5.1.

The following steps are taken to design the passive filters of this work:

Step 1: With the application of passive filter, the power factor is assumed to be improved from its initial given value of 0.95 to 0.989.

Step 2: Total kVAr to be supplied by the filter, which is the difference between kVAr requirement before and after application of filter is calculated.

Mathematically,

$$\begin{aligned}\Delta Q_C &= P[\tan(\cos^{-1}(0.95)) - \tan(\cos^{-1}(0.989))] \\ &= 1583kVAr\end{aligned}$$

Step 3: This reactive power is distributed in the filter elements to ensure that all of them will provide a certain amount of reactive compensation. This part is done initially by giving equal amount of reactive power and then adjustment is made with a great deal of simulation work. Finally, the following values of reactive power (Q_C) and quality factor (Q) are selected for each branch as shown in the Table 5.1 below. The quality factors in this analysis are considered in the range of 20 up to 100 for single tuned (band pass) filters and from 2 up to 10 for damped filter.

Table 5.1 : Reactive power and quality factor values used for simulation

h	3rd	5th	7th	9th
$Q_C(MVA)$	0.626	0.2925	0.2925	0.372
Q	100	85	90	10

Step 4 Based on the above table (Table 5.1) and using equations from 2.24 up to 2.28 the filter elements of each branch is calculated as follows

For h=3,

The capacitor reactance at fundamental frequency, $X_C = \frac{kV^2}{Q_C} = \frac{25^2}{0.626} = 998.4\Omega$

$$\Rightarrow C = \frac{1}{2\pi f X_C} = \frac{1}{2\pi * 50 * 998.4} = 3.2\mu F$$

The reactor size trapping the harmonic, $X_L = \frac{X_C}{h^2} = \frac{998.4\Omega}{9} = 110.9\Omega$

$$\Rightarrow L = \frac{X_L}{2\pi f} = \frac{110.9\Omega}{2\pi * 50HZ} = 0.352H$$

The characteristic reactance is $X_n = \sqrt{\frac{L}{C}} = \sqrt{\frac{0.352H}{3.2\mu F}} = 331.7\Omega$

$$\Rightarrow R = \frac{X_n}{Q} = \frac{331.7\Omega}{100} = 3.32\Omega$$

For h=5,

The capacitor reactance at fundamental frequency,

$$X_C = \frac{kV^2}{Q_C} = \frac{25^2}{0.2925} = 2136.75\Omega$$

$$\Rightarrow C = \frac{1}{2\pi f X_C} = \frac{1}{2\pi * 50 * 2136.75} = 1.4\mu F$$

The reactor size trapping the harmonic, $X_L = \frac{X_C}{h^2} = \frac{2136.75\Omega}{25} = 85.47\Omega$

$$\Rightarrow L = \frac{X_L}{2\pi f} = \frac{85.47\Omega}{2\pi * 50HZ} = 0.272H$$

The characteristic reactance is, $X_n = \sqrt{\frac{L}{C}} = \sqrt{\frac{0.272H}{1.4\mu F}} = 440.83\Omega$

$$\Rightarrow R = \frac{X_n}{Q} = \frac{440..83\Omega}{85} = 5.19\Omega$$

For h=7,

The capacitor reactance at fundamental frequency, $X_C = \frac{kV^2}{Q_C} = \frac{25^2}{0.2925} = 2136.75\Omega$

$$\Rightarrow C = \frac{1}{2\pi f X_C} = \frac{1}{2\pi * 50 * 2136.75} = 1.4\mu F$$

The reactor size trapping the harmonic, $X_L = \frac{X_C}{h^2} = \frac{2136.75\Omega}{49} = 43.61\Omega$

$$\Rightarrow L = \frac{X_L}{2\pi f} = \frac{43.61\Omega}{2\pi * 50HZ} = 0.139H$$

The characteristic reactance is, $X_n = \sqrt{\frac{L}{C}} = \sqrt{\frac{0.139H}{1.4\mu F}} = 315.1\Omega$

$$\Rightarrow R = \frac{X_n}{Q} = \frac{315.1\Omega}{90} = 3.5\Omega$$

For h≥9,

The capacitor reactance at fundamental frequency, $X_C = \frac{kV^2}{Q_C} = \frac{25^2}{0.372} = 1680.1\Omega$

$$\Rightarrow C = \frac{1}{2\pi f X_C} = \frac{1}{2\pi * 50 * 1680.1\Omega} = 1.89\mu F$$

The reactor size trapping the harmonic, $X_L = \frac{X_C}{h^2} = \frac{1680.1\Omega}{81} = 20.74\Omega$

$$\Rightarrow L = \frac{X_L}{2\pi f} = \frac{20.74\Omega}{2\pi * 50HZ} = 0.066H$$

The characteristic reactance is, $X_n = \sqrt{\frac{L}{C}} = \sqrt{\frac{0.066H}{1.89\mu F}} = 186.87\Omega$

$$\Rightarrow R = X_n Q = 186.87\Omega * 10 = 1868.7\Omega .$$

Table 5.2 Summarize the results obtained for each filter branch

Table 5.2: Passive filter elements

Filters	C (μF)	L (H)	R (Ω)
3rd	3.2	0.352	3.32
5th	1.4	0.272	5.19
7th	1.4	0.139	3.5
High pass	1.89	0.066	1868.7

5.2 Simulation Results with Application of Passive Filters and Discussion

In passive filter design of part, the reactive power compensation is discussed together with selection of filter elements. By these conditions, the simulations carried out under MATLAB/SIMPOWER environment show that the installation of three single tuned filters for third, fifth and seventh harmonics plus a high-pass filter for higher order harmonics would bring a significant improvement in %THD values of current and voltage at PCC, which is within the acceptable limits even in the most unfavorable situations.

Based on values given in Table 5.1 the filter elements are calculated analytically whereas MATLAB/SIMPOWERSYSTEM automatically assign the value of filter elements during simulation . The circuit diagram of the electric traction with application of filter is shown in figure 5.1.

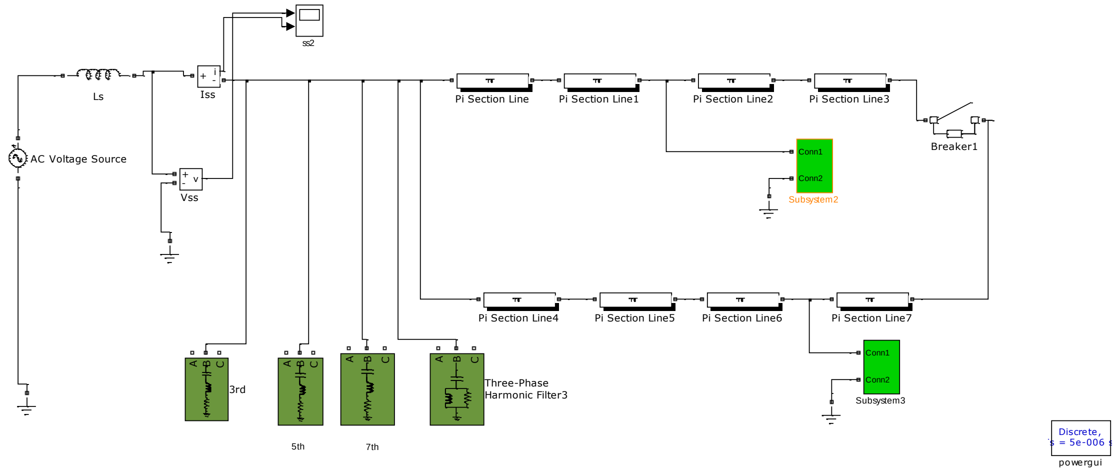

Figure5.1:Circuit diagram of the system under study in MATLAB/SIMPOWER environment [author]

Simulation results for the following unfavorable situations are given

- When each feeding section is loaded with a train (with full load) at their feeding section, Fig.5.1 and Fig.5.2 provide the result. This is to see how the worst voltage distortion that is observed before reduced within the limits (5%).
- When only one feeding section is loaded with a train at 3.38km from TSS, Fig.5.5 and Fig.5.6 shows the result. The aim of this simulation is to see how the worst case of single train with full load THD is reduced within the limit.
- When only one feeding section is loaded with a train at full load is located at the end of one feeding section, the result is illustrated in Fig.5.3 and Fig.5.4

Comparative analysis of THD values of current and voltage waveform are presented in Table 5.3, Table 5.4 and Table 5.5.

From Table 5.3, it is clear that with application of passive filter at LV side of TSS the THD of current and voltage are reduced by 34.04 % and 8.07% respectively. Moreover, the THD values of both current and voltage are below the recommended limit that is 5%

by 37.8% and 36.2% respectively. Added to this, Table c.1 comperes the individual distortion of the first three lower order dominant harmonics to show the improvement resulted due to the application of filters (see appendix C).

Table 5.3 : Comparison of %THD value of current and voltage for a train with full load at 3.38km from TSS simulation case

Conditions	%THD of current	%THD of voltage	Position of analysis
Without filters	37.15%	11.26%	PCC
With filters	3.11%	3.19%	PCC

As it can be seen from Table 5.4, the THD of current and voltage are reduced by 29.77 % and 6.92% respectively. Furthermore, the THD values of both current and voltage are below the recommended limit that is 5% by 18.2% and 43.6% respectively.

Table 5.4 :Comparison of %THD value of current and voltage for single train at the end of the feeding section simulation case

Conditions	%THD of current	%THD of voltage	Position of analysis
Without filters	33.86%	9.74%	PCC
With filters	4.09%	2.82%	PCC

As it can be seen from Table 5.5, the THD values of both current and voltage are below the recommended limit that is 5% by 2.2% and 9.4% respectively.

Table 5.5: Comparison of %THD value of current and voltage for the case two train at end of feeding section

Conditions	THD of current	%THD of voltage	Position of analysis
Without filters	29.14%	15.79%	PCC
With filters	4.89%	4.53%	PCC

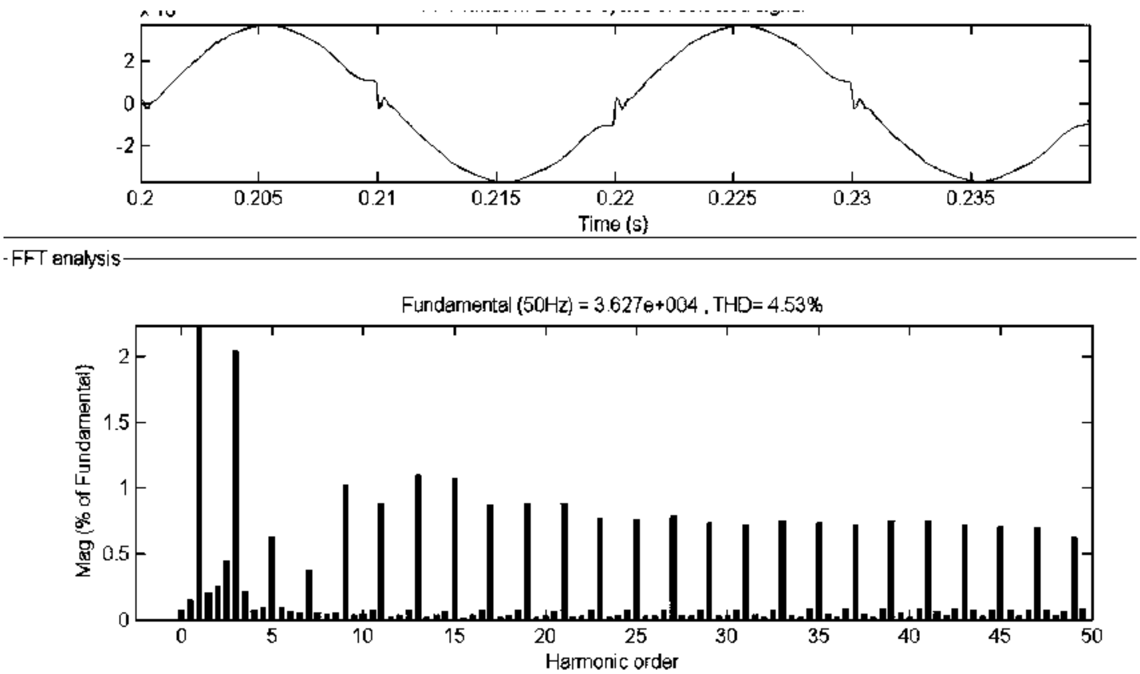

Figure 5.2: Voltage waveform and its harmonic spectrum at PCC when two train with full load is located at feeding end of each section of the double track

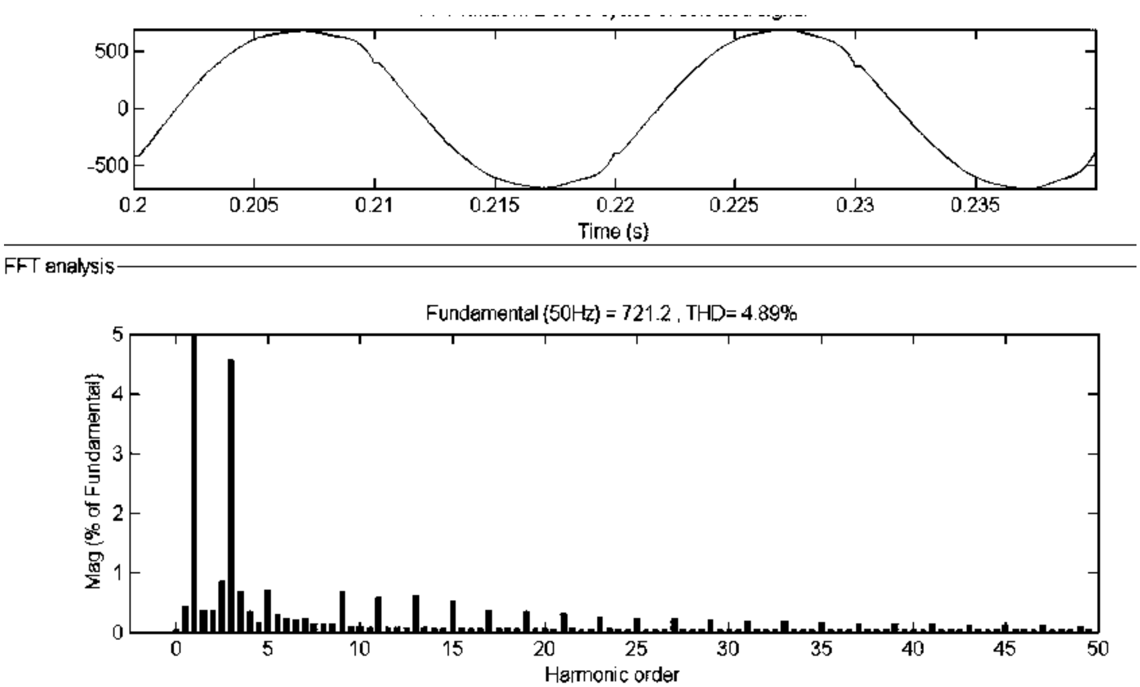

Figure 5.3: Current waveform and its harmonic spectrum at PCC when two train with full load is located at feeding end of each section of the double track

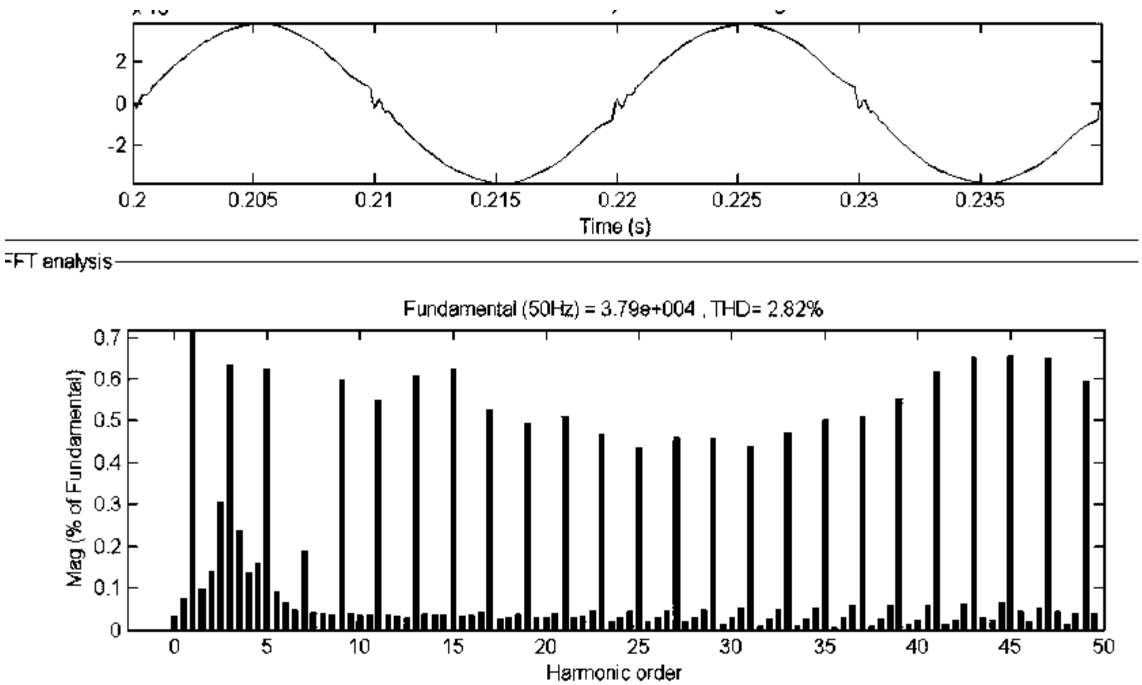

Figure 5.4:Voltage waveform and its harmonic spectrum at PCC when a train with full load is located at feeding end of one section.

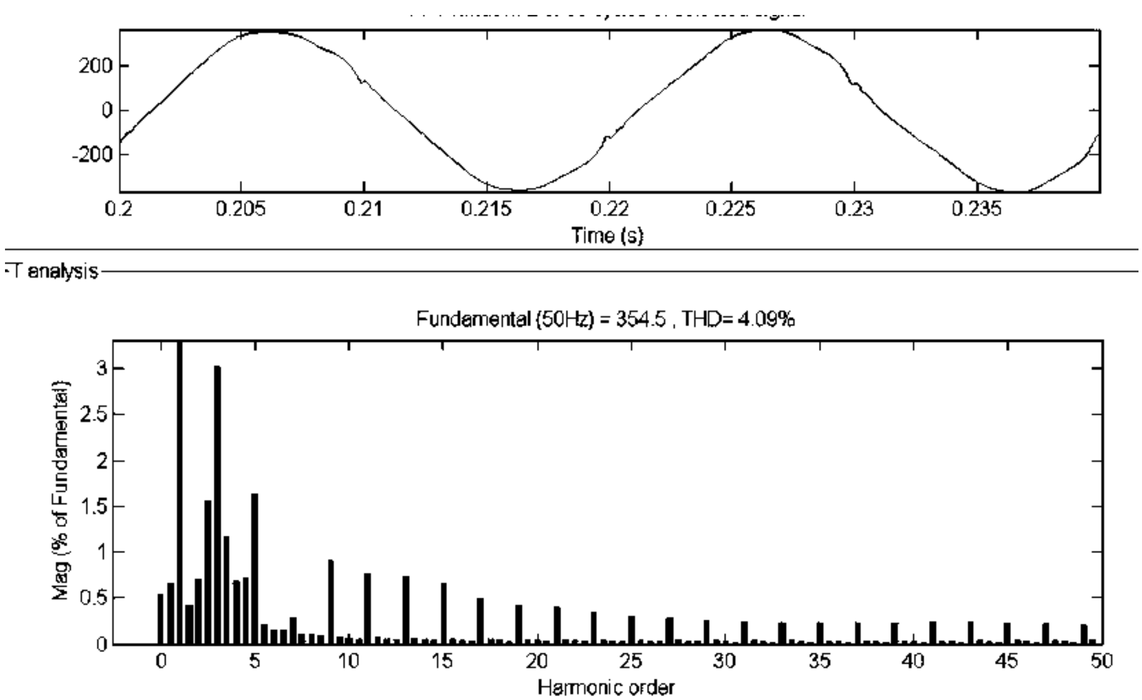

Figure 5.5: Current waveform and its harmonic spectrum at PCC when a train with full load is located at feeding end of one section.

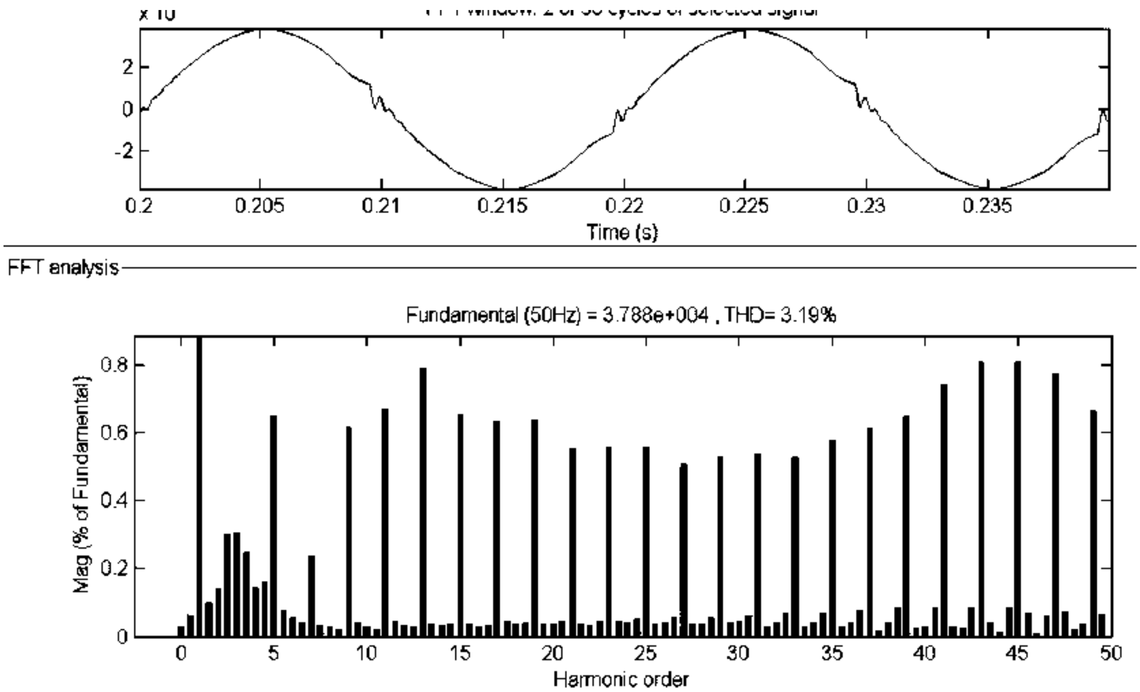

Figure 5.6: Voltage waveform and its harmonic spectrum at PCC when a train is located at 3.38 km from TSS of one section

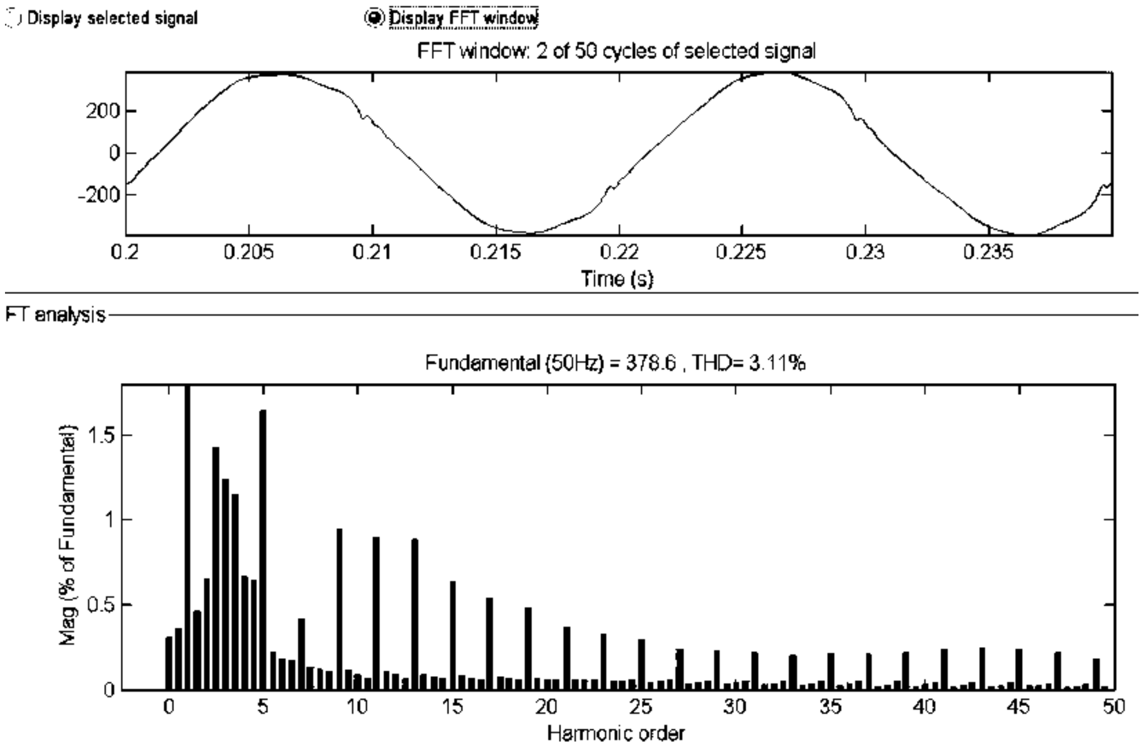

Figure 5.7: Current waveform and its harmonic spectrum at PCC when a train is located at 3.38 km from TSS of one section

From Table 5.3, Table 5.4 and Table 5.5, it is clear that in addition to satisfying the constraints ($\%THD_v \leq \%THD_v$ limit of IEEE 519; $\%THD_I \leq \%THD_I$ limit of IEEE 519) the allowable THD of voltage requirements of EN 61000-3-6 (6.5%) for electric traction systems with voltages between 1kV and 35kV, in percent of the operating voltage in terms of EMC also satisfied. Table B.1 of appendix B shows the allowable harmonic voltage distortion requirements of EN 61000-3-6 [29].

Table 5.6 shows comparison of the first three order even harmonics with the allowable harmonic voltage distortion requirements of EN 61000-3-6 and EN50160(Maximum values of individual even harmonic voltages at the supply terminal in public distribution networks).

Table 5.6: Comparison of the first three order even harmonics with the allowable harmonic voltage distortion requirements of EN 61000-3-6 and EN50160

Harmonic order	Simulation result with filter	% of nominal Voltage EN50160	% of nominal Voltage EN 61000-3-6
2	0.14	2%	1.6%
4	0.14	1%	1%
6	0.05	0.5%	0.3%

From Table 5.6 it can be seen that the even harmonics analyzed at PCC satisfied the harmonic voltage distortion requirements of EN 61000-3-6 and EN50160.

5.3 Goals Achieved in This Work

The author believes that after harmonic analysis is made relying on the model of the system developed in this thesis the following major goals have been achieved in the electric traction system under the study:

- The voltage and current distortion are quantified for different scenarios
- Fulfilling the requirement of IEEE 519-199.Which is harmonic limit standard for any power system voltage between 120V and 69kV this shows power quality improvement.
- Fulfilling the requirement of EN 61000-3-6, Harmonic distortion for electric traction systems with voltages between 1kV and 35kV, in percent of the operating voltage, Total harmonic distortion (THD) is limited to 6.5% to satisfy EMC issue (see appendix B). This reveals EMC improvement of electric traction system.
- Reduction of the additional power loss introduced due to harmonics currents.

CHAPTER SIX

6 CONCLUSIONS AND FUTURE WORK

6.1 Conclusion

This thesis presents problems in power quality issues of railway power supply system, especially harmonic pollution. In order to analyze harmonics, the proposed Ethiopian single-phase 25kV AC electrified system is considered as case study. The scope of this paper is narrowed studying voltage and current distortion in the Sebeta TSS feeding section due to harmonics injected by the traction loads. In addition, providing a concrete mitigation technique is part of this work.

A detailed literature survey of 25kv AC Electrification system and the fundamentals of harmonic studies together with related issues such as adverse effect of harmonics, methods of harmonic analysis and harmonic monitoring issues are reviewed and presented to summarize the state of the art techniques that are correlated to the methods proposed in this research.

A model to represent the harmonic sources plays an important role in the research. Therefore, this research work have develop a model for major components of the traction system (traction substation, overhead contact line and traction load) in terms of literature and the assumption made during the formulation of the model to make the simulation and modeling simpler without losing critical data. In addition, an overall traction power-supply system has been built to meet the requirement of the studies.

In this research, a series of deterministic simulations have been performed to investigate the harmonic levels under certain conditions. Thus, harmonic levels have been quantified for certain operational conditions. Traction load line side converter that is a single-phase nonlinear load was the main source of harmonic currents. As this current harmonics injected from an electric train propagate through power-feeding circuits, which in turn produced continuous distortion of voltage and current waveforms.

In this research, harmonic analyses have been made both at PCC and at loading point based on three different scenarios these are locomotive with full load, locomotive with half load and change in position of locomotive from traction substation. Added to this, plots of waveform and harmonic spectrum at PCC and loading point are provided for both current and voltage.

During harmonic analysis with computer simulation, it has been seen that with two-pulse power converter of the locomotive (AC/DC single-phase converter) all odd harmonics are generated. Also, as the harmonic number increase, the individual harmonic distortions of current and voltage waveform become lower due to increasing impedance presented to higher frequency components by the overhead catenary system inductive reactance. Therefore, typically for two-pulse rectifier, the third harmonic component was the highest.

The current and voltage distortion in general, have been varied with position of electric locomotive, the load characteristics of the locomotive and train traffic. From simulation results obtained in chapter 4, it can be conclude that the % THD of voltage at PCC decreases with increase in distance of locomotive from TSS, increases with increase in loading of the locomotive and increase with train traffic. During simulation in worst-case scenario for voltage, distortion at PCC a THD of 15.79% was observed that is around 63.3% higher than the limit recommended by IEEE 519 (5%).

In worst-case scenario for current distortion at PCC a THD of 45.26% was observed, which 88.95% above the recommended limit of (5%). In addition to this, individual current and voltage distortion of the most dominant harmonic orders were passed the recommended limit of IEEE 519 in the worst-case scenario. Generally, in all consider scenarios for simulation without filters the THD values of current and voltage waveform passes the acceptable limit set by IEEE 519. In account of all this result, it is possible to conclude that the power quality is poor in the absence of harmonic filters in the system.

This work have implemented HPFA from literature in order to characterize overhead contact line voltage distortion. In this regard, formulating the network impedance was required. Therefore, mathematical model for impedance of overhead contact line was developed based on two-port model for transmission lines. This modeling approach was adoption of literature and modified to develop a new one that works for our considered situation. The model was mainly intended to be used for calculation of OCS voltage distortion for most unfavorable simulated locomotive operating conditions.

The impedance of the overhead contact line as seen from the load terminal, affects both the voltage and current distortion. However, more importantly it was what will determine the amount of voltage distortion at the loading point (OCS voltage distortion) caused by the locomotive current. This is because the impedance of OCS as seen from load terminal was a function of both frequency and position of the locomotive from the TSS as it has been derived in chapter 3. Simulation result presented in chapter 4 shows that at a given frequency the OCS voltage distortion seen at the pantograph of the locomotive increases with increase in position of the locomotive from TSS.

In related to this, the comparisons of the simulation and the calculated results of OCS voltage distortion have been presented. The simulation results of the traction power-supply system have a good accordance with calculated results. The aim of the comparison was to verify that the proposed model of the railway supply network is reasonably accurate for harmonic characterization.

The proposed solution for harmonics mitigation in this work was based on passive power filtering. The analysis of passive filtering performances was made by simulation under MATLAB/SIMPOWER environment. Two filtering installations based on three single tuned filters and one high pass filters were taken into consideration in order to reduce the individual harmonics and the harmonic distortion factor of the current and voltage under the recommended limits of the IEEE 519 standard. The results of simulation after application of the proposed filters (Table 5.3,Table 5.4,Table 5.5 and Table 5.6) shows that the compensation technique allows respecting the standards even in the worst cases relating to harmonic distortion factor of voltage and the load current. Thus, the harmonic distortion at the points of common coupling would be within the required limits.

6.2 Recommendation

To maintain power quality in the proposed Ethiopian single-phase 25kV AC electric traction system, one of the major issues to be addressed should be the issue of harmonic distortion .In this regard, the Ethiopian railway corporation (ERC)

- must look first for preventive solutions aimed to avoid harmonics and their consequences or
- should be in position to take remedial solutions(techniques to overcome the existing problems)

Accordingly, it is possible to reduce adverse effects of harmonics on the traction equipment and to bring power quality improvement.

6.3 Future Work

The following issues need to be addressed furthermore in related to this work

- The effect of harmonic distortion on power supply equipment such as OCS, traction transformer (TTS), capacitors, reactors, etc.
- Effect of harmonic currents on the nearby telecomm cables (analysis of the EMI problem)
- Evaluation of filter capacitor duties (evaluating their contingency operation)
- Detail analysis of parallel and series resonance of the OCS including the contribution of passive filters, which most likely produce parallel resonance with source inductance.

APPENDIX A

IEEE 519 HARMONIC STANDARDS

The requirements of current distortion and voltage distortion of IEEE 519

Harmonic standard are given below for reference.

Table A.1: Shows the IEEE 519-1992 recommended voltage distortion limits.

Bus Voltage at PCC	**Individual Voltage Distortion (%)**	**Total Harmonic Distortion (%)**
69 kV and bellow	3.0	5.0
69KV - 161 kV	1.5	2.5
Above and 161KV	1.0	1.5

Table A.2 : Current distortion limits for general distribution systems (120 V through 69000 V)

Maximum Harmonics Current Distortion in Percentage of I_L					
Individual Harmonics Order (Odd Harmonics)					
I_{SC}/I_L	<11	$11 \leq h<17$	$17 \leq h<23$	$23 \leq h<35$	>35
<20	4.0	2.0	1.5	0.6	5.0
20-50	7.0	3.5	2.5	1.0	8.0
50-100	10.0	4.5	4.0	1.5	12.0
100-1000	12.0	5.5	5.0	2.0	15.0
>1000	15.0	7.0	6.0	2.5	20.0

APPENDIX B

EN 61000-3-6 HARMONIC STANDARD

The allowable harmonic voltage distortion requirements of EN 61000-3-6 are given below for reference

Table B.1 : EN 61000-3-6, Harmonic distortion for electric traction systems with voltages between 1kV and 35kV, in percent of the operating voltage

Odd harmonics, not multiples of 3		**Odd harmonics, multiples of 3**		**Even harmonics**	
h	IHD in %	h	IHD in %	h	IHD in %
5	5	3	4	2	1.6
7	4	9	1.2	4	1
11	3	15	0.3	6	0.3
17	1.6	21	0.2	8	0.4
19	1.2	>21	0.2	10	0.4
23	1.2			12	0.2
25	1.2			>12	0.2
>25	0.2+0.5*25/h				
Total harmonic distortion (THD) is limited to 6.5%, and inter-harmonic voltages are limited to 0.2%, per section 9 of the standard					

APPENDIX C

THE PERCENTAGE IHD VALUES OF CURRENT AND VOLTAGE AT PCC

The comparison of % IHD for current and voltage waveform at PCC is given here to show what improvement were brought by the filters in account of worst case scenario of single train with full load

Table C.1 :Comparison of IHD for current and voltage simulation results at PCC with out and with passive filters for mitigation of harmonics

	IHD of voltage in %		**IHD of current in %**	
h	Without passive filters	With passive filters	Without passive filters	With passive filters
3	8.55	0.30%	35.83	1.23%
5	3	0.65%	7.56	1.64%
7	2.17	0.23%	4.26	0.42%

SIMPLIFIED MODEL OF THE ELECTRIC LOCOMOTIVE

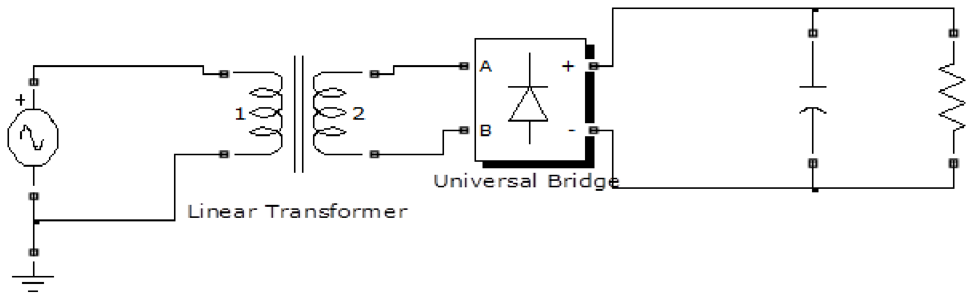

Figure C.0.1 : Simplified circuit model of AC locomotive

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