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AFRICAN RAILWAY CENTER OF EXCELLENCE

Power Quality Problem Investigation and Mitigation for Lebu - Adama AC Electrified Railway Line

A Thesis in Traction and Train Control

By

Tadele Lijalem

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A Thesis

Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science

The undersigned have examined the thesis entitled '**Power Quality Problem Investigation and Mitigation for Lebu - Adama AC Electrified Railway Line**' presented by **Tadele Lijalem**, a candidate for the degree of **Master of Science** and hereby certify that it is worthy of acceptance.

Dr. Mengesha Mamo ______________________ ______________________ ______________

Advisor Signature Date

______________________ ______________________ ______________

Internal Examiner Signature Date

______________________ ______________________ ______________

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I certify that the research work titled “Power Quality Problem Investigation and Mitigation for Lebu - Adama AC Electrified Railway Line” is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged/referred.

Tadele Lijalem

ABSTRACT

Power quality is the main concern in electric traction system due to the involvement of power electronic converters, transformers, and variable loads. It always requires an efficient, reliable and cost-effective power supply system. The Ethio-Djibouti railway line is a 752.6 km line runs from Addis Ababa, Ethiopia to Nagad, Djibouti, which is supplied by 25 kV, 50Hz AC overhead power supply. Power factor and reactive power problem have been recorded in the line from Lebu to Adama. The average power factor in August, 2018 was found to be 0.85 as well as the live record while the train was passing showed the power factor variation from 0.67 to 0.98. This thesis presents modeling, power quality assessment and improvement of traction power supply system for the case of Lebu to Adama railway line. Relevant data and parameters of traction power supply system's components have been collected to model the system and analyzed. Mathematical analysis and modeling of all major traction power supply system components; both constant and variable power models are done. The variable power model emulates the real phenomena of traction power fluctuation of running train. Train dynamics analysis is also undergone.

A STATCOM, that works with the algorism based on instantaneous active and non-active currents theory has been analyzed, modeled as a controller and applied to return good reactive power compensation, and enhancement of poor power factor while keeping line voltage in the prescribed range. It incorporates reference current generator, hysteresis band current controller as well as voltage source converter. Finally, the overall system, considering a static and dynamic power model, is simulated in MATLAB/Simulink environment and compared with the model of the existing system, without the introduction of the controller. As a result, 98.5 % of reactive power is compensated and power factor of 0.99 has been achieved throughout the course of motion after the inclusion of this technique.

Key Words: Ethio-Djibouti Railway line, Power quality, Dynamic power model, STATCOM, non-active current, MATLAB/Simulink

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ACRONYMS

AC	Alternating Current
DC	Direct current
EDR	Ethio-Djibouti Railway
ERC	Ethiopian railway Corporation
FACTS	Flexible AC transmission system
IEEE	Institute of Electrical and Electronics Engineers
IPFC	Interline Power Flow Controller
MC	Magnetic circuit
SSSC	Static Synchronous Series Compensator
STATCOM	Static Synchronous Compensator
SVC	Static VAR Compensator
SVG	Static VAR Generator
TCR	Thyristor-Controlled Reactor
TCSC	Thyristor-Controlled Series Capacitor
TCSR	Thyristor-Controlled Series Reactor
TCPST	Thyristor Controlled Phase Shifting Transformer
TCPAR	Thyristor Controlled Phase Angle Regulator
TCVR	Thyristor Controlled Voltage Regulator
TPSS	Traction power supply system
TSC	Thyristor-Switched Capacitor

TSR	Thyristor-Switched Reactor
TSSR	Thyristor-Switched Series Reactor
UPFC	Unified power flow controller
VSC	Voltage source converter

CHAPTER 1 INTRODUCTION

1.1 Motivation and Background

Electric Traction System uses electric power for its locomotion. That indicates the electrification system is used to supply electric power to railway trains or trams without any other on-board prime mover or fuel supply. Due to the enormous advantages including its high speed, high capacity, and low energy cost, electrified railway system have been constructed in the world widely.

In Ethiopia, electrified railway line is expanding in different regions of the country. As part of it, the new Standard-gauge Railway line, which connects Addis Ababa, the capital of Ethiopia, and NAGADA, the port of Djibouti, has been built replacing the century-old meter gauge. It is a 25 kV 50 Hz AC overhead line direct feeding system with return wire that restarted operation in January 2018. This 752.26 km long line paves the way to connect landlocked Ethiopia with the sea.

The electric power supplied should be reliable with good quality all the time. Power quality problems of traction power system, such as power unbalance, harmonics, and reactive power will result in extra line loses, under-voltage at the terminal of contact wire, and unbalanced current of the utility grid. The degree of the problem depends on the feeding electric railway traction loads, including train movement, tractive profile of electric locomotives, and power supply scheme. These problems present huge impact on the utility grid and the effective functioning of the railway [1].

Flexible Alternating Current Transmission Systems (FACTS) is used to alleviate power quality problems. FACTS Controllers can be divided into four categories which are Series Controllers, Shunt Controllers, Combined series-series Controllers, and combined series-shunt Controllers. Series controllers including Static Synchronous Series Compensator (SSSC), Thyristor-Controlled Series Capacitor (TCSC), Thyristor-Controlled Series Reactor (TCSR) and Thyristor-Switched Series Reactor (TSSR) inject voltage in series with the line whereas Shunt Controllers including Static Synchronous Compensator (STATCOM), Static VAR Compensator(SVC), Static VAR Generator (SVG), Thyristor-Controlled Reactor (TCR), Thyristor-Switched Capacitor (TSC), and

Thyristor-Switched Reactor (TSR) inject current into the system at the point of connection [2].

The combined series shunt controller that has multiple functional capabilities like a unified power flow controller (UPFC) can control the flow of real and reactive power by injection of a voltage. It is the most versatile of the FACTS controllers [3] even if it requires a complex control circuit. It is capable of performing simultaneously or selectively the compensation and control functions of different individual line compensators and controllers [4]. The cost of implementing this type of controller is huge.

This thesis focuses on the currently operating double track section of the Ethio-Djibouti line which runs from Lebu to Adama. Starting from Lebu up to Adama there are two traction substations named Endode and Mojjo. In this line, there have been problems related to reactive power and power factor that incurs unnecessary additional cost when the energy and power reading at Mojo and Endode Traction Substation in the last few months is taken as a sample. In this research, this traction power supply system is analyzed, modeled and simulated. Besides, those recorded power quality problems are alleviated by introducing STATCOM operating by the definition of Fryze's concept of active and non-active power theory.

1.2 Statement of Problem

The electric traction system requires efficient, reliable and cost-effective utilization of electric power supply. Unfortunately, it is susceptible to different power quality problems such as power unbalance, harmonics, voltage sag, reactive power, and poor power factor. This is because of the variation or fluctuation of load, involvement of various electric devices like transformer, voltage converters, line impedance and so on as well as the poor quality of supplied electric power. If there is a certain recoded quality problem, it should be controlled before leading to other problems.

Traction performances and the power supply conditions are better when there is no considerable amount of reactive power being drawn from the supply. This can lead to the system being overloaded with reactive power and thus unstable power supply operation in the feeding system [5]. The effects of reactive power flow in traction power supply networks include poor transmission efficiency, poor voltage regulation, low power factor and need of large-sized conductors [6].

In the Ethio-Djibouti railway line, the reading of energy meter for both real and reactive power shows a severe problem related to reactive power taking the sample of the month August 2018 at Mojjo and Endode Substation. At Endode, the total sum of real and reactive energy was 520,608.00 KWh and 300,960.00 KVarh respectively and at Mojo the reading was 427,680.00 KWh and 2,954,160.00 KVar respectively as indicated on the data shown in Appendix A. The live record of active power, reactive power and power factor at Endode substation shows also the power factor goes down up to 0.67. But According to Ethiopian Railway Corporation's design document the power factor at the substation should be greater than or equal to 0.95 [7]. The low power factor makes transmission line overloaded.

Currently, one passenger train and four freight trains are involved in the whole line per day. A single train will remain in one feeding traction substation like Mojo or Endode for about 55 minutes per day. That means every traction substation supplies power only for about 5hrs per day including the maintenance operation. It is expected that in the near future the service will be increased as the customers adapt and well informed about rail transport as an efficient means of cargo as well as passenger transportation. Thus, when the working hour doubled or tripled, the efficient use and transmission of energy becomes more important.

Reactive power compensation is an important issue in the control of electric power systems. Reactive power increases the transmission system losses and reduces the power transmission capability of the transmission lines. Moreover, reactive power flow through the transmission lines can cause large amplitude variations in the receiving-end voltage. At this point, comparatively the current good line voltage reading in the line will be altered as this high reactive power usage continues as it is. Thus, there should be a reactive power compensator that removes the flow of this power from the source to load and vice versa. The Power factor should be controlled to be close to unity (above 0.95).

1.3 Objectives

1.3.1 General Objective

The general objective is to model and analyze the traction power supply system of Lebu to Adama railway line and apply appropriate mitigation technique to improve the quality of power supplied.

1.3.2 Specific Objectives

- To investigate certain power quality problems of Lebu - Adama Railway line
- To model and analyze the traction power supply system of the railway line
- To introduce mitigation technique and improve the recorded problems
- To simulate the system using MATLAB and compare results with and without the introduced solution

1.4 Scope and Limitation of the Research

In this thesis, investigation of power quality problem and improvement considering the Lebu to Adama railway line is presented. Two types of traction power supply models, namely, static and dynamic models are presented. The model can be adapted to any other line which intended to focus on the analysis of AC traction power supply system. The power quality problem focused on reactive power and poor power factor is found and alleviated by selecting appropriate mitigation technique. The overall model has been simulated using MATLAB/Simulink. The simulation results consist of active power, reactive power, and power factor before and after mitigation technique is applied. STATCOM that is controlled based on active and non-active theory of instantaneous current is implemented as mitigation technique. The overall simulation results assure better traction power quality when compared to the model of the existing system. Besides, longitudinal train dynamics analysis and modeling are undergone to show the fluctuation of required mechanical power with the speed profile.

This Thesis also has its own limitation. The research work is accomplished based on the recorded data only. That means problem investigation, mitigation as well as modelling is performed using the available data. Due to this limitation, this work lacks to include all Scenarios involved in the line.

1.5 Methodology

The specified objectives are met while effective methods and procedures are being followed. The first task was reviewing pieces of literature including books, articles, and journals mainly related to longitudinal train dynamics, traction power system modeling, power quality issues of the electrified railway system and power factor improvement methods in traction system. Relevant data like record of line voltage, active and reactive energy reading, the train locomotive specifications, line impedance, and Substation parameters and real-time power flow reading have been collected. Active power, reactive power, power factor, line voltage and current recorded while the train was passing.

High reactive power energy consumption and poor power factor are recorded. Analyzing, international and national standards related to electric traction power quality followed by modeling of the existing system and simulate it in MATLAB/SIMULINK after performing mathematical analysis. Two types of traction power supply system modeling, static and dynamic power modeling are performed better representation of all traction system components like traction substation, catenary, and train load. Longitudinal train dynamics mathematical analysis is also performed to show how the variation of speed affects the required mechanical power.

Then the remedy is proposed and introduced to boost the quality of power. Modeling of the system and analyze the controller operation including mathematical analysis was the next task. STATCOM controlled by non-active current theory is introduced to both constant and variable power model of traction power supply system and simulation models are designed in MATLAB/SIMULINK 2018a.

Finally, the existing system with the integration of the introduced controller is simulated using MATLAB/SIMULINK and the results are compared with the original model.

The general methodology followed to accomplish this research is summarized as shown in the flow chart figure 1.

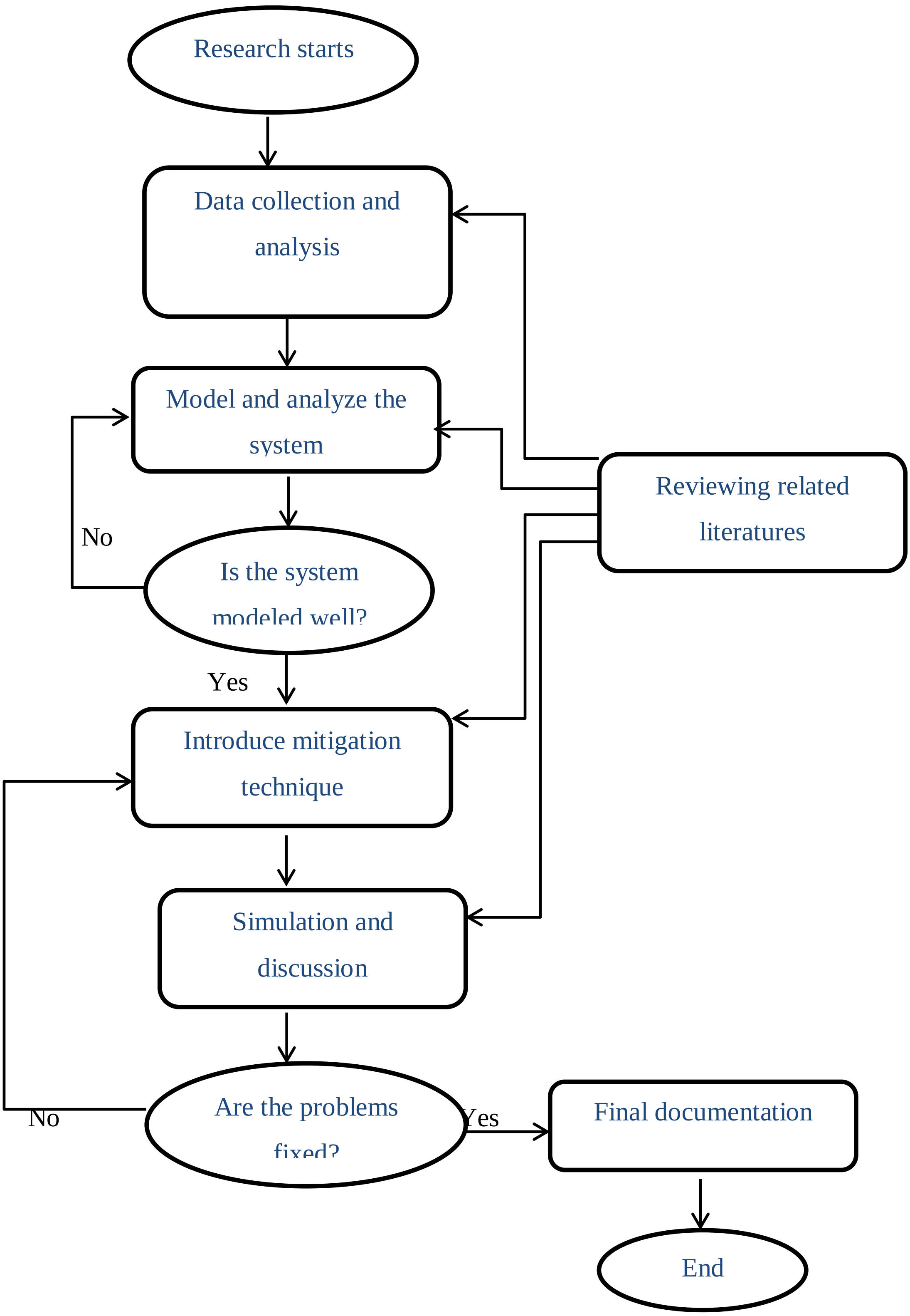
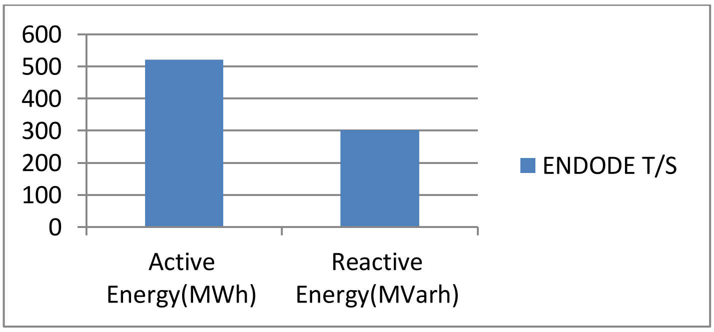


Figure 1-1: Flow chart of the overall methodology

1.6 Data Analysis

The double-track line of Ethio-Djibouti line covers from Sebeta to Adama which is around 115 km long. Currently, Lebu to Adama line, the focus area of this research, is functional. Endode and Mojjo traction substations are supplying the required power in the line. These substations are powered from Kaliti I, Akaki II, Nazreth II and Awash II substations of Ethiopian Electric Utility (EEU). The active and reactive energy meter readings have been collected from Ethio-Djibouti Railway Share Company (EDR) and the Figure 1-2 shows the summary of reading of August 2018. The collected row data is located in the appendix A.



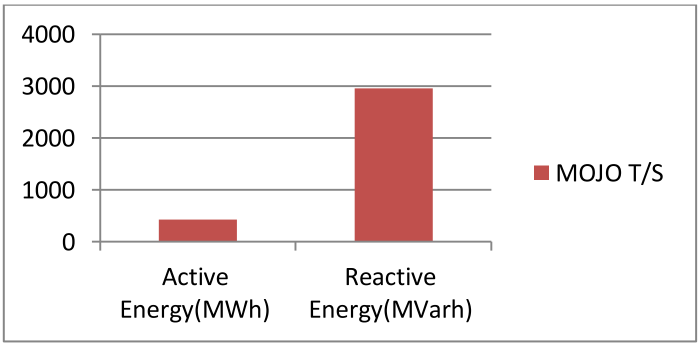


Figure 1-2: The active and reactive energy meter reading at Mojo and Endode traction substations in August, 2018

The above chart shows that there is a high reactive energy in both traction substations. This reveals that the reactive power generation is a severe problem in traction power supply system.

The recorded energy in Mojo traction substation shows the reactive energy is much greater than that of active energy and the average power factor based on energy meter reading in August, 2018 was below 0.2. Similar exaggerated results recorded as shown in the Appendix A, Table A-2. Thus, it needs diagnosis of the energy meter and the operating conditions in this station as it is difficult to undergo effective operation of traction power supply system. As this research work focuses on investigation of the problem and introducing effective mitigation technique, it failed to diagnose the cause of this much exaggerated reading of reactive energy.

The real-time recorded data indicating the value of voltage, current, active power, reactive power, is used for analysis and modeling in this research. The table shown in the Appendix A is generated from 15 minutes live recording of measurement at Endode traction substation while a train is moving from Lebu to Bishoftu. The sample is quantized in 30 seconds interval. The Figure 1-3 summarizes the measured power factor reading.

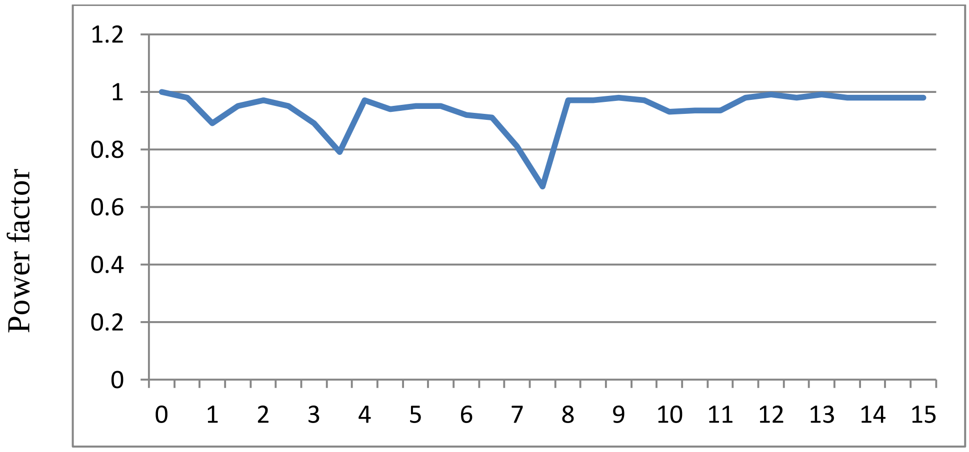


Figure 1-3: Power Factor Reading

The recommended power factor by ERC is 0.95 [7]. The power factor, indicates the efficiency of the load in utilizing the current drawn from the supply, has two parts. These are displacement and distortion power factors [8]. True power factor is the product of displacement and distortion factor.

$$P.F_{disp} = \mathbf{P} \Big/ \sqrt{\mathbf{P^2 + Q^2}}, \quad (1\text{-}1)$$

$$P.F_{dist} = \mathbf{1} \Big/ \sqrt{\mathbf{1 + THD_I}^2}, \text{ [9]} \quad (1\text{-}2)$$

The comparison between the true power factor which is measured directly and the displacement power factor calculated from measured active and reactive power is illustrated in the Figure 1-5.

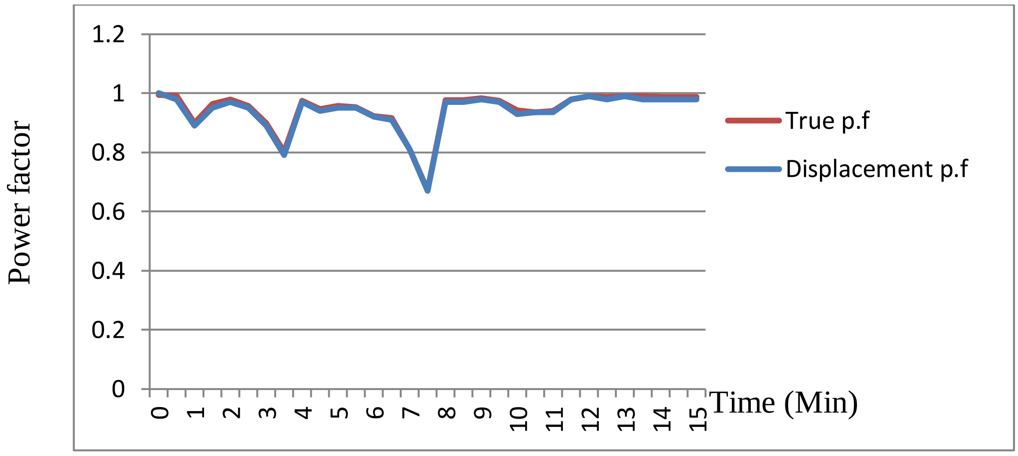


Figure 1-4: Comparison between true P.F and displacement P.F

In the network with low harmonics content, the displacement power factor is nearly equal to true power factor. Thus, it can be deduced that the harmonic content is low and the reactive power is the main cause for power factor reduction.

1.7 Organization of the Thesis

This thesis is organized in five chapters including this introductory chapter. It comprises chapters entitled as Introduction, Theoretical Background and Literature Review, Mathematical analysis and Modeling, Simulation results and Discussion as well as Conclusion and Recommendations.

The first chapter deals with the background of the study, statement of problem, objectives, and scope of the research, data analysis and the methodology of the research.

Chapter two outlines the main concepts and theories of an electrified railway line. It consists of the review of traction power supply system including different feeding arrangements. The power quality is defined and power quality problems with mitigation techniques are also discussed. Finally, the review of various pieces of literature related to the research work is discussed.

Chapter three focuses on the modeling of each component of traction power supply system. Substation, conductor line and train model including longitudinal train dynamics are presented.

Chapter four is dedicated to simulation results and discussions. It shows the results of simulation models and includes discussion on the results.

Chapter five draws overall conclusions for this research work and provides recommendations for future research work in areas related to modeling and power quality studies of electrified railway power supply systems.

CHAPTER 2 THEORETICAL BACKGROUND AND LITERATURE REVIEW

2.1 Review of Electric traction power supply system

In the history of an electrified railway system, which began in the nineteenth century, it has experienced remarkable development and, in every era, it promptly made the most of progress in electrical engineering, mechanical engineering, power electronics, and also automation, often creating an incentive for new technology research. Even though electric traction system requires huge investment, it has undisputed advantages in areas where levels of performance, safety, environmental compatibility, and economy of service must be guaranteed. The coverage of electrified railways is greater than 200,000 km, 17.2% of the global railway network [10]. The history of electric railways starts when T. Davenport fabricated a model electric car powered by voltaic cells 1835 [11].

The supply of electrified railways can be AC or DC supply. The common railway systems in the world are 3/1.5 kV DC voltage systems with the distance between substations 15-30 km, 0.6-1.4 kV DC low voltage systems with the distance between substations 1-6 km, AC 15kV/16.7Hz or 25kV/50Hz single-phase systems, and AC 25kV/50Hz three-phase systems [12].

DC supply is advantageous with modern power electronic traction control due to the compact size and weight of chopper and inverter drives. AC power to trains is economic for high-speed and heavy-haul railways. The high catenary voltage implies lower currents and smaller power losses, so fewer substations are required compared with the lower voltage DC traction networks. Commonly, low frequency, polyphase and standard frequency AC system are applicable. Low frequency reduces inductive voltage drop so that the number of substations required reduced. The polyphase AC system has not been widely applied due to the difficulty of power collection through pantograph or third rail of the rolling stock [13].

The basic structure of the DC and AC railway power system is represented as follows in figure 2-1.

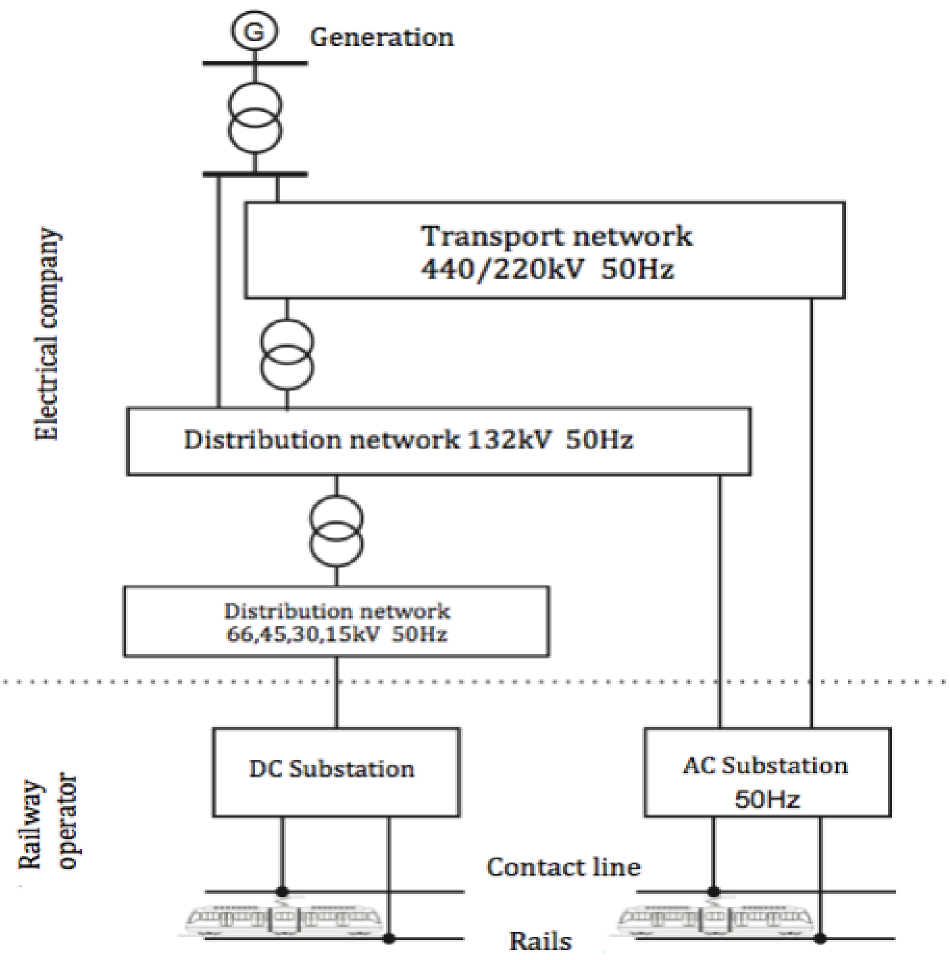


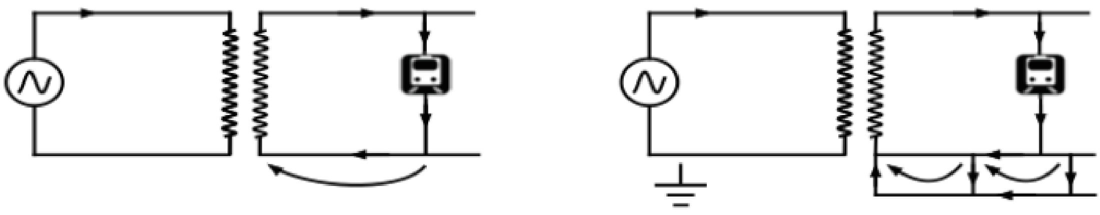
Figure 2-1: Structure of AC and DC railway power system [12]

2.2 Feeding Arrangements in AC traction power supply system

There are different feeding mode configurations of the AC traction power supply system. These are direct feeding configuration with and without return conductor, booster transformer and autotransformer power feeding system.

Direct Feeding Configuration

The direct feeding configuration is the cheapest and simplest way of supplying power. It is performed by the direct connection of the traction feed transformer to the catenary and rails of each substation. This configuration is disadvantageous since it has high feeding impedance with large losses, high rail-to-earth voltage and the earth currents that can cause interference in the nearby telecommunication circuits. A return conductor is added to provide lower impedance traction current return path and reduce the leakage current [12]. The Figure 2-2 illustrates direct feeding with and without return conductor.



(a). Direct feeding without return conductor (b). Direct feeding with return conductor

Figure 2-2: Direct feeding configuration without and with return conductor[12]

Booster Transformer Feeding Configuration

A Booster Transformer with unity turn ratio is installed every 4 km on the contact wire to boost the return circuit current on the negative line. As the current flows to the rail only in limited sections, the inductive interference on telecommunication lines will be minimized [13]. The primary is connected across a gap in the contact wire and the secondary is connected across an insulated rail section. The traction return current is forced from the rails and earth to flow through the transformer secondary.

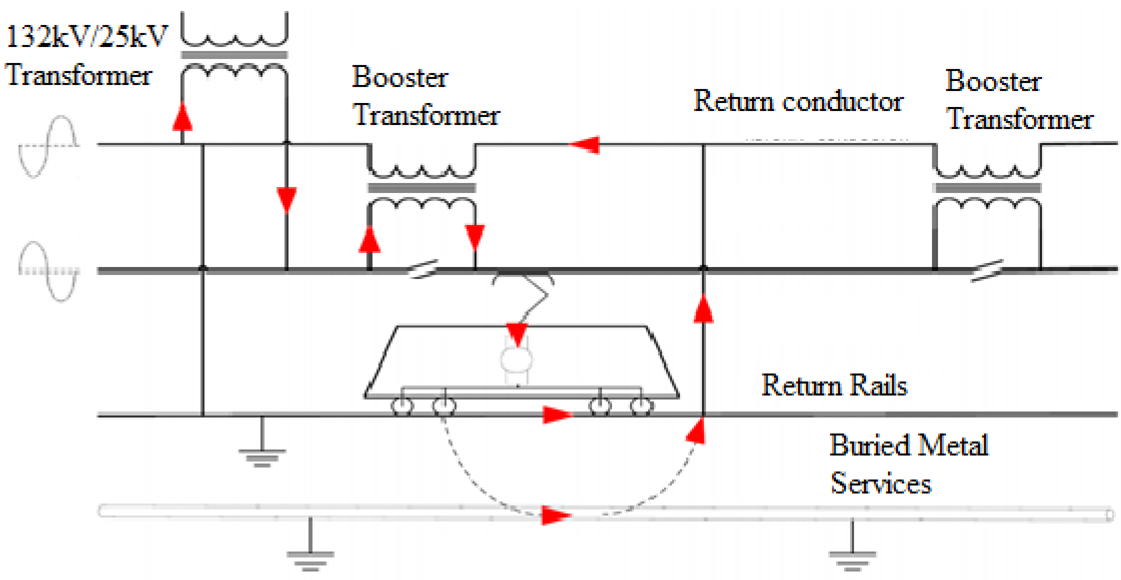


Figure 2-3: Booster Transformer Feeding Configuration [14]

Autotransformer Feeding Configuration

New standards for the AC electrification system are developed and more countries included ATs in their railway systems after AT was installed in Japan in 1972, and starting from 1981. This system was pioneered at Philadelphia in the US in the early 20th century, using 36kV transmission and 12kV supply [14]. It combines the advantage of higher voltage power transmission with the benefit of using standard 25 kV/50 kV equipment. The autotransformers along the catenary line are used to balance the voltages between the catenary and the earth, and the negative phase conductor and the earth, and then distribute the return current evenly between the two phases. As compared to direct and Booster Transformer feeding mode configuration, AT feeding mode has Lower losses due to higher voltage, longer distance between catenary feeder substations as well as better collection of returning stray currents [13]. Besides, it is also easier to maintain since the configuration allows separating a lot of substations [12]. Figure 2-4 shows the autotransformer feeding configuration.

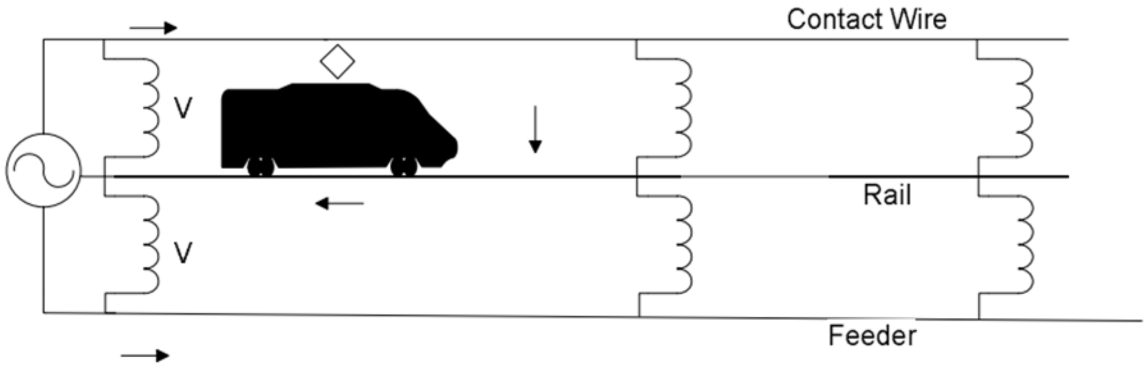


Figure 2-4: Autotransformer feeding model [13]

2.3 Power quality in Electrified railway system

Electrical Power quality can be expressed as the reliability of the supply that assures proper and efficient functioning of equipment. IEEE Standard defines power quality as the concept of powering and grounding sensitive equipment in a manner that is suitable for the operation of that equipment and compatible with the premise wiring system and other connected equipment [15]. Power quality, an important issue in all manufacturing and process control environment, can be referred to a wide area of parameters, such as voltage fluctuations, voltage and current imbalance, harmonics, reactive power and such that, between which the most problematic ones in case of railway industry are system unbalance, voltage/current harmonics and reactive power, [16] as has been explained more in the coming subsections. In railway systems, power quality has become an increasing concern.

The traction load is among the worst kinds of load for an electrical utility to supply. It is highly intermittent, irregular, low load factor (average load divided by the peak load in a specified period of time) and poor power factor. That is the moving characteristic of the train, the connection scheme, and type of single-phase load connected to the traction system, worsen the power quality feed by the utility. The severity of the problem is dependent on traction load which varies with the path the train travels, the loading of the train and the power supply configuration [1], [17], [18].

The impact of traction loads on the power grid system can be categorized with the following characteristics [19]:

- Power quality decline
- Produce additional loss, vibrations increase large and the heat increases in the internal of the rotation motors and the transformer and generators
- Increase system power loss, interfere with the normal operation of telecommunications equipment;
- Cause frequent start or lose the lock of the relay protection containing negative sequence components or composite voltage components, may causing the malfunction of phase-difference High-frequency protection and the protection of generator negative sequence current
- Harmonics may also trigger system inductors, capacitors resonance, and amplified the resonant, threat to the security of power grid.

The major power quality problems in the railway power supply system like Harmonics, System Unbalance, Reactive Power, Voltage problems, Arcing are discussed as follows.

Harmonics

Harmonics are voltage or current waveforms that operate at a frequency which is an integer multiple of the fundamental frequency. These are unwanted higher frequencies which superimposed on the fundamental waveform creating a distorted wave pattern. Harmonics are mainly caused by power supply switching circuits such as rectifiers, power converters, and thyristor power controllers as well as most non-linear electronic phase-controlled loads due to the fact that the controlled current drawn by the load does not exactly follow the sinusoidal supply waveforms. Thus, distortion creates a complex waveform made up of a number of harmonic frequencies which can have an adverse effect on electrical equipment and power lines. Figure 2-5 illustrates the effect of 5th harmonic.

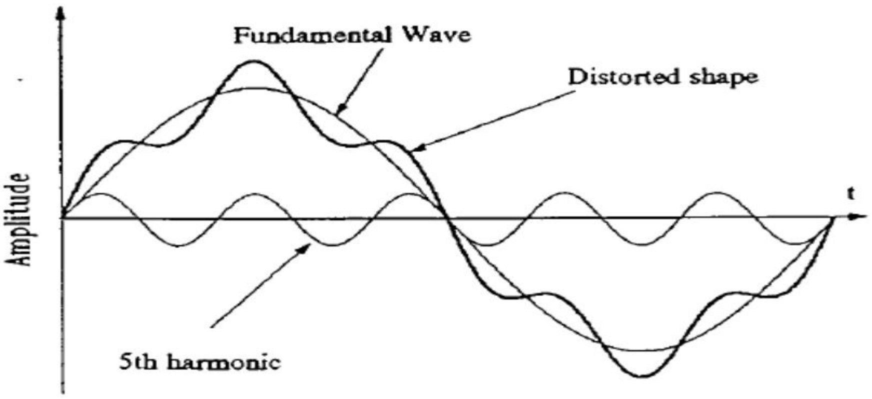


Figure 2-5: Fundamental sine wave with 5th harmonics [13]

In both AC and DC railway power supply systems, harmonic current may be produced due to the involvement of inverter, chopper, rectifier and different converters. Pulse width modulation controlled or thyristor controlled converters generate harmonic current. Thus, harmonic problem is also a concern in electric traction system.

Reactive Power

Reactive power is both the problem and the solution to the network of power systems. The existence of high reactive power causes voltage drop and heating of the line. It limits the amount of real power transferred in the network. Dynamic reactive power compensation controller can be realized by thyristor switching capacitor or other power electronic switches for electric traction power supply system since the static ones couldn't adopt in accordance with load changing nature of traction load in order to track compensation automatically.

System Unbalance

A balanced three-phase system has voltages and currents with equal amplitude and phase difference of 120^0. As most traction loads are supplied by a single-phase power supply system, it results in power unbalance. The unbalance affects not only the supply system's operation but also various devices connected to it. The voltage unbalance from the railway electrification load will have to be limited to one percent allowing for one percent ambient unbalance from other sources [13]. This problem can be mitigated using passive or active techniques. The passive one is applied by using different connection of transformer like Leblanc-connected, scott, or V/V connected transformers. Controllable high voltage power electronic equipment is used for active type of load balancing.

Even though Scott connection of transformer is costly and complex, it is capable enough to convert balanced three-phase to a balanced two-phase system using the arrangement shown in Figure 2-6b. Its high cost prohibited from implemented widely around the world [20]. Two single-phase transformers can also be connected as V/v configuration shown in Figure 2-6a. This configuration is not only simple in structure but also cheap in price. Extension of another feeding is required to balance the three-phase system and reduce voltage unbalance.

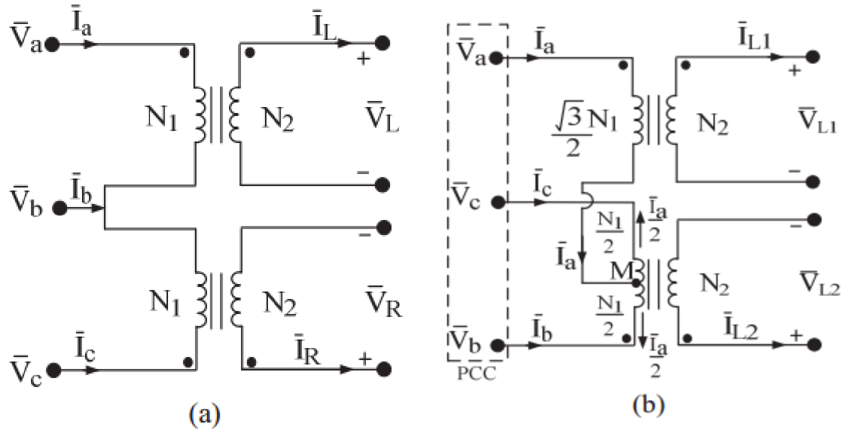


Figure 2-6: V/v and Scott connection of traction transformers respectively [20]

Voltage Variation

Unbalanced currents produce unbalanced voltages. The quick variation of the traction current results in sudden variation of voltage at the substation connection point and, to a lesser degree, on other utility busbars. The frequent problems of voltages are associated with their magnitudes [16]. Traction power supply system is subjected to voltage fluctuation including sag or swell as it encounters significant load change. Various power electronics-based controllers can be applied to maintain voltage value in a prescribed limit.

Arcing

Arcing occurs due to the interaction of pantograph and overhead line or between the shoe of the train and third rail since there is a variation in the air gap because of unavoidable mechanical oscillation. At the section isolators of overhead systems or ramps of third rail, arcs will frequently occur. It can distort voltage and current waveforms and produce unwanted transient DC component in the AC systems causing a breakdown of dielectrics [16].

2.4 Mitigation Techniques

Various power quality conditioners and compensation technologies have been developed to ensure a better quality of power for electrified railway system. Many ways of power quality improvement have been investigated and applied to be able to achieve a system with fewer problems to both AC and DC railway traction systems. Problems involved in traction systems are different from those found in other transmission lines or distribution systems working at the same voltage level. This is due to continuous movement of locomotive load, change in the length of the line during operation, and the high levels of harmonic distortion.

The Table 2-1 illustrates the ability of different compensation with more asterisks indicating better ability or high cost of the compensation strategy.

Table 2-1: Comparison of different controllers [16]

Compensation strategies	Harmonic Compensation	Imbalance Compensation	Reactive power Compensation	Total cost
Balanced Transformers		*		*
SVC		**	**	**
Passive Filter	*			*
APQC	**	**	**	***
HPQC	***	***	***	***

For effective controlling of system voltage, active and reactive power, there should be an understanding of relative importance of controllable parameters. These are the phasor difference between end voltages, line impedance, and the phase angle. The relative importance of those controllable parameters is discussed below [2].

- Control of the line impedance can provide a powerful means of current control.
- When the angle is not large control of line impedance or the angle substantially provides the control of active power.
- Injecting a voltage in series with the line, and perpendicular to the current flow, can increase or decrease the magnitude of current flow. Since the current flow lags the driving voltage by 90 degrees, this means an injection of reactive power in series can provide a powerful means of controlling the line current.
- Injecting voltage in series with the line and with any phase angle with respect to the driving voltage can control the magnitude and the phase of the line current. This requires injection of both active and reactive power in series.
- When the angle is not large, controlling the magnitude of one or the other line voltages can be a very cost-effective means for the control of reactive power flow through the interconnection.
- Combination of the line impedance control with a series Controller and voltage regulation with a shunt Controller can also provide a cost-effective means to control both the active and reactive power flow between the two systems.

2.5 Overview of FACTS Devices

Flexible Alternating Current Transmission Systems (FACTS) technology opens up new opportunities for controlling power and enhancing the usable capacity of present as well as new and upgraded lines. They are developed due to the advancement of power electronic technology and sophisticated electronic control method.

The possibility that current through a line can be controlled at a reasonable cost enables a large potential of increasing the capacity of existing lines with larger conductors, and the use of one of the FACTS Controllers to enable corresponding power to flow through such lines under normal and contingency conditions.

These controllers are mainly used to alleviate power quality problems in traction systems. FACTS can control the flow of current by controlling voltage drop, line impedance and/or angle [2]. There are different types of FACTS controllers like series, shunt, series-series and series-shunt controllers. Series controllers inject voltage in series with the line whereas shunt controllers inject current in parallel with the line into the system. Both can consume or supply variable reactive power if the injected voltage/current is in phase quadrature with the line current/voltage. A series-series controller is applicable for multiline systems. Combined series-shunt controllers utilize the operation of both series and shunt controller together.

Table 2-2: Type of FACTS devices [4]

Types of connection		Controlled Parameters
Shunt connected(SVC and STATCOM)		Q
Series connected(TSSC, TCSC, and SSSC)		P
Combined series and shunt connected	TCPST and TCPAR	P
	TCVR	Q
	UPFC and IPFC	P and Q

Series Controllers

Series FACTS devices might be variable impedance, such as capacitor, reactor, or power electronics-based variable source of main frequency and harmonic frequencies (or a combination) to serve the desired need. In principle, all series FACTS devices inject voltage in series with the transmission line.

The major applications of series controllers are [21]:

- Reduction of series voltage decline over a power line,
- Reduction of voltage fluctuations within defined limits during changing power transmissions,
- Improvement of system damping,
- Limitation of short circuit currents in networks or substations,

There are various types of series-connected controllers. Among them SSSC [2] and TCSC [21] are common ones and explained below.

Static Synchronous Series Compensator (SSSC) is a static synchronous generator operated without an external electric energy source as a series compensator whose output voltage is in quadrature with, and controllable independently of, the line current for the purpose of increasing or decreasing the overall reactive voltage drop across the line and thereby controlling the transmitted electric power. The SSSC may include transiently rated energy storage or energy absorbing devices to enhance the dynamic behavior of the power system by additional temporary real power compensation, to increase or decrease momentarily, the overall real (resistive) voltage drop across the line.

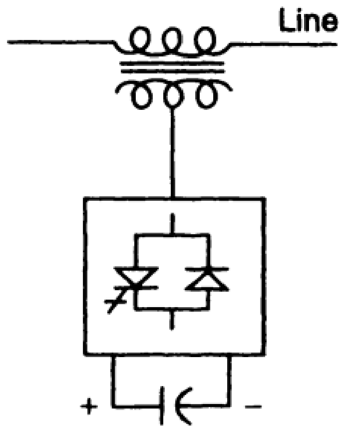


Figure 2-7: General scheme of SSSC [2]

Thyristor Controlled Series Capacitors (TCSC) is also another type of series-connected controller. It has a series capacitor bank shunted by a Thyristor controlled reactor in order to provide a smoothly variable series capacitive reactance. The main principles of the TCSC concept are to provide electromechanical damping between large electrical systems by changing the reactance of a specific interconnecting power line and to change apparent impedance the aims of the controller are achieved with the TCSC, using efficient control algorithms.

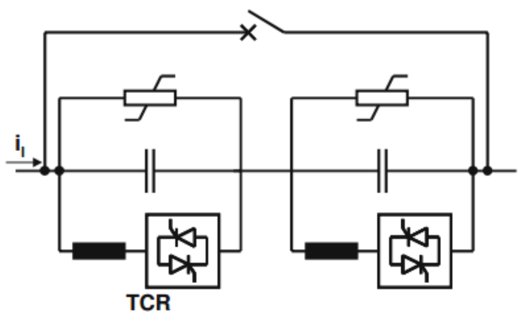


Figure 2-8: Thyristor Controlled Series Compensation (TCSC) [21]

Shunt Controllers

Shunt connected FACTS devices may be variable impedance, variable source, or a combination of these. They inject current into the system at the point of connection. Shunt compensation is used basically to control the amount of reactive power that flows through the power system. Both series and shunt controllers can be implemented with current-source or voltage-source converters.

The main applications of those shunt connected controllers in various areas of power system networks include [21]:

- Reduction of unwanted reactive power flows and therefore reduced network losses,
- Improvement of power quality especially for high load fluctuation demand areas like industrial machines, metal melting plants, railway or underground train systems with good reactive power compensation
- Compensation of Thyristor converters in conventional HVDC lines as well as improvement of static or transient stability.

The shunt controllers have got extensive use and popularity as FACTS controllers due to simple, cost-effective solutions in load compensation as well as their design to ride through dynamic overloads, and short circuit currents.

SVC and STATCOM are among the main shunt controllers.

Static Var compensator (SVC) is a static Var generator whose output is varied to exchange capacitive or inductive current so as to maintain or control specific parameters of the electric power system, typically bus voltages according to IEEE and CIGRE. In comparison to mechanically switched capacitors (MSCs) or mechanically switched reactors (MSRs), usually connected at a high voltage bus, the SVCs have a very rapid reaction and good reliability. The most popular configurations for continuously controlled SVCs are the combination of either fixed capacitor-thyristor controlled reactor (FC-TCR) or thyristor switched capacitor-thyristor controlled reactor [22]. By using power thyristors, the static compensators present many advantages from several points of view, such as high reaction speed, insignificant contribution to the short-circuit power, and low maintenance. The static compensator overcame mechanical commutation problems [4].

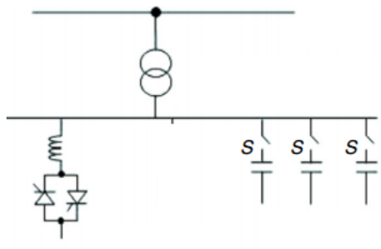


Figure 2-9: SVC with TCR structure [22]

A Static Synchronous Compensator (STATCOM) is also the most common shunt controller that can act as a regulating device on alternating current electricity transmission networks. It is based on a power electronics voltage-source converter and can act as either a source or sink of reactive AC power to an electricity network. If connected to a source of power it can also provide active AC power. Static shunt compensation influences the natural electrical characteristics of the transmission line to increase the steady-state transmittable power and to control the voltage profile along the line. In principle, all shunt-type controllers inject additional current into the system at the point of common coupling (PCC) through the means of a voltage source converter [23].

STATCOM can provide full capacitive output current at any system voltage, practically down to zero, in contrast with the SVC which can supply only diminishing output current with decreasing system voltage as determined by its maximum equivalent capacitive admittance. Furthermore, STATCOM may have an increased transient rating in both inductive and capacitive operating regions, whereas the conventional SVC has no means to transiently increase the Var generation since the maximum capacitive current it can draw is strictly determined by the size of the capacitor and magnitude of the system voltage.

The terms “compensator” and “synchronous” indicate that the device is equivalent to an ideal synchronous generator, which produces a set of three-phase fundamental frequency sinusoidal voltages. “Static,” mainly implies it is applicable without moving parts which are power electronic components [4].

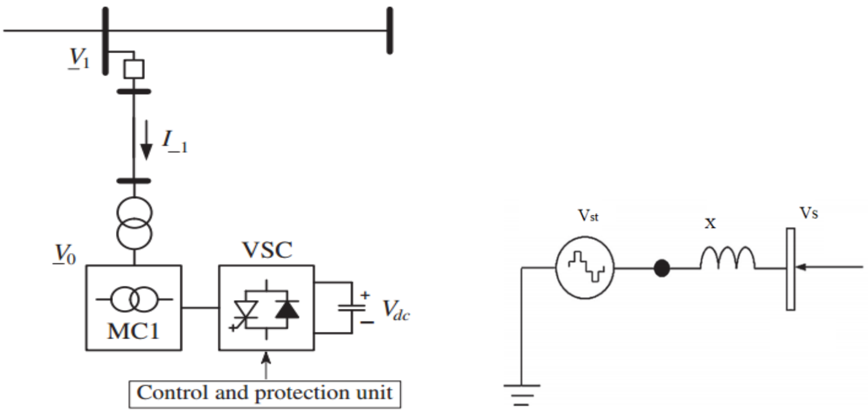


Figure 2-10: General scheme and equivalent circuit of STATCOM [4]

The current and reactive power transferred can be expressed as:

$$I_t = \frac{V_{st} - V_s}{X}, \tag{2-1}$$

$$Q_t = \frac{V_{st}^2 - V_{st} * V_s \cos\alpha}{X}, \tag{2-2}$$

where, I_t and Q_t are the current and reactive power transferred to the line from the STATCOM respectively; α is the angle between the AC side voltage of STATCOM and line voltage.

Comparison of SVC and STATCOM

Compared to SVC and other conventional reactive power compensators, STATCOM has several advantages listed below [2], [22], [24]:

- STATCOM has a dynamic performance than the other Var compensators.
- The overall system response time of STATCOM can reach 10 milli seconds or less.
- STATCOM has the ability to maintain full capacitive output current at low system voltage.
- Large capacitor bank including its protection and switching equation is not required for STATCOM configuration
- Sized reduced by 30-40% of SVC

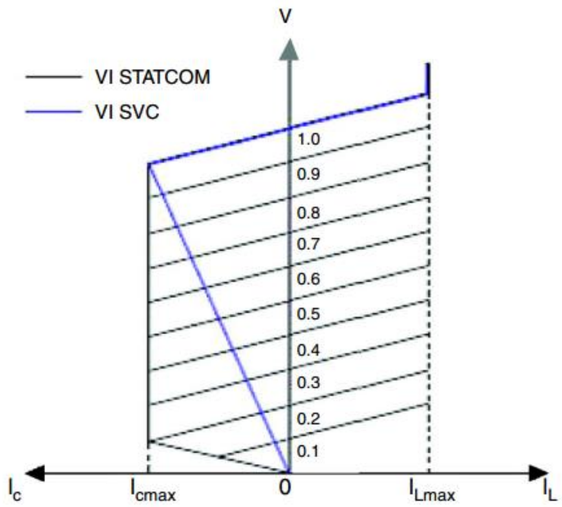


Figure 2-11: VI curve of SVC and STATCOM [22]

As shown in Figure 2-11, STATCOM can continue to supply the full rated reactive current to the system even at lower voltage value. The output current is independent of the system voltage, whereas the compensating current of the SVC decreases linearly with the system voltage.

2.6 Literature Review

Power quality is the major concern in electrified railway system since it generates various quality problems due to the incorporation of transformers, motors, line impedances, and different converters as well as its moving nature. These quality problems include voltage fluctuation, low power factor, poor power flow control, voltage drop and the like that have an impact on even to its distribution network. There have been kinds of literature to give the remedy to these problems occurred in electric traction network. Many researchers tried to give remedies to those problems using various techniques. Literatures related to modeling of traction power supply system, power quality problems of traction system and mitigation techniques especially for reactive power is reviewed in coming sections.

Boullanger [25] models and simulates train power supply structure with the interaction of train traffic schedule. Train Power System Simulator is applied based on the existing Swedish Railway system. Modeling includes catenary, High voltage line, frequency converter station 50 Hz to 16.7 Hz and train model. The catenary model includes booster transformer and autotransformer configuration. All the models are static and don't consider the reality of time-variant nature.

Ho, Chi and et al [26] introduce the development of simulation and modeling of traction power supply system including the remark railway system simulation challenges. The train is modeled as passive impedance load consisting of resistance and inductance. The model describes deterministic and probabilistic simulation approach. Deterministic approach has detailed account of the electrical behavior of the power systems and trains whereas in probabilistic simulation approach considers the range of parameter variation on probabilistic basis skipping the tedious process.

Worku and Kebede [27] also present modeling, analysis, and simulation of 2 × 25 kV traction power supply system. It includes modeling and analysis of various subsystems like traction load, the substation power transformer, autotransformer, and the catenary line impedance. MATLAB simulation performed to undergone a comparative analysis with a direct power supply system in terms of voltage profile along the traction network by applying different headway distances on the trains and by increasing the number of trains along the feeding section. The result reveals the train voltages of both direct-fed and autotransformer fed traction network change with distance and the number of trains. But, the work shows the voltage profiles of autotransformer fed supply are always greater than that of direct-fed traction power supply mode. The autotransformer traction power supply system indicates fewer voltage variations over distance from the substation, which in turn decreases the number of traction substations.

Khambudda [20] studies direct feeding configuration of AC railway traction power supply system with simulation. It proposes different situation incorporating various speed and number of trains entertain at a time in the double-track railway line with five simulation scenarios. It starts from single train in both up and down track up to six trains operating in both tracks. Matpower cooperating with Matlab has been applied. The analysis was done focusing on voltage drop in each section at the stated five scenarios of simulation. Large voltage drop is found on the line with longer feeder line and/or more number of trains at a time. The paper didn't apply or recommend any mitigation technique to upgrade the recorded voltage sag.

Gazafrudi [16] highlights on power quality issues in railway electrification development and investigates the necessity of power quality and system requirements for appropriate power quality in a comprehensive perspective way including the comparison of compensation strategies. The most important power quality problems in electric railway systems like system imbalance, harmonics, reactive power, voltage problem, and arcing have been investigated.

Li, Xu and et al [28] apply power quality analysis system on Power system Analysis Software package (PSASP) in order to calculate harmonic current and voltage unbalance. PSASP comprises unified graphic and data support platforms, data entry, analysis and output of results for power quality analysis of electrified railway systems. Virtual nodes are used in the analysis system to make the two-phase traction power supply system and three-phase power system unified in topology so that three-phase calculation method can be used. The voltage unbalance is compared in different traction transformer specifically Scott, V/V, YND11 traction transformer. The results also reveal the voltage unbalance of scott wiring transformer is minimum and that of V/V is the highest with similar traction load.

Kiran and Laxmi [29] discuss the principles of shunt and series compensation techniques. The paper presents an overview of the reactive power and static VAR compensation technologies. Improvement of voltage regulation, transmission efficiency, and power factor is assessed considering a certain typical case study. The comparison of uncompensated line, series compensated and shunt compensated line has been carried out. According to the generated results, shunt capacitive arrangement highly reduces total active power loss and has better improvement of system power factor than that of series arrangement. The paper didn’t stipulate clearly its methodology.

Gebretinsae [30] aims to control power variables using Proportional integral (PI) controlled shunt connected Static Var Compensator (SVC). Firing angle control of the compensating device is continuous. Matlab Simulink is used to simulate the system. The terminal voltage is regulated to the rated value when the firing angle of the TCR is varied between 90^0 and 180^0. After compensation, it is shown that the reactive power loss is minimized and the voltage is kept 0.975 pu.

Kumari, Bihari, and et al [3], single machine infinite bus system model is developed using MATLAB Simulink. Unified power flow controller (UPFC) is used for real-time control and dynamic compensation of AC transmission system with multifunctional flexibility. It has basic operating modes of shunt converter mode to draw controlled current, reactive power control mode to correct reactive power and automatic voltage control mode for voltage regulation. The paper compares the Simulink model outputs of single machine infinite bus system with and without UPFC especially in terms of phase angle deviation. The comparison approves UPFC in single machine infinite bus system can stabilize unwanted deviations. The paper fails to clearly indicate the compensated reactive power level.

Dai, Lao and et al [6] apply hybrid railway power conditioner (HRPC) to reduce reactive power, relieve system unbalance and suppress harmonics by varying the operating voltage with the compensating currents over a wide range. Simulation models using PSCAD/EMTDC and small capacity HPRC prototype was built in the laboratory and testing results are also provided to verify the design and control method. The power factor, source current total harmonic distortion (THD) and current unbalance improved to 0.95, 9.1% and 26% from 0.76, 28.6% and 92.2% respectively after applying HRPC with full compensation.

Kannan, Jayaram and et al [31] presents a real and reactive power coordination controller. The problem of real power coordination between the series and the shunt converter control system as well as the problem of excessive Unified power flow controller bus voltage excursions during reactive power transfers requiring reactive power coordination has been addressed.

In [32], the implementation of STATCOM by the definitions of instantaneous active and non-active currents to calculate the non-active current in the load current to three-phase balanced RL load, three-phase unbalanced RL load, diode rectifier load and single-phase load is presented. The research was based on experimental testing. It shows the STATCOM can perform instantaneous non-active power compensation, and both the fundamental non-active component and the harmonics are eliminated from the utility so that nearly unity power factor can be achieved in all four mentioned cases. Thus, the paper demonstrates the theory of non-active current can be applied for power compensation of three-phase balanced or unbalanced RL load, a diode rectifier load, and a single-phase load.

In [22], [24], the advantage of STATCOM over the other shunt Controllers has been indicated.

As stated above, there have been so many researches on modeling traction power supply system and increasing the power quality of electrified railways through different techniques including applying flexible alternating current transmission system (FACTS) devices. The models implemented to represent the train are static and is not able to show the dynamic nature of the traction system. As there is also still a gap in alleviating those stated problems effectively, the area is open for efficient modeling of traction power supply system (TPSS) and investigating different approaches to mitigate traction power quality problems. This research tries to contribute its side as it come up with both static and dynamic models of traction power supply system considering the Erhio-Djibouti railway line. Besides, the reactive power is compensated and unity power factor is achieved by inclusion of STATCOM controlled by the theory of instantaneous non-active current.

CHAPTER 3 MATHEMATICAL ANALYSIS AND MODELING

In this chapter, mathematical analysis and modeling of train dynamics and mainly traction power supply system is presented. Modeling of train dynamics is aimed to show how the variations of the train's speed affect the required power. The longitudinal train dynamics analysis has done to find the resultant of all forces acting upon the train moving in a leveled track line including force due to acceleration and deceleration. The traction power modeling, which is the main concern, has been performed as explained in the coming sections of this chapter.

3.1 Train Dynamics Modeling

Various forces involved in a moving train. Longitudinal forces acting on a moving train includes:

- Rolling (Mechanical) resistance force (F_m)
- Aerodynamic resistance Force(F_{ad})
- Acceleration/deceleration Force (F_a)
- Force due to the gradient (F_g)
- Force due to curvature (F_c)

Rolling resistance and aerodynamic can be expressed using the Davis formula as quadratic equation as follows [33]–[36]:

$$F_R = A + BV + CV^2 , \qquad (3\text{-}1)$$

where A, B, and C are constants. A represents rolling resistance that doesn't depend on speed (V) of the train, BV represents the mechanical resistance dependent on both speed and weight of the train where CV^2 shows the aerodynamic resistance, highly dependent on speed.

The numerical values of constants A, B and C depend on the types of the rolling stock (Passenger/ Freight), wheel-rail friction as well as the atmosphere. Various railways have developed empirical formulas using Davis equation to get the numerical values of these parameters. Since the research focus is not to generate empirical formula for Ethio-Djibouti railway, this thesis work uses empirical formula developed by French railways as it has the flexibility to apply for different weight of the train as well as electric passenger train. The resistance force can be calculated as[33]:

$$F_R\left(\mathrm{N}\right)=\left(1.3\sqrt{10/m}+0.01*V\right)*M+CV^2, \tag{3-2a}$$

$$C=0.0035*A+0.0041\,p*l/100+0.002*N, \tag{3-2b}$$

where, M is total mass of the train (in tons), m is mass per axle (in tons), V is speed (Kilometer per hour), A is front cross-sectional area (in meter per second), p is partial perimeter of the train down to the rail level (in meters), l is train length (in meters) and N is number of raised pantographs.

Based on the document of rolling stock technical specification considering YZ25G hard seat passenger car [37], the rolling resistance force (in Newton) of the train with 4 axles having 118 passengers is expressed in terms of speed(km/hr) as:

$$F_R=74.86+0.75V+0.076V^2. \tag{3-3}$$

Force due to curvature and gradient

The other forces involved are force due to gradient and curves in the track line. The curve resistance depends on the friction between wheel flange and rail, the radius of curvature and the wheel slippage on the rails. This can be expressed as a function of mass and radius of curvature as[33]:

$$F_c=0.001K/R*M, \tag{3-4}$$

where, K can be 500 up to 1200 on average being 800 and R is a radius of curvature in horizontal plane (meters).

The effect of curve resistance is small when the radius of curvature is greater than 250 meters. The resistance due to gradient can be positive or negative based on whether the train is moving up to the hill or down respectively.

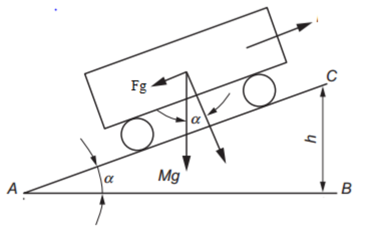


Figure 3-1: Gradient resistance force representation

The resistance force due to the gradient for gradient of 1 in X length inclined plane can be calculated as:

$$F_g = Mg\sin\alpha = {Mg}/{X}, \quad (3\text{-}5)$$

Force due to Acceleration/deceleration

This force arises due to the variation of train's speed during its motion. The train will accelerate at starting up to free-running speed and also decelerates to come to stop. There are also various speed variations through the course of motion due to the alignments of track line.

$$F_a = M_t * a, \quad (3\text{-}6)$$

where M_t is the summation of rotational and deadweight of the train and usually regarded as 1.1 times dead mass of the train (M).

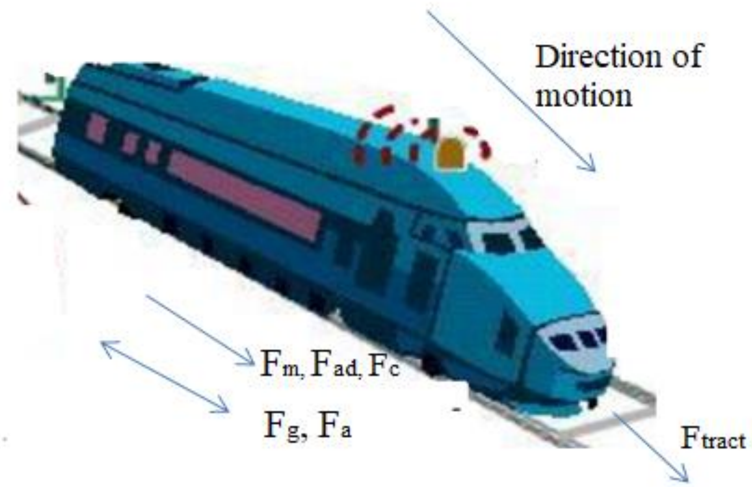


Figure 3-2: Forces acting on a moving train [Author]

Considering train motion in a leveled tack line, forces due to mechanical friction, aerodynamic drag, acceleration/deceleration as well as tractive force will be involved. The total tractive force required as a function of speed is therefore calculated using newton's second law of motion as shown below.

$$\sum F = M_t * a \, , \tag{3-7a}$$

$$F_{tract} - \sum F_{res} = M_t * a \, . \tag{3-7b}$$

From equation (3-3) and (3-7), the tractive force will be:

$$F_{tract} = 1.1Ma + 74.86 + 0.75V + 0.076V^2 \, . \tag{3-8}$$

Substituting the total train mass (M) and in terms of speed in m/sec, equation (3-8) can be rewritten as:

$$F_{tract} = 8.259 * 10^3 \frac{dv}{dt} + 74.86 + 2.7V + 0.99V^2 \, . \tag{3-9}$$

Speed –time curve

Depending on the resultant force acting on the train, the train will move with constant velocity, acceleration or deceleration. First, the tractive force applied is increased greater than the summation of all resistive forces so as to generate acceleration motion up to a speed required for free running. At constant speed period (during time t_2 in Figure 3-3) the tractive force will be equal to the summation of all resistive forces. Then considering the braking distance the braking force will be applied so that the train will decelerate and finally stops at the required station. There might be the coasting period before applying the braking force in which only the resistive forces acting on the train. The approximate speed time curve of the train that runs from Lebu to Adama showing accelerating, free running and decelerating period is shown in the Figure 3-3.

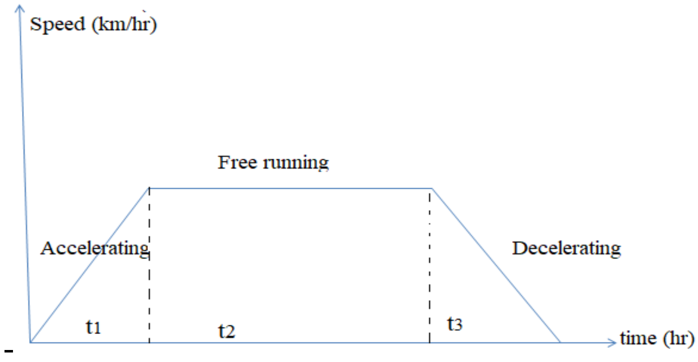


Figure 3-3: Speed profile (speed – time curve)

The passenger train in Ethio-Djibouti line departs from Lebu Station and stops temporarily in Adama station. The total distance covered is 93.55km. The maximum speed is designed to be 120 km/hr. The acceleration and deceleration values of the train has been chosen depending on the distance within which the train must attain maximum speed, braking distance as well as the type of rolling stock whether it is passenger or freight.

The maximum acceleration should not exceed 1.0 m/sec^2 to keep ride comfort [33]. Typical acceleration/deceleration values for various types of rolling stock are as shown in the Table 3-1 below.

Table 3-1: Values of acceleration and deceleration in various rolling stock [33]

Type of train		Acceleration (m/sec^2)	Deceleration (m/sec^2)
Freight	Conventional	0.2-0.4	0.1
	express		0.25
Passenger	intercity	0.4-0.6	0.4-0.5
	Suburban	0.6-0.8	0.6
	Metros	0.8-1	-

For this case, intercity passenger train the average recommended acceleration/deceleration value, is, therefore, suitable to be 0.4 m/sec^2.

The total time (t_1+t_2+t_3) elapsed to cover the whole distance can be calculated as follows:

$$t_1 = \frac{\frac{120km}{hr} - 0}{\frac{1.44km}{hrsec}} = 83.33sec,$$

$$t_3 = \frac{0 - 120km/hr}{1.44km/hrsec} = 83.33\ sec.$$

The distance traveled during acceleration, free running and deceleration time:

$$s_1 = s_3 = 0.5 * 120 * \frac{83.33}{3600} = 1.4km,$$

$$s_2 = 93.55 - 1.4 - 1.4 = 90.75km.$$

Then, the time taken to cover the free-running speed (t_2) and the whole distance will be:

$$t_2 = \frac{90.75}{120} = 0.756hr = 27.22sec.$$

Total time will be the summation of the time taken to cover these three sections which is around 2890 second (0.8hr).

3.2 Traction power supply system Modeling

An electrified traction system, both AC and DC, is composed of various components that need to be modeled in various ways depending on the aim of the study. The mathematical, as well as simulation models of Ethio-Djibouti line traction power supply system, are described in the following sections. The model includes the major traction powers supply system components like substation, feeder line, and the locomotive.

3.2.1 Substation model

The traction substation is responsible for the monitoring of the traction power supply system. It converts 132 kV line into 27.5 kV and equipped with efficient control and safety devices. V/v type traction transformer is installed and helps to minimize system unbalance problem usually occurred in traction systems.

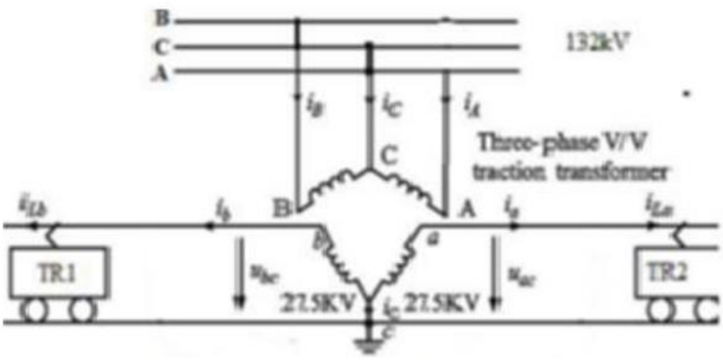


Figure 3-4: Configuration of V/V transformer [38]

The simplified representation of the substation including the Thevenin's equivalent circuit considering point A and B is as shown in Figure 3-2. It is represented by a series connection of infinite bus bar, which is ideal voltage source, with grid impedance and traction transformer.

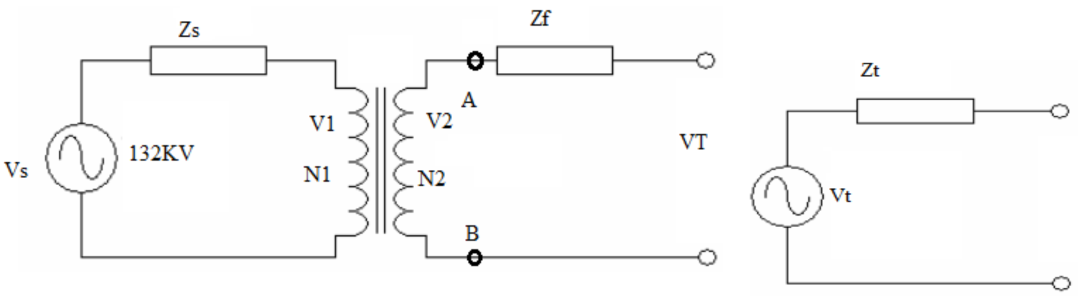


Figure 3-5: Simplified model of the substation and its Thevenine's equivalent circuit

The parameters of the Thevenin circuit are computed as follows.

$$V_T = V_2 = \frac{N_2}{N_1}V_1 = \frac{N_2}{N_1}V_s$$

$$I_{sc} = \frac{N_1}{N_2}I_1 = \frac{N_1}{N_2}\frac{V_s}{Z_s},$$

$$Isc = (N_1 / N_2)^2 V_t / Z_s \tag{3-10}$$

$$Zt = V_t / I_{Sc} = (N_2 / N_1)^2 Z_s = Z_s / a^2 \tag{3-11}$$

Where, $a = {}^{N_1}/_{N_2}$

I_1 is the current passing through the primary winding.

I_{sc} is the short circuit current through point A and B.

Z_s is the summation of the grid and transformer impedance.

Table 3-2: Transformer specification (nameplate data) [Author]

Rated power	(20,000+20,000) kVA
Rated voltage	132/27.5kV
Rated current	151.5/262.4/151.5A, 727.3/1259.7/727.3
Short circuit impedance	8.33%
No-load current	0.1 %
No-load loss	26.721 kW
Load loss	158.471 kW
Vector group	Vv0(Vv6)

Based on the reading of the traction transformer's nameplate data, located at Endode substation, per unit and actual impedance of the transformer is computed as shown below.

$$Rpu = R_{actual} / R_{base}, L(pu) = L_{actual} / L_{base}, Lbase = X_{base} / 2\pi f, \quad Z_{base} = V_{rated}{}^{2} / S_{rated} \tag{3-12}$$

Percentage impedance of a transformer is the percentage of the rated voltage applied at one side (primary side) to circulate rated current on timer kipping secondary winding under short circuit condition.

Considering S_{base} = 20MVA, which is the rated power of the traction transformer.

V_{base} (high voltage) = 132 kV = V_{rated} (primary side)

V_{base} (low voltage) =27.5kV= V_{rated} (secondary side)

The actual impedance is required on the secondary side (interested on the secondary side). Thus; the secondary side base voltage will be used to get the base impedance.

$$Z_{base} = \frac{V_{base}^2}{S_{base}} = \frac{(27.5\times10^3)^2}{20\times106} = 37.8125\Omega$$

The actual impedance of the transformer will be calculated using the percent impedance given in the nameplate of the transformer located in Endode Traction Substation.

$$Z_{actual} = \%Z\times \frac{V_{rated}^2}{S_{rated}} = \frac{\%8.33\times27.5^2}{20\times10^6} = 3.15\Omega$$

The Per Unit (pu) impedance of the transformer is:

$$Z_{pu} = \frac{Z_{actual}}{Z_{base}} = \frac{3.15}{37.8125} = 0.0833,$$

$$R_{p.u} = \frac{R_{actual}}{Z_{base}} = \frac{P_{load\ loss}}{S_{base}} = \frac{158.47}{20*10^6} = 0.007926,$$

$$R_{actual} = 0.007926 \times 37.8125 = 0.2997\Omega,$$

$$X_{p.u} = \sqrt{{Z_{p.u}}^2 - {R_{p.u}}^2} = \sqrt{0.0833^2 - 0.007926^2} = 0.082859,$$

$$\text{Therefore, } X_{actual} = 3.134\Omega \text{ and } L = \frac{3.134}{2*\pi*50} = 0.01H.$$

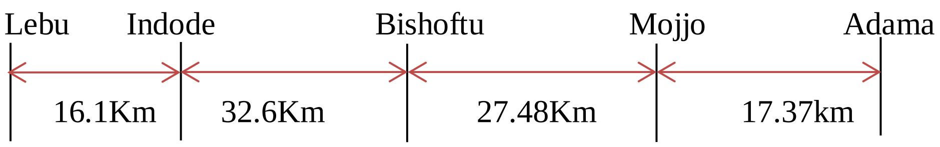
Therefore, the equivalent impedance of transformer referred to secondary will be:

$$Z_{transformer} = 0.2997 + j3.134 \text{ pu}.$$

Considering only inside the substation and thus grid impedance is not considered in this substation model.

3.2.2 Line Modeling

The impedance of traction network is designed to have 0.130081+j0.392381Ω/km for the double-track line Lebu to Adama section [7].



The transmission line parameters include series resistance, series inductance, and shunt capacitance. The line model depends on its length. It can be classified as short line for the lines less than 80km long, medium line for the lines is between 80 km and 250 km and long line model for the lines is longer than 250 km.

For the short line, the series impedance is assumed to be lumped and the shunt capacitance is almost negligible. The lumped impedance will, therefore, be the product of impedance network per km and the length in km of the line.

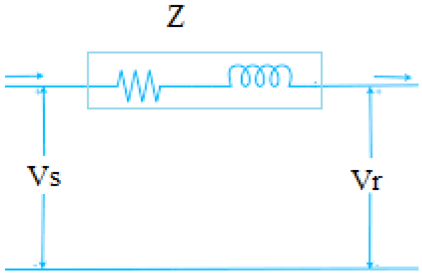


Figure 3-6: Short line transmission model

3.2.3 Train Model

There are freight and passenger trains operating in the line. The train can be modeled as impedance, current or power model. The impedance model requires a power factor interpretation of phase angle at the train whereas the effective current model seeks the phase angle. Fortunately, the power model can be applied by using active and reactive power reading. Thus, power model is used in this thesis. It is accomplished based on the measured parameters.

Table 3-3 shows the line record of current, active power and reactive power including the average value while a certain passenger train emulates from Lebu to Endode over 15 minutes period. In this section there is no freight train passing regularly, therefore only passenger train is considered.

Table 3-3: I, P and Q Measurement

Time(Minute)	**I(A)**	P(kw)	Q(kvar)
0	58.6	1591.23	161.1
0.5	119.62	3263.04	443.13
1	56.15	1369.67	664.69
1.5	68.31	1812.8	503.56
2	176.4	4753.56	986.97
2.5	92.78	2437.21	745.28
3	56.15	1369.67	664.69
3.5	40.28	866.11	644.56
4	184.33	4914.7	1148.1
4.5	53.71	1369.67	1463.27
5	64.7	1671.8	1503.56
5.5	98.37	2558.66	805.7
6	67.75	1691.95	704.98
6.5	61.64	1571.09	684.84
7	44.56	946.68	684.84
7.5	39.67	604.27	664.69
8	59.21	1591.24	342.41

8.5	95.31	1722.37	382.7
9	73.85	2014.22	382.7
9.5	62.87	1671.9	382.7
10	43.95	1127.96	402.84
10.5	45.78	1118.39	422.99
11	45.17	1168.25	422.99
11.5	70.8	1913.5	402.844
12	89.11	2437.2	362.56
12.5	92.17	2517.18	382.7
13	93.39	2558.06	362.56
13.5	93.39	2558.06	382.7
14	94	2558.06	402.84
14.5	94	2558.06	402.84
15	91.56	2497.6	382.7
Average	78.30903	2025.941	590.1624

The measurement in Table 3-3 indicates that the active and reactive power load at the substation. The average measurement has been taken and the active and reactive drop subtracted in the half of the line runs from Lebu to Endode. Hence, it is assumed that the rest power other than the feeder line is consumed by the train. Half of the whole distance, from Lebu to Endode, is used as an average distance since the train is moving from end to end.

The line impedance = (0.130081 + j0.392381) Ω/km

Total distance = 16.1km, half of the distance = 8.05 km

The average current during the whole recorded travel was 78.309A.

The line impedance (Z) =8.05*(0.130081 + j0.392381) = 1.04715205 + j3.15866705

The power drop in the line (S_L) = I^2*Z=6421.45 + j19369.58 kVAR.

Active power = 6.42145 kW.

Reactive power = 19.36958 kVAr.

Therefore, the passenger train operating at Ethio-Djibouti line can be modeled as constant power of the value:

Active power =2025.94 - 6.42145= 2019.52 kW

Reactive power = 590.162- 19.36958 = 570.79242 kVAr

Thus, the constant power model of the locomotive considered in this research can be modeled with this average value, 2.02 MW active power and 0.570MVAr reactive power. Whereas the dynamic power model is designed considering the reading of variable power as it is. This model is better as it emulates the real phenomena of running train based on real measured data of active and reactive power.

3.2.4 STATCOM Modeling

STATCOM is in a general shunt connected controller that injects or absorbs reactive current in a dynamic fashion. Shunt controllers are preferable for reactive control, among them, this is the powerful one. This research applies the theory of active and non-active currents for the operation of STATCOM so as to achieve unity power factor. The functional model of STATCOM implemented here is as shown in the Figure 3-7.

This method is selected due to the following reason [39].

- Flexibility to meet various compensation objectives
- Valid for non-sinusoidal and periodic systems
- Valid for single-phase and polyphase systems

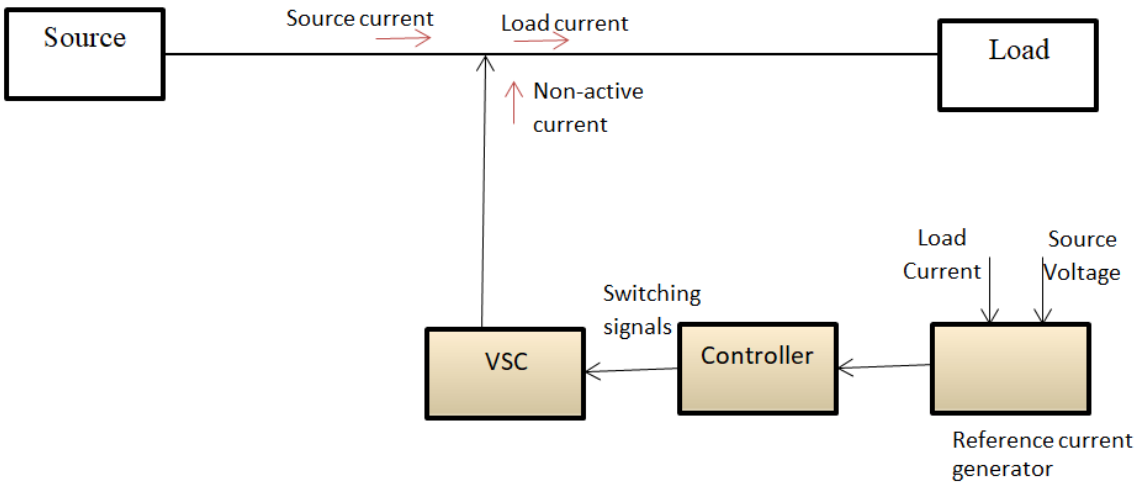


Figure 3-7: STATCOM system configuration

It has three main parts, namely reference current generator, controller and voltage source converter.

Reference Current Generator

Reference current generator is required to extract the unwanted current signal from the total load current signal. The component of the extracted current is thought as non-active current. That means, it doesn't contribute to the active power transfer between source and load. This enables the source to supply only for resistive impedance load. The extraction of non-active current is based on Fryze's concept of active and non-active current [40].

The instantaneous power for an n-phase circuit can be calculated as the sum of each phase instantaneous power as:

$$p(t) = \sum_{1}^{n} v_n(t) i_n(t) \quad (3\text{-}13)$$

Considering the single-phase circuit,

$$P(t) = v(t)i(t) \quad (3\text{-}14)$$

The non-active power which referred as useless power that causes increased line current loses as well as generation requirements for utilities circulates among phases and between sources and load. Hence, the average value is zero [39]. The average value of instantaneous power over the interval (t-Tav, t) is the active power.

$$P = 1/Tav \int_{t-Tav}^{t} p(\gamma)d\gamma \quad (3\text{-}15)$$

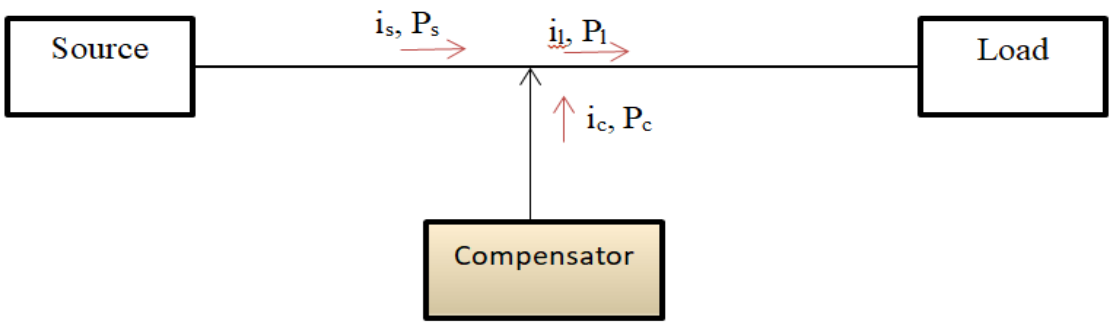


Figure 3-8: Scheme of compensation

Considering Figure 3-8:

$$P_s + P_c = P_l,$$

$P_s = P_l$, since P_c is zero as time goes to infinity.

Then, the instantaneous active current and non-active current are calculated using the following equations [39]–[41]:

$$i_a(t) = \frac{P}{V_r^2} v_r(t), \qquad (3\text{-}16)$$

$$i_n(t) = i_l(t) - i_a(t), \qquad (3\text{-}17)$$

where, P is the average active power load over the averaging interval,

$V_r(t)$ is the RMS value of the reference voltage,

$v_r(t)$ is the instantaneous reference voltage,

$i_a(t)$ is the instantaneous active component of load current,

$i_n(t)$ is the instantaneous non-active component of load current.

The averaging interval (T_{av}) and the reference voltage $v_r(t)$ can be selected based on the compensation strategy. The value of T_{av} may be from zero up to infinity. When T_{av} is zero, the average power will be equal to instantaneous power and the instantaneous non-active power will be zero. This is not convenient for the non-active current generation. On the other way, the averaging interval should not be infinity value as it impractical for any power system.

The source current will follow the reference voltage by choosing the averaging interval (T_{av})=nT/2, where T is the period of the system and n is an integer. In [39], this scenario is proved. Here, T/2 is used to get the average and RMS values of power and voltage respectively.

The other important parameter is the reference voltage. The active component of current ($i_a(t)$) can have different waveforms based on the selected reference voltage. As the source voltage is sinusoidal wave and to make the source current in phase with source voltage, source voltage $v_s(t)$ is used as reference voltage.

Thus taking source voltage as a reference voltage half of the period has averaging interval and using equation (3-6) and (3-7) non-active current is generated. This non-active current is considered as reference current so that it will be an input to the controller. The Simulink model that generates this reference current signal (waveform) is as shown in Figure 3-9.

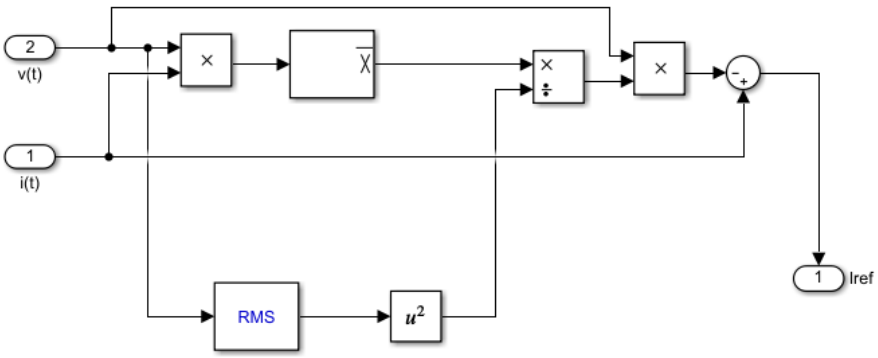


Figure 3-9: Simulink model of reference current generator

Controller

The controller has to receive a reference current signal and send switching signals for power electronics switches of the converter to let it follow the reference current generated previously. Hysteresis band current controller technique is selected as it has excellent dynamic response and low implementation cost [42].

Hysteresis band current controller method can control a voltage source in a way that output current is generated following reference current waveform. It is implemented with a closed-loop system as shown in the Figure 3-10.

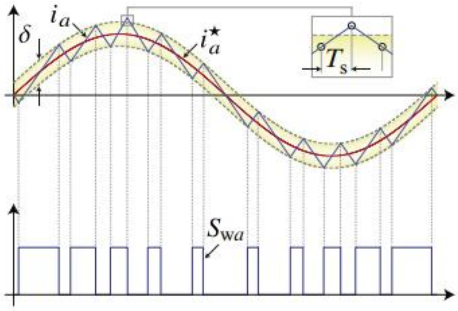


Figure 3-10: operational waveform of HBCC [43]

The control of the switches in Voltage Source Converter is dependent on the error signal which is the difference of the reference signal (desired signal) and the actual signal (the current being injected by the VSC). The current is forced to go up and down when the error signal reaches the upper limit and lower limit respectively by controlling the state of switches of Voltage Source Converter. The optimal value of the hysteresis band is selected based on the desired output current quality and the acceptable losses of the power electronics switches[42]. The output current stays within the prescribed limits following desired current even if the reference current keeps changing.

Voltage Source Converter

Full bridge, single-phase, two-level voltage source converter is used due to its efficient utilization of the DC side voltage and switch cells. It is one of the basic building blocks of STATCOM implemented in this research. The schematic model of the voltage source converter is shown in the Figure 3-11.

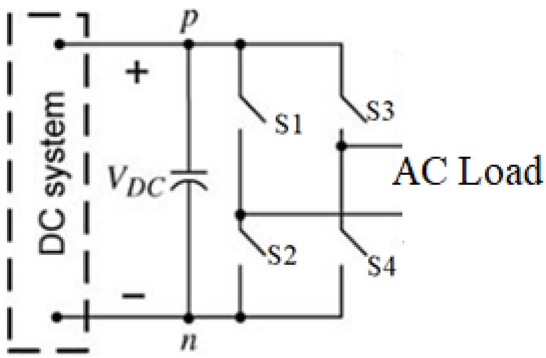


Figure 3-11: Scheme of VSC

The switches are controlled by the gate signal generated by the HBCC block. Switch S_3 and S_2 controlled together and S_1 and S_4 are also controlled together with the same signal. When the feedback converter output signal is equal to upper hysteresis band limit switch S_3 and S_2 will turn on and switch S_1 and S_4 will turn off. When the converter output signal reaches lower limit of hysteresis band, switch S_1 and S_4 will turn on and switch S_2 and S_3 will turn off. In this way the converter will have an output current that tracks the reference signal.

3.2.4.1 Rating and Cost Estimation

The size of components will be selected in such a way that it can compensate all reactive power and results in unity power factor throughout the train movement. Besides the control circuit, STATCOM is comprised of voltage source converter, capacitor as DC voltage supply as well as coupling inductor to prevent short-circuiting and discharging of capacitor rapidly. The value and/or type of these devices depend mainly on the power/current transfer requirement and the implemented control technique that is based on Fryze's concept of non-active current.

The DC voltage source should be greater than 27.5 kV to have a voltage minimum of 27.5 kV in the AC side of the converter for effective transfer of reactive power. The capacitor value can be calculated considering the highest reactive power (1148.1kVAr) that should be compensated as follows.

$$X_c = {V_s^2}/{Q} \sin\varphi \, . \tag{3-18}$$

$$\sin\varphi = {Q}/{S} = 0.228 \, , \tag{3-19}$$

$$X_c = \frac{(27.5*10^3)^2}{1.15*10^6} * 0.228 \simeq 150\Omega \, . \tag{3-20}$$

Then, the minimum value of the capacitor should be:

$$C = {1}/{2\pi f X_c} = 4.25*10^{-5} F \, . \tag{3-21}$$

The switches of the converter should also be capable enough for this medium voltage (25kV) application. Power electronic switches like IGBT that operate with high-voltage and high current capability can be used.

It has been investigated that FACTS equipment cost represents only half and the rest expenses like civil works, installation, commissioning, insurance, engineering and project management supplement the other half. Operating costs are often neglected. The significant disadvantage of power electronic-based controllers is their price as compared to similar conventional equipment even though they can offer good control to enhance electric power quality.

The overall cost depends on the specific costs of coupling inductor, the capacitor, the power electronic switches and the respective protection and control circuit. The total cost is expressed as a function of the rated electrical capacity of FACTS device. As there are various options available for optimum design and implementation, it is difficult to know the exact cost figure for this type of controller configuration. Reports have given the approximate prices of FACTS devices and clearly show that the price of FACTS devices varies over a large range [44].

Considering the summary of different reported costs in [44] and the price of Static Synchronous Compensator (STATCOM) for medium voltage, dynamic reactive power compensation products from Shandong Hoteam Electric Co. Ltd, the cost of installing this mitigation technique is roughly estimated. The cost of about 1.5 MVAr capacity will be around 60,000$ applying 40$/KVAr. To efficiently track the sinusoidal source voltage for the generation of reference current, it is better to install at each traction substation. But, it can also be installed at each rolling stock. Thus, approximately 600,000$ should be invested for the inclusion of this type of mitigation technique in 10 trains currently operating in Ethio-Djibouti line.

3.3 Overall Compensation Operational Principle

As explained earlier, the aim of introducing the above modeling is to prohibit the source from supplying the reactive power and to increase the system power factor. This happens when the source can only see the resistive impedance of the load (train) and the transmission line (Catenary). That means the source current only has the waveform that contributes to active power load. The remaining current that doesn't contribute to active power will be supplied by the compensator. The supplying of this non-active current is performed through the use of reference current generator, controller as well as voltage source converter.

The instantaneous power is the product of instantaneous voltage and current. The average value of this instantaneous power over a period of averaging interval (T_{av}) is the active power.

$$P=\frac{1}{T_{av}}\int_{t-T_{av}}^{t}P(\gamma)\,d\gamma=\frac{1}{T_{av}}\int_{t-T_{av}}^{t}v(\gamma)\,i(\gamma)\,d\gamma\,. \tag{3-22}$$

The reference (source) voltage and load current, respectively, are:

$$v_s(t)=V_m\sin wt=\sqrt{2}V_s\sin wt\,, \tag{3-23}$$

$$i_l(t)=\sqrt{2}\sum_{n=1}^{\infty}I_n\sin(nwt-\phi_n)\,. \tag{3-24}$$

Substituting the above two equations, equation (3-23) and (3-24) into equation (3-14):

$$p(t)=2V_sI_1\cos\phi_1(1-\cos 2wt)+2V_sI_1\sin wt\cos wt\sin\phi_1+\sum_{n=2}^{\infty}I_n\sin wt\sin(nwt-\phi_n)\,, \tag{3-25}$$

From equation (3-22) and(3-25),

$$P=\frac{1}{Tav}\int_{t-Tav}^{t}p(t)=V_sI_1\cos\phi_1=P_a\,, \tag{3-26}$$

$$\mathrm{P_{na}}=\mathrm{p(t)}-\mathrm{P_a}\,, \tag{3-27}$$

where, P_a and P_{na} are active and non-active power.

Thus, from equation (3-16), (3-23) and (3-26), the active current component will be:

$$i_a(t)=\sqrt{2}I_1\cos\phi_1\sin wt\,. \tag{3-28}$$

Here, this current $(i_a(t)$ is in phase with source voltage. The remaining unwanted component of current (non-active current) which regarded as reference current will then be:

$$\begin{gathered}i_R(t)=i(t)-i_a(t),\\ i_R(t)=-\sqrt{2}I_1coswtsin\phi_1+\sqrt{2}\sum_{n=2}^{\infty}I_nsin(nwt-\phi_n).\end{gathered} \tag{3-29}$$

This will be the reference current generated from the reference current generator block model in the Figure 3-9. The hysteresis band current controller will receive this reference current and controls the output current of voltage source converter. The HBCC checks whether the VSC output current follows reference current or not through a closed-loop system. Thus, it forces the current to go up and down to track reference current efficiently.

Therefore, as shown in the Figure 3-8, the source current is the only active component of load current whereas the remaining parts will be given through compensator. In this way the power factor will be improved effectively.

3.4 Simulation Models

The simulation models and the simulation tool are required in order to simulate the overall system. The simulation tool should have enough libraries to represent all subsystems; the parameters should be modified; there should be a graphical user interface to understand easily and it should be available for free. Based on the above criteria, MATLAB/Simulink is selected as simulation tool for this research.

In this research mainly four simulation models are implemented besides the dynamics modeling which shows the relationship between tractive force, speed and required power in a level track line. The train dynamics model is as shown in the Figure 3-12.

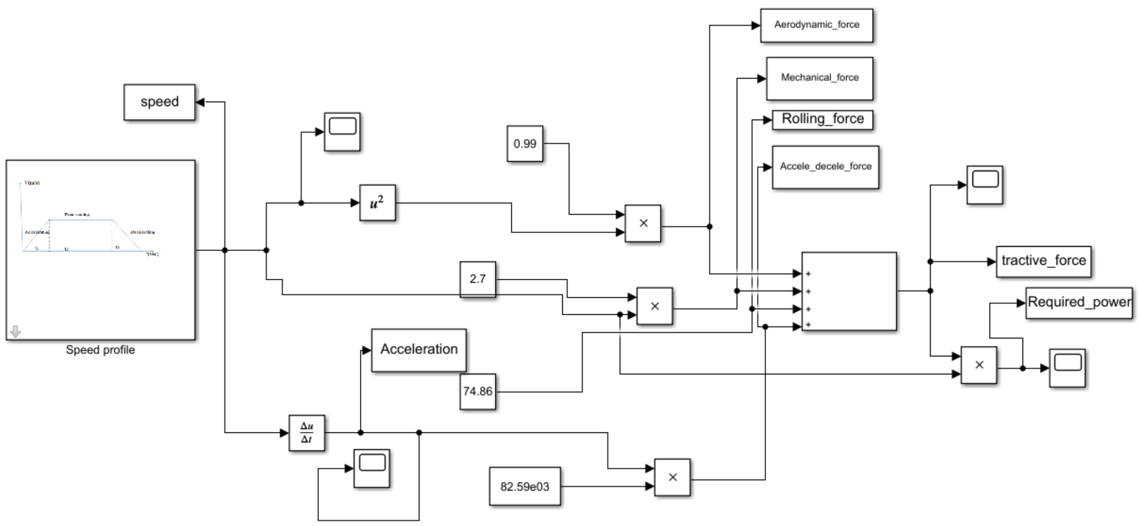


Figure 3-12: Train dynamics model

The simulation model consists of the substation, feeder line, and locomotive model with/without the controller model described in the mathematical modeling section.

The simulation model shown in the Figure 3-13 is based on a constant power model. The representation of the existing system and with the inclusion of controller can prevent the source from delivering unnecessary current so that the system power factor can increase. The connection of blocks in the Figure 3-13 and 3-14 with in the same row or different row have been shown using ‘go to’ block of Simulink library. The simulation is a discrete solver type with variable sampling time and runs for 2.0- seconds.

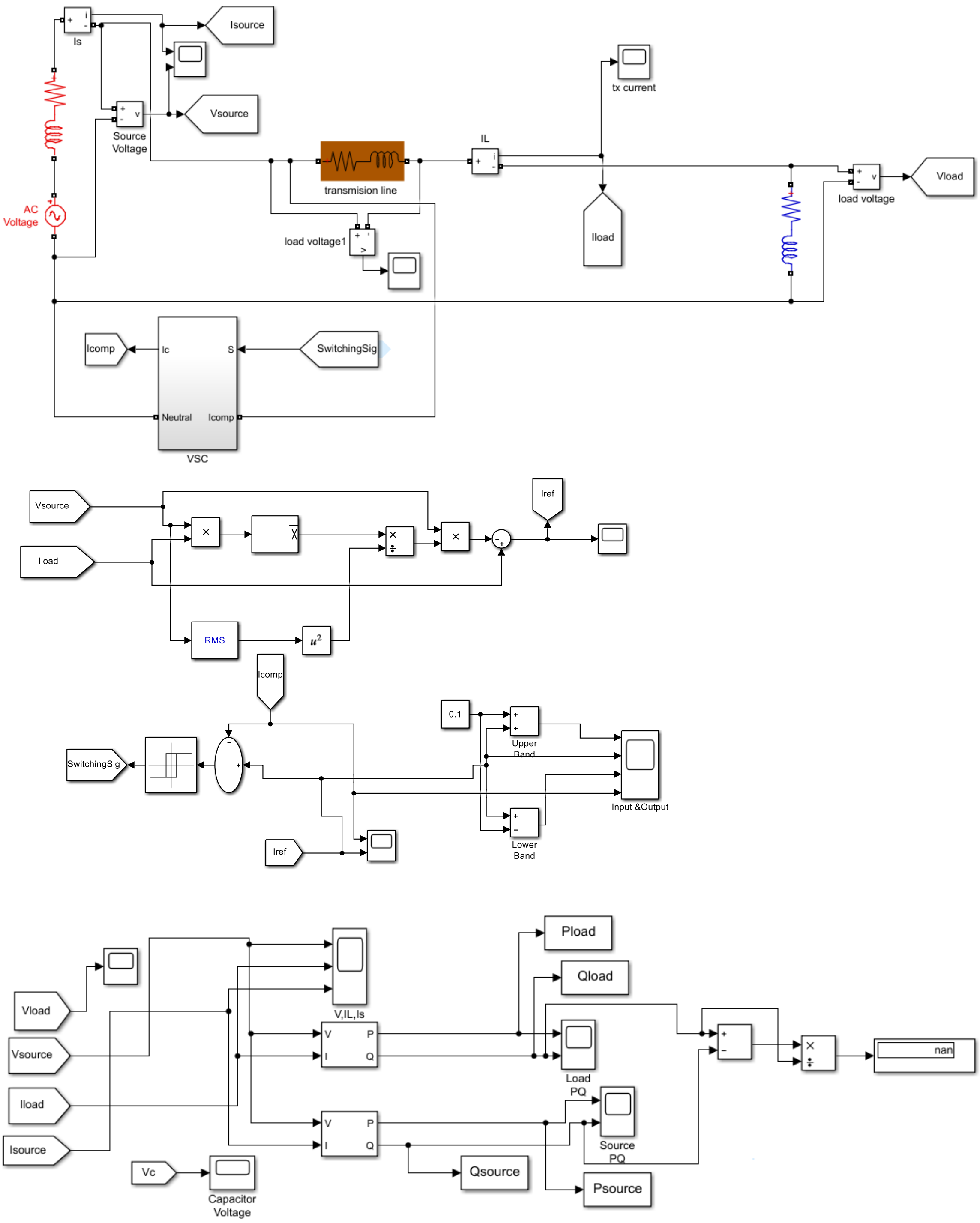


Figure 3-13: Constant power model with controller

The next simulation model shown in the Figure 3-14 emulates the real scenario of traction power supply running train by applying dynamic power model to represent the moving train. The simulation time is 30 seconds to replicate the train movement for 30 minutes. A continuous solver is configured to run this model.

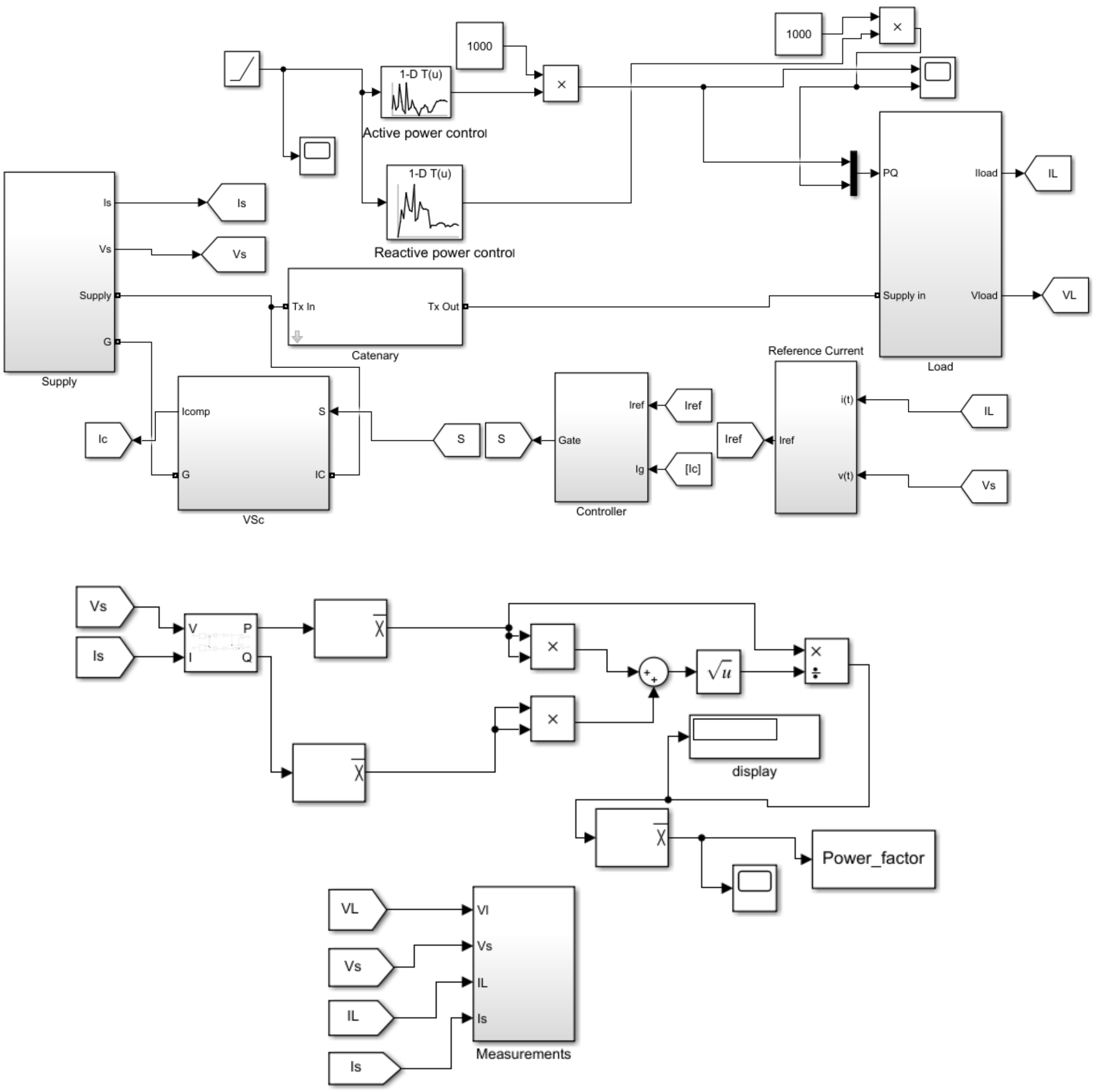
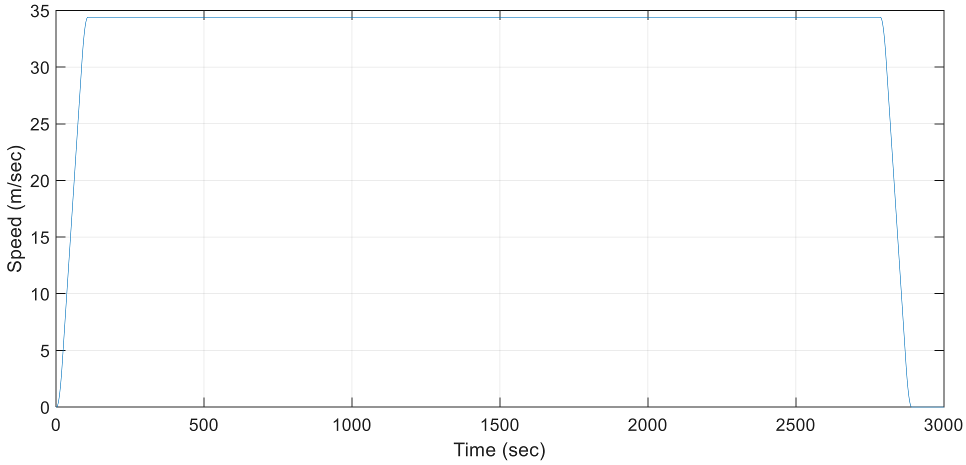


Figure 3-14: Dynamic power model with controller

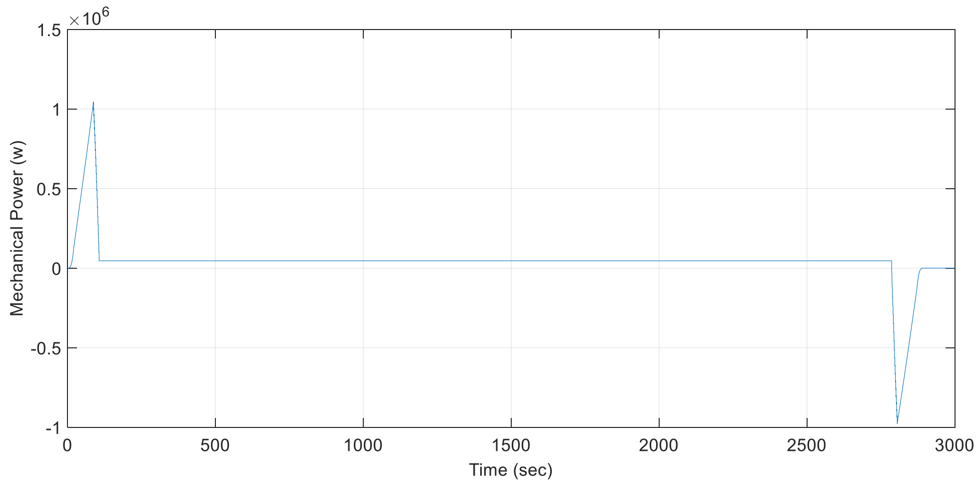
CHAPTER 4 SIMULATION RESULTS AND DISCUSSIONS

In this chapter, the simulation results of the five models described in previous chapter is presented and results have been discussed. One of the models is longitudinal train dynamics model to state the relationship between variation of speed and the mechanical power required. The rest four simulation models are the model to represent traction power supply system based on static/dynamic power model with and without introducing the described mitigation technique.

The Figure 4-1 shows the speed-time curve and required mechanical power as a function of time with speed variation. The model runs for 3000 simulation times to show the real-time based on mathematically calculated total time required (2890seconds). The solver's fundamental sampling time was set to be 0.01 second to make it convenient for generating acceleration/deceleration using derivative block.



(a) Speed time curve



(b) Required mechanical power

Figure 4-1: (a) Speed time curve and (b) Required mechanical power

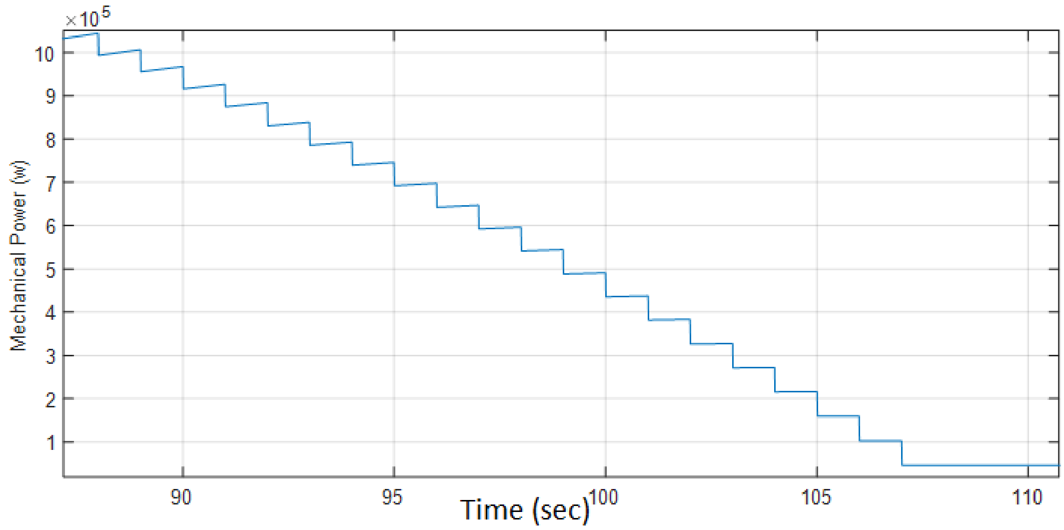


Figure 4-2: Zoomed view of required power variation

As it can be seen from the Figure 4-1, the power required by a moving train is highly affected with rate of change of speed and the value of speed. As the rate of speed variation increases the required mechanical power will also vary. Figure 4-2 is also assured the fluctuation of load with speed variation. This figure 4-2 is the zoomed view of power time curve around the time the train reaches free running speed. This fluctuation indicates that the electrical load power required has to vary finely to meet these demands.

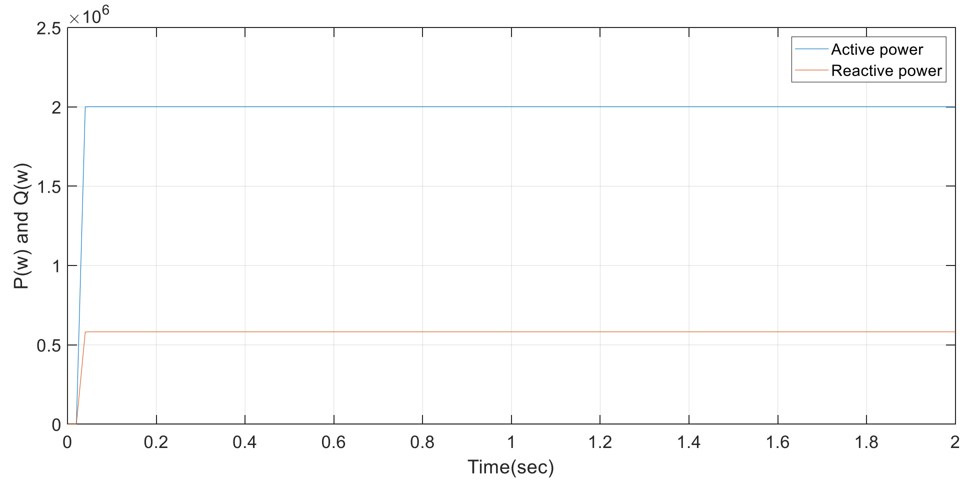


Figure 4-3: P and Q of the static model without controller

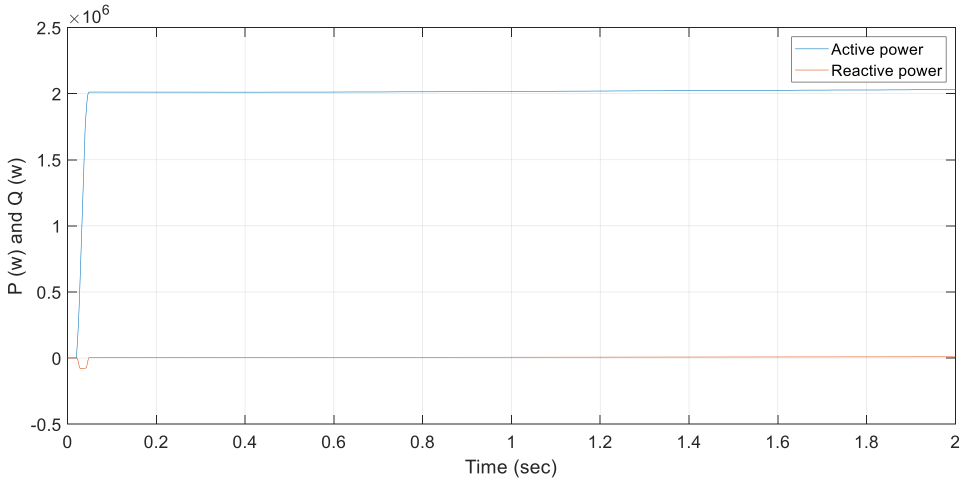


Figure 4-4: P and Q of the static model with controller

The Figure 4-3 and 4-4 show that the introduced controller which is STATCOM modeled based on active and non-active current theory enables to control the reactive power emanated from the source. The power factor after introducing the stated mitigation technique becomes close to unity. The percentage decrement of reactive power after the introduction of the compensator has been calculated. The result indicates

98.51 percent of the reactive power delivered by the source is removed after the inclusion of this controller.

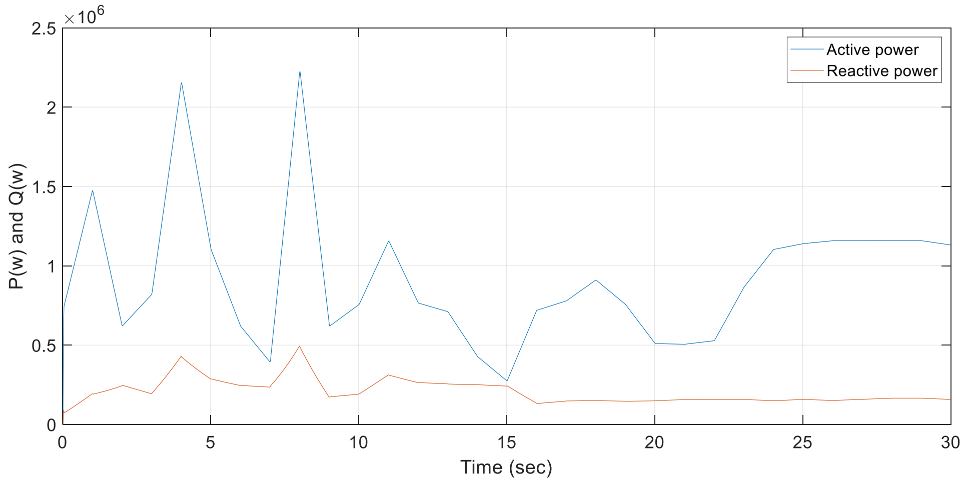


Figure 4-5: Dynamic power model P and Q reading without the controller

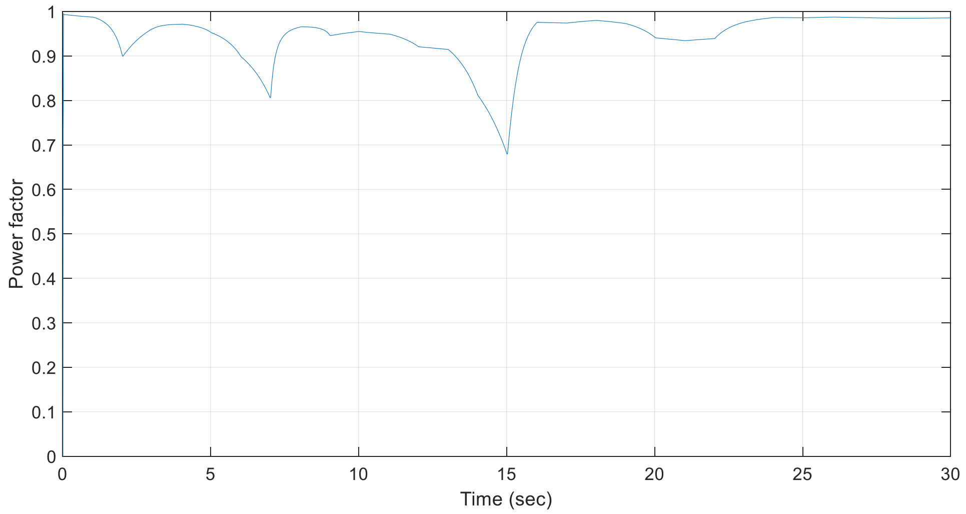


Figure 4-6: Dynamic power model power factor reading without the controller

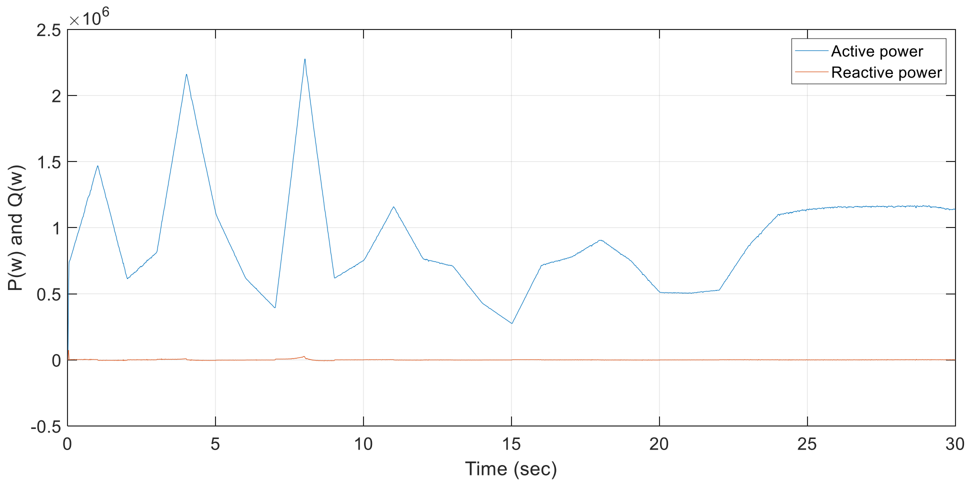


Figure 4-7: Dynamic power model P and Q reading with the controller

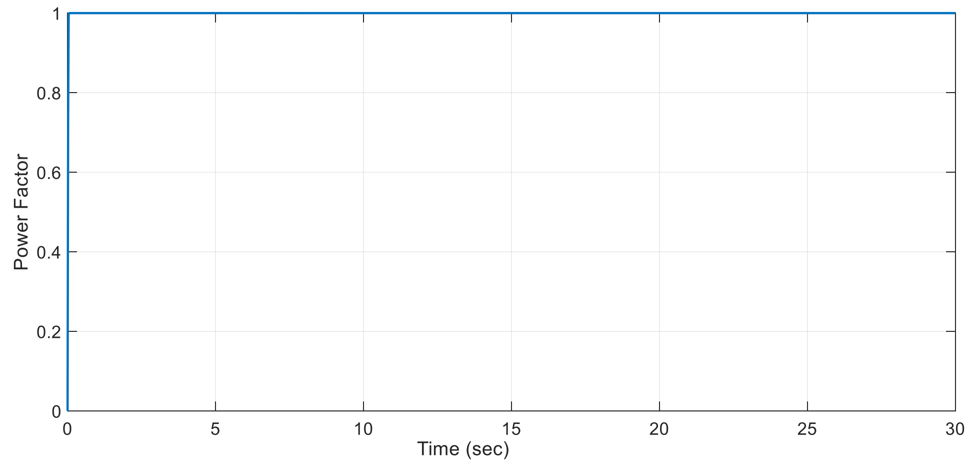


Figure 4-8: Dynamic power model power factor reading with the controller

The previous results from the Figure 4-5 up to Figure 4-8 reveal that the introduced model flexibility towards variable power load experienced in traction power system. The Figure 4-5 shows the active and reactive power delivered by the source when the train model uses a variable power model based on the actual power supplied for the passenger train in Ethio-Djibouti line. The power factor reading of the respective model varies down up to 0.67 during the whole course of movement as shown in the Figure 4-6.

Active and reactive power reading displayed after introducing the controller/compensator in Figure 4-7 shows that the reactive power values are diminished nearly to zero. Importantly, the power factor remains unity throughout the whole running time as displayed in Figure 4-8.

Thus, it is assured that the introduced compensator model, STATCOM operating based on non-active theory control algorism, effectively can handle the high reactive power reading and enhance the poor power factor in the traction power supply system.

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

Investigation of some power quality problems, modeling of traction power supply system as well as effective mitigation technique has been applied to improve the power quality particularly in terms of compensating reactive power and improving poor power factor. The goal of this research work was to model the system and develop an efficient mitigation technique to improve power quality level of Ethio-Dibouti line particularly from Lebu to Adama line.

A detailed survey of kinds of literature about AC traction power supply systems, power quality problems in TPSS as well as their improvement methods for high reactive power reading and poor power factor problems have been reviewed. Literatures that deal with the modeling of traction power supply components like traction substation, transmission line (catenary system) and/or train (load) have also been surveyed.

Mathematical analysis and modeling of the traction power supply system considering Lebu to Endode line have been carried out. Both static and dynamic power model is implemented. The dynamic power modeling of the train is able to show the actual phenomena of running train in terms of power fluctuations as the model uses real measured operating data collected from Endode traction substation.

The research enables to show how STATCOM can operate using active and non-active current theory and implements to traction power supply system to alleviate the problem of high reactive power and poor power factor which the research work investigated primarily as a problem and focused to deal with.

STATCOM controlled by non-active current theory is introduced to both constant and variable power models of traction power supply system and simulated in MATLAB/SIMULINK 2018a. The results reveal that the percentage of reactive power after the introduction of the controller decreased by 98.51% as compared to the previous reactive power reading and the power factor remains close to unity throughout the course of running time.

Generally, this thesis develops a flexible model of AC traction power supply system. Moreover, an efficient mitigation technique that can alleviate the problem of reactive power and poor power factor has been implemented and assured its interesting operation. The simulation results shown from the Figure 4-3 up to Figure 4-8 reveal that better power quality has been achieved.

5.2 Recommendations for future works

It will be worthwhile adding the following works.

- Further investigation of power quality problems of the line in depth including their causes.
- The detail cost/benefit analysis of implementation.
- Study the precision of energy readings in the traction substations as well as the root causes.
- Model and asses the whole line in terms of the effectiveness of the mitigation technique used in this thesis.

Again, it is recommended to Ethio-Djibouti Railway Share Company to consider the developed model in this research for its traction power supply system.

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APPENDIX A

The total sum of active and reactive energy reading measured in railway energy meter reading at the Ethio-Djibouti railway line in August 2018.

Table A-1: Energy meter reading of August 2018

No.	Line Name	Total Active Energy in kWh	Total Reactive Energy in Kvarh
3	KALITI-I C10 TO ENDODE T/S (Control Room)	520,608.00	300,960.00
4	AKAKI-II E02 TO ENCODE T/S		
5	NAZARETH II E07 TO MOJO T/S	427,680.00	2,954,160.00
6	AWASH II HEPP E12 TO WULUNCHITI T/S		
7	METEORA E03 TO MELKA JILO T/S	683,484.00	5,317,648.00
8	AWASH 7-KILOE05 TO AWASH T/S		
9	AWASH 7-KILO E06 TO SIRBA KUNKUR T/S	490,788.00	4,379,008.00
10	ASEBE TEFERI E05 TO MIESSO T/S		
11	ASEBE TEFERI E04 TO AFDEM T/S (EXISTING LINE)	426,880.00	7,219,840.00
12	HURSO D10 TO HURSO T/S (NEW ONE) 230KV		
13	HURSO E01 TO GOTA T/S (EXISTING LINE) 132 KV	422,400.00	2,925,120.00
14	ADIGALA TO ADIGALA T/S		
	Total	**2,971,840.00**	**23,096,736.00**

The total sum of active and reactive energy reading measured in railway energy meter reading at the Ethio-Djibouti railway line in July 2018.

Table A-2: Energy meter reading of July 2018

No.	Line Name	Total Active Energy in kWh	Total Reactive Energy in Kvarh
1	SEBETA II LINE I TO SEBETA T/S	-	29,696.00
2	SEBETA II D10 LINE II TO SEBETA T/S		
3	KALITI-I C10 TO ENDODE T/S (Control Room)	29,945,367.00	3,888,801.00
4	AKAKI-II E02 TO ENDODE T/S		
5	NAZRETH II E07 TO MOJO T/S	213,840.00	2,170,080.00
6	AWASH II HEPP E12 TO WULUNCHITI T/S		
7	METEHARA E03 TO MELKA JILO T/S	905,256.00	4,963,464.00
8	AWASH 7-KILOE05 TO AWASH T/S		
9	AWASH 7-KILO E06 TO SIRBA KUNKUR T/S	222,806.00	969,368.00
10	ASEBE TEFERI E05 TO MIESSO T/S		
11	ASEBE TEFERI E04 TO AFDEM T/S (EXISTING LINE)	167,040.00	2,852,960.00
12	HURSO D10 TO HURSO T/S (NEW ONE) 230KV		
13	HURSO E01 TO GOTA T/S (EXISTING LINE) 132 KV	195,360.00	1,208,400.00
14	ADIGALA TO ADIGALA T/S		
	Total	**31,649,669.00**	**16,082,769.00**

The table has been generated from 15 minutes live recording as the train was moving from Lebu to Bishoftu through Endode traction substation. It is recorded at Endode traction substation and sampled in 30 seconds interval to get discrete data as shown in the table below.

Table A-3: V,I,P,Q and power factor real time record

Time(Minute)	**V(kv)**	**I(A)**	**P(kw)**	**Q(kvar)**	**Power Factor**
0	27.79	58.6	1591.23	161.1	1
0.5	27.68	119.62	3263.04	443.13	0.98
1	27.65	56.15	1369.67	664.69	0.89
1.5	27.65	68.31	1812.8	503.56	0.95
2	27.63	176.4	4753.56	986.97	0.97
2.5	27.62	92.78	2437.21	745.28	0.95
3	27.7	56.15	1369.67	664.69	0.89
3.5	27.66	40.28	866.11	644.56	0.79
4	27.49	184.33	4914.7	1148.1	0.97
4.5	27.6	53.71	1369.67	463.27	0.94
5	27.6	64.7	1671.8	503.56	0.95
5.5	27.57	98.37	2558.66	805.7	0.95
6	27.58	67.75	1691.95	704.98	0.92
6.5	27.81	61.64	1571.09	684.84	0.91
7	27.6	44.56	946.68	684.84	0.81
7.5	27.57	39.67	604.27	664.69	0.67
8	27.66	59.21	1591.24	342.41	0.97
8.5	27.62	95.31	1722.37	382.7	0.97
9	27.57	73.85	2014.22	382.7	0.98
9.5	27.64	62.87	1671.9	382.7	0.97
10	27.61	43.95	1127.96	402.84	0.93
10.5	27.6	45.78	1118.39	422.99	0.936
11	27.6	45.17	1168.25	422.99	0.935
11.5	27.57	70.8	1913.5	402.844	0.979
12	27.63	89.11	2437.2	362.56	0.99
12.5	27.63	92.17	2517.18	382.7	0.98
13	27.61	93.39	2558.06	362.56	0.99
13.5	27.64	93.39	2558.06	382.7	0.98
14	27.65	94	2558.06	402.84	0.98
14.5	27.62	94	2558.06	402.84	0.98
15	27.63	91.56	2497.6	382.7	0.98

APPENDIX B

Longitudinal train Dynamics

Technical specification of passenger car operated in the Ethio-Djibouti Line.

Table B.1: Technical description of YZ25G hard seat passenger car[37]

Railway Gauge		1435mm
Maximum speed operation		120 km/hr
Construction speed		140 km/hr
Car dimension	Length	25500mm
	Width	3105mm
	Height	4433mm
	Vehicle Center distance	18000mm
Rated seat		118 persons