



**ADDIS ABABA UNIVERSITY**

**ADDIS ABABA INSTITUTE OF TECHNOLOGY**

**SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING**

**Reactive Power Compensation and Harmonic Mitigation in 25 kV**

**AC Railway System Using Shunt Active Filter**

**A Thesis Submitted to the School of Electrical and Computer Engineering,**

**Addis Ababa University in Partial fulfillment for the Degree of Master of**

**Science in Electrical Engineering for Railway Systems**

**By**

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**DEPARTMENT OF POST GRADUATE IN ELECTRICAL**

**ENGINEERING FOR RAILWAY SYSTEM**

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System Using Shunt Active Filter

**By**

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## Declaration

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

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## Abstract

The AC railway systems show typically poor power quality due to their inherent electrical load characteristics. The moving and non-linear load characteristics of the locomotives consume the large reactive power and produce high harmonic currents, so that the total power factor becomes adversely affected. These power quality problems in the AC railway system can constrain the amount of power delivered to the locomotive and have a negative effect on themselves as well as on the public grid. As a result, detailed study of reactive power and harmonic mitigation is required in traction substation.

The thesis deals on compensating reactive power consumption and harmonic mitigation of 25 kV electrified railway system of Addis Ababa-Djibouti railway line as case study. The active power filters have gained much more attention because of their performance to mitigate the harmonics and reactive power issues.

The performance of active filter depends upon the control theory that is employed to formulate the control algorithm of active filter and controller of the active filter is the key and heart of the filter which greatly affects its performance. So, design of shunt active filter to mitigate the harmonics and reactive power problems with controller based on Synchronous (d-q) reference frame theory is the core area of this work. MATLAB/Simpower computer simulation is used as a simulation tool for the thesis.

When the Shunt Active Power Filter is connected to the system, we can observe from the simulation result that THD of load current has reduced from 20.5% to 4.6% which is below 5% the harmonics limit imposed by IEEE 519 standard. The reactive power demand is reduced to nearly zero value, the power factor and pantograph voltage of traction system also improved. Thus, the simulation results after implementing the proposed filter shows that shunt active power filter can effectively compensate reactive power and harmonics.

**Key word:** Shunt Active Power Filter, Reactive Power, Harmonics, Synchronous Reference Frame Theory Control

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## List of acronyms and Symbols

APF	Active Power Filter
AC	Alternating current
AT	Autotransformer
BT	Boost Transformer
CSAF	Current Source Active Filter
$C_{DC}$	DC-link Capacitor
DC	Direct current
ERC	Ethiopian Railway Corporation
ERS	Electrified Railway System
$F_{sw}$	Switching Frequency
HCC	Hysteresis Current Control
$I_L$	Load current of the traction
$I_s$	Source Current
$I_c$	Compensating current
$I_{ref}$	Reference current
IEEE	Institute of Electrical and Electronics Engineering
IGBT	Insulated Gate Bipolar Transistor
$K_p$	Proportional gain
$K_i$	Integral control gain
$L_f$	Interfacing Inductor
LPF	Low Pass Filter
OCS	Overhead Contact System
P	Active power
PCC	Point of Common Coupling
PF	Power Factor
PI	proportional Integral control
PWM	Pulse Width Modulation
Q	Reactive power
RCG	Reference Current Generation

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S	Apparent power
SAPF	Shunt Active Filter
SRF	Synchronous reference frame
THD	Total Harmonic Distortion
TSS	Traction Substation
$V_s$	Source Voltage
$V_{DC}$	Actual DC-link Voltage
VSAF	Voltage Source Active Filter
VSC	Voltage Source Converter
$V_{DC, ref}$	Reference DC-link Voltage
VSI	Voltage Source Inverter

# Chapter One

## 1. Introduction

### 1.1. Background

The development of railway has been significant since the beginning of 20th century. Railway transportation is playing a significant role not only in peoples' daily life but also in global economic growth. Railway development beginning from steam engines in early 19th century, through time, the first electrically powered locomotive is demonstrated at Berlin Commerce in 1897 by Siemens. The electrified railway is considered to be an important environment friendly transport way because of its high speed and remarkable transportation capability with great efficiency. The electrified railway has a higher density traffic, which needs a more reliable and large traction power. The 25 kV 50 Hz single-phase supply system is now widely regarded as one of a number of standard railway electrification schemes. Due to the high voltage it uses for transmission, it is particularly attractive for high-speed, heavy haul and long distance routes [1]. There are currently many such railway systems installed around the world and our county Ethiopia has planned to construct an estimated length of 5060 km railway line and now working on it. In such a system, power is delivered to the locomotives through dedicated overhead transmission wires that span tens and hundreds of kilometers [2].

The two most common electrification power supply systems for high speed rail are: 1x25 kV and 2 x 25 kV systems. Such railway systems are usually fed by specialized traction substations which the main designs of them include the selection of a single phase 25 kV or two phase 2x25 kV systems which feed the train sets through the transformers and autotransformers in the traction substations [3]. 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 system considered under this study is the Addis-Ababa-Djibouti single-phase 25 kV AC electrified system. The system is supplied from state grid, normally at 132 kV voltage levels. This voltage is further step down by the traction transformer to 25 kV nominal voltage at traction substation using 132/27.5 kV (no load voltage) transformers. Each traction substation has two

132 kV independent power lines. Branch connection is used at 132 kV side and single bus bar section is applied at 25 kV bus bar [2]. In this study, Power supply mode for traction system is the direct feeding system with return line is applied for the single-phase power supply AC 25 kV with 50 Hz standard frequency [2].

## 1.2. Power Quality Problems in Electric Railway

Power quality in a newly constructed electrified railway system is a hot issue. This is because, poor power quality not only causes energy loss within the systems but it could also result in the malfunctioning of the electric traction equipment integrated and connected to the systems. AC electrified railway systems typically show low power quality due to their inherent electrical characteristics. The inductive and the non-linear load characteristic of the locomotives instigate the consumption of a considerable amount of reactive power and the generation of higher harmonic currents. This in turn causes the power factor of the electric power systems delivered to the locomotives will reduce. The power quality problems in the AC electrified railway systems defined to above could have a harmful impact on the railway system as well as on all the other electric equipment connected to them [4].

The railway electrification load is one of the worst kinds of load for an electrical utility to supply. The only load which gives more challenge to the utility is arc furnace load. The railway electrification load is highly intermittent, irregular, low load factor and poor power factor. The railway electrification load creates system voltage and current unbalance, generates harmonics and results in voltage flicker. Because of the above characteristics the railway electrification load generally requires oversized substation facilities. It stresses the electrical utility equipment more and also causes interference with other customer loads and often complaints from the other utility customers, etc. [1].

An electrified railway line resembles a typical power transmission and distribution system. The major difference is that the loads (trains) move and change operation modes frequently. Power demand varies over a wide range and a load may even become a source when regenerative braking is allowed. Other uncertainties are resulted from a number of factors, such as service scheduling, train speed, traffic demands, track layout, traction equipment control and drivers behavior to name a few [1].

The electric trains that are fed by single phase 25 kV AC catenary line are shown in Figure 1.1. A single-phase load is an unbalanced load to the three-phase power system. In an electric train, the single-phase AC power is rectified into the DC power. This leads to the generation of harmonic currents. As a result, an electric railway load is a large unbalanced and harmonic-generating load. Dividing the catenary line to the in-coming and out-going sides makes it possible to present each side as a separate single-phase load [1].

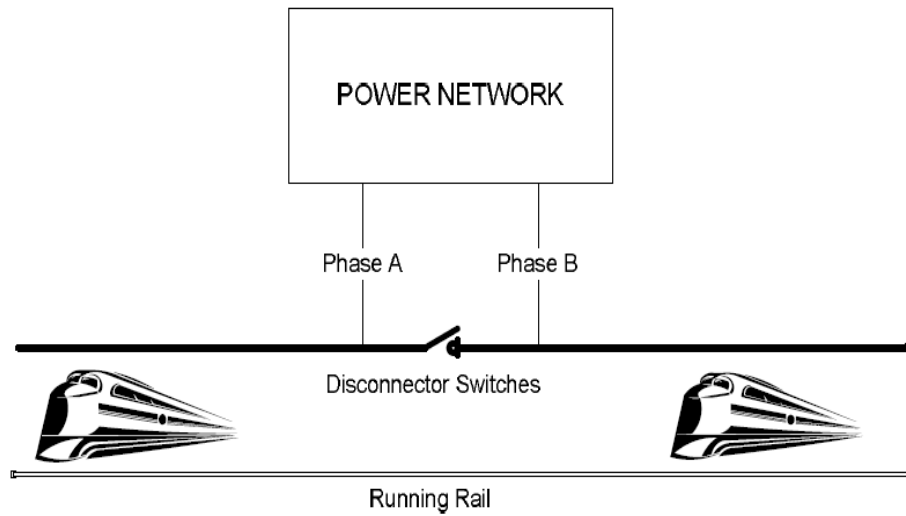


Figure 1.1: Single-phase AC catenary line supplies the electric train [1]

The major power quality problems in 25 kV AC railway systems could be listed as in below.

- ✚ Unbalanced load due to single phase catenary connection
- ✚ Unbalanced load due to moving and changing loads (train)
- ✚ Harmonic current generated by train rectifiers
- ✚ Reactive power due to big power demands of trains
- ✚ Voltage flicker due to moving load from one section to another

Therefore, a power quality compensator is required to improve the power quality in the AC electrified railway systems. Either passive or active power filters are used in order to improve the power quality in these systems. Passive power filters are simpler in construction and less expensive than active power filters. However, they are not suitable for the AC electrified railway systems because their compensation performance depends on the systems varying parameters and they are sensitive to resonance problems.

In order to solve the harmonic current generated and reactive power due to big power demand of train problems proposed topology will be presented and simulated in this thesis. The simulation of model will be done with MATLAB/SIMULINK.

### **1.3. Problem Statement**

In a new electrified railway line can happen a power quality problem of huge reactive power consumption, voltage drop, and harmonics because of the load characteristics of the electric traction. The nonlinear load characteristics of locomotive consume large reactive power, produce harmonic voltage and current at the pantograph, as result traction substation delivers insufficient power to the locomotive. Unless remedial action is taken, the result will be deterioration of power quality, not only harmful traction system itself, but also prone to spreading through the supply grid, disturbing other users of power in the same grid.

Poor power quality problem can affect safety, reliability and the whole operation of railway system. Since our country is constructing thousands of kilo meters of freight and passenger railway route, studying of the power quality problem is a critical issue. Shunt active filter based on synchronous reference frame theory is preferable in order to compensate the reactive power and harmonics mitigation of the traction power supply.

### **1.4. Objective**

#### **1.4.1. General Objective**

The general objective of this study is solving power quality problems in 25 kV electrified railway system. Mainly, the thesis deals on reactive power compensation in the rail network and mitigating the harmonic distortion of pantograph current in electric traction power supply with proposed method.

#### **1.4.2. Specific Objective**

The specific objective of the thesis is to mitigate the distorted pantograph current, and providing compensated reactive power to maintain the feeder voltage. In addition, this thesis basically deals on:

- ✓ Modeling of shunt active filter

- ✓ Describing the load current in the stationery or synchronous (d-q) reference frame theory to extract the reference compensating current
- ✓ Design of VSI to inject the compensating current & Controlling the DC-link voltage
- ✓ Designing hysteresis current control to generate the switching pattern of the voltage source inverter
- ✓ Simulation of shunt active filter

## 1.5. Organization of the Thesis

This thesis work is organized as in following chapters:-

**Chapter one** presents about the introduction and background of the study, briefs the power quality problem in electrified railway system, statement of the problem, and describes the objective of the thesis work.

**Chapter two** describes about electrified railway system. It provides brief understanding of AC electric traction system, Power feeding mode for AC traction, utility grid for traction power supply system, and traction transformer. Gives overview about AC electrified traction system Addis Ababa - Djibouti Railway line.

**Chapter three** presents a literature review of other related works that has been done for both general power system and electric traction system. A brief discussion on active power filter, the impact of harmonics and much reactive power in the railway network line. Describes harmonic reduction and reactive power compensation techniques and presents control techniques of active power filter.

**Chapter four** describe the methodology of the research is summarized. Describe the model of traction substation, feeder line and locomotive modeling. Discussed in detailed about the design and mathematical modeling of shunt active power filter.

**Chapter five** presents the MATLAB/SIMULINK modeling, simulation results and analysis of the reactive power consumption and harmonics in different cases for traction power network with and without shunt active power filter.

**Chapter six** presents conclusion, recommendation and future work.

## Chapter Two

### 2. Electrified Railway System

#### 2.1. Over View of AC Traction Systems

AC distribution of electrical 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. Standard AC distribution equipment and switchgear is used. Three-phase AC transmission, normally the most efficient means of distributing high-power electricity, would be advantageous for traction due to the inherent regenerative capability of three phase induction motors. However, it has not been widely applied because of the difficulty of power collection by moving locomotives. A number of systems were tried in the early 1900s on mountain railways in Italy, Switzerland and USA. The last major line, from Genova to Torino, was converted from three-phase at 3.6 kV, 162/3 Hz to 3 kV in 1964 [1].

In the early 20th century, low-frequency single-phase traction networks were established to combine the economies of high-voltage AC transmission with the advantages of using AC commutator motors. In Europe, the 15 kV, 16 2/3 Hz networks are very extensive and have been expanded despite the need for frequency converters or special generating stations. In the USA, some sections of the 12 kV, 25 Hz electrification system in the New York area have been converted to 60 Hz, facilitated by the ready availability of dual-frequency traction equipment. Nowadays, the standard supply for main line systems is 25 kV single-phase AC at 50 or 60 Hz. The system was first widely exploited in France in the early 1950s. The economy of high-voltage transmission is combined with the compatibility of national utility electric grid networks. The development of rectifier locomotives with DC traction motors and tap changers, using mercury arc rectifiers, semiconductor diodes and finally thyristor phase control, ensured the success of the 25 kV systems. New lines at 25 kV, 50/60 Hz have been constructed adjacent to existing 3 kV DC networks in, for example, France, Russia and South Africa. 25 kV remains the standard voltage although since 1980 some freight railways in North America and South Africa have been electrified at 50 kV, 50/60 Hz [1].

There are lots of different applications of AC system electrification. We can divide into three part AC system as in common use.

- ✓ Low Frequency AC System
- ✓ Poly phase AC System
- ✓ Standard Frequency AC system

### **2.1.1. Low Frequency AC System**

The low frequency electrified railway system has been in operation for over a century in Sweden, Germany and other European countries. With the modern day power electronics technology available for frequency conversion, and the high power quality demanded by the utility power customers, the low frequency system is likely to make the railway electrification system more affordable and desirable.

Frequency conversion is not only possible, but is becoming an economically attractive alternative. The frequency conversion is being used for accurate speed control, energy and power savings in several industrial processes. The cost of power frequency conversion is dropping and the reliability is constantly improving. Modern day control systems are making the conversion very precise and efficient. Frequency conversion systems can be applied to the railway electrification systems to obtain the advantages of industrial frequency for power generation and the low frequency system for power distribution on the catenary. The 60 Hz frequency can be converted to 15 or 20 Hz for railway electrification. When converting the frequency, the low frequency system can be operated as a single phase system. The frequency conversion can be done using a cyclo-converter, or it can be done using an AC/DC/AC system conversion. The AC/DC/AC conversion is used extensively in Adjustable Speed Drives. This would solve multitudes of problems related to power quality, reduce the cost of electrification, etc. [1].

A low frequency system decreases the cost of electrification by increasing the distance between two successive substations, and reducing civil engineering modification costs by enabling lowering the catenary voltage from the 25 kV voltage commonly used in the U.S. to 16.5 kV at 15/20 Hz. Such a system would enable paralleling the catenaries between two substations on the second- side, thus increasing the capabilities of the catenaries and reducing the power quality and unbalance voltage problems. The various advantages that can be derived from low frequency operation are [1]:

**a. Longer Substation Beat/Less Substation Installations**

A lower frequency system will reduce the inductive voltage drop in the catenary. A 15 Hz system would have approximately one fourth the inductive voltage drop as compared to a 60 Hz system, thus it would enable the substations to be located at 3 to 4 times the distance compared to a 60 Hz system based just on the voltage drop criterion. The number of substations required could be reduced to 30-40 percent.

**b. Parallel Operation of Catenary from Adjacent Substation**

The catenaries of the traction system can be all in phase. They can be paralleled on the secondary side. Paralleling the secondary's will enable the power to be drawn from two or more substations, thus decreasing the voltage drop further in the catenary and also distributing the load on two or more substations. There will be a smoother transition of load from one substation to the other as the train moves along.

**c. Reduced Voltage Operation at 15-16.5 kV**

Since the substation beat can be increased because of a lower frequency and parallel operation of the catenary system, lower catenary voltage could be used and substantial savings are achieved in civil engineering modifications by reducing the electrical clearance requirements at the reduced voltage level. The lower voltages have been used in Germany and Sweden with success. Reducing the voltage level; however, would increase the current in the catenary and would increase losses which may require a higher size catenary conductor or an additional feeder circuit.

**d. Lesser Electrical Clearances and Civil Engineering Requirements**

Lower voltages will result in lower clearance requirements. This could be useful where bridges have to be raised, tracks have to be lowered or when the tunnels do not permit adequate clearances for the 25 kV systems.

**e. Reduced Substation Voltage Capacity Or Better Utilization Of Substation and Catenary Capacity**

With the 25 kV single-phase, 50Hz system, each substation has to be designed to provide full power for the trains within the substation beat and half the adjacent substation. By paralleling the traction system on the secondary side and sharing the loads among the adjacent substations, it is quite possible to reduce the substation capacity or to provide larger train frequency.

#### **f. Reduced Unbalance Voltage Problem**

The traction load, as explained earlier, is one of the worst kinds of load as it is often supplied from one or two phases of a power system. The single phase load creates voltage unbalance and other power quality problems. With a low frequency traction system, the load will appear as a balanced load on the utility system. There would be little unbalanced voltage or current problems. The frequency conversion system would also separate traction load from the rest of the customers.

#### **g. Reduced Harmonics in the System**

With the low frequency system, harmonics would be generated in the conversion equipment. Appropriate filtering can be provided doing with the conversion equipment to limit the harmonics to acceptable levels. The modern day electric locomotives have onboard power factor correction and harmonic filtering. The frequency conversion equipment filters on the system would further reduce the harmonics generated from the locomotives and reduce the harmonics entering into the utility system.

#### **h. Lower Voltage Utility Substations**

The unbalance voltage caused by the trains can become the single most important factor which will dictate the selection of the substation primary voltage. Adequate short circuit duty and voltage levels are required to limit the voltage unbalance and the harmonics at the substation.

### **2.1.2. Poly phase AC System**

Three-phase AC transmission, normally the most efficient means of distributing high-power electricity, would be advantageous for traction due to the inherent regenerative capability of three phase induction motors. However, it has not been widely applied because of the difficulty of power collection by moving locomotives. A number of systems were tried in the early 1900s on mountain railways in Italy, Switzerland and USA. The last major line, from Genova to Torino, was converted from three-phase at 3.6 kV, 16 2/3 Hz to 3 kV in 1964 [1].

This was abandoned in the 1960's because of the complexity of the current collection, especially at points and crossings. There were some railways that used two or three overhead lines, usually to carry three-phase current to the trains. Nowadays, three-phase AC current is used only on the Gornergrat Railway and Jungfrauoch Railway in Switzerland, the Petit train de la Rhune in France, and the Corcovado Rack Railway in Brazil; until 1976 it was widely used in Italy. On

these railways the two conductors of the overhead lines are used for two different phases of the three-phase AC, while the rail was used for the third phase. The neutral was not used. Some three-phase AC railways used three overhead wires. These were an experimental railway line of Siemens in Berlin-Lichtenberg in 1898 (length: 1.8 kilometers), the military railway between Marienfelde and Zossen between 1901 and 1904 (length: 23.4 kilometers) and an 800 meter-long section of a coal railway near Cologne, between 1940 and 1949 [1].



Figure 2.1: Three Phase pantograph on a Corcovado Rack Railway train in Brazil [1]

### 2.1.3. Standard Frequency 25kV 50Hz Electrification Supply System

Only in the 1950s after development in France did the standard frequency single-phase alternating current system become widespread, despite the simplification of a distribution system which could use the existing power supply network. The first attempts to use standard-frequency single-phase AC were made in Hungary in the 1930s, by the Hungarian Kálmán Kandó on the line between Budapest-Nyugati and Alag, using 16 kV at 50 Hz. The locomotives carried a four pole rotating phase converter feeding a single traction motor of the poly phase induction type at 600 to 1100 volts. The number of poles on the 2,500 HP motor could be changed using slip rings to run at one of four synchronous speeds. Today, some locomotives in this system use a transformer and rectifier that provide low-voltage pulsating DC current to motors. Speed is controlled by switching winding taps on the transformer. More sophisticated locomotives use thyristor or IGBT transistor circuitry to generate chopped or even variable-frequency AC that is then directly consumed by AC traction motors [1].

The 25 kV A.C, 50 Hz electrification system has been developed specifically for railway traction purposes. The main feature that separates this system from the conventional three-phase and neutral HV distribution network of the public supply authority is that the railway system is a single-phase system with one pole earthed [3].

The 25kV rail network has been designed to meet the needs of a fast, intercity, multi-track railway network carrying a variety of trains at frequent intervals. This operation requires an overhead system that is inherently safe for employees and passengers, reliable and provides a high degree of security of the supply to the traction units. This security will ensure that the electrification supply system is able to provide the required power levels to fulfill the performance of the traction units. It should be recognized that if the service or loads are increased the performance of the electrification system should be reviewed [1].

The average distance between substations ranges from 20 - 40 miles. It subjects the utility with high voltage and current unbalances, flicker and harmonics. The other disadvantages are that the phases between adjacent substations cannot be paralleled. It requires high short circuit duty substations and thus a strong utility network. It also requires redundant substation capacity to feed power for substation outages [1].

## **2.2. Utility Grid for Traction Power Supply System**

The electrified railway systems have several different options and products in the market. Due to size and power demand of projects the feeding arrangements are also changing. The transmission line voltage levels have several application levels and basically the voltage level can be different from one country to another like 110kV, 132 kV, 154 kV, 220 kV, 275 kV, 380 kV, 400kV. Railway electrification schemes draw a single-phase supply from the national electricity HV supply system. It is inevitable therefore that train loads will create unbalanced current within the HV three phase supply system, harmonic distortion and voltage fluctuation to the supply system [1].

Single phase transformers are connected to different phase pairs of the grid supply at successive feeder stations along the railway route, so as to provide the grid system with a load that is distributed between the three phases. The level of the traction load and the availability of the grid will decide the point of connection. At the railway feeder stations two incoming circuits are normally made available, both of the feeds being capable of individually carrying the total

traction load under normal traffic conditions, this will provide a power supply with a high degree of security. It is not sensible to provide an incoming feeder arrangement, which had a level of security that was less than the 25kV overhead traction system it is feeding. To increase the security of the supply the railway 25kV busbar are fed from independent parts of the HV network or by two HV busbar being fed independently by the HV system. If there is a failure on one of the supplies the fault does not interrupt the supply to the second railway feed. The two railway feeders could be independent or may be banked with 33 kV or 11 kV transformers feeding local industry or distribution networks. If there is a total loss of supply at a feeder station, supply to the overhead railway network is transferred so that the adjacent feeder station supplies power up to the non-functioning feeder station. This new feeding arrangement will give rise to loss of train performance due to the increased voltage drop between the operational feeder stations and individual locomotives. Any loss in time to the traction unit, due to the outage of a feeder station should be recoverable in the next normally fed feeding section [1].

Power for AC railway traction is obtained from utility supply system, at transmission or sub-transmission voltage level, through traction feeding substations as illustrated in Figure 2.2. The rail line is usually divided in to a number of isolated feeding sections and each section is feed by single phase supply from transformer. Within the section, power is collected by the train through overhead catenary and current takes the rails as return paths.

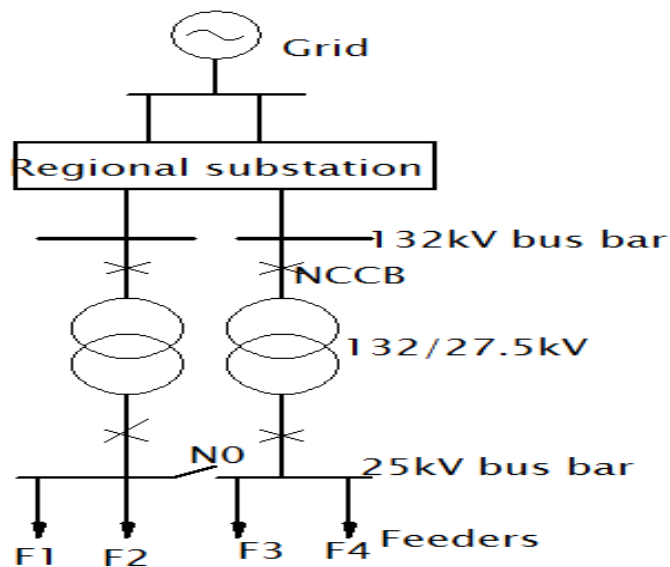


Figure 2.2: Single line diagram of the main 132/25kV traction substation [3]

### 2.2.1. Traction Transformer

Mostly, for railway electrification purpose traction transformers with special connection-i.e. single-phase, single-phase Vee-Vee (V/V), three-phase Vee-Vee (V/V), Wye-Delta, YNd11, three-phase/two-phase balancing connection (Scott, Le-Black, and Wood-bridge), impedance-matching balance connection; are selected on the basis of electrical performance, physical profile of the network and economic issues and limit the level of power quality problems improving the efficiency and power factor of the utility grid. Each connection scheme has different impact on the power system but also different investment, operation and maintenance costs [3].

In traction power system studies and analysis, traction transformer modeling and evaluation, especially, recalling voltage unbalance and the effects of harmonics and negative phase sequence currents, protection methods analysis, traction transformer and transmission line utilization factors analysis, are inevitable. Besides understanding the general and specific ideas and principles behind each transformer type and connection scheme, these studies have enabled scholars of the field to evaluate the effectiveness of the railway power supply system for the specific purpose the supply system is designed for [5].

#### a. Single Phase Transformer

In this arrangement of the traction substations, a single phase transformer is used to feed the traction system which is fed through two phases. One of the two output phases is connected to the catenary feeding the trains along the track and the other is connected to the running rails as the negative return current path [1]. The structure of such an electrification system is shown in Figure 2.3.

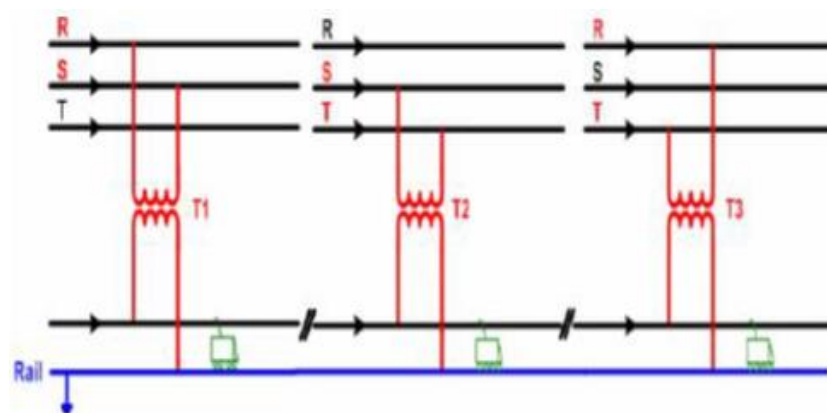


Figure 2.3: Arrangement of traction electrification system with single phase transformer [1]

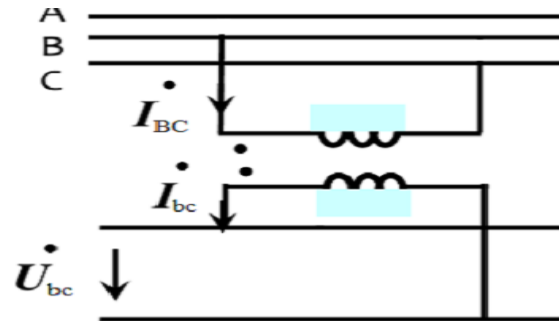


Figure 2.4: Equivalent circuit of single phase transformer [3]

### b. Three Phase V/V Connection of Traction Transformers

In three phases V/V-connection scheme the primary side is the utility side balanced three phase electrical; utility grid side, power source while the secondary side is a combination of two single phase transformer arrangements. Moreover, the phasor diagram shows that the secondary side voltages,  $U_{bc}$  and  $U_{ac}$  are in phase with the primary side line voltages  $V_{BC}$  and  $V_{AC}$  respectively but  $60^\circ$  out-of phase from each other [5].

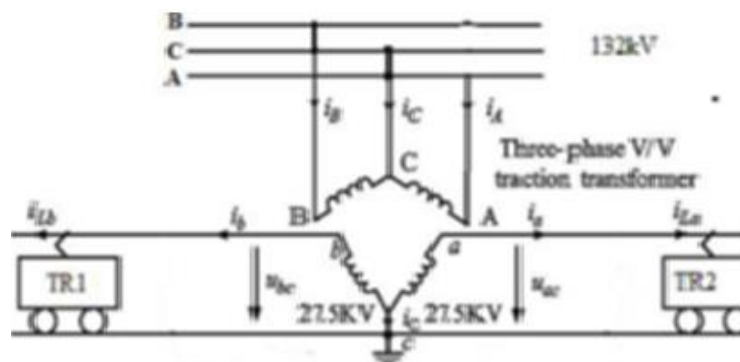


Figure 2.5: Three Phase V/V-Connected Traction Transformer Connection Scheme [5]

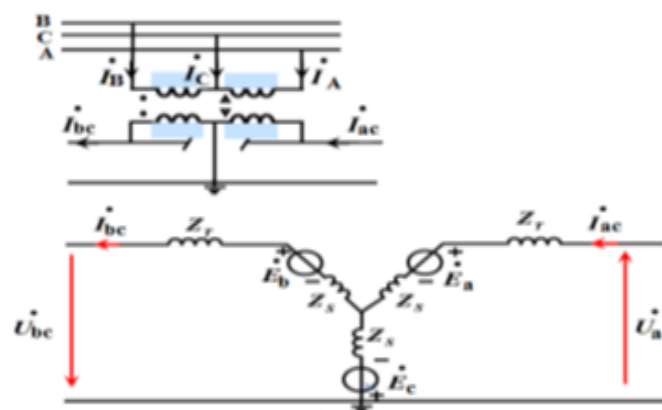


Figure 2.6: Equivalent Circuit of Three Phase V/V-connected Traction Transformer [5]

### 2.3. Power Feeding Mode in AC Electrified Railway

The practical details of AC power feeding are concerned with maintaining the quality of the supply. On the traction side, catenary feeding systems have been developed to improve transmission efficiency and system regulation [1]. Some basic feeding mode configurations which are widely used for feeding electric trains in mainline AC railways are:

#### 2.3.1. Direct Feeding Configuration

The direct feeding configuration is quite simple and the least capital-intensive way of feeding power. The feeding transformer is connected directly to the overhead catenary and the rails at each substation. However, it has some disadvantages with this configuration like high feeding impedance with large losses, high rail-to-earth voltage (a potential safety hazard) and the production of earth currents which can cause interference in adjacent telecommunications circuits. To reduce those effects, the addition of an extra conductor (Return Conductor) paralleled and tied to the rails at typically 5 or 6 km is needed and this can reduce electromagnetic interference in parallel communication lines by 30% [3]. Figure below shows the diagrams of the direct feeding configuration.

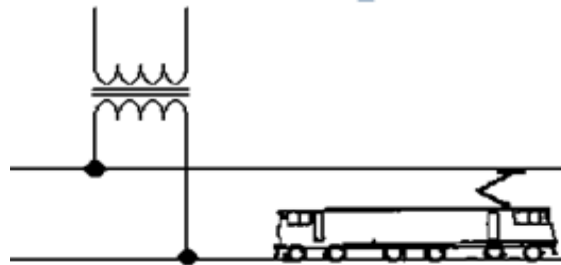


Figure 2.7: Typical diagrams of the direct feeding configuration [1]

#### 2.3.2. Direct Feeding with Return Conductor

In this configuration major part of the traction current returns from negative return line and the remaining current returns from rail. It has simple structure, less investment, maintenance and high reliability as directly power mode. Compared with direct power supply mode, in direct power supply with return line configuration rail potential and communication interference are improved. Because of low rail potential and traction network impedance is reducing, power feeding length is increased to extend 30% and it has less interference on extra low voltage( ELV) system [3].

Compared with boost transformer power supply configuration, direct power supply with return line configuration has simple structure, less investment and maintenance. In direct power supply with return line configuration traction network impedance is reducing and feeding length is increased.

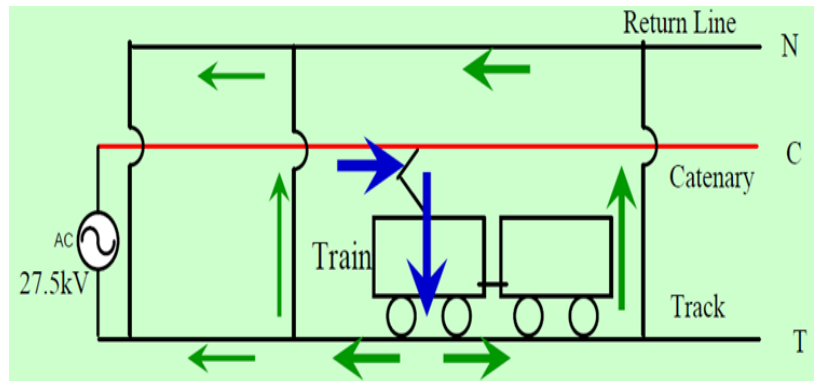


Figure 2.8: Direct feeding with return line mode [3]

### 2.3.3. Booster Transformer Feeding System

Booster transformers (BTs) are placed along the catenary at 3-4 km intervals and represent a further improvement in the feeding circuit. The BT primary is connected across a gap in the contact wire and the secondary across an insulated rail section. The turn's ratio is unity and traction return current is forced from the rails and earth to flow through the transformer secondary to equalize the Ampere-turns in the core setup by the primary current. The preferred configuration is to incorporate a conductor in parallel with the rails for the return current, as shown in figure bellow [1]

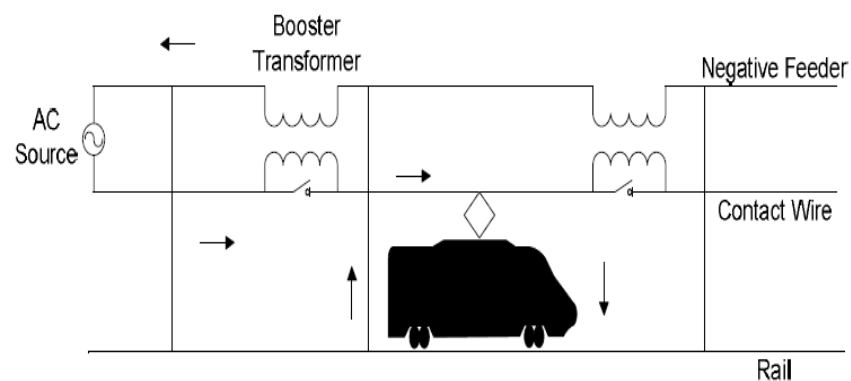


Figure 2.9: BT feeding system [1]

Figure 3.9 shows the composition of a BT feeding circuit. A BT is installed every 4 km on the contact wire to boost the return circuit current on the negative line. This design minimizes the inductive interference on telecommunication lines because the current flows to the rail only in limited sections. In particular, when an electric car passes a BT section, a large arc is generated in the section, and a large load current can cause a very large arc that can damage the overhead line. Consequently, capacitors are often inserted in the negative feeder to compensate for the reactance and reduce the amount of current intercepted by the pantograph, thereby reducing arcing, and also helping to prevent voltage drop [1].

### 2.3.4. Autotransformer Power Feeding System

The AT winding is connected between the catenary and an auxiliary feeder, with the rails tied to an intermediate point. Traction current goes through train and returns from negative feeder. In a two-phase fed catenary system, the rail and the earthed return conductor are connected to the midpoint of the catenary autotransformer. One pole of the autotransformer is connected to the catenary phase, and the other pole to the negative phase conductor. With this connection, the power is fed to the locomotive with double voltage compared to the voltage of the locomotive itself. This means that the phase currents are reduced to half and the feeder losses to the fourth part compared to the single-phase feeder. The task of the autotransformers along the catenary line is 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 [1]. The advantages that are obtained with this connection compared with single phase feeding and booster transformers are the following, depending on the objectives:

- Lower losses due to higher voltage
- Longer distance between catenary feeder substations
- Better collection of returning stray currents
- Reduced interference for communications (ABB Railway Transformers)

Autotransformer (AT) feeding combines the advantage of higher-voltage power transmission, hence increased substation spacing, with the convenience of using standard 25kV traction equipment.

The train draws current from two adjacent ATs, the total supply current being half the train current. Rail currents flow through the AT windings as shown in order to maintain Ampere-turn

balance in the cores. In contrast to BT current balancing, the AT system operates by balancing voltages. For ideal ATs, no current will flow in the rails of unoccupied sections, and since the AT midpoints are grounded, the earth current will be maximum at some point between the train and each AT, and minimum at the AT locations.

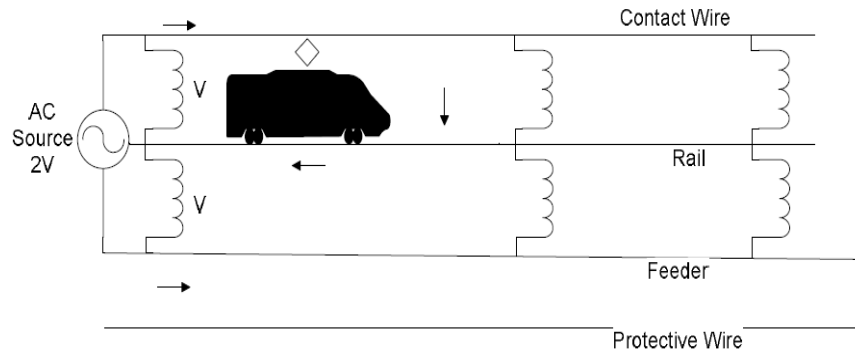


Figure 2.10: AT feeding system [1]

## 2.4. AC Electrified Traction System of Addis Ababa-Djibouti Railway Line

Electrified railway systems (ERS) are used widely around the world as a significant means of mass and public transportation. They are expanding at great speed throughout the world. Like many other nations, Ethiopia is also working to have the worldwide High Speed/High Capacity (HS/HC) railway lines that use the AC power supply system. The SEBETA - ADAMA section is double track, with a length of 110.298km; the ADAMA - MIESO section presents single track, with a length of 208.663km. It is temporarily suggested that: single-phase traction transformers shall be used in both SEBETA and MIESO (terminations) traction substations with conditions for 3-phase V/V connection reserved, and 3-phase V/V connection traction transformers shall be used in other traction substations. Fixed back-up shall be applied for all traction transformers. Totally 11 new traction substations i.e. SEBETA, INDODE, BISHOFTU, MOJO, WACHULALU, CHISA, HARO, AJO TERE, AWASHISHT, ADELE and MIESO traction substations and 4 new section posts i.e. LABU, DK48, DK82 and ADAMA section posts are proposed to be built along the line [2].

One power dispatching office is proposed to be set at LABU in the new traction power supply system. Two dispatching consoles will be set for dispatching control of traction substation facilities in SEBETA-MIESO section.

The two most common electrification power supply systems for high speed rail are 1x25kV and 2 x 25kV. In Ethiopia the single-phase power frequency (50Hz) AC 25kV and the direct feeding system with return wire is applied for the power supply system [3].

In this system, the traction transformers are supplied from state grid, normally at 132 kV voltage levels. This voltage is further step down to 25 kV nominal voltage at traction substation using 132/27.5kV transformers. Distribution of the traction power supply facilities shall meet the requirements of long-term traction load and shall be designed with a capacity to meet passenger and freight transportation. Voltage of OCS shall be as follows: nominal voltage, 25 kV; maximum working voltage, 27.5 kV; maximum short-time voltage, 29 kV; minimum working voltage, 20 kV and working voltage under abnormal conditions, 19 kV. The electric traction substation with load shall be supplied by two independent and reliable power supplies and those two power supplies shall be hot backup for each other i.e. each traction substation has two 132 kV independent power lines [2].

Table 2.1: Ethio-Djibouti Railway General System Technical Specifications [2], [5]

Description	Sebeta to Negad
Gauge	1435mm
Number of main line	Sebeta to Adama: Double line Adama to Negad: Single line
Targeted speed	Passenger: 120km/h Freight: 80km/h
Locomotive type	Passenger: SS9 Freight: HX <sub>D3B</sub>
Traction power supply system	
Feeding system	Standard 25KV,50Hz, Direct power feeding with return line
Nominal voltage	25KV
Short term	29KV (maximum)
Operating voltage	20KV(minimum)
Abnormal operating voltage	19KV
Traction substation	

Primary side voltage	Two separate and reliable 132kV from utility side
	System short circuit capacity 400MVA
Traction transformer	Single-phase (at Sebeta and Nagad Substations)
	Three-phase, Vv-connection (at the rest stations)
	27.5kV secondary side voltage

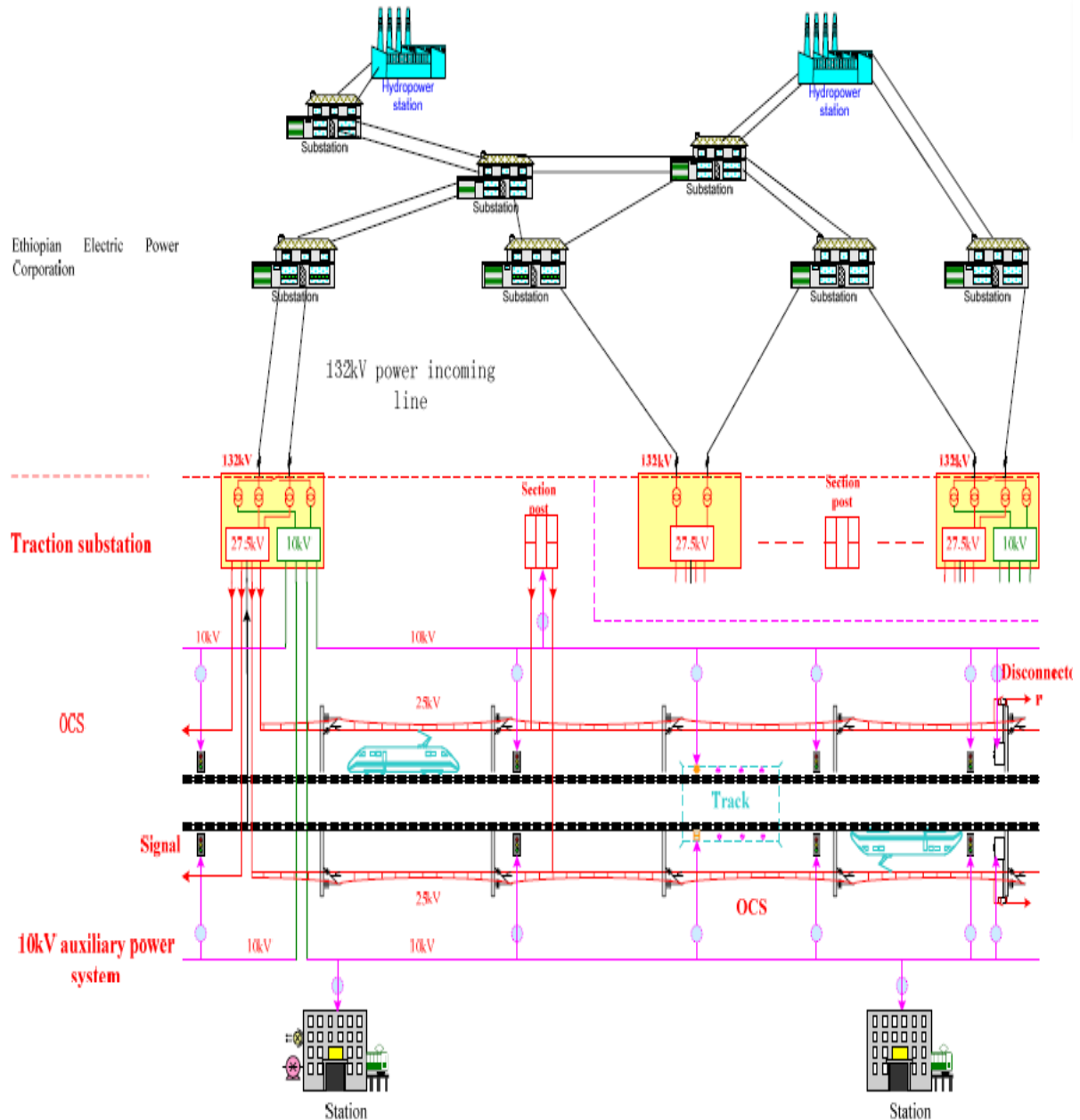


Figure 2.11: The Scheme of the double-track Section [2]

## Chapter Three

### 3. Literature Review

#### 3.1. Effect of Power Quality Problem in Electric Traction

Electric railways are the major pollution sources of the power quality in the public power system. The low power factor and current harmonics caused by AC-DC locomotives are the difficult problems needed to be dealt with for long time. Many countries are imposing the penalty for the consumers for polluting the utility system by means of harmonics. The consumers are also being penalized for maintaining lower power factor and leading power factor. Hence, remedial measure suitable for the individual system should be taken to avoid penalty.

The growing number of power electronics base equipment has produced an important impact on the quality of electric traction supply. Therefore, power quality problems may originate in the system or may be caused by the consumer itself. For an increasing number of applications, conventional equipment is proving insufficient for mitigation of power quality problems [6].

Among all traction network electrification systems, the system which is most commonly used all around the world is the 25 kV industrial frequency systems. This high voltage system makes it possible to supply power via simple permanent way installations to trains with high power consumption by limiting the amount of current send from the OHL to the pantograph [7].

It usually gets the power from the three-phase grid, and supplies to the inductive, single phase locomotives. Transformer is the only device that acts as the adapter between the three-phase source and the single-phase load in this system at present. Considering the load's random distributing in time and location, no matter what kind of transformer is adopted, the traction system causes load unbalance problem to the three-phase power distribution system. Because of the nonlinear characteristics of railway electrification load generates harmonic current and consume big reactive power and it can cause malfunction of traction equipment and the whole electrified system. Although it can be solved by adopting high performance vehicle, this problem cannot be neglected considering the large amount of rectifier locomotives that are running [1].

Reference [8], deals about the Compensation of Power Quality Problems in Traction Power System Using Direct Power Compensator, it try to improve the power factor and eliminate harmonic currents in high-speed traction systems.

Reference [9], the paper entitled by “Reactive Power Compensation in Railways Using Active Impedance Concepts,” IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE) ISSN: 2278-1676 Volume 4, Issue 1 (Jan. - Feb. 2013); the author study about compensation of reactive power in electric traction substation using active power filter. It explains also the negative impact of harmonics and reactive power in electric traction system.

The harmonics and reactive power have negative influences on the power supply system. To compensate reactive power, fixed capacitors have been widely used. One of the main disadvantages of fixed capacitor is that its compensation amount is also fixed and cannot be changed with the variation of load. Another one is that resonance may occur between the fixed capacitor and the impedance of power supply system. Recently TSF (Thyristor Switched Filter) has been used in traction system.

There are several group of passive filter in TSF, with the variation of reactive power, an appropriate number of groups of TSF are switched on. Thus the compensation amount of TSF can be adjusted with the variation of load. However, resonance will still possible to occur between TSF and the impedance of power supply system.

Traction systems are huge consumers of reactive power. It due to the presence of inductive reactance in traction transformer, traction motors, auxiliary motors, smoothening reactor. Reactive power keeps on varying in a traction substation as the number of locomotives increases and decreases in its working environment. As a result of this a detailed study of reactive power is required in traction substation and the traditional fixed capacitors should be replaced with active power filter.

In reference [10] the paper titled “Reactive Power Compensation and Harmonic Mitigation of Distribution System using SAPF Compensator,” International Journal of Engineering Science and Innovative Technology (IJESIT) Volume 2, Issue 3, May 2013; the author describes topology of SAPF to compensate reactive power and harmonics in power distribution system. It uses PI controller for DC voltage balancing and Hysteresis current controller (HCC) for gating pulse generation is implemented.

### **3.1.1. Harmonic Distortion**

Harmonics are sinusoidal voltages or currents having frequencies that are whole multiples of the frequency at which the supply system is designed to operate (e.g., 50 Hz or 60 Hz). An

illustration of fifth harmonic distortion is shown in figure below. When the frequencies of these voltages and currents are not an integer of the fundamental they are termed inter-harmonics.

Both harmonic and inter-harmonic distortion is generally caused by equipment with non-linear voltage/current characteristics.

In general, distorting equipment produces harmonic currents that, in turn, cause harmonic voltage drops across the impedances of the network. The main detrimental effects of harmonics are:

- Malfunction of control devices, main signaling systems, and protective relays
- Extra losses in capacitors, transformers, and rotating machines
- Additional noise from motors and other apparatus
- Telephone interference
- The presence of power factor correction capacitors and cable capacitance can cause shunt and series resonances in the network producing voltage amplification even at a remote point from the distorting load [1].

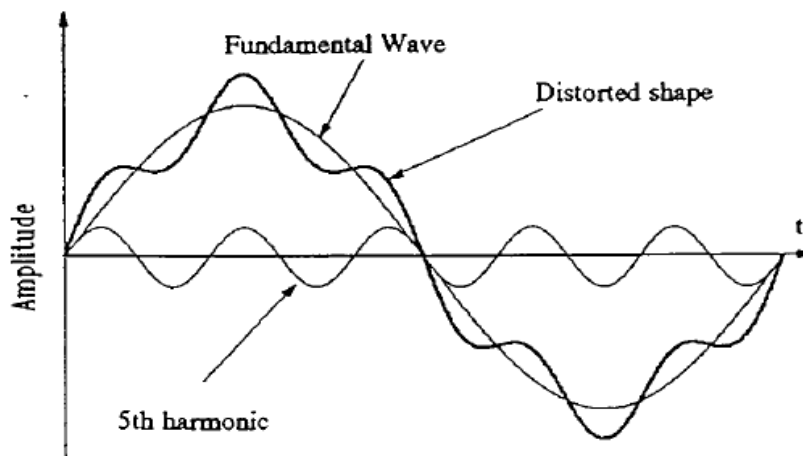


Figure 3.1: Example of a distorted sine wave [1]

Most nonlinear loads as well as loads controlled by the power electronics system are harmonic source. Fluorescent lighting and AC/DC converters in power electronic system are typical example in point. All electricity companies are concerned about harmonic pollution, especially from large nonlinear loads such as railway system connected to their power system network.

Nowadays, there have been considerable developments in industrial processes which rely on controlled rectification for their operation. Railway systems are one of the important users of the technology and consequently they are a large source of harmonic [1].

As we mentioned before there are two system of electrical supply to railway; AC and DC system. Each system has its own harmonic characteristics, which depended on the network components used in the system. In DC systems, chopper and inverter equipment produces harmonic currents and switching transients. In AC systems, the use of converter equipment's modifies the nature of the traction current spectrum, generally increasing magnitude of odd harmonics at some values of train speed when compared what is obtained with tap changer equipment [1].

Electric trains having thyristor or pulse width modulation (PWM)-controlled converters inject harmonic currents into the feeding overhead lines. Harmonic currents in the electric train are one of the biggest concerns, and the load current model to represent electric trains is proposed. The current harmonics injected from an AC electric train propagate through power-feeding circuits. Being a distributed RLC circuit, the feeding circuit can experience parallel resonance at a specific frequency. The harmonic current is amplified by the resonance, and the amplified harmonic current usually induces various problems, including interference in adjacent communication lines and the railway signaling system, overheating, and vibration at the power capacitors, and erroneous operation at the protective devices. Therefore, the harmonic current flow must be assessed exactly in the designing and planning stage of the electric traction system. Since the harmonic current flows through the catenary system, it needs to be accurately modelled to analyze and assess the harmonic effect on the power-feeding system [1].

### **3.1.2. Reactive Power**

Reactive Power can best be described as the quantity of “unused” power that is developed by reactive components, such as inductors or capacitors in an AC circuit or system. In a DC circuit, the product of “volts x amps” gives the power consumed in watts by the circuit. However, while this formula is also true for purely resistive AC circuits, the situation is slightly more complex in an AC circuits containing reactive components as this volt-amp product can change with frequency [11].

In an AC circuit, the product of voltage and current is expressed as volt-amperes (VA) or kilo-volt-amperes (kVA) and is known as Apparent power, symbol S. In a non-inductive purely resistive circuit such as heaters, irons, kettles and filament bulbs, etc. their reactance is practically zero, and the impedance of the circuit is composed almost entirely of just resistance.

For an AC resistive circuit, the current and voltage are in-phase and the power at any instant can be found by multiplying the voltage by the current at that instant, and because of this “in-phase” relationship, the RMS values can be used to find the equivalent DC power or heating effect.

However, if the circuit contains reactive components, the voltage and current waveforms will be “out-of-phase” by some amount determined by the circuit's phase angle. If the phase angle between the voltage and the current is at its maximum of  $90^\circ$ , the volt-amp product will have equal positive and negative values [12].

In other words, the reactive circuit returns as much power to the supply as it consumes resulting in the average power consumed by the circuit being zero, as the same amount of energy keeps flowing alternately from source to the load and back from load to source. Since we have a voltage and a current but no power dissipated, the expression of  $P = IV$  (rms) is no longer valid and it therefore follows that the volt-amp product in an AC circuit does not necessarily give the power consumed. Then in order to determine the “real power”, also called Active power, symbol P consumed by an AC circuit, we need to account for not only the volt-amp product but also the phase angle difference between the voltage and the current waveforms given by the equation [12]:

$$P = VI \cos\phi \quad (2.1)$$

Then we can write the relationship between the apparent power and active or real power as:

$$\text{Active power, (P)} = \text{Apparent power, (S)} \times \text{powerfactor}$$

$$\text{pf} = \frac{P}{S} = \cos\phi$$

Note that power factor (PF) is defined as the ratio between the active power in watts and the apparent power in volt-amperes and indicates how effectively electrical power is being used. In a non-inductive resistive AC circuit, the active power will be equal to the apparent power as the fraction of P/S becomes equal to one or unity. A circuit's power factor can be expressed either as a decimal value or as a percentage.

But as well as the active and apparent powers in AC circuits, there is also another power component that is present whenever there is a phase angle. This component is called Reactive Power (sometimes referred to as imaginary power) and is expressed in a unit called “volt-amperes reactive”, (VAr), symbol Q and is given by the equation:

$$Q = VI. \sin\phi \quad (2.2)$$

Reactive power, or VAr, is not really power at all but represents the product of volts and amperes that are out-of-phase with each other. The amount of reactive power present in an AC circuit will depend upon the phase shift or phase angle between the voltage and the current and just like active power, reactive power is positive when it is “supplied” and negative when it is “consumed”.

The relationship of the three elements of power, active power, (watts) apparent power, (VA) and reactive power, (VAr) in an AC circuit can be represented by the three sides of right-angled triangle. This representation is called a power triangle as shown:

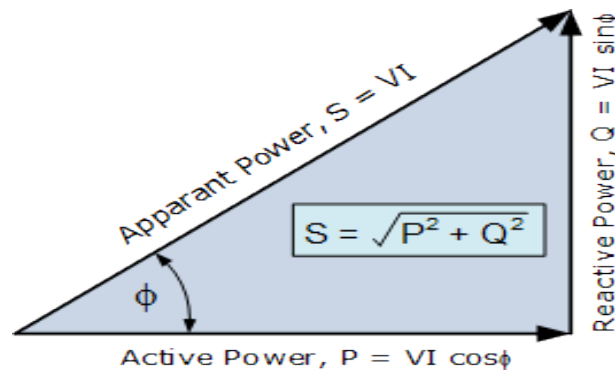


Figure 3.2: Representation of power triangle [12]

From the above power triangle we can see that AC circuits supply or consume two kinds of power: active power and reactive power. Also, active power is never negative, whereas reactive power can be either positive or negative in value so it is always advantageous to reduce reactive power in order to improve system efficiency.

But for many industrial power applications, reactive power is often useful for an electrical circuit to have. While the real or active power is the energy supplied to run a motor, heat a home, or illuminate an electric light bulb, reactive power provides the important function of regulating the voltage thereby helping to move power effectively through the utility grid and transmission lines to where it is required by the load [11].

Reducing reactive power to improve the power factor and system efficiency is a good thing, one of the disadvantages of reactive power is that a sufficient quantity of it is required to control the voltage and overcome the losses in a transmission network. This is because if the electrical network voltage is not high enough, active power cannot be supplied. But having too much reactive power flowing around in the network can cause excess heating ( $I^2R$  losses) and undesirable voltage drops and loss of power along the transmission lines [12].

In reference [13], the paper entitled “modeling and simulation of FC-TCR for reactive power compensation using the MATLAB/Simulink,” International Journal of Advances in Engineering & Technology, Jan., 2015; the author describes how SVC (Static VAR Compensator) is used to improve reactive power and voltage profile in AC transmission system.

### **3.2. Harmonic Reduction and Reactive Power Compensation Techniques**

Mitigation or cancellation of harmonics can be done by using passive or active filters. The harmonic filter connected to AC system has two objectives to minimize the effect of harmonic voltage and current in the power system below an acceptable level and to compensate the reactive power required by the loads.

#### **3.2.1. Passive Filter**

The passive filter requires resistors, inductors, and capacitors and they do not depend upon any type of external power source. By proper selection of L and C, they are tuned to bypass a particular harmonic component. Multiple numbers of passive filters are connected in parallel to nullify higher order of harmonics as shown in Figure3.3. Though passive filters were widely used as harmonic improvement and reactive power compensation devices in the power distribution system, their performances is not satisfactory due to following reasons [11]:

- A separate filter is necessary for each harmonic frequency
- Passive filter must be designed in considering with current provided by nonlinear load.
- Source impedance affects the compensation characteristics of LC filters
- When the content of harmonics in the AC line increases, the filter will be loaded
- Frequency variation of AC source and tolerances in the filter components will affect the compensation characteristics of LC filters. If the system frequency varies in wide range, components required for attaining tuned frequency become impracticable

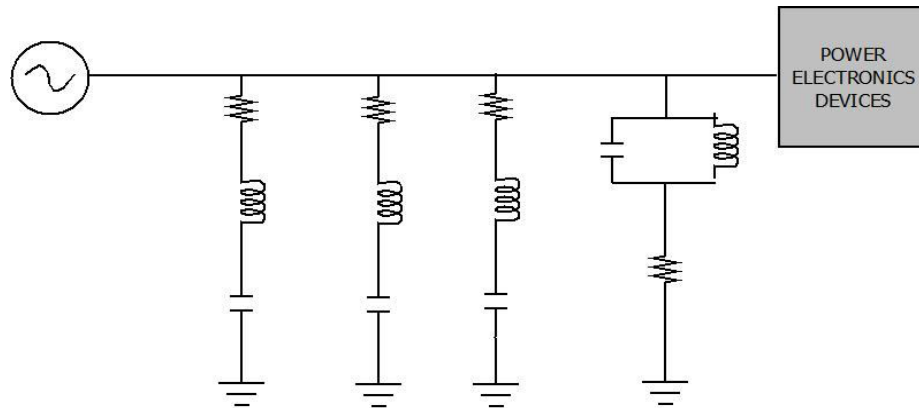


Figure 3.3: Block diagram for passive filter connected power system [11]

With the above mentioned disadvantages the passive filter are less frequently used compared to active power filter. The practice of using the active power filter is the future trend of harmonic improvement in power distribution system because of its excellent dynamic characteristics. A flexible and handy solution to harmonic problem is provided by active power filters. Presently they are based on PWM converters and connected to low and medium voltage distribution system either in shunt or series.

### 3.2.2. Active Power Filter

Active power filters (APF) are constructed using both passive and active elements. For their operation they need external power source. They are connected to AC mains through coupling reactors. Harmonic distortion has traditionally been dealt with the use of passive LC filters. They are easy to design, have simple structure, low cost and high efficiency, and were also employed for the power system quality enhancement. However, the application of passive filters for harmonic over compensation of reactive power at fundamental frequency, and poor flexibility for dynamic compensation of different frequency harmonic components and bulky in size [11]. To overcome these disadvantages, active power filters are introduced which compensate for the current harmonics and compensate reactive power.

The advantage of active filtering is:

- It automatically adapts to changes in the network and load fluctuations
- They can compensate for several harmonic orders
- Eliminating the risk of resonance between the filter and network impedance and
- Takes very little space compared with traditional passive compensators.

The controller of the active filter is the key and heart of the filter which greatly affects its performance. Its main power circuit of active power filter consists of a current controlled voltage source inverter with a DC link capacitor. An active power filter operates by generating a compensating current with 180 degree phase opposition and injects it back to the line so as to cancel out the current harmonics introduced by the nonlinear load. This will thus suppress the harmonic content present in the line and make the current waveform sinusoidal. So the process comprises of extracting the harmonic component present in the load current, generating the reference current, producing the switching pulses for the power circuit, generating a compensating current and injecting it back to the line [14].

Reference [11], deals about improving power quality problems using active power filter. These Power Electronic converters and loads are the sources of harmonics and reactive power which greatly affect the performance of the power system network.

In the past tuned passive filters were used to solve the problem of harmonics distortion but these filters offered some drawbacks like they filter only the frequencies they are tuned for, their operation cannot be limited to a certain load, resonances can occur because of the interaction between the passive filters and other loads with severe effects. To compensate these drawbacks, recent efforts have been made on the development of an important group of power system conditioning circuits commonly known as Active Power Line Conditioners (APLC) or simply Active Power Filters (APF). The performance of an active filter mainly depends on the reference current generation strategy, control technique and topology of the filter inverter.

In reference paper[1], presents the power quality problems in the 25 kV AC railway system and decrease the harmful effects to utility electric network using EPLL based single phase active power filter that can compensate the load reactive and harmonic current with Scott transformer can decrease unbalanced voltage on the network.

Modern semiconductor switching devices are currently employed in a wide variety of domestic and industrial loads. These loads are often referred to as “power electronic loads”. They are often reliable and economical solutions to control electric power from a few watts to many megawatts. The nonlinear characteristic of semiconductor devices as well as operational function of most power electronics circuit makes distorted currents and voltage waveform on the supply system. In contrast with the conventional linear loads, the power electronic load are categorized as nonlinear loads. An example of a nonlinear load is a six pulse bridge rectifier with smoothing

reactor. These loads are commonly referred to as “power system polluters” or “distorting sources” in relevant literature. The presence of power electronics related distorting elements in virtually all major industrial loads viewed by the power distribution authorities as the major cause of an alarming amount of harmonic distortion in electronic power systems. The problems caused by these types of loads are a part of Electric Power Quality studies.

The development of the energy improving technologies, widely used for industrial loads, has already been expanded to domestic electric appliances. This has resulted in a further significant increase in the background distortion level of harmonic frequencies within electric power system reducing the adverse effects of cumulative distortion, caused by aggregated small industrial and domestic loads, requires complicated and innovative power filtering techniques. The problems associated with harmonically polluted power systems are well known. Among often-cited problems caused by harmonic distortion in supply system, the poor use of the AC source and distortion wiring volt-ampere capacity as well as distortion of the line voltage waveform caused by harmonic current in particularly in “weak” system buses are considered highly important. Nuisance tripping of computer-controlled industrial processes and medical equipment, excessive heating in transformers and equipment failure due to resonant over voltages are other severe distortion problems. It is interesting to note that the power semiconductor-based loads which are the major contributors to power system pollution tend to be sensitive to pollution caused by other nonlinear loads.

Synchronous condenser can be very effective for system var flow/ voltage control. However because of their relatively slow response time, they are unable to compensate fully for undesirable effects of rapidly changing loads. An alternative approach to the use of controllable reactive power devices utilizes the “static var compensator (SVC)” systems, which have faster response and a good potential for lower initial and operating costs. The contribution to suppression of harmonics and transition harmonic correction is non-existent for the SVC's. Passive filters are being used widely for harmonic elimination. However they may create system resonances, need to be significantly over-rated to account for possible harmonic absorption from power system, must be coordinated with reactive power requirements of the loads and need a separated filter for each harmonic frequency to be cancelled.

The problems associated with performing switching operation on a large scale capacitors and inductors within the static var compensators, simultaneously with using frequency filters to

absorb harmonic distortion generated by nonlinear load and the SVC itself, motivated the investigation of utilizing fast switching technology to generate the required “corrective” or “compensating” waveform. This waveform has to be injected into carefully selected point in a power system to correct the voltage or current waveform on distorted bus-bar. The approach is based on the principle of injecting harmonic current into the AC system, of the same amplitude and the reverse phase to that of the load current harmonics. The concept of injecting the compensating waveform into a power system bus is commonly referred to as “active power filtering” [1]. The switching compensator itself has been known by different names such as active power filter, active power line conditioner and static var and distortion compensator. Some interesting features normally associated with active power filtering approach can be outlined as follows

- While passive filter have to be designed with a KVA rating based on the worst case total distortion at each frequency, the active power filters can be designed for the lower KVA rating than the worst case total distortion.
- They do not introduce system resonance like passive filter.
- They are capable of reducing the effect of distorted current/voltage waveforms as well as compensating fundamental displacement component of current drawn by nonlinear loads.
- Because of high controllability and quick response of semiconductor devices, they have faster response time than conventional SVC`s
- They primarily utilize power semiconductor device rather than conventional reactive components (storage elements). This results in reduced overall size of a compensator and expected lower capital cost in future due to continuously downward trend in the price of the solid state switches. They are usually called system with “minimum storage elements” or “no storage elements”.
- Active power filters are better for compensating low order harmonics such 3rd, 5th and 7th, while passive filter better for compensating higher order harmonics such as the 11th, 13th and higher. The reasons of this may be listed as follows.
  - ✓ Active filtering of high order harmonic components need high switching frequencies and high di/dt capability for the active power filter. However this not the case for a passive filter.
  - ✓ Size of the passive filter becomes larger for compensating lower order harmonics.

By implementing the APF for power conditioning, it provides functions such as reactive power compensations, harmonic compensations, harmonic isolation, harmonic damping, harmonic termination, negative-sequence current or voltage compensation and voltage regulation [12]. The main purpose of the APF installation by individual consumers is to compensate current harmonics or current imbalance as well as power factor improvements of their own harmonic-producing loads. Besides that, the purpose of the APF installation by the utilities is to compensate for voltage harmonics, voltage imbalance or provide harmonic damping factor to the power distribution systems [1].

### **3.2.2.1. Classifications of Active Power Filter**

In references [1, 15, 11], the classification of Active power filter and their operating principle are explained.

The basic principle of APF is to produce specific currents components that cancel the harmonic components draw by the nonlinear load. The APF acts as a harmonic source which is same in magnitude but opposite in direction to the harmonics caused by the nonlinear load. Reactive power required by the load also provided by APF and thus improve the power factor of the system. APF consists of an inverter with switching control circuit. The inverter of the APF will generate the desired compensating harmonics based on the switching gates provided by the controller. The crucial part of this APF is designing the suitable controller and develop the filters configuration [1].

On the basis of the above, the published work in this field can be classified using the following criteria [1, 11].

- Power rating and speed of response required in compensated systems;
- Power-circuit configuration and connections;
- Control techniques employed; and
- Technique used for estimating the reference current/voltage.

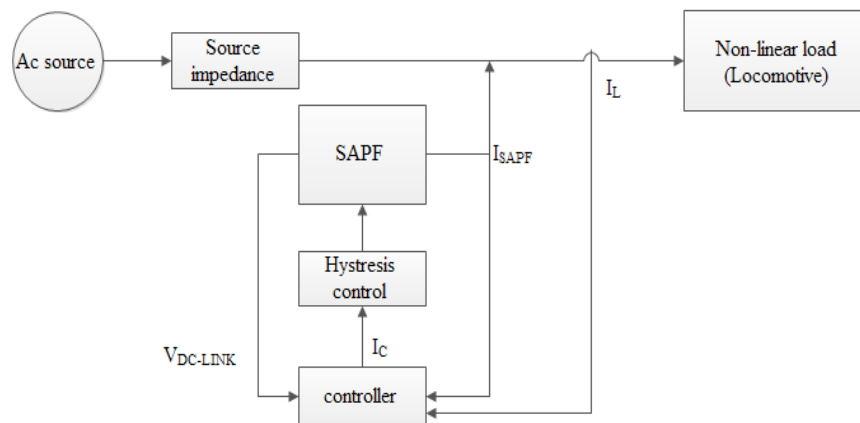


Figure 3.4: Generalized block diagram for active power filters

One of the active power filters, the shunt active filter has been researched and developed, and it has gradually been recognized as a feasible solution to the problems created by nonlinear loads. It is used to eliminate the unwanted harmonics and compensate fundamental reactive power consumed by nonlinear loads with injecting the compensation currents into the AC lines [15].

### I. Classification of Active Filters Based On Power Rating and Speed of Response

The size of non-linear loads plays a major in making decisions to implement the control strategies of the active filters. The filter required for compensation must be practical for the load and this affects the speed of response. The block diagram in Figure 2.5 shows the classification of APFs according to power rating and speed of response of filters.

#### a. Low Power Applications

APFs of this category have power ratings below 100kVA. These APFs usually employed in residential areas, commercial buildings hospitals and for medium sized factory loads, and for motor drives systems. APFs for this power range use sophisticated techniques with number of PWM pulses and voltage or current source inverters. The response time for smaller application is relatively much faster than high power range and is in the range of microsecond to ten milliseconds. It consists of single phase and three phase system [11].

#### b. Medium Power Applications

The power systems having power rating in the range of 100kVA-10MVA fall into the category of medium power. The major objective is the elimination of current harmonics as the impact of

phase unbalance is less. The speed of response of this range of application is the order of tens of milliseconds [11].

### c. High Power Applications

The power systems having power rating above 10MVA fall into the category of high power applications. The required response time for this case is in the range of tens of seconds, which is sufficient for contactors and circuit breakers to operate after taking the optimal-switching decision. Power fluctuations in the range of a few seconds are, on the other hand, treated by the generating stations' ancillary devices [11].

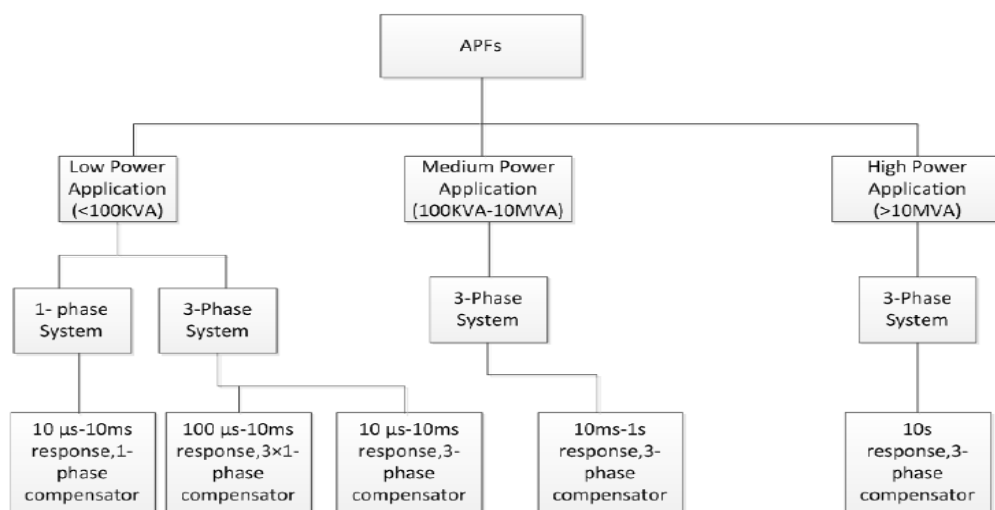


Figure 3.5: Classification of active filters based on power rating and speed of response [11]

## II. Classification of active filter based on topology

Based on topology, there are two kinds of active filters which are current source and voltage source active filters.

### a. Current source active filters (CSAFs)

Current source active filters (CSAFs) employ an inductor as the DC energy storage device. In voltage source active filters (VSAFs), a capacitor acts as the energy storage element. VSAFs are less expensive, lighter, and easier to control compared to CSAFs [15].

Presently available APFs are basically of pulse width modulated inverters (current source or voltage source). Current fed PWM inverter act as non-sinusoidal current source to cancel out the




harmonic current produced by nonlinear load. Current fed PWM based APF's use is limited to low power application [15].

### **b. Voltage Source Active Filters (VSAFs)**

The most dominant type of active filter is the voltage source inverter-type active filter, which has been designed, improved, and used for many years and is now in the commercial stage [4]. Their losses are less than CSAFs and they can be used in multilevel and multistep configurations. It consists of a DC-bus capacitor as energy storage and power electronic switches to generate harmonics currents according to the signal from controller. Voltage source inverter (VSI) is the most popular one for implementing active power filtering and VSI based APFs have high power rating and lower switching frequency [4,15].

## **III. Connections (Configuration) of Active Power Filter**

When APFs are classified according power circuit connections and configurations, it greatly affects its efficiency and accuracy for compensation. It is therefore very important to choose the right kind of configuration for compensation. Active power filter can be connected in several power circuit configurations. In general, Active power filter can be classified into three categories as per their connection to the PCC, which are:-

-  Shunt active power filter
-  Series active power filter
-  Hybrid active power filter

### **a. Shunt Active Power Filter**

It is a device used in parallel, it compensates the current harmonics and also helps in reactive power compensation there by improving the power factor, increasing efficiency, reduces the losses caused by the harmonics. As a result the total current drawn from the AC traction mains gets sinusoidal. The large scale use of power electronics equipment has led to increase in harmonics in the power traction. The nonlinear loads generate harmonic current which distorts the voltage waveform at the pantograph. These current harmonics will result in a power factor reduction, decrease in efficiency, power system voltage fluctuations and communications interference. So harmonics can be considered as a pollutant which pollutes the entire electrified railway system [4].

The shunt-connected active power filter, with a self-controlled dc bus, has a topology similar to that of a static compensator (STATCOM) used for reactive power compensation in power transmission systems. Shunt active power filters compensate reactive power and load current harmonics by injecting equal-but opposite harmonic compensating current. This connection is most widely used in active filtering applications [15]. It consists of a voltage or current source configurations. The voltage source inverter (VSI) based shunt APF is the most common type used today due to its well-known topology and straight forward installation procedure [15].

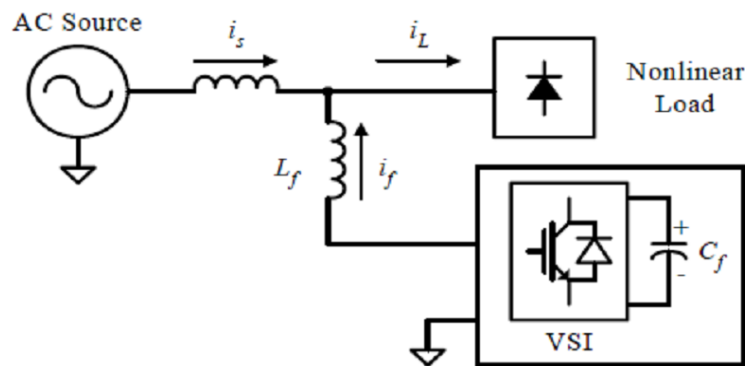


Figure 3.6: Configuration of a VSI based shunt APF [15]

Figure 3.6 show a configuration of a VSI based Shunt APF. It consists of a interfacing inductors ( $L_f$ ) and VSI which is combination of a DC-bus capacitor ( $C_f$ ) and power electronic switches. Shunt APF acts as a current source, compensating the harmonic currents due to nonlinear loads. The operation of shunt APF is based on injection of compensation current which is equals to the distorted current, thus eliminating the original distorted current. This is achieved by generates the compensation current waveform ( $i_f$ ), using the VSI switches. The shape of compensation current is obtained by measuring the load current ( $i_L$ ) and subtracting it from a sinusoidal reference. The aim of shunt APF is to obtain a sinusoidal source current ( $i_s$ ) using the relationship:  $i_s = i_L - i_f$

### b. Series Active Power Filter

The series APF is shown in Figure 3.7. It is connected in series with the distribution line through a matching transformer. VSI is used as the controlled source, thus the principle configuration of series APF is similar to shunt APF, except that the interfacing inductor of shunt APF is replaced with the interfacing transformer [15].

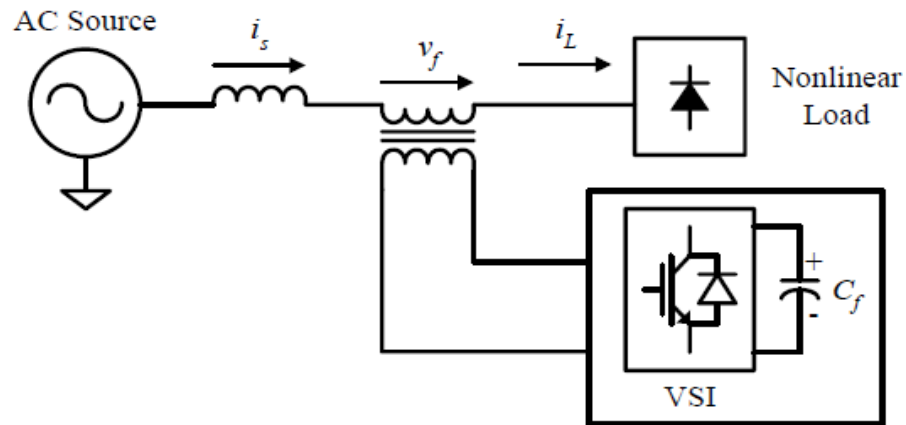


Figure 3.7: Configuration of a VSI based series APF [15]

The operation principle of series APF is based on isolation of the harmonics in between the nonlinear load and the source. This is obtained by the injection of harmonic voltages ( $v_f$ ) across the interfacing transformer. The injected harmonic voltages are added or subtracted, to or from the source voltage to maintain a pure sinusoidal voltage waveform across the nonlinear load. The series APF can be thought of as a harmonic isolator as shown in Figure 3.7. It is controlled in such a way that it presents zero impedance for the fundamental component, but appears as a resistor with high impedance for harmonic frequencies components. That is, no current harmonics can flow from nonlinear load to source, and vice versa.

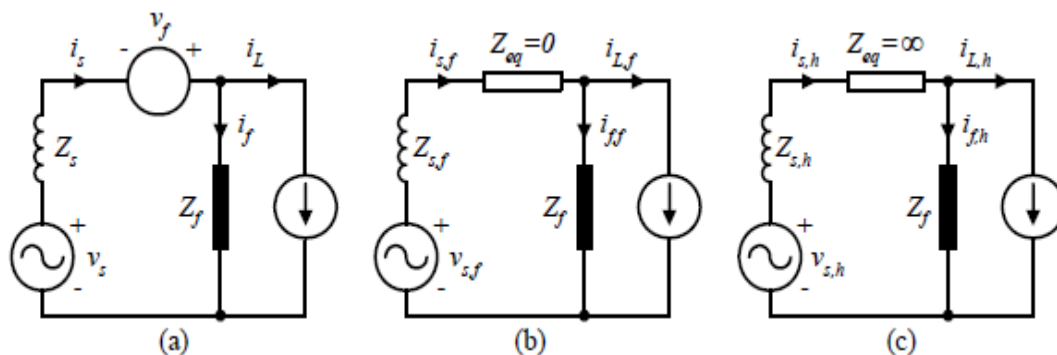


Figure 3.8: Operation principle of series APF: (a) single-phase equivalent of series APF, (b) fundamental equivalent circuit, and (c) harmonic equivalent circuit [15]

Series APFs are less common than the shunt APF. This is because they have to handle high load currents. The resulting high capacity of load currents will increase their current rating compared with shunt APF, especially in the secondary side of the interfacing transformer. This will

increase the  $I^2R$  losses [15]. However, the main advantage of series APFs over shunt is that they are ideal for voltage harmonics elimination. It provides the load with a pure sinusoidal waveform, which is important for voltage sensitive devices. With this feature, series APF is suitable for improving the quality of the distribution source voltage [15].

### c. Hybrid Active Power Filter

The series-shunt active filter is a combination of the series active filter and the shunt active filter. The shunt active filter is located at the load side and can be used to compensate for the load harmonics. On the other hand, the series portion is at the source side and can act as a harmonic blocking filter. This topology has been called the Unified Power Quality conditioner. The series portion compensates for supply voltage harmonics and voltage unbalances, acts as a harmonic blocking filter, and damps power system oscillations. The shunt portion compensates load current harmonics, reactive power, and load current unbalances. In addition, it regulates the dc link capacitor voltage. The power supplied or absorbed by the shunt portion is the power required by the series compensator and the power required to cover losses [11].

### 3.3. Control Techniques of APF

Different kinds of control techniques are used to control APF. Many control techniques have been used to obtain the reference currents [16]. These techniques such as instantaneous reactive power theory, notch filters, flux based controller, power balance theory, and sliding mode controller have been used to improve performance of the active filters. However, most of these control techniques include a number of transformations and are difficult to implement.

The performance of APF is based on three control technology; design of power inverter, types of current controllers used and methods used to obtain the reference current [16, 22].

In reference [19], the author explains the synchronous reference frame (SRF) theory, which is commonly applied to three phase systems, is believed to be one of the simplest and most attractive techniques. It is also describes SRF theory is possible to apply for single-phase APFs in which the required compensating current is generated using synchronous reference frame generation technique by sensing the load current.

DC capacitor voltage is regulated to estimate the reference current template. Selection of DC capacitor value has been described in [15, 17].

### 3.3.1. Reference Signal Estimations

Reference [18], deals with the design of a novel method called the synchronous reference frame (SRF) to extract the reference compensating current for single-phase shunt active power filters (APFs) and its effectiveness is investigated by means of detailed mathematical analysis.

The first step of operation for SAPF is to generate the reference current. The reference signal to be processed by the controller is the key component that ensures the correct operation of APF. There are mainly two methods namely time domain and frequency domain methods for reference current generation.

The frequency domain methods include, Discrete Fourier Transform (DFT), Fast Fourier Transform (FFT), and Recursive Discrete Fourier Transform (RDFT) based methods. The frequency domain methods require large memory, computation power and the result obtained during the transient condition may be imprecise. On the other hand, the time domain methods require less calculation and are widely followed for computing the reference current. The two mostly used time domain methods are synchronous reference (d-q-0) theory and instantaneous real-reactive power (p-q) theory [19].

In reference paper [20], the authors compared the two current control methods of shunt active power filter under unbalance and non-sinusoidal condition. That means, the comparison between instantaneous p-q theories (instantaneous reactive power theory), synchronous d-q reference frame theory for the reference current generation. As per the result d-q method is the best one which used in any voltage condition.

To generate the reference compensating current for single-phase shunt APFs, different techniques can be applied [18]. Among them, the synchronous reference frame (SRF) or dq theory, which is widely applied to three phase systems, is believed to be one of the simplest and most attractive techniques. The SRF theory offers the potential for achieving fast and accurate extraction of the harmonic contents and reactive component of a distorted current, but the application was dedicated to three-phase APFs. Saitou et al. extended the SRF theory to single-phase APFs [18]. In their method, the fundamental component of the single phase signal is shifted by  $90^\circ$  to generate a fictitious phase signal. Thus, it is possible to represent the single-phase APF as a pseudo two phase ( $\alpha\beta$ ) system.

A single-phase synchronous reference frame for extraction of harmonic and reactive current components Active Power Filters (APF), the system is based on synchronous reference frame theory and its features [18], [21] with respect to other methods are as follows

- It simultaneously extracts harmonic and reactive current components independently
- Its structure is adaptive with respect to frequency
- Its structure is robust with respect to the setting of the internal parameters
- Its performance is immune to noise and external distortions
- Accuracy and speed of its response are controllable

### 3.3.2. Hysteresis Control

Hysteresis current control method is used for pulse generation to control VSI and most commonly proposed control method in time domain. This method provides instantaneous current corrective response, good accuracy, extreme robustness, good stability, allows fast current control and has got simple operation [15, 19]. The basic principle of current hysteresis control technique is that the switching signals are derived from the comparison of the current error signal with a fixed width hysteresis band. As long as the error is within the hysteresis band, no switching action is taken. Switching occurs whenever the error hits the hysteresis band. This control scheme is shown in Figure 3.9. The outputs of the comparator are switching gating signals to the inverter.

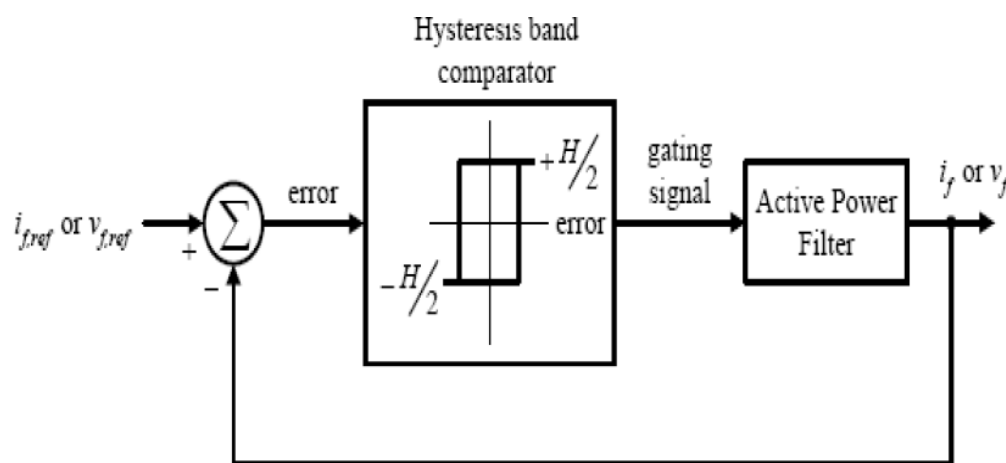


Figure 3.9: Hysteresis control technique [15]

The APF is therefore switched in such a way that the peak-to-peak compensation current/voltage signal is limited to a specified band determined by upper band and lower band as illustrated by Figure 3.10. To obtain a compensation current with switching ripples as small as possible, the value of upper band and lower band can be reduced. However, doing so results in high switching frequency increases losses on the switching transistors [15].

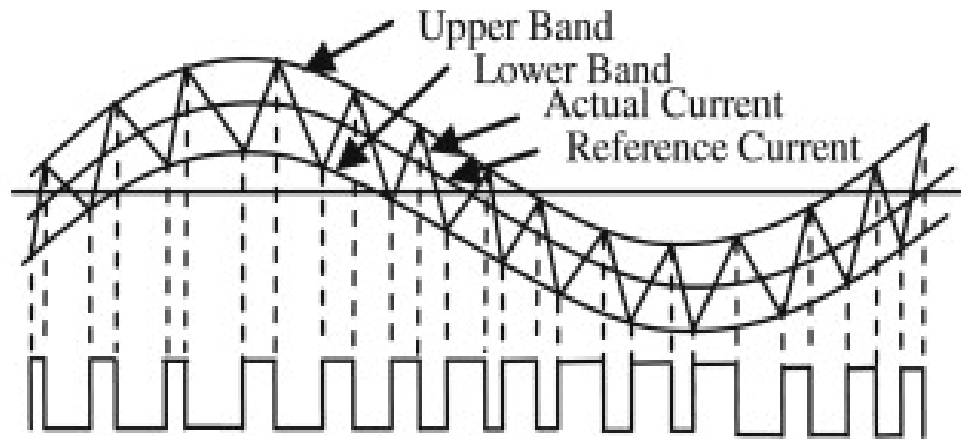


Figure 3.10: Gating signal generation [15]

This paper basically deals with the modeling and simulation of shunt active filter with hysteresis current control method for harmonic compensation and power filtering and then studied the compensation principle used for current harmonics compensation and harmonic control method provides a quick and easy response in the system.

### 3.3.3. DC Voltage Regulation

The DC bus voltage must be regulated in order to set the amplitude of reference current for harmonic and reactive power compensation [15]. Practically, there are switching losses in the APF that increase with the increase in the active power or reactive power demand of the load. These losses are supplied by the capacitor, and its voltage drops. Similarly, the capacitor voltage will increase if the reactive or real power demand of the load decreases. Hence, by monitoring the capacitor voltage, the real power supplied by the APF can be estimated and the amplitude of the fundamental active component of the supply current was estimated indirectly [15].

Reference [22] presents an instantaneous real-power compensator based cascaded shunt active power filter for the harmonics and reactive power elimination. The paper also presents a p-q theory method to get the reference current and uses PI controller to maintain DC-link voltage.

For regulating and maintaining the DC link capacitor voltage, the active power flowing into the active filter needs to be controlled. If the active power flowing into the filter can be controlled equal to the losses inside the filter, the DC link voltage can be maintained at the desired value. The quality and performance of the SAPF depends mainly on the method implemented to generate the compensating reference currents. In order to maintain DC link voltage constant and to generate the compensating reference currents a PI controller is used. PI controllers are particularly common, since derivative action is very sensitive to measurement noise.

## Chapter Four

### 4. Design and Modeling

#### 4.1. Overview of the Research Methodology

This chapter will describe the method that will be used in this thesis in order to achieve the desired objectives. The research development begins by the modeling of the single-phase AC electrified railway system which consists of power supply, catenary line and locomotive load model. Extensive literature reviews were done on related knowledge to assist in any ways that it may. Such reviews are based on international publications, websites, and engineering books. The next step is followed by design and modeling of the shunt active filter to compensate the harmonic distortion of pantograph current, reactive power, and enhance overhead line voltage drop. The control strategy is based on synchronous d-q reference frame theory for reference current generation, PI controller for DC link voltage balancing and Hysteresis current controller (HCC) for gating pulse generation is implemented. Simulation will be done using MATLAB/Simulink. Generally, the proposed model consists of the following parts to mitigate the Harmonic current and compensate reactive power in traction distribution line.

1. Power Supply
  - a. Transmission line
  - b. Catenary line
2. Loads
3. Active power filter
  - a. Power circuit
    - i. Voltage source inverter
    - ii. Interface inductor
    - iii. DC Link capacitor
  - b. Control circuit
    - i. Reference current generation
    - ii. Current control
    - iii. PI-controller to regulate DC link voltage

The Figure 4.1 shows the AC electrified railway system with the SAPF. Thus, the overall electric system consists of the source impedance, the feeder line and the active power filter. The load current  $I_L$ , is the current flowing into the locomotive. The load current, the SAPF current,  $I_{SAPF}$  and the DC-link voltage,  $V_{DC-link}$ , are monitored for the active power filter controller input signals and the hysteresis control method is adopted for the current control of the filter.

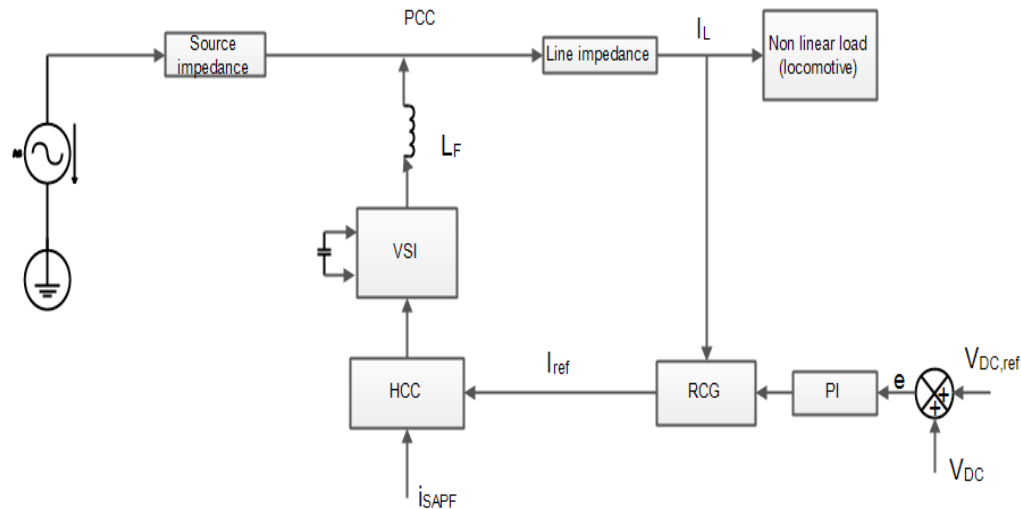


Figure 4.1: Overview of the modeled system block diagram

## 4.2. Traction Substation Model

The system considered under this study is the Addis Ababa-Djibouti single-phase 25 kV AC electrified railway. In this system, the traction transformers are supplied from state grid, normally at 132 kV voltage levels. This voltage is further step down to 25 kV nominal voltage at traction substation by using 132/27.5 kV (no load voltage) transformer. The traction substation can be represented by Thevenin equivalent that consists of an ideal source and its equivalent inductance. The modeling approach is given below

- Considered Sebeta substation [2]
  - ✓ 132/25 kV, 21 MVA single-phase transformer
  - ✓ Short circuit capacity of grid is 400 MVA.

The Substation equivalent circuit mode reduced to load side is

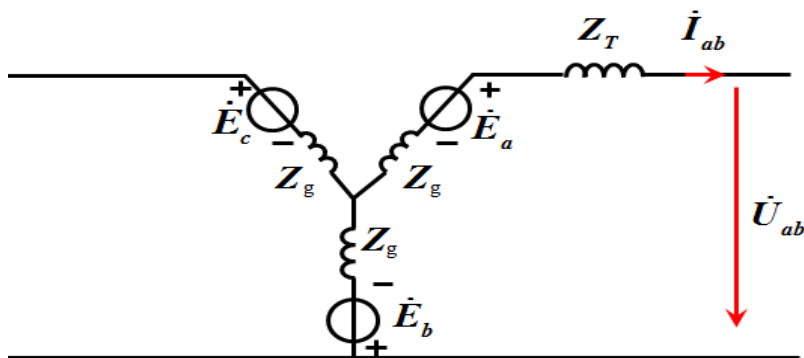


Figure 4.2: TSS equivalent circuit

$$I_{SC} = \frac{\text{fault MVA}}{\sqrt{3}kV} \quad (4.1)$$

Where  $I_{SC}$  is three-phase short circuit current

$$I_{SC} = \frac{400MVA}{\sqrt{3}(132kV)} = 1.749KA$$

✓ Line to line (L-L) short circuit current will be:-

$$I_{LL} = I_{SC} \times \frac{\sqrt{3}}{2} = 1.5146kA \quad (4.2)$$

For single phase AC traction, the system impedance should be:-

$$Z_{grid} = \frac{V_{LL}}{I_{LL}} \quad (4.3)$$

$$Z_{grid} = \frac{132KV}{1.5146kA} = 87.15\Omega$$

Converting to secondary side 27.5kV (the no load voltage)

$$Z_{grid} = a^2 \times Z_{grid} \quad (4.4)$$

Where  $a$  is transformer turns ratio

$$Z_{grid} = \left(\frac{27.5}{132}\right)^2 \times 87.15 = 3.78\Omega$$

Transformer impedance to LV side

➤ Taking transformer percentage impedance 12% [5]

$$Z_T = Z_{pu} \times Z_{base} \quad (4.5)$$

$$\text{Where, } Z_{pu} = \frac{Z\%}{100} = \frac{12}{100} = 0.12$$

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

$$Z_T = Z_{pu} \times Z_{base} = 29.76 \times 0.12 = 3.57\Omega$$

By assuming purely inductive impedance, the Thevenin equivalent of the source reduced to load side is:-

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

$$L_S = \frac{X_S}{2\pi f} = \frac{7.35}{2\pi(50)} = 23.407mH$$

The figure below shows the simplified model of Thevenin equivalent form.

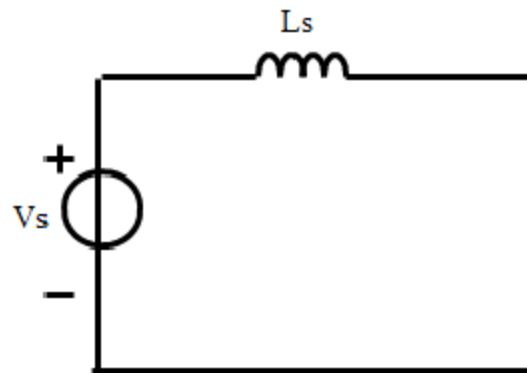


Figure 4.3: Thevenin equivalent of traction substation [5]

### 4.3. Modeling of Overhead Line System (Catenary System)

Electric train's takes power from contact wire using pantograph. Overhead line system is some kind of power distribution system for electric trains. The catenary system have different types of geometry due to system design, speed of train, environmental conditions, voltage level, substation distance, voltage drop, impedance etc.

An overhead line system behaves as a transmission line and has certain values of capacitance, inductance and resistance per unit length that are determined by physical characteristics such as the diameter of the copper conductor and its height above the ground. As a result the overhead has characteristic impedance which by transmission line theory can be shown to alternate between capacitive and inductive values in the form of a hyperbolic curve. The supply from the grid to the feeder station is essentially inductive and resonant conditions exist between the supply and the overhead, i.e. the system has a set of characteristic resonant frequencies [1].

The traction system considered in this thesis is 25KV AC single phase electrified railway system. The distribution circuit associated with this system is considered to constitute lumped circuits. The feeder line is represented by the circuit consisting of three  $\pi$  sections of resistance,  $R$ , in series with an inductance,  $L$ , and a parallel capacitance  $C$  [14]. This feeder is modeled as three pi sections, each having a longitudinal impedance of  $0.130081+j0.39238 \Omega/\text{km}$  at 50 HZ and shunt capacitance of  $0.011 \mu\text{F}/\text{km}$  feed from a substation step down [2]. Figure 4.4 shows the modeling of the feeder line.

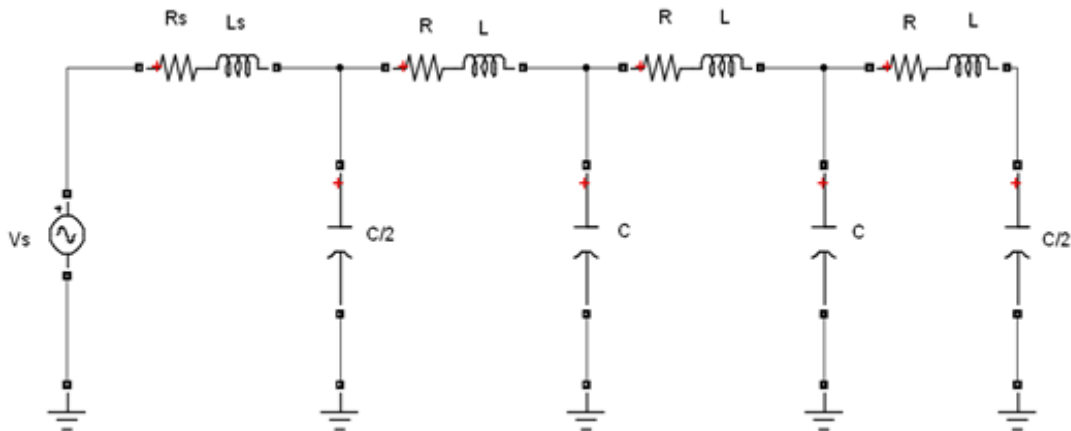


Figure 4.4: Modeling of the AC electrified railways system feeder line

#### 4.4. Locomotive Load Modeling

Power drawn from the load (train) depends upon the train's speed and operation mode which are in turn determined by the traction equipment characteristics, train weight, aerodynamics, track geometry and train control strategies etc. The power demand may thus vary significantly within a very short period of time during an inter-station run.

The fact that the train is moving only further perplexes the load flow calculation and it signifies the difference between a conventional power system and a supply system in railways. The number of trains in a feeding section is also vital to the calculation as they may be running at different speeds, drawing (or feeding) different amount of power and thus posing different effects on the supply system. Nominal separation among trains is yet another important consideration and it should follow the timetables or dispatching schedules of the train services [1].

As a summary of explanation, determining load that takes power from catenary has lot of difficulties and several different conditions have to be taken care, these conditions can be listed as in below.

- Number of load can change due to traffic.
- Size of load can change due to different vehicles and different traction motors.
- Changing speed of vehicles in time interval due to driver behavior and time scheduling.
- Load differences on different sections of catenary system.

Many single-phase 25-kV electrified AC railway systems have been operated to supply power to a range of locomotives with a significant proportion of the locomotives still employing ac-dc phase-controlled thyristor converters to feed dc motor drives. These railway systems are found in several countries, and are expected to power older thyristor-based locomotives, operating in coexistence with the newer generation of gate turn-off thyristor (GTO) or insulated-gate bipolar transistor (IGBT) locomotives for many years to come since the average locomotive life is about 30 years. It is well reported now that thyristor-based locomotives draw current with a low displacement power factor and rich harmonic content. In particular, the lagging load current causes a significant amount of reactive voltage drop along the feeder line, while the flow of harmonic load current through the feeder impedance results in a distorted pantograph voltage waveform that has a reduced (rectified) average value [1].

The former effect low root mean- square (RMS) voltage can significantly limit the distances between substations and also the number of locomotives that the system can support. As a standard, IEC specification 349 has stipulated that the minimum pantograph voltage must be above 19 kV continuously and 17.5 kV for short periods [1].

In this study the load block is represented by a single phase bridge rectifier with RL-load, which generates the harmonic currents and the reactive power demand. The parameter values of bridge rectifier with RL-load is taken from reference [1] as  $R=20\Omega$  and  $L=10\text{mH}$ . Finally simulation will be done in several load conditions and different position of the locomotive.

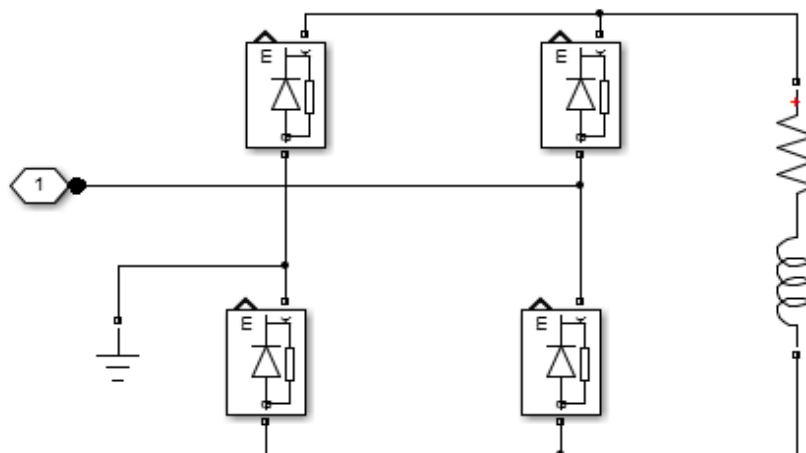


Figure 4.5: The AC locomotive load model representation

## 4.5. Design of Shunt Active power Filter (SAPF)

The active filter configuration investigated in this study based on voltage source inverter that interfaces to the system through an interface reactor. In this configuration, the filter is connected in parallel with the load being compensated. Therefore the configuration is often referred to as single phase shunt active filter [17].

A Shunt Active Filter (SHAF) is commonly used for harmonic elimination and reactive power compensation of a non-linear load. The control scheme is based on extracting the load current and generating the compensating current required by the nonlinear load. The DC capacitor voltage is regulated to estimate the reference current [23].

The approach is based on the principle of injecting harmonic current into the AC system, of the same amplitude and reverse phase to that of the load current harmonics [1]

### 4.5.1. Compensation principle of SAPF

The basic compensation principle of a shunt active power filter is shown in Figure 4.6. It is controlled to draw/supply a compensating current  $i_c$  from/to the utility, so that current harmonics gets cancelled on the AC side and makes the source current almost sinusoidal.

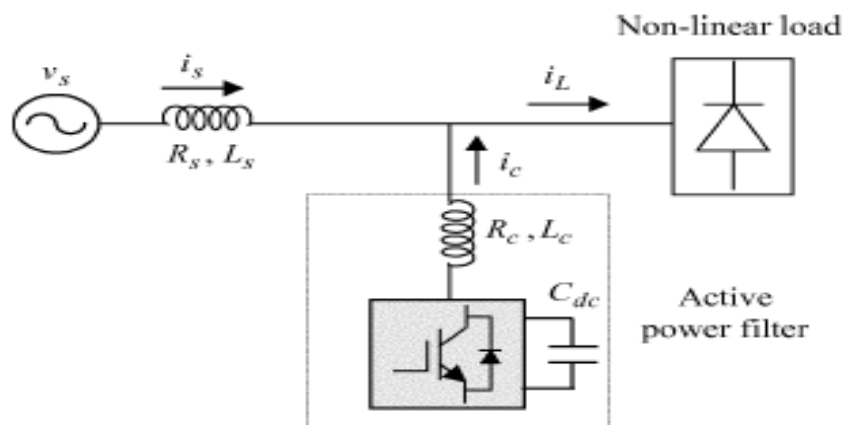


Figure 4.6: Basic Compensation Principle of SAPF [17]

Shunt Active Power Filter is a pulse width modulated VSI that is connected in parallel with the load. Shunt active power filters compensate current harmonics by injecting equal-but opposite harmonic compensating current. In this case the shunt active power filter operates as a current source injecting the harmonic components generated by the load but phase-shifted by  $180^\circ$  [1].

From figure 4.6, the instantaneous currents can be written as [17]

$$i_s(t) = i_L(t) - i_c(t) \quad (4.6)$$

Source voltage is given by

$$V_s(t) = V_m \sin(\omega t) \quad (4.7)$$

If a nonlinear load is applied, then the load current will have a fundamental component and harmonic components, which can be expressed as given in equation 4.8

$$i_L(t) = I_1 \sin(\omega t + \phi_1) + \sum_{n=2}^{\infty} I_n \sin(n\omega t + \phi_n) \quad (4.8)$$

Where,  $I_1$  and  $I_n$ : Fundamental and  $n^{\text{th}}$  order current harmonic component.

The instantaneous load power can be given as in equation (4.9),

$$\begin{aligned} P_L(t) &= V_s * i_L(t) \quad (4.9) \\ &= V_m I_1 \sin^2 \omega t * \cos \phi_1 + V_m I_1 \sin \omega t * \cos \omega t * \sin \phi_1 + V_m \sin \omega t * \sum_{n=2}^{\infty} I_n \sin(n\omega t + \phi_n) \\ &= P_f(t) + P_r(t) + P_h(t) \end{aligned}$$

From equation (4.9), the real power drawn by the load is expressed as in equation (4.10)

$$P_f(t) = V_m I_1 \sin^2 \omega t * \cos \phi_1 = V_s(t) * i_s(t) \quad (4.10)$$

If the active filter provides the total reactive and harmonic power, then  $i_s(t)$  will be in phase with the utility voltage and purely sinusoidal. At this time, the active filter must provide the following compensation current given by:

$$i_c(t) = i_L(t) - i_s(t)$$

Hence, for accurate and instantaneous compensation of reactive and harmonic power it is necessary to estimate  $i_s(t)$ , (i.e. the fundamental component of the load current as the reference current).

The principal components of the SAPF are the VSI, a DC energy storage device and the associated control circuits. The performance of a SAPF depends mainly on the technique used to compute the reference current and the control method used to inject the desired compensation current into the line [1, 17]. Shunt Active filter design consists of the following two main parts.

- A. Power circuit
- B. Control circuit

### 4.5.2. Power circuit design of SAPF

The design of the power circuit of a SAPF includes three main parameters, namely

- Voltage source inverter
- Selection of DC side capacitor,  $C_{DC}$
- Selection of reference value of DC side capacitor voltage,  $V_{DC, ref}$ .
- Selection of interfacing inductor,  $L_C$

#### 4.5.2.1. Voltage Source Inverter

The voltage source inverter used in the active filter makes the harmonic control possible. This inverter uses a DC capacitor as the supply and can switch at a high frequency to generate a signal which will cancel the harmonics from nonlinear load. The DC capacitor is initially charged before system operation and during operation, in order to maintain a constant DC voltage in storage elements, only a small fundamental current is drawn to compensate the active filter losses. The active filter does not need to provide any real power to cancel harmonic current from load. The current waveform for cancelling harmonics is achieved with the voltage source inverter and an interface reactor. The interface reactor converts the voltage signal created by the inverter to a current signal. The desired waveform is obtained by accurately controlling the switches in

the inverter. Control of current wave shape is limited by switching frequency of the inverter and by the available driving voltage across the interface reactor.

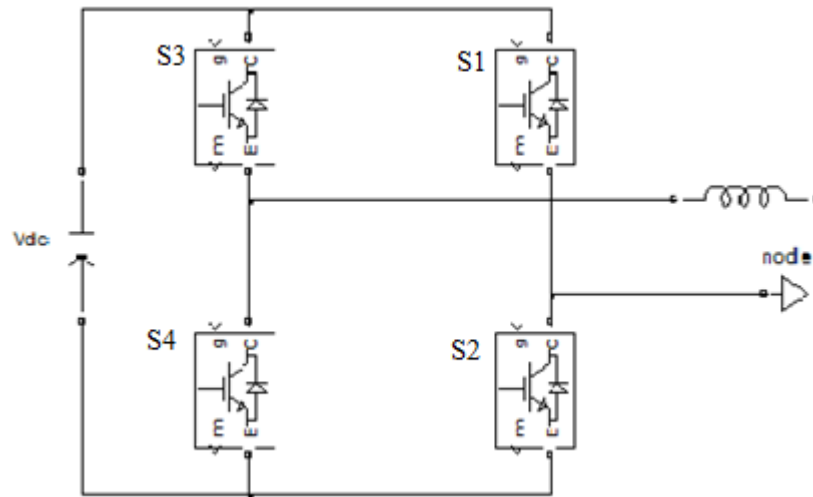


Figure 4.7: Topology of voltage source inverter for active filters

The driving voltage across the interface reactor determines the maximum  $di/dt$  that can be achieved by the filter. This is important because relatively high values of  $di/dt$  may be needed to cancel higher order harmonic components. The rate of change of an inductive current is related to available change in voltage across the reactor.

$$V_L(t) = L \frac{di}{dt}$$

Where,  $V_L(t)$  - voltage across the inductor,  $L$  - Inductance of inductor, and  $i(t)$  - current flowing through the inductor.

With a constant interface reactor  $L$ , the driving voltage for the active filter is the potential difference between the DC voltage stored on the DC capacitors and the instantaneous value of the AC system voltage on the other side of the inductor.

This means that the filtering effectiveness is also dependent on the relative position of the current waveform harmonics with respect to the voltage waveform. The voltage source inverter is the heart of the active filter [1].

#### 4.5.2.2. Role of DC Side Capacitor

The DC side capacitor serves two main purposes:

- (i) it maintains a DC voltage with small ripple in steady state, and

- (ii) Serves as an energy storage element to supply real power difference between load and source during the transient period.

In the steady state, the real power supplied by the source should be equal to the real power demand of the load plus a small power to compensate the losses in the active filter. Thus, the DC capacitor voltage can be maintained at a reference value. However, when the load condition changes the real power balance between the mains and the load will be disturbed. This real power difference is to be compensated by the DC capacitor. This changes the DC capacitor voltage away from the reference voltage. In order to keep satisfactory operation of the active filter, the peak value of the reference current must be adjusted to proportionally change the real power drawn from the source. This real power charged/discharged by the capacitor compensates the real power consumed by the load. If the DC capacitor voltage is recovered and attains the reference voltage, the real power supplied by the source is supposed to be equal to that consumed by the load again [17, 24].

#### 4.5.2.3. Design of DC bus Capacitor

During steady state condition, the reactive and harmonic load currents will charge and discharge the DC-bus capacitor during the source voltage period. The total reactive and harmonic load current to be compensated is the principle factor that causes voltage fluctuation in the DC bus capacitor. To get a good compensation performance, voltage fluctuations must be avoided. This can be achieved by proper sizing of the DC-bus capacitor.

The size determination of the DC-bus capacitor is based on the energy balance principle. Using this concept, the following equation (4.11) can be derived [8], [17] [16]:

$$\frac{1}{2} C_{DC} (V_{dc,ref}^2 - V_{dc,min}^2) = \Delta E_{dc}$$

Where  $\Delta E_{DC}$  is the rate energy stored in the capacitor

$$\frac{1}{2} C_{DC} (V_{dc,ref}^2 - V_{dc,min}^2) = \frac{1}{2} \sqrt{2} V_s * \Delta I_L * T$$

The size of the DC-bus capacitor is determined by the following equation (4.11):

$$C_{DC} \geq \frac{\sqrt{2} V_s * \Delta I_L * T}{(V_{dc,ref}^2 - V_{dc,min}^2)} \quad (4.11)$$

Where,  $V_{dc,ref}$  is the DC bus voltage reference,  $V_s$  is the rms value of the source voltage,  $\Delta I_L$  is the peak rms value of the reactive and harmonic load currents and  $T$  is the time period of the source voltage.

Considering the passenger locomotive type SS9, the load power is 4.8MW [2] the load current can be calculated as:

$$P = V_s * i_L * \cos\Phi$$

$$\Delta I_L = 4.8\text{MW}/25\text{KV} * 0.85$$

$$\Delta I_L = 225.88\text{A}$$

#### 4.5.2.4. DC Capacitor Voltage

The minimum DC bus voltage should be greater than twice of the peak of the phase voltage of the system at the PCC mainly on the basis of reactive power compensation capability [17]. The reference DC bus voltage is calculated as:

$$V_{DC,ref} = 2\sqrt{2} \frac{V}{\sqrt{3} m}$$

For single phase system

$$V_{DC,ref} = 2\sqrt{2} \frac{V}{m} \quad (4.12)$$

$$V_{DC,ref} = 70.71 \text{ kv}$$

Where,  $m$  is the modulation index and is considered as 1. Thus  $V_{dc,ref}$  is obtained as 70.71 for  $V$  of 25 KV and it is selected as 72 KV.  $V_{DC, min}$  is the drop in dc bus voltage allowing in transient, considering a 2.5% reduction in dc bus voltage during transients  $V_{DC, min} = 72\text{kv} - 2.5\%$  of  $72\text{kv} = 70.2\text{kv}$ . Now we can calculate the DC-link capacitor by considering  $V_{DC, ref} = 72 \text{ KV}$ ,  $V_{DC, min} = 70.2\text{kv}$ ,  $\Delta I =$  respective phase current for nonlinear load ( $\Delta I_L = 225.88\text{A}$ ) and  $T = 400\mu\text{s}$ , so the calculated value of  $C_{DC}$  is approximated to  $2000\mu\text{F}$ .

#### 4.5.2.5. Selection of Interfacing Inductor

The interface provides the isolation and filtering between output of the voltage source inverter and the power system where the active filter is connected.

The inductance allows the output of the active filter to look like a current source to the power system. The inductance makes it possible to charge the DC capacitor to a voltage greater than the AC line to line peak voltage [17]. The inductance also functions like a commutative impedance.

It limits the magnitude of a current spike during commutative and prevent switching device from seeing and excessive rated of current charge. Besides these, it is not possible to connect a sinusoidal voltage supply to the non-sinusoidal output of the voltage inverter without a reactor. Sizing of the inductor value must take into account control of the inverter switching frequencies and characteristics of the nonlinear load to be compensated [1].

The inductances used in the active power filter smoothens the ripples from the voltage source inverter. These Inductances are designed with information on the carrier signal frequency and the hysteresis bandwidth of the filter current.

By applying KVL at the PCC and inverter pole point

$$L_c \frac{dI_c}{dt} + V_f = V_{pcc}$$

Where  $V_f$  is the instantaneous value of the PWM voltage at the inverter pole point and  $V_{pcc}$  is the instantaneous voltage at the PCC.

The design of these components is based on the following assumptions [17] [24]:

1. The AC source voltage is sinusoidal.
2. To design of  $L_c$ , the AC side line current distortion is assumed to be 5%.
3. Fixed capability of reactive power compensation of the active filter.
4. The PWM converter is assumed to operate in the linear modulation mode (i.e.  $0 \leq m_a \leq 1$ ).

As per the compensation principle, the active filter adjusts the current  $I_c$  to compensate the reactive power of the load [22]. If the active filter compensates all the fundamental reactive power of the load,  $I_s$  will be in phase and  $I_c$  should be orthogonal to  $V_s$ .

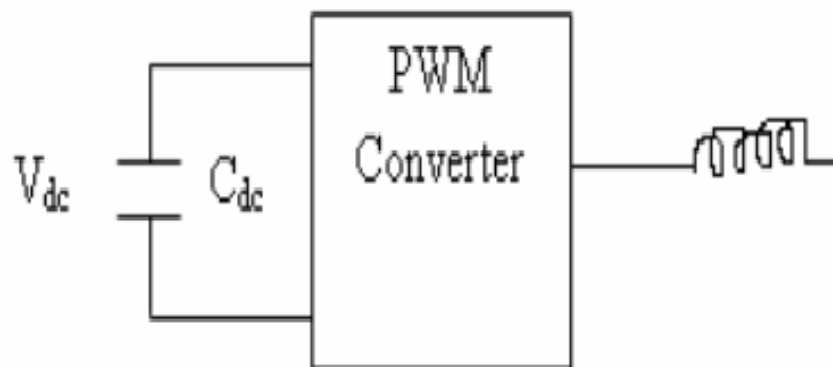


Figure 4.8: Active power filter with interfacing inductor [17]

The desired compensation current waveform is obtained by controlling the switching of the Insulated Gate Bipolar Transistors (IGBTs) in the VSI. The switching ripple ( $i_{sw}$ ) of the compensation current is determined by the available driving voltage across the interfacing inductor, the size of the interfacing inductor and switching frequency. In the proposed scheme, the driving voltage is the DC-bus voltage ( $V_{dc}$ ). As shown in Figure 4.9, the bipolar DC-bus voltage across the interfacing inductor determines the peak-to-peak switching ripple ( $\Delta I_{sw, p-p}$ ).

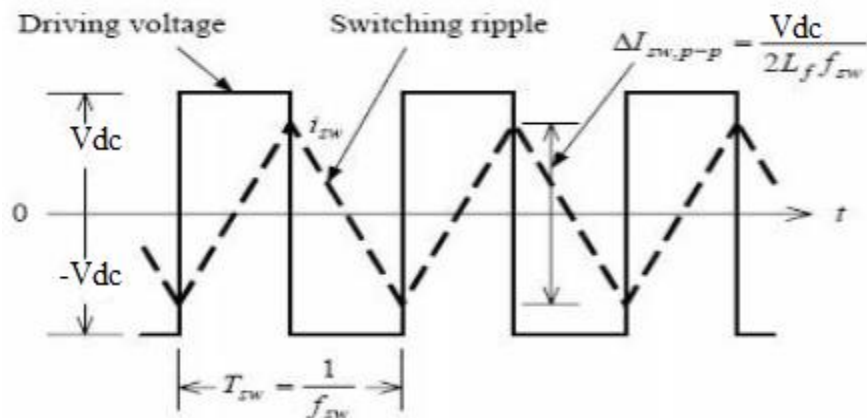


Figure 4.9: Switching ripple of the compensation current [17]

From Figure 4.9, the selection of the ac inductance ( $L_f$ ) depends on the current ripple,  $i_{sw}$  (p-p) switching frequency  $f_{sw}$ , dc bus voltage ( $V_{DC}$ ). Thus the required minimum interfacing inductor ( $L_{f, min}$ ) can be calculated as in equation (4.13),

$$L_{f, min} = \frac{V_{dc}}{2 * (\Delta I_{sw, p-p}) * f_{sw, max}} \quad (4.13)$$

Where  $f_{sw, max}$  is maximum frequency of the switching ripple and  $\Delta I_{sw, p-p}$  is the peak-to-peak switching ripple of the compensation current.

As the switching frequency is not fixed with the hysteresis controller, a practically feasible value of 20 kHz has been assumed. Considering  $\Delta I_{sw, p-p} = 15\%$  of peak compensation current  $F_{sw, max} = 20$  kHz,  $V_{dc} = 72$  kV, the  $L_{f, min}$  value is calculated and round off value 5mH is selected for nonlinear load.

### 4.5.3. Control Strategy of Shunt Active Filter

Since the performance of active power filter mainly depends on the control method we will discuss here the details of SAPF control mechanism.

Single-phase shunt APF control system consists of three main parts [18], these are

- I. Reference current generation (RCG) block, which is responsible for extraction of the total harmonic contents and, reactive component of the distorted current drawn by the non-linear load;
- II. DC-link voltage control block, which regulates the active power balance between the APF and the grid; and
- III. Current control block, which generates the appropriate gating signals for the voltage source inverter (VSI), so that the output current of the VSI tracks the reference command delivered by the RCG block.

#### **4.5.3.1. Reference Current Generation**

Reference current generation is the first step in active power filter control, and it is responsible to extract harmonic content and reactive component of the load current. In this research, the synchronous reference algorithm is chosen to extract the reference current

##### **a. Synchronous Reference Frame Algorithm**

The synchronous reference frame theory or d-q theory is based on time-domain reference signal estimation techniques. It can perform the operation in steady-state or transient state for voltage and current waveforms. Synchronous reference frame method is utilized to extract the harmonic content of the load and thus allows controlling the active filters in real-time system. This theory transforms the corresponding fundamental current or harmonics to become DC components and other untargeted frequency components still to AC component in the frame. Therefore, these components can be filtered out by low pass filtering (LPF). After an inverse d-q transformation in the respective frame, the unfiltered DC components are transformed back to corresponding harmonic. A targeted frequency component can then be separated from other frequency components in harmonic load currents [19].

The important features of this algorithm is that it require only load current for generating reference current and hence source disturbances or voltage distortion has no effect on the performances of active power filter system. As this method involves synchronous frame of reference, a separate PLL is required for each phase to synchronize reference current with its corresponding phase to neutral voltage [18].

### b. Single-phase d-q transformation

The d-q transformation is inherently developed for 3 phase system, where they are first transferred to two orthogonal components representing instantaneous active and reactive power component. If these orthogonal components are rotated at the fundamental frequency of the supply voltage then d-q transformation is obtained also known as Park Transformation. For single phase system to apply these transformations more quantities are required [18].

A single-phase system can directly convert into  $\alpha$ - $\beta$  frame without any matrix transformation. Create an imaginary load current by phase shifting the existing load current by  $90^\circ$  such that two orthogonal signals in  $\alpha$ - $\beta$  frame having identical characteristics were obtained [14]. The d-q transformation was applied on these orthogonal components using the rotation matrix. The required synchronizing signal for transformation can be obtained through Phase Locked Loop subsystem.

$$\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \begin{bmatrix} i_L(\omega t + \phi) \\ i_L(\omega t + \phi + \pi/2) \end{bmatrix} \quad (4.14)$$

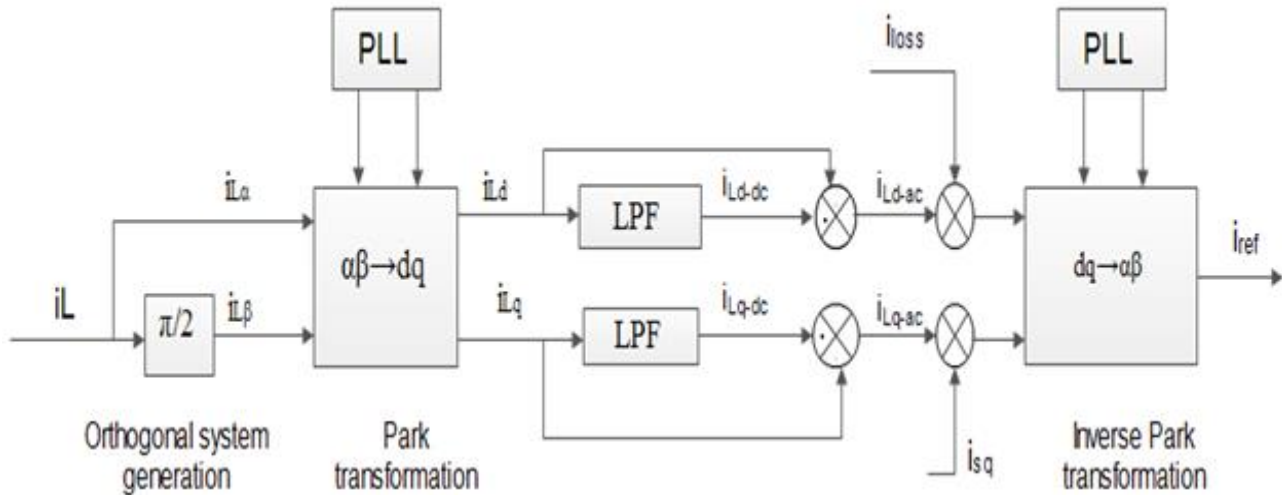


Figure 4.10: Reference signal generation using single-phase d-q transformation [14] [18]

The transformation matrix is obtained as [14]

$$T = \begin{bmatrix} \cos \omega t & \sin \omega t \\ -\sin \omega t & \cos \omega t \end{bmatrix}$$

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} = T \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \begin{bmatrix} \cos \omega t & \sin \omega t \\ -\sin \omega t & \cos \omega t \end{bmatrix} \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix}$$

From  $i_{Ld}$  and  $i_{Lq}$  we can derive fundamental active, fundamental reactive, harmonic active, and harmonic reactive by using appropriate filters.

### c. Harmonic Compensation Algorithm

The single-phase voltage and current signals can be handled on the stationary reference frame by assuming the imaginary values  $90^\circ$  phase-shift. The imaginary value can be calculated from the practical value through the various methods such as the Transport Delay, the Hilbert Transform, the Inverse-park Transform, and the Adaptive Notch Filter. On the basis that the Inverse park Transform and the Adaptive Notch Filter are reported to be relatively superior to the other methods [14], the Inverse-park Transform is applied in this paper. The  $\alpha$ - $\beta$  axis values of source voltage and load current can be expressed as

$$v_s(t) \triangleq v_{s\alpha} = V_s \cos \omega t + \sum_{n=3,5,7\dots}^{\infty} V_s(n) \cos n\omega t \quad (4.15)$$

$$i_L(t) \triangleq i_{L\alpha} = I_L \cos(\omega t - \phi) + \sum_{n=3,5,7\dots}^{\infty} I_L(n) \cos(n\omega t - \phi_n) \quad (4.16)$$

$$v_{sI}(t) \triangleq v_{s\beta} = V_s \sin \omega t + \sum_{n=3,5,7\dots}^{\infty} V_s(n) \sin n\omega t \quad (4.17)$$

$$i_{LI}(t) \triangleq i_{L\beta} = I_L \sin(\omega t - \phi) + \sum_{n=3,5,7\dots}^{\infty} I_L(n) \sin(n\omega t - \phi_n) \quad (4.18)$$

Where,  $V_s$ ,  $I_L$ , and  $n$  denote the maximum value of source voltage, the maximum value of load current, and the harmonic order, respectively. The  $\alpha$ -axis value is measured from the system and the  $\beta$ -axis value is calculated from the measured  $\alpha$ -axis value. From (4.15) to (4.18), it is possible that the source voltage and the load current vectors can be assumed and expressed on the stationary reference frame coordination as shown in Figure 4.11.

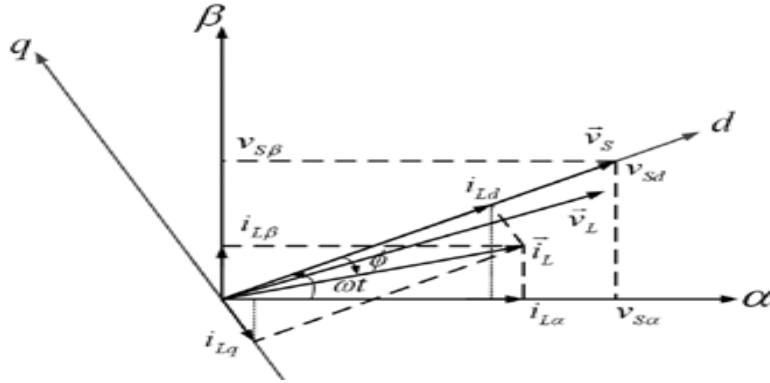


Figure 4.11: Voltage and current vector representation [14]

The voltage and current vectors in Figure 4.11 can be projected onto the synchronous reference frame rotating at the source frequency. The corresponding  $d$ - $q$  axis values of the load current are derived as [14]:

$$\begin{aligned}
 \begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} &= T \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \begin{bmatrix} \cos \omega t & \sin \omega t \\ -\sin \omega t & \cos \omega t \end{bmatrix} \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} \\
 &= \begin{bmatrix} I_L \cos \phi + \sum_{n=3,5,7,\dots}^{\infty} I_L(n) \cos[(n-1)\omega t - \phi_n] \\ -I_L \sin \phi + \sum_{n=3,5,7,\dots}^{\infty} I_L(n) \sin[(n-1)\omega t - \phi_n] \end{bmatrix} \\
 &= \begin{bmatrix} \bar{i}_{Ld} + \tilde{i}_{Ld} \\ \bar{i}_{Lq} + \tilde{i}_{Lq} \end{bmatrix} \quad (4.19)
 \end{aligned}$$

Where, the upper bar and the upper tilde mean the DC value and the AC value of  $d$ - $q$  axis. It is known that the load current has both the fundamental and harmonic components. The AC value depends on the harmonic contents of load current. The DC value represents the fundamental load current and is easily obtained using the low pass filters (LPF) without any phase-shifting. When the  $d$ - $q$  axis DC values are subtracted from the  $d$ - $q$  axis load currents, only the  $d$ - $q$  axis AC values to be compensated remain [14]. These components are provided as the current reference for the harmonic compensation to the controller.

#### d. Reactive Power Compensation Algorithm

The load current is expressed as follows:

$$i_L = I_L \cos(\omega t - \phi)$$

Here,  $I_L$  denotes the maximum value of the load current. This single-phase load current can be described in the stationary ( $\alpha$ ,  $\beta$ ) or synchronous ( $d$ ,  $q$ ) frames of reference. Assuming that the

harmonic currents have already been compensated by the SAPF and the  $d$ -axis is aligned on the source voltage vector, the source voltage and current are sinusoidal, and expressed as

$$\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} = \begin{bmatrix} \bar{i}_{Ld} \\ \bar{i}_{Lq} \end{bmatrix} = \begin{bmatrix} I_s \cos \phi \\ -I_s \sin \phi \end{bmatrix} \quad (4.20)$$

$$\begin{bmatrix} v_{sd} \\ v_{sq} \end{bmatrix} = \begin{bmatrix} \bar{v}_{sd} \\ \bar{v}_{sq} \end{bmatrix} = \begin{bmatrix} v_s \\ 0 \end{bmatrix} \quad (4.21)$$

Where,  $I_s$  denotes the magnitude of source current. The source voltage and current vector are represented by the  $d$ - $q$  axis components on the synchronous reference frame as follows from (4.22) and (4.23), the following equation can be considered.

$$\bar{v}_s = v_{sd} + jv_{sq} \quad (4.22)$$

$$\bar{i}_s = i_{sd} + ji_{sq} \quad (4.23)$$

$$\bar{v}_s \cdot \bar{i}_s^* = (v_{sd}i_{sd} + v_{sq}i_{sq}) + j(v_{sq}i_{sd} - v_{sd}i_{sq}) \quad (4.24)$$

By substituting (4.20) and (4.21), (4.24) is expressed as follows

$$\begin{aligned} \bar{v}_s \cdot \bar{i}_s^* &= V_s I_s \cos \phi + jV_s I_s \sin \phi \\ &= P_{dq} + jQ_{dq} \end{aligned} \quad (4.25)$$

Using (4.15), the single-phase instantaneous power can be represented as follows

$$\begin{aligned} p(t) &= \frac{1}{2} V_s I_s \cos \phi [1 + \cos(2\omega t)] + \frac{1}{2} V_s I_s \sin \phi \sin(2\omega t) \\ &= \frac{1}{2} P_{dq} [1 + \cos(2\omega t)] + \frac{1}{2} Q_{dq} \sin(2\omega t) \\ &= \frac{1}{2} v_{sd} i_{sd} [1 + \cos(2\omega t)] - \frac{1}{2} v_{sd} i_{sq} \sin(2\omega t) \end{aligned} \quad (4.26)$$

The first term of (4.26) is defined as the single-phase instantaneous active power and the second term is defined as the single-phase instantaneous reactive power [4.23]. It is known from (4.26) that when the source voltage is constant, the single-phase instantaneous active power depends on the  $d$ -axis current and the single-phase instantaneous reactive power relies solely on the  $q$ -axis current. Therefore, the SAPF can compensate the reactive power demand by controlling the  $q$ -axis value of source current to be zero instead of controlling the instantaneous reactive power.

Figure 4.12 shows the overall control scheme of the SAPF. The  $d$ - $q$  transform block includes both the single-phase to two-phase transformation and the transformation into the synchronous reference frame. The reference of  $q$ -axis source current in the reactive power compensation loop is set at zero. The error between the reference and the actual value of the  $q$ -axis source current

enters the PI controller, and then it is added to the  $q$ -axis current reference for the harmonic compensation because the  $q$ -axis source current determines the instantaneous reactive power. No additional current sensor to measure the source current is required. Among the outputs of inverse  $d$ - $q$  transform block, only the  $a$ -axis value becomes the current reference for the hysteresis controller. The DC-link voltage regulator plays a role in compensating the power losses of the SAPF as well as the voltage regulation.

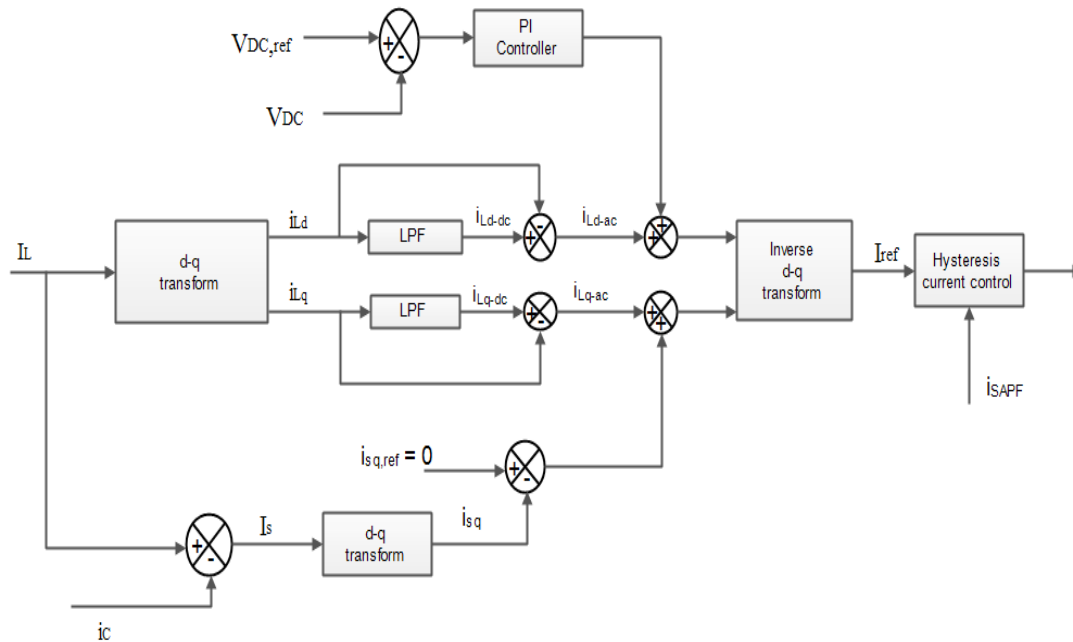


Figure 4.12: Overall control scheme of SAPF

The heart of the active power filter system is its controller. Proper control scheme enables active power filter to carry out harmonic elimination as well as reactive power compensation.

The controller of shunt active power filter is divided into two parts i.e.

1. DC link voltage control loop
2. Current control loop

#### 4.5.3.2. DC link Voltage Control Using PI Controller

The control schematic diagram of the shunt active power filter is realized in the figure below. The actual capacitor voltage is compared with a set reference value.

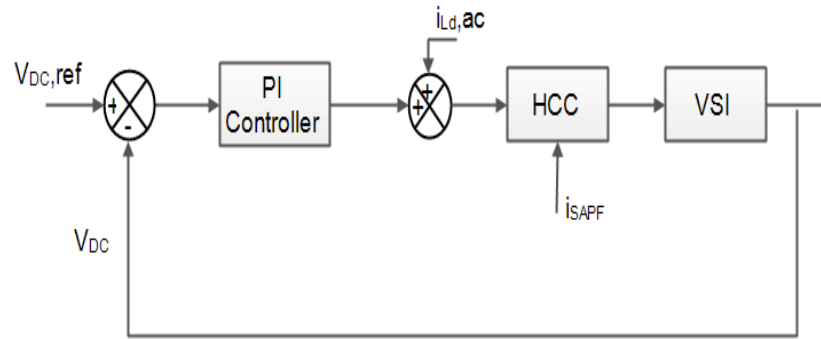


Figure 4.13: APF Control scheme with PI controller

The error signal is fed to PI controller. The output of PI controller has been considered as peak value of the reference current. It is further summed with the d-axis current ( $I_{Ld, ac}$ ) in phase with the source voltages to obtain the reference currents ( $I_{ref}$ ). These reference currents and actual currents are given to a hysteresis based, PWM current controller to generate switching signals of the VSI. The difference of reference current template and actual current decides the operation of switches. To increase current of particular phase, the lower switch of the PWM converter of that particular phase is switched on, while to decrease the current the upper switch of the particular phase is switched on. These switching signals after proper isolation and amplification are given to the switching devices. Due to these switching actions current flows through the filter inductor  $L_f$ , to compensate the harmonic current and reactive power of the load, so that only active power drawn from the source.

#### a. DC Voltage Control Loop

The block diagram of the voltage control loop is shown in figure below.

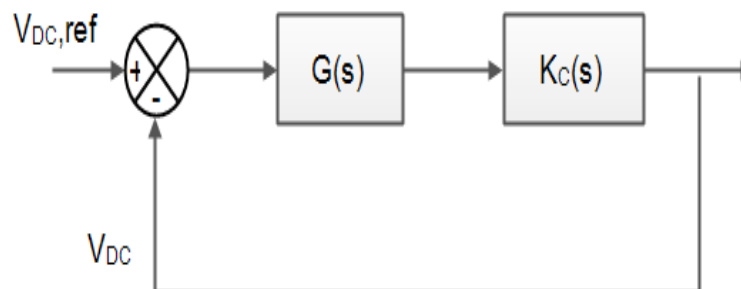


Figure 4.14: Block diagram of voltage control loop

Where,  $G_C$  is the gain of the PI controller and  $K_C$  is the transfer function of the VSI of SAPF.

## b. Transfer Function of VSI ( $K_C$ )

The derivation between input (ac link) and output (dc link) quantities of the PWM converter is obtained by equating average rate of change of energy associated. Equating the average rate of change of energy quantities of input and output side of the PWM converter.

$$P_t = P_{\text{conv}} - P_{\text{input}}$$

In order to linearize the power equation a small perturbation  $\Delta I_C$  is applied in the input filter current of converter  $I_C$ , about a steady state operating point  $I_{C0}$ , the average dc link voltage will also get perturbed by a small amount  $\Delta V_{dc}$ , about its steady state operating point ( $V_{dc,ref}$ ). The transfer function of the PWM converter for a particular operating point can be obtained as [17]

$$K_C = \frac{V_{DC}}{I_C} = \frac{V_s - L_f I_C S}{C_{dc} V_{dc,ref} S}$$

The characteristic equation of the voltage control loop is used to obtain the constants of PI controller in this case, can be written as:

$$1 + \left( K_p + \frac{K_i}{S} \right) \frac{V_s - L_f I_C S}{C_{dc} V_{dc,ref} S} = 0 \quad (4.27)$$

Thus a second order transfer function can be found for the closed loop system. This characteristic equation is used to found the components of PI controller. The analysis of this characteristic equation shows that  $K_p$  determines the voltage response and  $K_i$  defines the damping factor of the voltage loop. The PI controller has been designed on the basis of 5% overshoot, to step the change in the amplitude of voltage reference. The proper values of  $K_p$  and  $K_i$  should be find by PI-tuning.

To control DC bus voltage, it is required to take care of little amount of power flowing into DC capacitor, thus compensating for switching and conduction losses. The dc link voltage control loop does not require being as fast as it responds to steady state operating condition.

The actual DC link voltage is compared with a reference DC link voltage and passed through a PI controller. To maintain dc-link voltage at a fixed reference value, the dc-link capacitor requires a certain amount of real power, which is directly proportional to the difference between the reference and actual voltages. The block diagram is shown in the Figure 4.15

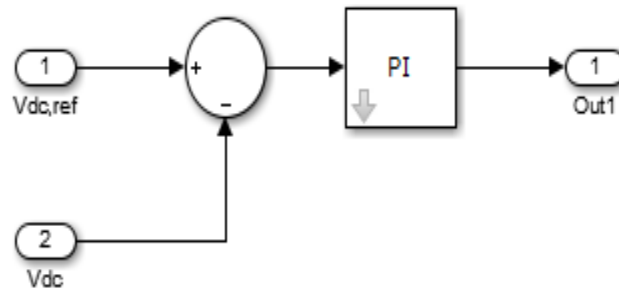


Figure 4.15: DC-link PI controller

The control signal coming from PI controller to regulate DC link voltage can be expressed as

$$P_{dc-link} = K_p(V_{dc,ref} - V_{dc}) + K_i \int (V_{dc,ref} - V_{dc}) dt \quad (4.28)$$

Where,  $K_p$  and  $K_i$  are proportional and integral gains of the PI controller. By increasing proportional gain ( $K_p$ ) reduces rise time and steady-state error but it causes increase in the overshoot and settling time. Similarly increase of integral gain ( $K_i$ ) reduces steady state error but it increases overshoot and settling time. Now PI element gains,  $K_p$  (proportional gain) and  $K_i$  (integral gain) should be tuned to obtain a better system response. The effect of each parameters value on increasing is given in table below.

Table 4.1: PI controller tuning [22]

Response	Rise Time	Overshoot	Settling time	Steady state error
$K_p$	Decrease	Increase	Minor change	Decrease
$K_i$	Decrease	Increase	Increase	Eliminate

#### 4.5.3.3. Hysteresis Current Controller

The hysteresis band current controller is used to generate pulses for the switching pattern of the inverter. There are numerous current control methods, but quick current controllability and easy implementation make hysteresis current control method much more superior than other current control methods. Some of the better properties possessed by hysteresis band current controllers are robustness, excellent dynamics and fastest control with minimum hardware [17].

Other than that, hysteresis band current control method is used because implementation of this control is not expensive. Hysteresis current control is a method of controlling a voltage source inverter so that generating appropriate gating signals for the power switches that forces the filter current follow derived reference current. However, as a disadvantage, its switching frequency might fluctuate which is the matter of importance in this study [15].

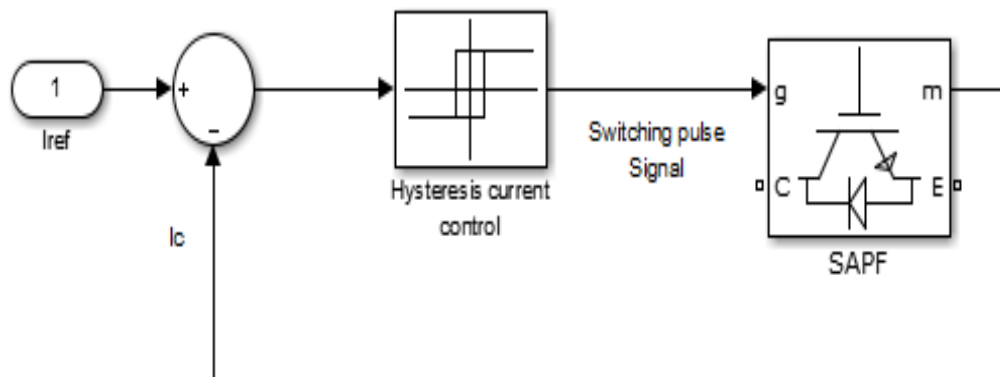


Figure 4.16: Hysteresis control technique

The operating principle of the hysteresis band current controller which is shown in Figure above depends on comparing of measured APF output current with its reference by the hysteresis comparator. The hysteresis comparator is implemented by presetting the upper and lower tolerance limits which need to be compared to the actual filter signal. The outputs of the comparator are the power switch gating signals.

This method switches the transistor when the current error fed to it exceeds the fixed band. Smaller the band width better is the accuracy. If current becomes more than the upper limit of the hysteresis band (+h), the switch in the upper part of the inverter arm becomes turned off and the switch in the lower arm becomes turned on. Hence, the current starts decreasing. While decreasing if the current falls below the lower limit of the hysteresis band (-h), the lower switch of the inverter arm becomes turned off and the upper switch becomes turned on. Consequently, the current gets back into the hysteresis band. So, the actual current is forced to follow the reference current within the hysteresis band. If the measured filter current is within the tolerance band, there will be no switching action for the filter [15].

Operating principle of hysteresis current controller is depicted in the Figure 2.17 Variable switching frequency is the disadvantages of this method.

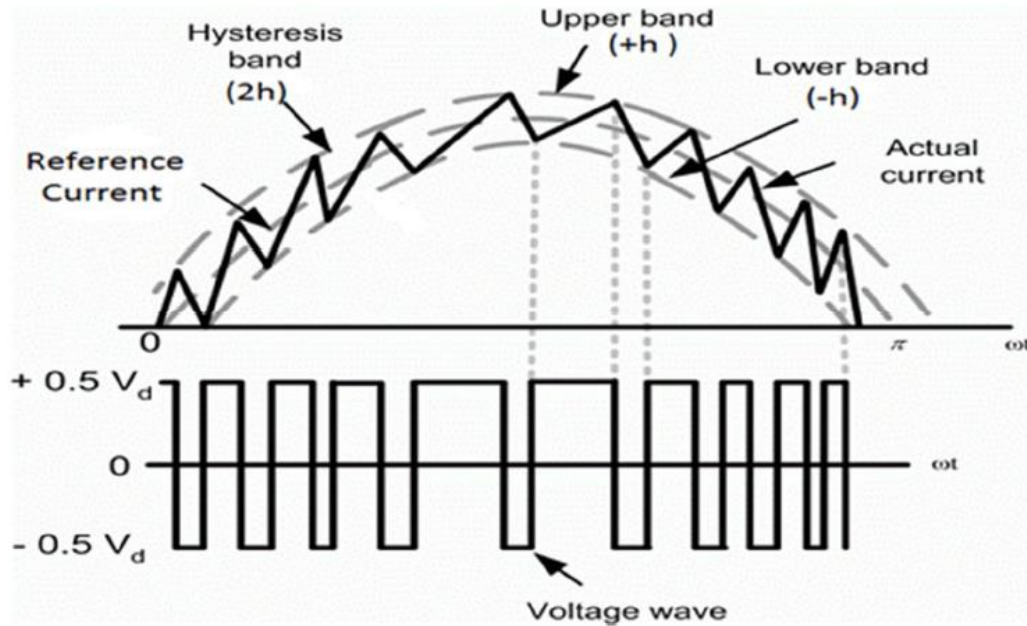


Figure 4.17: Operating principle of hysteresis current control waveform [15]

Figure above illustrates the ramping of the current between the two limits where the upper hysteresis limit is the sum of the reference current and the hysteresis bandwidth and for the lower hysteresis limit, it is the subtraction of the reference current and the hysteresis bandwidth. The operations of the hysteresis control technique are described below:

$$\text{If } i_{\text{actual}}(t) > i_{\text{ref}}(t) + H: \text{ S1 and S4 ON, S2 and S3 OFF} \quad (4.29)$$

$$\text{If } i_{\text{actual}}(t) < i_{\text{ref}}(t) - H: \text{ S2 and S3 ON, S1 and S4 OFF} \quad (4.30)$$

Where S1, S2, S3, and S4 are the power switching devices of the VSI shown in Figure 4.7 and H is the hysteresis bandwidth in ampere.

### a. Selection of hysteresis band

The selection of hysteresis band is very important for selecting the switching frequency and there should be a typical range of H to keep the THD within 5% as specified by IEEE. For this study fixed-band hysteresis current control (FBHCC) is selected because of its simplicity and less expensive. In FBHCC, the bandwidth of HCC is constant. The value of the HB (hysteresis bandwidth) is usually 5-10% of the maximum compensating current to obtain the best performance of an APF [24]. This can be found as;

$$H = 5-10\% I_{C, \text{max}}$$

$$H = k * I_{C, \text{max}} \quad (4.31)$$

Where,  $k = 0.05 \sim 0.15$ . Although there are several advantages associated with hysteresis band controllers as mentioned earlier, the only disadvantage is the varying switching frequency with the system voltage. This can be overcome by fixing the switching frequency with a modified or variable hysteresis controller but then the complexity in the system control may increase. For this study, it is selected 8 HB value with fixed 20 KHz switching frequency.

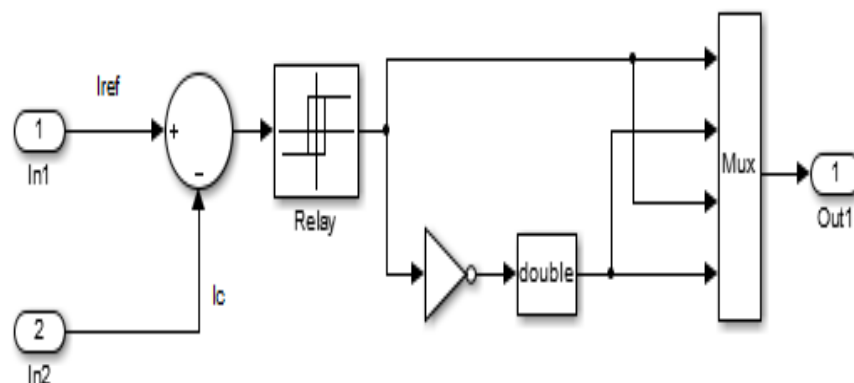


Figure 4.18: Hysteresis Current Controller implemented in MATLAB SIMULINK

## Chapter Five

### 5. Simulation Result and Analysis

This chapter is dedicated to the Simulink modeling and simulation of traction power system for the proposed method. The electric traction system under consideration is investigated together with and without installation of the SAPF. This investigation is carried out using MATLAB/PowerSim Systems tool box computer simulations. The selected system parameters for the simulations are obtained from ERC available data and from the calculated value of the design. Finally, analysis on the reactive power consumed and Total Harmonic Distortion (THD) in the traction system due to the locomotive load with and without Shunt APF is carried out.

#### 5.1. Electric Traction Simulation without Installation of SAPF

When SAPF is not installed, the electric railway system consists of power supply, catenary feeder line and the locomotive load. The power supply represented by AC voltage source in series with the internal impedance. The feeder line represented by three  $\pi$ -sections and the locomotive is represented by a solid state AC to DC bridge rectifier with RL-load. The system parameters for the simulation are shown in the following Table 5.1.

Table 5.1: System parameters for simulation without SAPF

Voltage source	Nominal voltage	25KV
	Rated frequency	50Hz
Source impedance	$L_s$	23.4mH
	$R_s$	100 $\Omega$
Catenary line (double track)	Longitudinal impedance	0.13008+j0.392 $\Omega$ /km
	Shunt capacitance	0.011 $\mu$ f/km
Locomotive load	Inductor	10mH
	Resistor	20 $\Omega$

The Simulink model is shown in Figure 5.1.

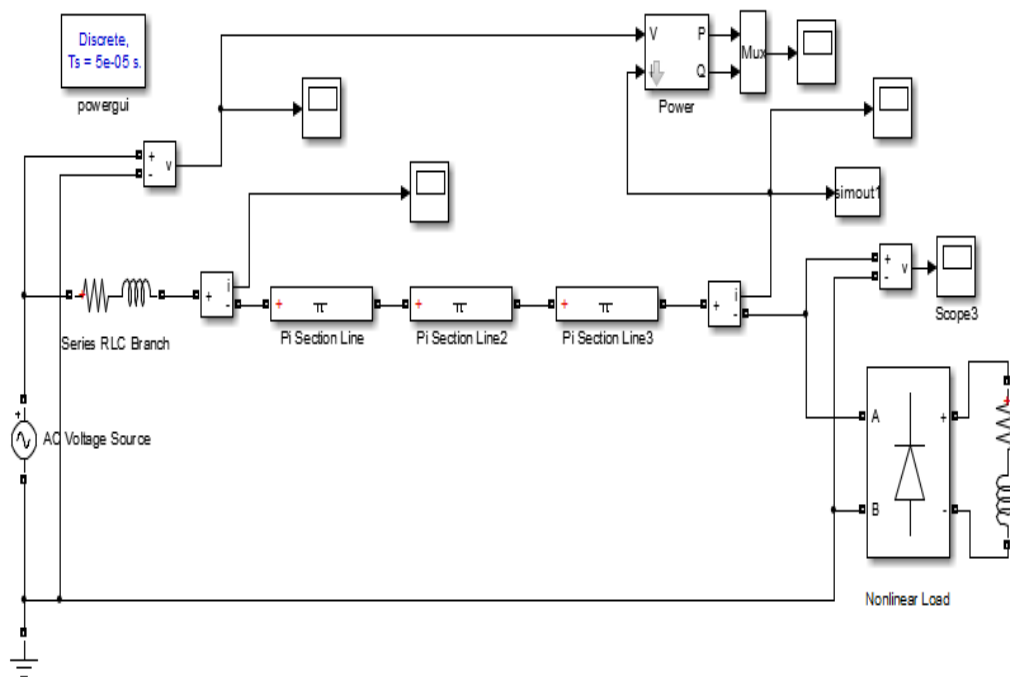


Figure 5.1: Simulink model of electric traction system without shunt APF

A single-phase bridge rectifier with RL-load is applied to the system in order to obtain the distorted load current.

### Case 1:

Assuming single train in service in the feeding section, when the locomotive is 10 km away from the substation the simulation result of voltage, current waveform and the active and reactive power demand of the locomotive without any type of compensation is as shown below, and the harmonic distortion content of the load current is demonstrate by FFT analysis.

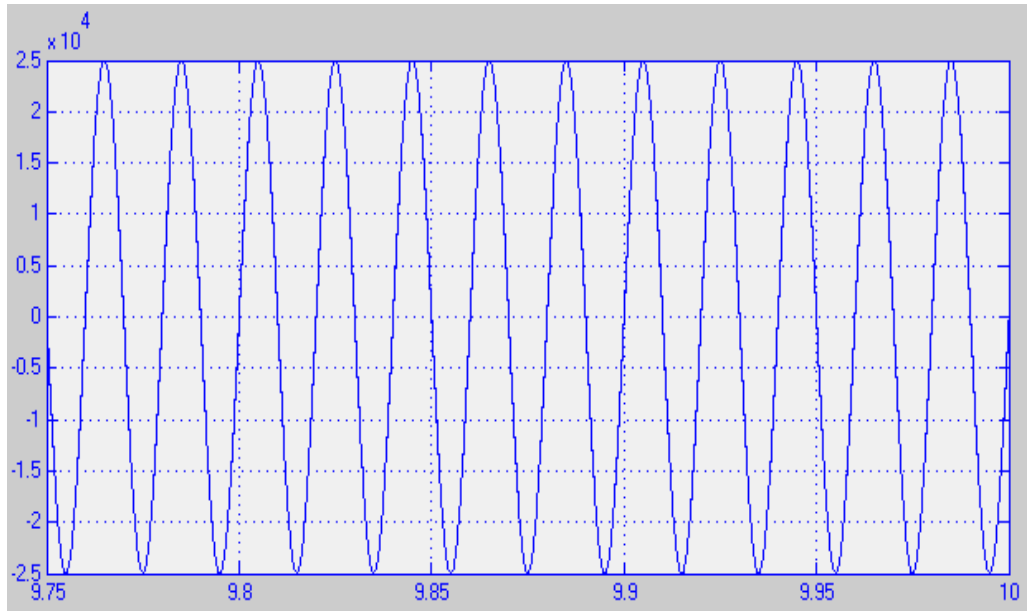


Figure 5.2: Source voltage without SAPF when the locomotive is 10km away from TSS

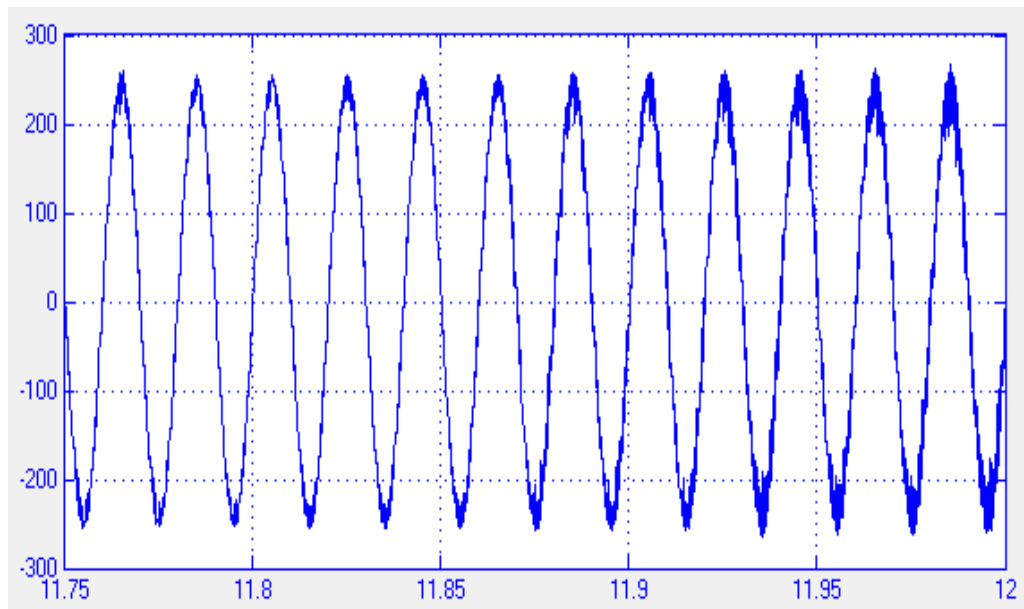


Figure 5.3: Source current wave form without SAPF when the train is 10km away from TSS

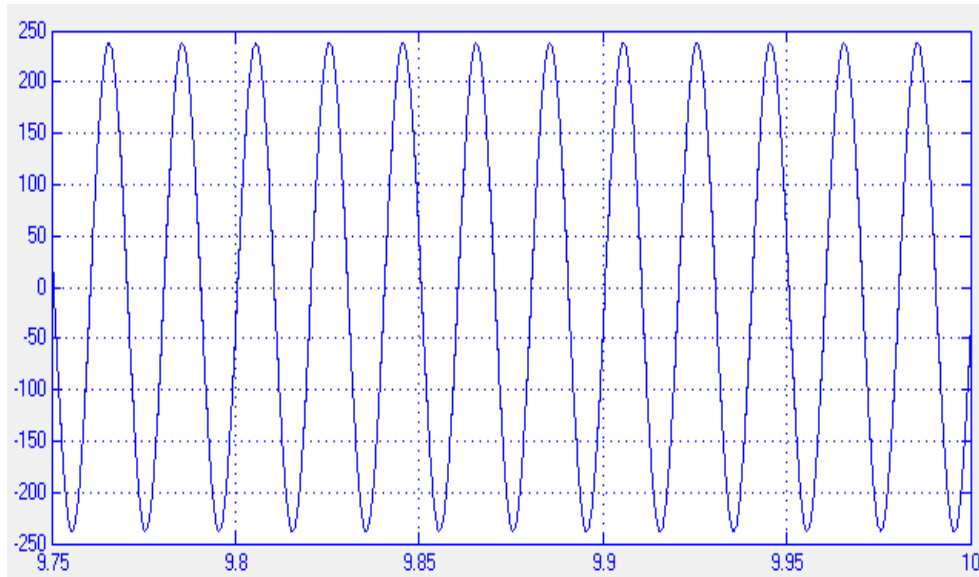


Figure 5.4: Load current wave form without SAPF when the locomotive is 10km away from TSS

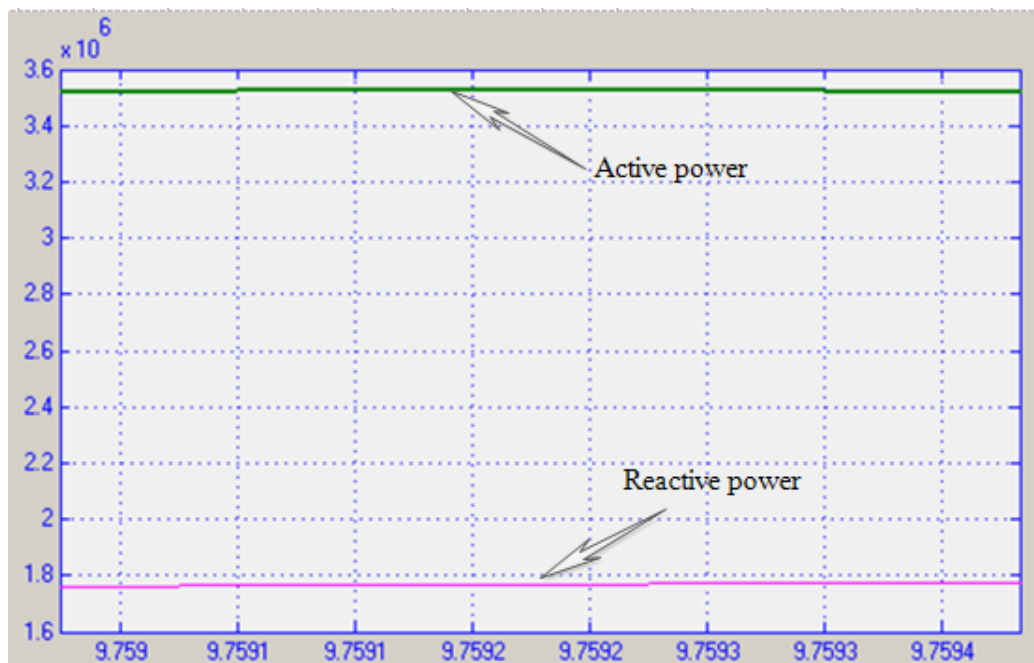


Figure 5.5: Simulation result of Active and reactive power supplied from source without SAPF when the train is 10km away from the SS

In order to demonstrate the harmonic distortion content in the current waveform a spectral analysis tool (FFT) is applied to the source current waveforms without the SAPF

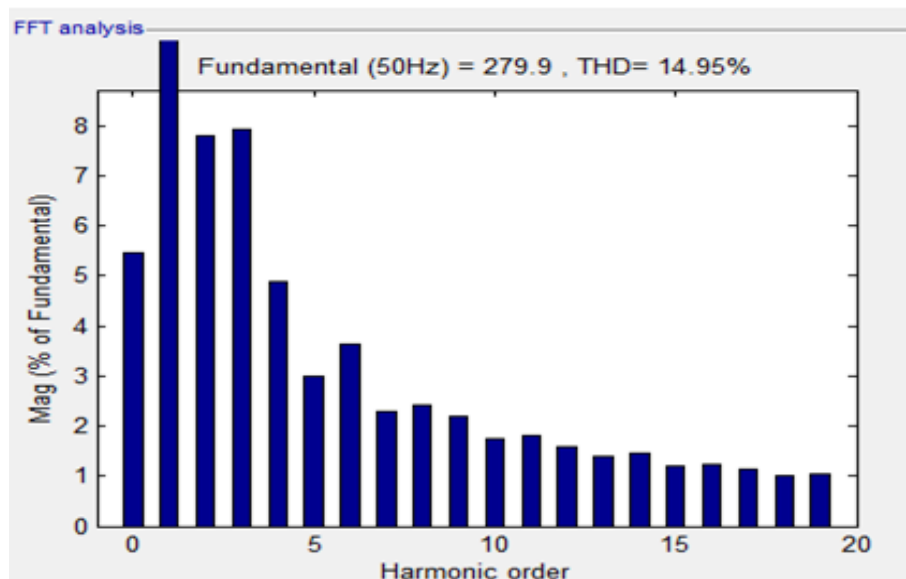


Figure 5.6: FFT spectrum analysis of the load current without SAPF when the train is 10km away from TSS

Table 5.2: Simulation result of FFT analysis harmonic order list relative to fundamental when the train is 10 km away from SS

Harmonic order (%)	Value
Fundamental harmonics	100%
3 <sup>rd</sup> harmonics	8.36 %
5 <sup>th</sup> harmonics	3.06 %
7 <sup>th</sup> harmonics	2.89 %
9 <sup>th</sup> harmonics	2.71 %
11 <sup>th</sup> harmonics	1.98%
13 <sup>th</sup> harmonics	1.72%
THD,%	14.95%

As we can see from Figure 5.6 and Table 5.2 the harmonic distortion has significant content, which is above the IEEE standard limit.

**Case 2:**

When the locomotive position is 20 km away from the TSS, the corresponding simulation results are plotted as follows.

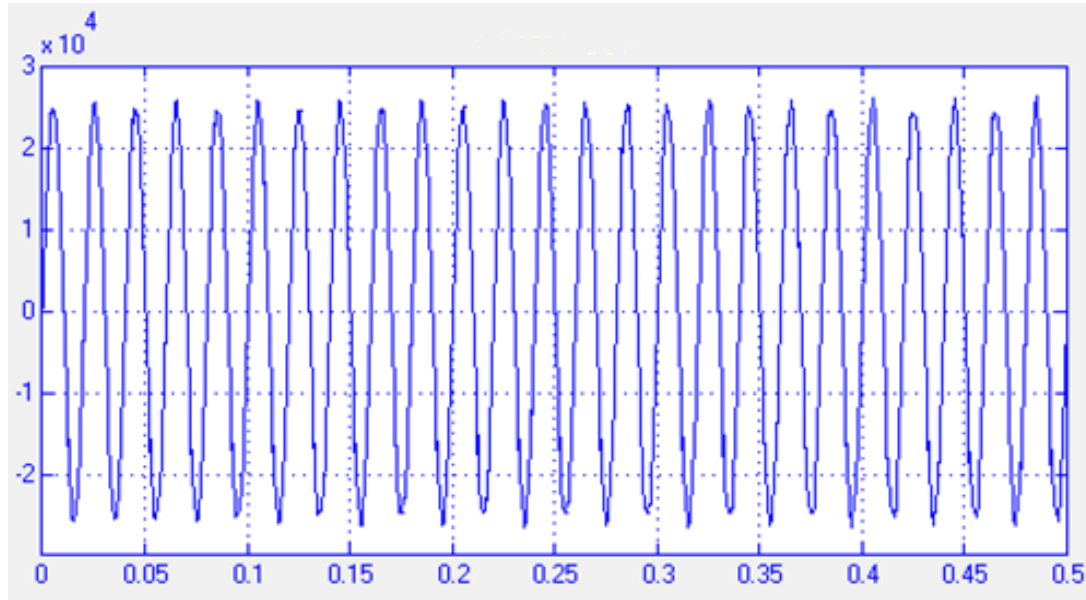


Figure 5.7: Source voltage wave form without SAPF when the train is 20km far from TSS

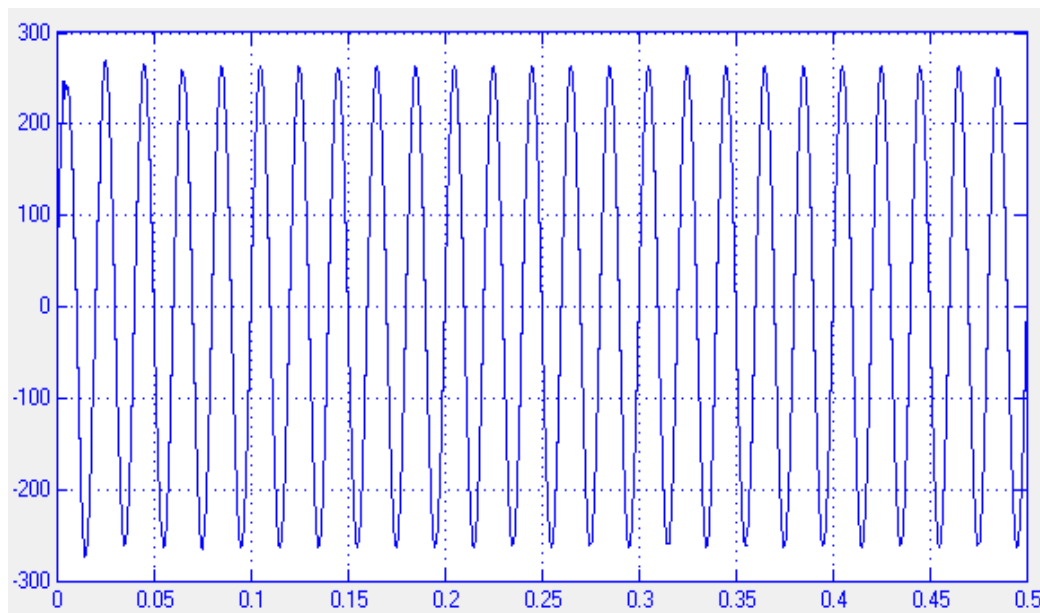


Figure 5.8: Source current wave form without SAPF when the train is 20km away from TSS

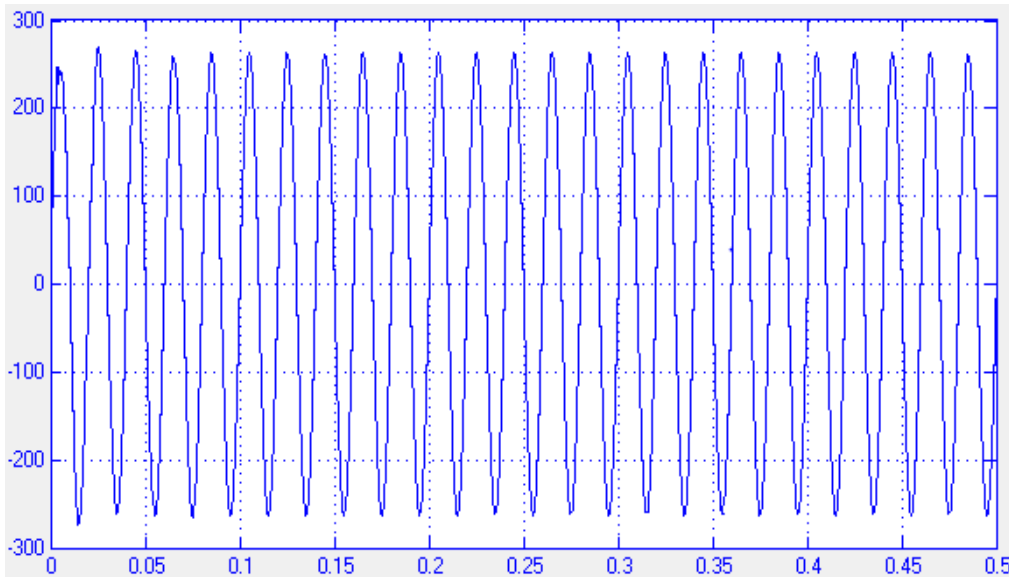


Figure 5.9: Load current wave form without SAPF when the train is 20km position from TSS

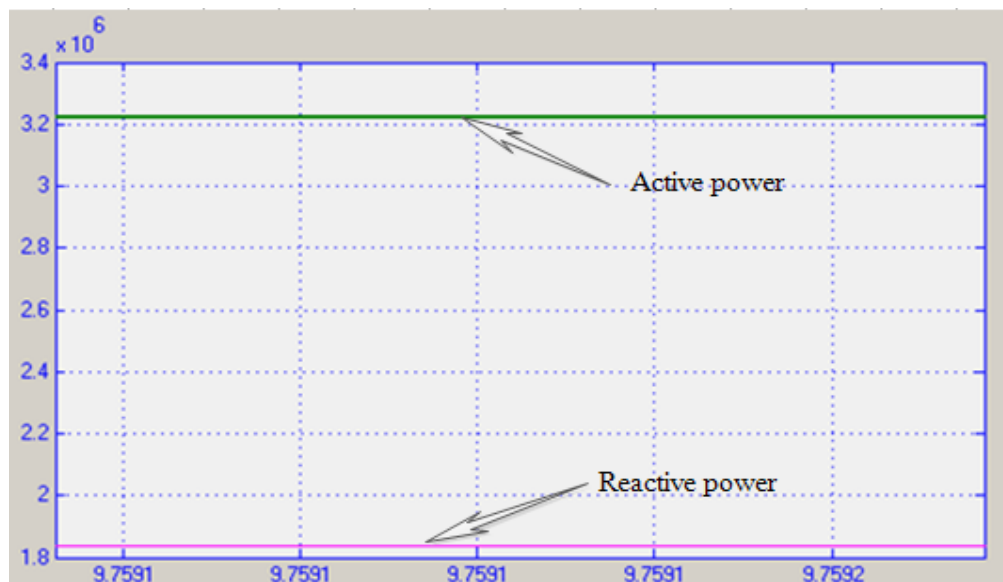


Figure 5.10: Active and reactive power supplied from source without SAPF when the locomotive is 20 km away from TSS

As we can see from figure 5.9, the resulting load current is highly distorted with the harmonic profile of the source current due to the electrical non-linearity of the locomotive. The active and reactive power demand by the locomotive is about 3.2 MW and 1.83 MVAR respectively.

The harmonic distortion content in the current waveform can be demonstrated by a spectral analysis tool (FFT).

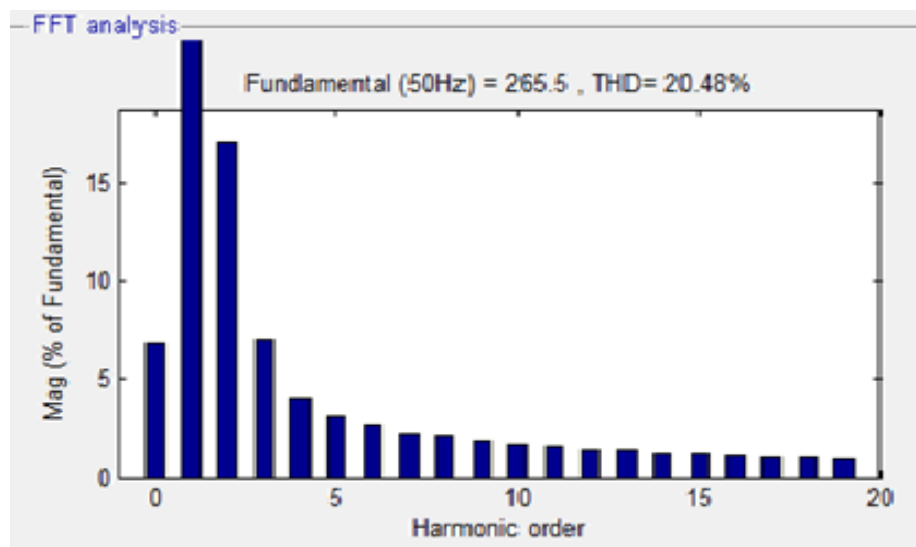


Figure 5.11: FFT spectrum analysis of the source current without SAPF

Table 5.3: Simulation result of FFT analysis harmonic order list relative to fundamental when the train is 20km away from SS

Harmonic order (%)	Value
Fundamental harmonics	100%
3 <sup>rd</sup> harmonics	7.35%
5 <sup>th</sup> harmonics	4.49%
7 <sup>th</sup> harmonics	3.83%
9 <sup>th</sup> harmonics	3.14%
11 <sup>th</sup> harmonics	2.3%
13 <sup>th</sup> harmonics	1.53%
THD,%	20.48 %

As we see in Figure 5.11, when the SAPF is not installed the source current has large amount of the harmonic contents. The THD of the load current is as high as approximately 20.5% which the load current has a significant harmonic content.

In this case, we have observed when the locomotive is going away from the TSS the reactive power supplied by the source is increased whereas active power supplied is reduced. The load current wave form is distorted due to electrical non linearity of the locomotive and the THD factor is considerable, which is above the standard limit.

## 5.2. Electric traction System Simulation with SAPF

In this case the overall electric railway system consists of AC voltage source in series with source impedance, feeder line and SAPF with its control mechanism connected in parallel with the locomotive load. The simulation parameter used in this study is given in the following table.

Table 5.4: System with shunt active power filter (SAPF) simulation parameters

Voltage source	Nominal voltage	25kV
	Rated frequency	50Hz
Source impedance	$L_s$	23.4mH
	$R_s$	100 $\Omega$
Catenary line	Longitudinal impedance	0.13008+j0.392 $\Omega$ /km
	Shunt capacitance	0.011 $\mu$ f/km
Locomotive load	Inductor	10mH
	Resistor	20 $\Omega$
SAPF parameters	DC-link capacitor	$C_{dc} = 2000\mu$ f
	Interfacing inductor	$L_f = 5$ mH
	DC-link reference voltage	$V_{DC,ref} = 72$ kV
	PI-controller gain	$K_P = 3, K_I = 2$

In this case, the system Simulink model should include single-phase source supplied by a sinusoidal 25 kV having 50 Hz frequency, pantograph feeder line, non-linear load and SAPF with controller.

The SAPF consists of a single-phase full-bridge voltage source PWM inverter, a DC bus capacitor  $C_{dc}$  and an inductor  $L_C$ . The inductance, through which the inverter is connected to the power supply network, ensures, firstly, the controllability of the active filter current and acts, secondly, as a first-order passive filter attenuating, thus, the high frequency ripples generated by the inverter. The filter operates as voltage source, which cancels the current-type harmonics and exchanges the necessary reactive energy required by the non-linear load. A single-phase diode bridge rectifier feeding a series R-L circuit is chosen to represent the non-linear load.

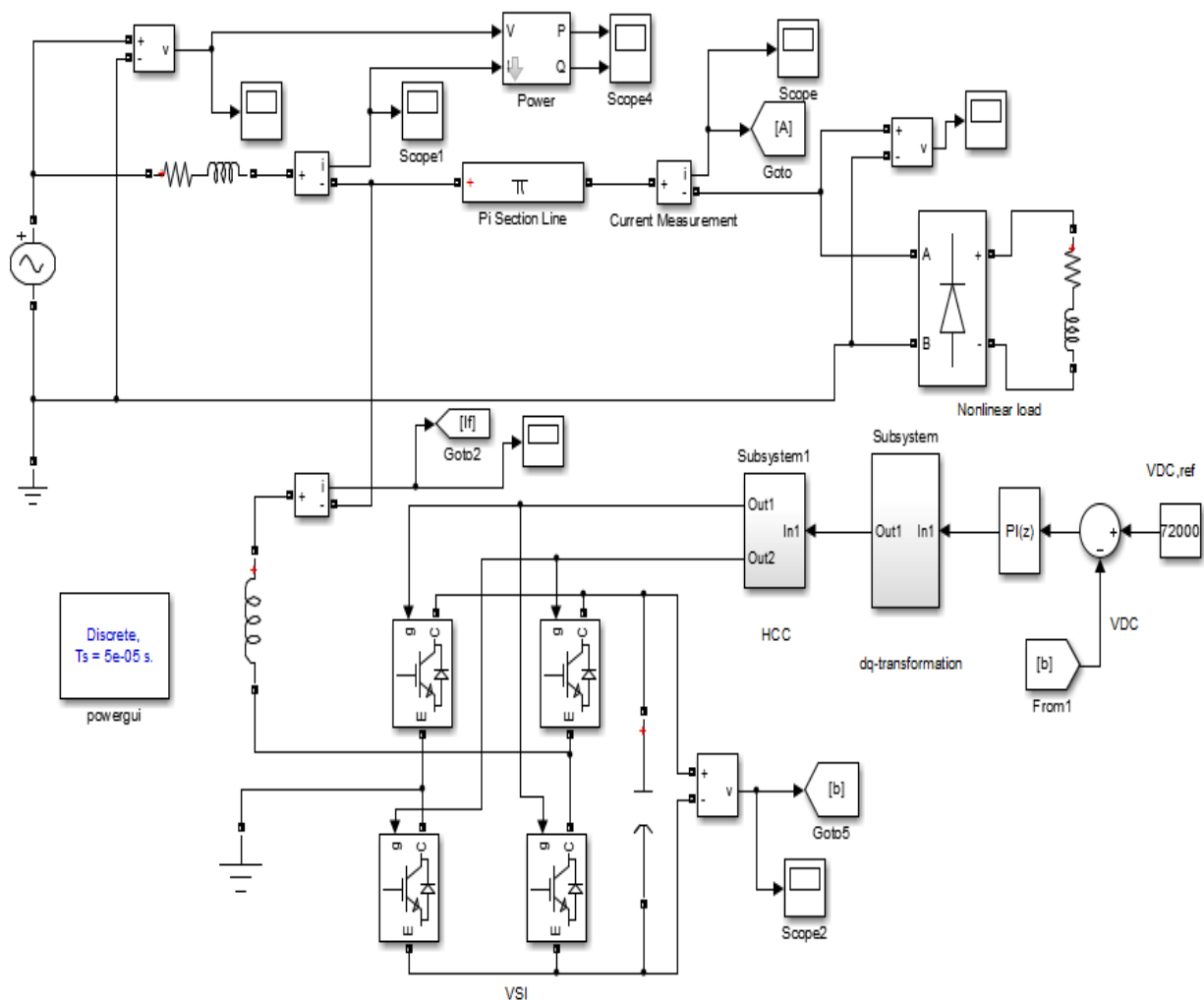


Figure 5.12: MATLAB Simulation Model of electric traction system with Shunt Active Filter

When the SAPF is installed at the SS, the simulated results of corresponding waveforms are shown in figure bellow.

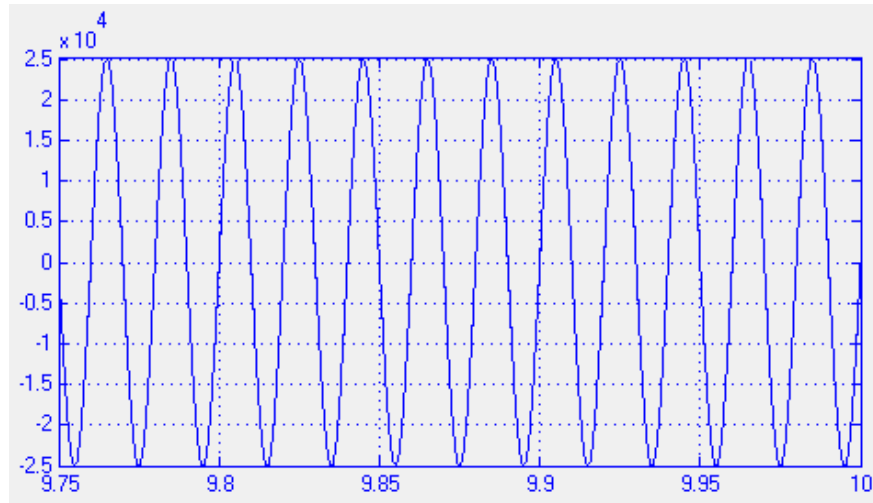


Figure 5.13: Source voltage wave form with SAPF when the train is 20km away from TSS

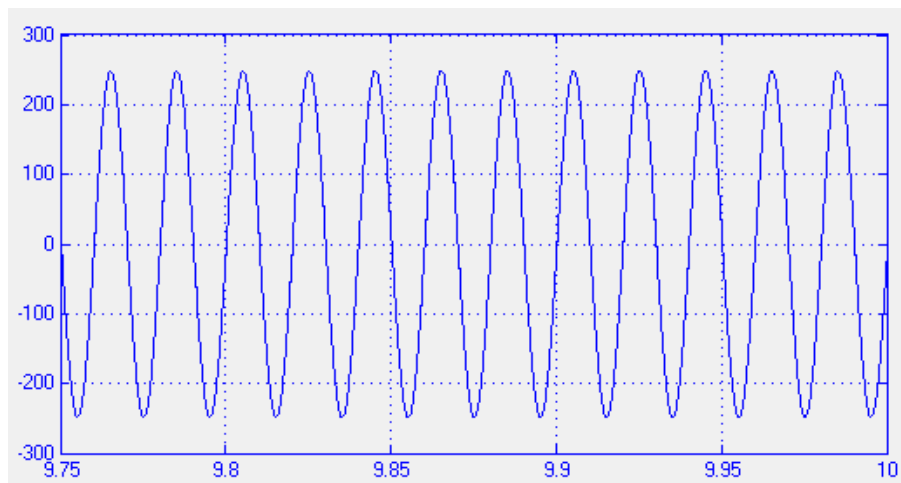


Figure 5.14: Source current wave form with SAPF when the train is 20 km away from TSS

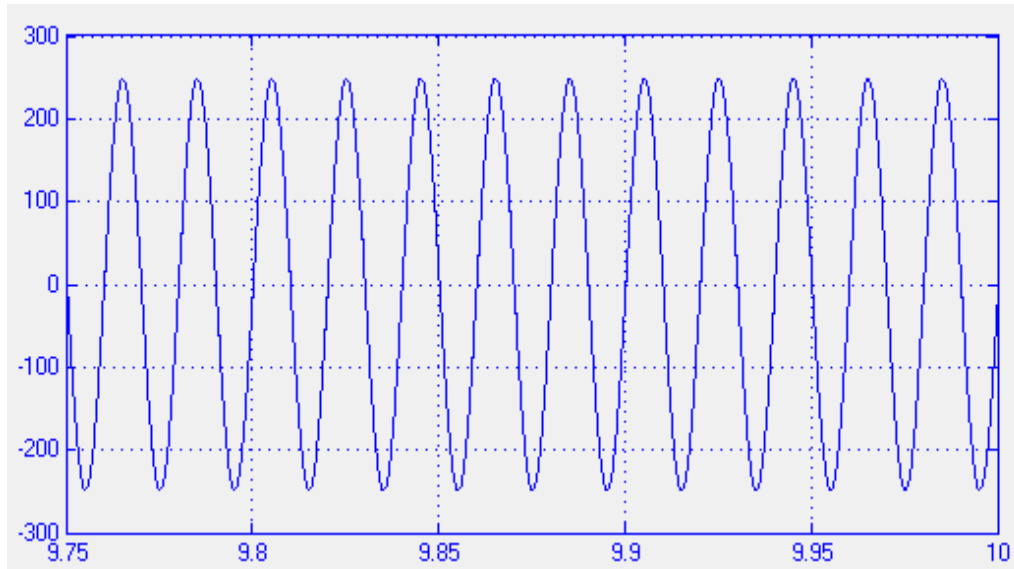


Figure 5.15: Load current with SAPF when the train is located at 20km from TSS

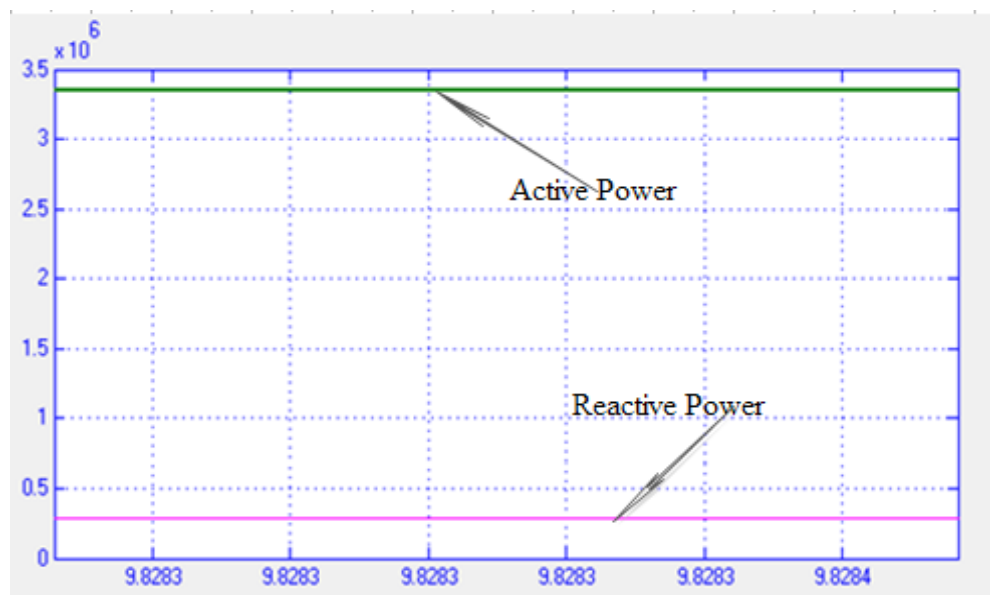


Figure 5.16: Active and reactive power supplied from the source with SAPF when the locomotive is 20km away from TSS

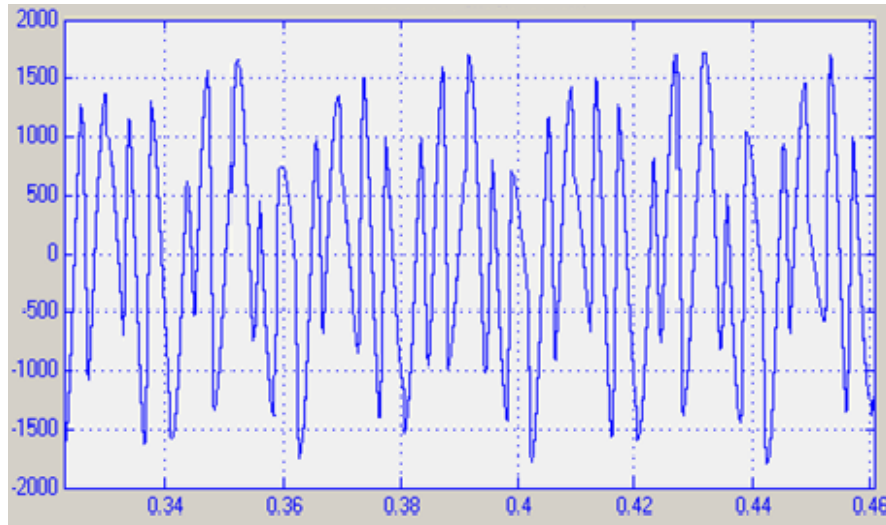


Figure 5.17: The compensating current with SAPF when the train is 20 km away from the TSS

It can be seen that the source current has very little harmonic currents because the SAPF compensates the harmonic currents effectively. In addition, the reactive power supplied from the source is nearly zero because the SAPF compensates the reactive power demand effectively.

The total harmonic distortion of the load current is demonstrated by the FFT analysis, and its result is as shown below in figure 5.18.

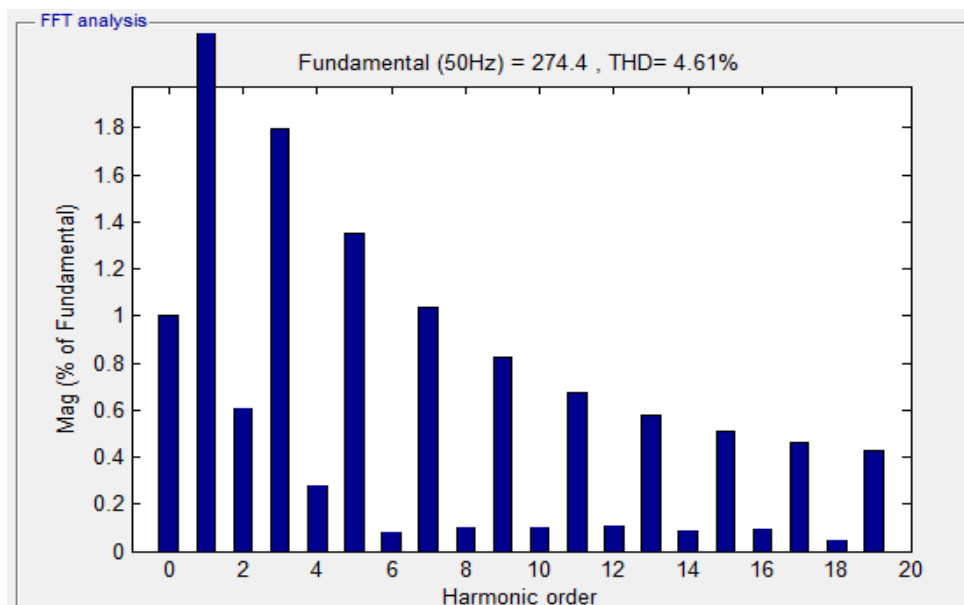


Figure 5.18: The harmonic distortion FFT spectrum analysis when SAPF is installed at the TSS

Table 5.5: Simulation result of FFT analysis harmonic order list relative to fundamental when SAPF is installed

Harmonic order (%)	Value
Fundamental harmonics	100%
3 <sup>rd</sup> harmonics	1.79%
5 <sup>th</sup> harmonics	1.38%
7 <sup>th</sup> harmonics	1.04%
9 <sup>th</sup> harmonics	0.82%
11 <sup>th</sup> harmonics	0.67%
13 <sup>th</sup> harmonics	0.58%
THD,%	4.61 %

Figure 5.18 and Tables 5.5 shows the FFT results of the load current and verifies the THD when the train is 20 km away from SS and then the value is within the standard limit.

We can also verify the voltage drop due to locomotive nonlinear load. When SAPF is not installed, the magnitude of voltage drop at the terminals of the pantograph is about 17.4 kV which is below the normal operating condition according to IEC-349 standard stipulated that the minimum pantograph voltage must be above 19 kV continuously and 17.5 kV for short periods.

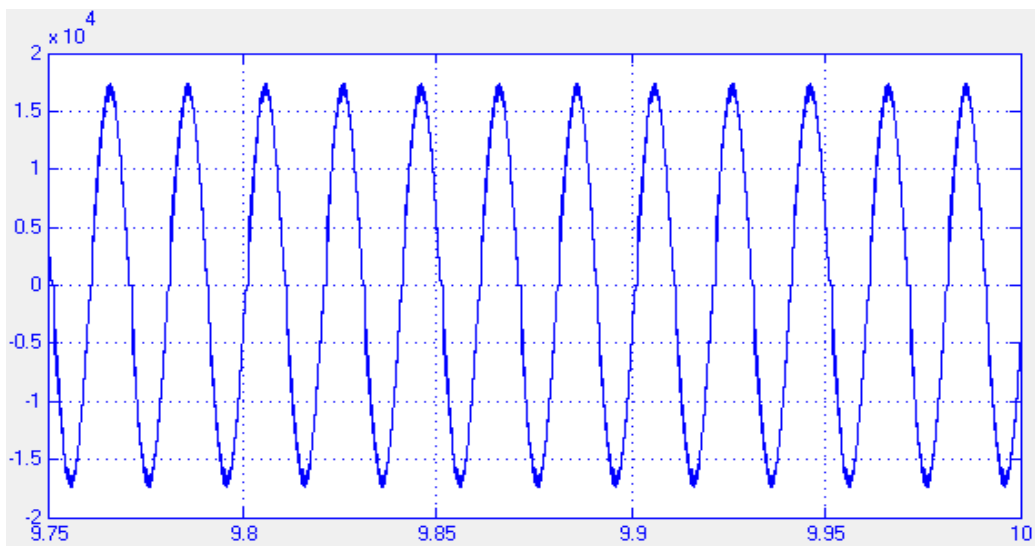


Figure 5.19: voltage drop to the locomotive when SAF is not installed

The voltage down to the locomotive is about 20 kV when SAPF is installed i.e. the voltage drop due to nonlinear load is reduced. It fulfill the standard based on IEC-349 stipulated that the minimum pantograph voltage must be above 19 kV.

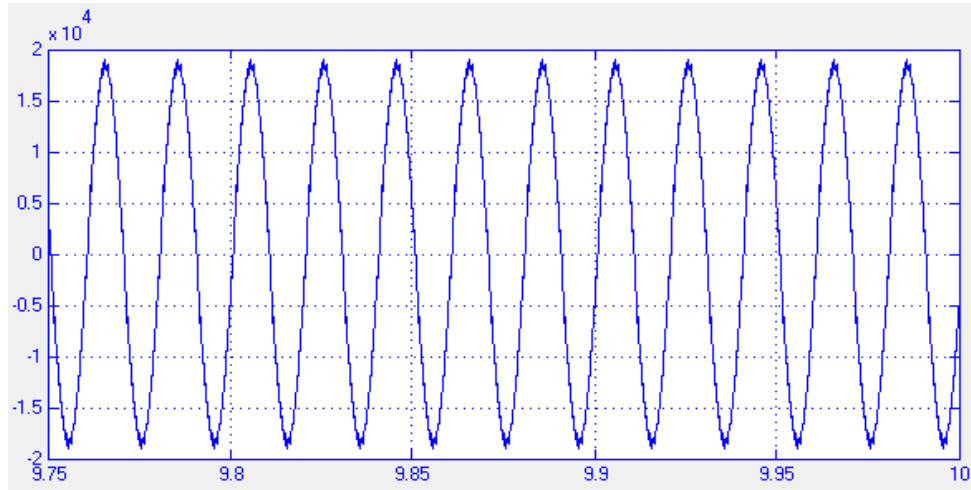


Figure 5.20: voltage down to the locomotive when SAF is installed

Table 5.6: Comparisons of THD and power factor with different scheme

	10 km	20 km
THD without SAPF	14.95	20.48
THD with SAPF	4.58	4.61
Power factor without SAPF	0.86	0.85
Power factor with SAPF	0.97	0.97

It can be seen from Figure 5.11 that the load current has large amount of the harmonic contents when the SAPF is not provided. In this case, the THD of the load current is as big as about 20.5%, big reactive power consumed and the power factor is poor. When the SAPF is installed the corresponding FFT result of load current shows the effectiveness of the SAPF proposed to mitigate the harmonic contents in the load current. It verifies that the THD performances of each compensation method do not show a big difference according to the position of locomotive away from the TSS. And also it compensate the reactive power effectively. As a result, we have seen that the power factor has improved from 0.85 to 0.97 and pantograph voltage can be enhance to 20kV when we implement SAPF.

## Chapter Six

### 6. Conclusion, Recommendation and Future Work

#### 6.1. Conclusion

In this thesis, a shunt active power filter has been investigated for power quality improvement. The single phase SAPF is designed for the single phase Addis Ababa – Djibouti electric traction line. Based on the data from Sebeta traction substation (TSS), various simulations with and without SAPF in different locomotive position are carried out to analyze the performance of the system. Hysteresis current control and PI controller based Shunt active power filter are implemented for harmonic and reactive power compensation of the non-linear load. A model has been developed in MATLAB SIMULINK and simulated to verify the results.

It is found from simulation results that shunt active power filter improves power quality of the electric traction power system by compensating reactive power and mitigating harmonics of the load current, which makes the load current sinusoidal and in phase with the source voltage.

As the SAPF is not provided, the voltage and current waveforms of the railway system with no compensation is distorted and is not sinusoidal due to the electrical non-linearity of the locomotive. The total harmonic distortion and reactive power demand have been varied with position of electric locomotive and the load characteristics of the locomotive. From simulation results obtained, the THD of load current increases with increase in distance of locomotive from TSS, reactive power increases and active power decrease with increasing the distance from the substation. Without any compensation facility in the traction substation, we have observed that THD is around 20.5% higher than the limit recommended by IEEE 519 and there is big consumption of reactive power.

When the SAPF is connected to the system, we can observe the simulation result that THD on source side has reduced from 20.5% to 4.6% and the reactive power demand is reduced to nearly zero value. The THD of the load current is below 5%, the harmonics limit imposed by IEEE 519 standard. Thus, the simulation results after implementing the proposed filter shows that SAPF can effectively compensate both harmonic and reactive powers.

## 6.2. Recommendation

The major issue to be addressed in the Ethiopian single phase 25 kV AC electrified railway system should be the issue of power quality problem such as big consumption of reactive power and harmonic distortion. So, the Ethiopian Railway Corporation should give attention to overcome these power quality problems and their consequence. In addition, it should take remedial actions and deal on techniques how to reduce the harmonic distortion in the electric railway line and to compensate big reactive power consumption.

## 6.3. Future Work

In related this thesis further works are addressed here for the future:-

- The control strategy of SAPF need further study in detail, since the performance of active filter depends on the control technique
- Designing single-phase shunt active power filter based on neural network or fuzzy logic controller could be implemented and
- Applying adaptive hysteresis current controller for better performance of SAPF
- Evaluation of SAPF to compensate other power quality problem in electrified railway system in addition to harmonics and reactive power consumption.

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