



ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY, AAiT

SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING

DEPARTMENT OF POST GRADUATE ELECTRICAL

ENGINEERING FOR RAILWAY SYSTEMS

**Hybrid Power Quality Compensator Design for Co phase
Power Supply System in Electrified Railway**

By

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

in Partial Fulfillment of the Requirements for the Degree of Masters of

Science in Electrical Engineering For Railway Systems

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Addis Ababa, Ethiopia

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DECLARATION

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

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Abstract

Poor power quality and phase splitting are the main issues in electric railway system. Co phase traction power supply system provides continuous power to traction loads without neutral sections. In this thesis hybrid power quality compensator design for minimum DC operation voltage under comprehensive fundamental and harmonic compensation is being proposed and introduced. The hybrid power quality compensator (HPQC), in which a capacitive coupled LC structure is added, is thus proposed for lower operation voltage. The proposed HPQC is composed of a single phase back to back converter with a common DC link. It is connected to the secondary side of a 132kV/27.5kV V/V transformer. Since locomotive loadings are mostly inductive, a capacitive coupled impedance design is adopted in proposed HPQC to reduce the compensator operation voltage. Reduction in operation voltage can effectively reduce the device ratings and the initial cost of the compensator.

The operation voltage of proposed HPQC can be minimized when the parameters are properly designed. The design procedures of HPQC parameters are explored using vector diagrams and mathematical derivations. The parameter design for minimum HPQC operation voltage is derived based on constant rated load power factor and capacity.

The HPQC operation voltage rating is around 0.4824 under comprehensive compensation. This corresponds to a DC link voltage of around 17.06KV. This shows that under comprehensive compensation, with a proper LC parameter design, a lower dc voltage operation can be achieved.

Co phase traction power supply system with HPQC is modeled and simulated using Matlab/Simulink. The simulation result shows that the three phase source harmonics and unbalance are eliminated. This can be verified by its harmonic distortions of current 0.54%, 0.51% and 0.08% at phase A, phase B and phase C respectively, and unbalance of 2.43%. Since the negative sequence current 12.69 is smaller than the threshold value 34.99 then the system unbalance satisfies the standard. Simulation results show the HPQC could compensate unbalance current and current harmonics simultaneously.

Keywords: –Co phase traction power supply system, hybrid power quality compensator, V/V transformer, minimum dc operation voltage, unbalance current and current harmonics

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List of Abbreviation and Symbols

A	Ampere
AC	Alternate Current
APC	Active power compensator
AT	Autotransformer
BT	Boost transformer
C	Catenary
DC	Direct current
ELV	Extra low voltage
F	Negative Feeder
HS/HC	High Speed/High Capacity
HRPC	Hybrid railway power conditioner
HPQC	Hybrid power quality compensator
Hz	Hertz
i_A, i_B, i_C	Currents at the primary side of traction transformer
i_a, i_b, i_c	Currents at the secondary side of traction transformer
i_L	Current of traction loads
i_{L1p}, i_{L1q}	Active and reactive component of fundamental frequency component of load current
i_{pa1_set}	The fundamental frequency compensating current of phase A under a set load Condition
i_{Lh}	Harmonic component of traction load current

i_{pa}, i_{pb}, i_{pc} Compensating currents inject to the secondary side of traction transformer

K the ratio of turns of traction transformer

Km Kilometer

KV Kilovolt

KW Kilowatt

MVA Megavolt ampere

MW Megawatt

N Negative return line

NS Neutral section

OCS Overhead contact system

PQ Power Quality

PWM Pulse width modulation

RES Electrified railway systems

RPC Railway power conditioner

SSs Substations

T Track

V_A, V_B, V_C Voltages at primary side of traction transformer

$V_{inv\alpha 1}$ fundamental frequency component of output voltage of α -phase converter

$V_{inv\alpha h}$ harmonic component of output voltage of α -phase converter

$V_{inv\alpha}, V_{inv\beta}$ Output voltage of α -phase and β -phase converter

V_{LC} Voltage across coupling impedance at α -phase

V_L Voltage across coupling impedance at β -phase

V_α, V_β Voltages at secondary side of traction transformer

X_L Coupling impedance between β -phase converter and supply system

X_{LC} Coupling impedance between α -phase converter and supply system

$\cos \varphi_1$ Displacement power factor of traction load

Chapter One

1 Introduction

1.1 Motivation and Background

Electrified railway systems (RES) 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 also working to have the worldwide High Speed/High Capacity (HS/HC) railway lines that use the AC power supply system. The two most common electrification power supply systems for high speed rail are: 1x25KV and 2 x 25KV systems [1]. Such railway systems are usually fed by specialized traction substations which the main designs of them include the selection of a single phase 25KV or two phase 2x25KV systems which feed the train sets through the transformers and autotransformers in the traction substations [1]. 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.

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 [2]. Due to the single phase nature of railway contact lines system, balancing of the phase currents and voltages is always a huge challenge. Reactive power, harmonics and unbalanced active power are the outstanding problems in traditional traction supply system [3]. These problems directly influence the three-phase industrial grid through traction substations. With the rapid development of high speed and heavy load railway system, these problems are gradual prominence.

Power quality problems of traction power system, such as power unbalance, harmonics, and reactive power will result in extra line losses, under voltage at the terminal of contact wire, and unbalanced current of utility grid. The degree of the problem depends on the feeding electric railway traction loads, including trains movement, tractive profile of electric locomotives, and power supply scheme [4]. These problems present huge impact to the utility grid [4].

Neutral section (NS) needs to be inserted for separating the supply system to electrically isolated sections and it restricts the speed promotion of high-speed train, which influences the safety, reliability and economy of railway operation [5]. The length of the NS varies from several hundred meters to more than 1km. The fact that electric locomotive needs to slide across the NS without power supply, affects its speed and may make the passengers feel uncomfortable. Expensive automatic switches and their controllers are required for switching the power supply of the locomotive at each neutral section [5]. In addition, the traction power supply system still suffers from the system unbalance, since loads cannot be distributed evenly among sections. These problems directly influence the three-phase industrial grid through traction substations. As locomotives based on PWM converter are widely used, the distortion of reactive power and harmonics is decreased partially, but the unbalance becomes more significant than before [3]. Although the problem of low power factor has been well dealt with by using four quadrant pulse rectifiers to feed electrical locomotives, the problem with negative sequence and harmonic currents generated from the electric locomotives still remains [3]. This creates adverse impacts on the electric devices and threatens the safe and economic operation of the grid, such as increasing power losses of the electric devices and feeder line, reducing the output ability of the traction transformer, disturbing the relaying protection devices to do miss operations, etc [6]. As a result, this problem has attracted more and more attentions from the researchers [6].

Co phase traction power supply system which can supply the traction loads without neutral sections. The number of NS is cut down by half in the co-phase power supply system [5]. The remained NSs are replaced by section separator, for which the requirement of insulation is reduced since the terminal voltage difference between the two neighboring sections is much smaller. In the substation of the co-phase power supply system, a hybrid power quality compensator (HPQC) is used together with the V/V feeding transformer to feed the single-phase traction loads. The primary side of the three phases V/V feeding transformer is connected to the three-phase power grid. It provides two single-phase outputs at the secondary side, and one of them directly supplies the traction loads. The other phase supplies the loads indirectly via the HPQC. By controlling the HPQC, the feeding transformer draws three phase balanced currents from the grid. In addition, the harmonic and reactive power of the traction loads can be compensated by the HPQC.

In this work hybrid power quality compensator (HPQC) for co phase traction power supply is designed to solve unbalance problem and harmonic filtering in the electrified railway traction system.

1.2 Statement of the Problem

The electrical railway transport is more economical and environmental friendly mass transit. The electrified railway traction system is a source of large varying non-linear loads and polluting the electrical system by means of harmonics. Due to the single phase nature of railway contact lines system, balancing of the phase currents and voltages is always a huge challenge. The unbalanced system is usually a cause for overloading and reduced efficiency. The power quality of traction power supply system has some characteristics such as low power factor, high content of negative sequence and harmonic currents because the speed and load are changing constantly.

In traditional traction power supply system, the single phase load of electric railway will produce particularly poor power quality, such as reactive power current, harmonics, and unbalanced active power current. These problems directly influence the three phase industrial grid through traction substations (SSs).

As locomotives based on pulse width modulation (PWM) converter are widely used, the distortion of reactive power and harmonics is decreased partially, but the unbalance becomes more significant than before. In traditional traction power supplies, the scheme using two phase feeding wires in one SS supply section is widely adopted in order to balance the two phase loads. If a balance feeding transformer is adopted, the two phase's balanced secondary currents will results in three phase's balanced primary currents. There are several balance transformer connection schemes, such as modified wood bridge, Scott, and roof delta transformers. All of them have their properties and performances as a feeding transformer. But the balance transformers cannot entirely balance the three phase currents if the two phase currents are unbalanced.

Unfortunately, because the speed and load condition of locomotives in two phase feeding system will change frequently, the feeding currents in two phase traction supply system are commonly

unbalanced. Additionally, the balance transformer is helpless against reactive power and harmonics.

Unless remedial action is taken, the result will be deterioration of power quality, not only harmful the traction system itself, but also prone to spreading through the supply grid, disturbing other users of power in the same grid. Therefore a means for solving the power quality issue is must. In this thesis hybrid power quality compensator is designed for co phase traction power supply system to solve the problems of power quality of unbalanced three phase, large harmonics and cancel neutral section in electrified railway traction power supply system.

1.3 Objectives

1.3.1 General Objectives

The main objective of this work is to design hybrid power quality compensator (HPQC) for co phase traction power supply system in the electrified railway traction system taking sebata traction substation as a case study.

1.3.2 Specific Objectives

The following are the specific objectives of this work

- Modeling traction substation
- Parameter design of the hybrid power quality compensator (HPQC) for co phase traction power supply
- Balancing of three phase currents and harmonic filtering when evaluated at the grid side
- Simulation verification using MATLAB/Simulink.

1.4 Methodology

In order to achieve the main aim of the study there are various procedural tasks to be followed. Therefore in this work the method discussed below will be used to achieve the proposed objectives.

- ✓ First, reviewing of co-phase traction power supply is done.
- ✓ Collecting data of the traction substation
- ✓ Modeling the traction substation and the co phase traction power supply
- ✓ Next, hybrid power quality compensator is designed for co-phase traction power supply system for the case of sebeta substation.
- ✓ At last, verification of hybrid power quality compensator (HPQC) is done through MATLAB / SIMULINK simulation.

1.5 Literature Reviews

Much investigation has been done considering electrified railway traction power supply quality issues. In this work some of the related works will be discussed.

Natesan P, Madhusudanan G [17], Power quality problems in power systems have been increased due to nonlinear loads. A hybrid power compensator (HPC) is proposed in this paper to eliminate the harmonic currents, compensate power factor and voltage unbalance problems created by the nonlinear loads present in three phase systems. A HPC contains back to back converter by sharing the same DC link power and V/V transformer to provide a voltage balance in transmission line.

Qunzhan Li et al [18], Poor power quality and phase splitting are the main issues in electric railway. Co phase traction power Supply system is adopted in electrified railway for active power balance, reactive power compensation and harmonic filter. But in this paper there is no theoretical support or mathematical derivation to design the conditioner and its rating.

Zeliang Shu et al [4], Poor power quality of single phase electric railway systems with industrial three phase power supply will result in extra line losses, under voltage at the terminal of contact wire, and unbalanced current of utility grid, etc. To address all of the above problems, in this paper, a co phase traction power supply system is adopted using YNvd type transformer and active power compensator (APC) based on single phase back-to-back converter. This provides fast and dynamic response but the device rating is high.

Ning YiDai et al [16], Co phase traction power supply system provides continuous power to traction loads without neutral sections. In order to reduce system unbalance, compensate reactive power and harmonics, a railway power conditioner (RPC) operates together with traction transformer in each substation. In this study, the RPC is designed to achieve three phase balance and unity power factor (PF) at the grid side. The device rating is high as a result the initial cost of the compensating device will be high.

Ning Yi Dai [5], Co phase traction power supply system was proposed for supplying the long-distance electrified railway without neutral sections. However, a railway power compensator (RPC) needs to be installed in each substation together with the traction transformer for improving the power quality. The RPC is mainly constructed by a back-to-back converter, which can reduce the unbalance currents by active power transfer and compensate reactive current and harmonics at the same time. A hybrid railway power conditioner (HRPC) is proposed for the co-phase traction power supply system in this paper. The HRPC uses a LC coupling branch between the converter and the traction supply. This paper mainly focused on the fundamental compensation but not with harmonic consideration.

Keng Weng Lao et al [20], A hybrid power quality compensator (HPQC) is proposed in this paper for comprehensive compensation under minimum DC operation voltage in high-speed traction power supplies. Reduction in HPQC operation voltage can lead to a decrease in the compensation device capacity, power consumptions, and installation cost. The parameter design procedures for minimum DC voltage operation of HPQC are being explored. A HPQC is able to provide system unbalance, reactive power, and harmonic compensation in co phase traction power with reduced operation voltage. The co phase traction power supply with proposed HPQC is suitable for high speed traction applications. But this paper suggested that the resonant frequency of passive LC branch of hybrid structure of compensator can be tuned to the frequency where the system harmonics are mostly concentrated at to minimize the DC operation voltage of the compensator. However, the idea still lacks theoretical support or mathematical derivation.

N.Y. Dai et al [19], Power quality conditioners based on modern power electronics technology were proposed to solve the power quality problems of the electrified railway power supply system. Large capacity power converters are used as the main circuits of the compensator, which is one of the main reasons for the high initial cost of the railway power conditioner.

A hybrid power quality conditioner (HPQC) for co phase power supply system in electrified railway is proposed in this study. The HPQC adopts a single phase back to back converter. It connects to the feeding phase of the balance feeding transformer via an L–C branch and to the other phase via a coupling transformer. To inject the same compensating currents to the traction power supply system, the DC bus voltage of the HPQC could be much lower. As a result, the cost of the power quality conditioner is reduced. This paper focused on the fundamental compensation but with harmonic consideration.

1.6 Scope of the Thesis

Designing hybrid power quality compensator (HPQC) of co phase traction power supply system taking the case of sebeta traction substation and its verification is done using simulation based on MATLAB/Simulink.

1.7 Organization of The Thesis

This thesis is organized in five chapters.

Chapter one includes introduction which provides clear information about the background of the thesis work, statement of the problem, research method and literature review of the thesis.

Chapter two is about electrified railway traction power supply system. This section provides clear understanding of traction system which is about types of traction system, external power grid for traction power supply system, overview of AC electrified traction system Addis Ababa - Djibouti Railway and Power supply mode for traction system.

Chapter three discussed about the development of mathematical modeling of co phase traction power supply system and design of HPQC. It provides a clear mathematical model and derivation of equation using phasor diagrams.

Chapter four provides the simulation results and discussions about co phase traction power supply system with and without hybrid power quality compensator.

Chapter five presents conclusion, recommendation and future work.

Chapter Two

2 Electrified Railway Traction Power Supply System

2.1 Overview of Electric Railway Systems

The development of railway has been significant since the beginning of 20th century. Railway transportation is playing a significant role not only in peoples' daily life but also in global economic growth. In 1897, Siemens displayed the first electrically powered locomotive at the Berlin Commerce Fair. The maximum speed of this train was 13-kilo meter per hour, and the output energy came to about 2.2 kilowatt. Since then, electrified railways have been improved dramatically due to the rapid development of power electronics and manufacturing industries. Nowadays, the transportation capability of a single locomotive has been increased to thousands of tons [7].

The main advantage of electric traction is a higher power-to-weight ratio than forms of traction such as diesel or steam that generate power onboard. Electricity enables faster acceleration and higher tractive effort on steep gradients. On locomotives equipped with regenerative brakes, descending gradients require very little use of air brakes, as the locomotive's traction motors become generators sending current back into the supply system and/or on-board resistors, which convert the excess energy to heat. Other advantages include the lack of exhaust fumes at point of use, less noise and lower maintenance requirements of the traction units. Given sufficient traffic density, electric trains produce fewer carbon emissions than diesel trains, especially in countries where electricity comes primarily from non-fossil sources [7].

With electric traction it is also possible to further increase efficiency through regenerative braking, which means that a slowing-down train can use its electric motors as generators and recycle energy back into the system for other electric trains to use. Electric traction offers significantly improved performance when ascending gradients, plus the possibility of using regenerative braking to cost efficiently maintain safety whilst descending.

For passengers the advantages of electric traction includes improved overall performance and less vibration which results in faster, more comfortable, smoother and quieter journeys. The

improved acceleration also means that extra stations can be served with less time penalty - this is especially beneficial to users of minor stations which might otherwise have a less frequent service. Experience has shown that the very act of investing in railway electrification also gives passengers greater confidence that the line is 'valued' by the railway operators and therefore has a secure future. The sparks effect is a well proven phenomena whereby passenger numbers significantly increases when a line is electrified.

If most of an existing rail network is already electrified, there are benefits to extend electrified lines to allow through running.

The main disadvantage is the capital cost of the electrification equipment, most significant for long distance lines that do not have heavy traffic. Suburban railways with closely spaced stations and high traffic density are the most likely to be electrified, and main lines carrying heavy and frequent traffic are also electrified in many countries.

Basically the major advantage and disadvantages of electrification can listed as in below.

Advantages:

- Lower running cost of locomotives and multiple unit
- Higher power-to-weight ratio, resulting in
 - Fewer locomotives
 - Faster acceleration
 - Higher practical limit of power
 - Higher limit of speed
- Less noise pollution
- Lower power loss at higher altitudes
- Lack of dependence on crude oil as fuel

Disadvantages:

- Upgrading brings significant cost
 - Especially where tunnels and bridges and other obstruction have to be altered for clearance

- Alteration or upgrades will be needed on the railway signaling to take advantage of the new traffic characteristics.
- Increased maintenance cost of the lines (although reduced maintenance cost and multiple units)

Power is transmitted to electric railway locomotives and vehicles using DC or AC networks. The parallel development of traction technology in the industrialized countries has led to a plethora of different electrification systems.

For new railways, the type of network is influenced by technical considerations such as:

- operational requirements (for urban metro, high-speed passenger or heavy-haul freight)
- physical route characteristics (such as gradients, and bridge and tunnel clearances)
- proximity of generating plant and utility or railway-owned power networks
- available traction technology (converters, traction motors and regenerative capability).

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

- ✓ Direct current (DC) systems (750/1500/3000 V)
- ✓ Medium voltage alternate current (AC) systems (15/25 kV, 50/60 Hz)
- ✓ High voltage AC systems (50/2x25 kV, 50 Hz)
- ✓ Low frequency systems (15 kV, 15-162/3 Hz)

The low voltage DC system is used for light rails usually supplied at 750 Volts (metro transit) and for commuter and intercity trains usually supplied at 3000 Volts ,which is the case of the traditional Italian traction system [8].

The medium voltage AC system was adopted in order to reduce voltage losses. The 25 kV systems was practically born in France and had great development in USA, UK, Russia and

several other countries thanks to the various advantages it offered such as the simplicity of substations and of single contact wires. It is typically used for commuter trains or freight trains.

The high voltage AC systems are the 50-kilovolt and 2x25 kV (or ± 25 kV) ones. The 50 kV systems, adopted in USA and in South Africa, exalt the economic advantages of the medium voltage systems. The system has been used where the traction load is high and the traction distances are large. Typically, it can be used for traction in rural areas and may be difficult in urban areas for the insulation requirements. Generally, RPSS are, for practical reasons, single phase AC or DC systems. The AC systems may be operated either at the same frequency as the public power grid or at a different frequency, normally a lower frequency [8].

Electricity is delivered to the trains in different ways often through an overhead contact system/line (OCS) normally called the catenary. The physical catenary goes somewhat above the actual OCS. It is however normal to denote the entire system of conductors hanging from the poles alongside the railway line as the catenary system. For subways, it is common with conductors on ground level, similar to the third-rail system common mainly in Great Britain [8].

2.2 DC Railway Electrification Supply System

Railway electrification has in the past been dominated by overhead contact wire and DC third, fourth conductor rail electrification systems. The historical reasons for this have been the success of the DC traction motor and the necessity of a DC supply. Mercury arc rectifiers were originally used to provide rectification at substations with the DC power being transmitted to the traction equipment by the conductor rail or overhead wire. Success in producing mercury arc rectifiers capable of being operated on board the railway vehicle enabled railway AC electrification system to become a reality in the 1950/60's [9].

It should be noted that DC is still the most common form of railway electrification system in the world.

Most silicon rectifiers on traction systems use a three phase 50 Hz national or railway supply intake. Three phase rectification arrangement is used to reduce harmonic distortion at the point of common coupling and to reduce harmonic content in the DC supply. Where the mercury arc rectifier have been replaced by a silicon rectifier the double star transformer with inter phase

transformer is employed. The advance of the silicon rectifier makes more simple arrangements of design [9].

DC system can be divided into two main parts.

1. Voltage Level

There are some standard levels for application: 600V, 750V, 1500V, 3000V etc...

2. Feeding Conductor Type

Overhead Line System, Third Rail, Fourth Rail, Overhead Rigid Conductor etc...

2.3 AC Traction Power Supply System

Traction power supply system consists of traction substation, section post and traction electric network. Traction substation is three-phase and 110kV (external power supply is 132kV) power receiving equipment brings in high-voltage current supplied by external power transmission line and controls opening and closing. Then the traction transformer transforms incoming three-phase electricity into 27.5kV single phase electricity. Finally electric energy will be feed into traction network with single-phase feeder equipment. The section post construct down and up feeders of electrified railway in parallel to increase the voltage level of feeding sections which is at the end of the feeders and balance the current of up and down feeding sections and reduce the loss of electricity energy [10]. The substation is a part of an electrical generation transmission and distribution system. The functions of the substations is change the voltage from high to low or to the reverse or perform any of several other relevant functions. The interval of generating station and consumer electric power may flow through several substations at different voltage levels. Substations may be goods and worked by an electrical utility or may be goods by a large industrial or commercial customer [11].

AC electric traction systems are mostly operated as single phase systems. Electric traction systems, which are supplied via the public transmission grid, operate at a nominal. The voltage is 25 kV and at frequencies of 50Hz or 60Hz. An overhead contact system (OCS) supplies the power to the electric trains. In order to reduce the unbalance imposed by the single phase traction load neighboring overhead contact system (OCS), feeding points are often connected to different

phase pairs of the transmission system. At the midpoint between the feeding points the OCS sections are separated by a neutral section (NS). A result of this arrangement is single end fed OCS sections. The running rails and earth act as return circuit. Amongst others the OCS usually consists of a catenary, which is a contact wire held level to the track by a suspension wire. The catenary wires are electrically paralleled. Along the contact wire the current collecting pantograph of the trains establish the conductive connection between the OCS and the traction drives on the trains. Overhead contact systems serve two main purposes; firstly they distribute the power to the electric trains and secondly they establish the electrical connection between the stationary power supply and the moving traction load. Hence, the strains imposed onto the OCS are not only due to thermal effects of the current flowing through the catenary conductors but also caused by the contact force and friction of the pantographs [12]. 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 2.1. 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 with in the section power is carried to the train through overhead catenary and current takes the rails as return paths.

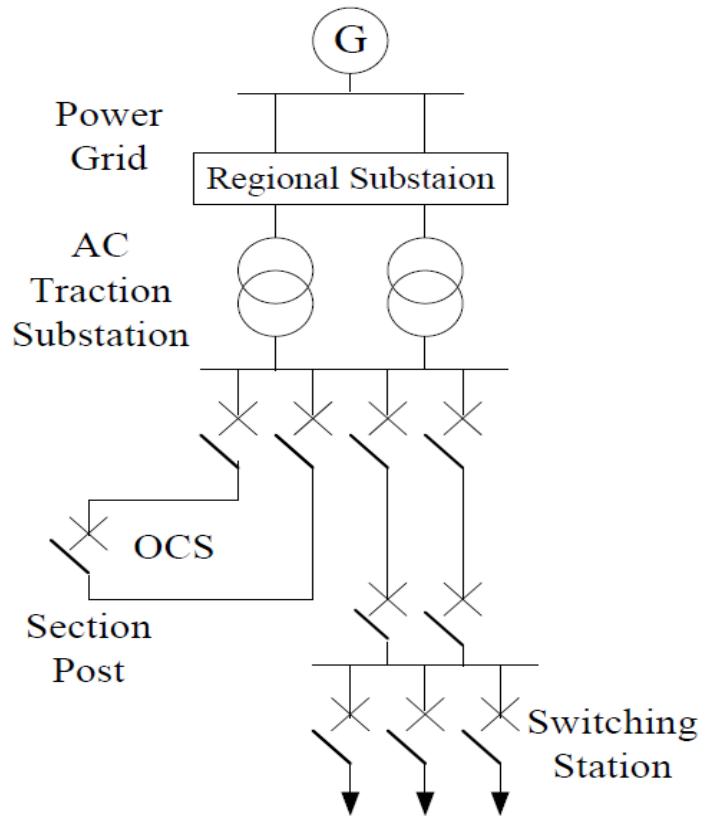


Figure 2.1 AC traction power supply system [Author]

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
- Polyphase AC System
- Standart Frequency

2.3.1 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 [9].

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 [9]. The 60 Hz frequency can be converted to 15 or 20 Hz for railway electrification [9]. 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 [9].

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 [9]. 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:

2.3.1.1 Advantages of a Low Frequency

i. 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 [9].

ii. 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 secondaries 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 [9].

iii. 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 [9].

iv. 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 [9].

v. Reduced Substation Voltage Capacity or Better Utilization of Substation and Catenary Capacity:

With the 25kV single phase, 60Hz 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 [9].

vi. 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 [9].

vii. Reduced Harmonics into 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 [9].

viii. 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 [9].

2.3.2 Polyphase 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 [9]. This was abandoned in the 1960's because of the complexity of the current collection, especially at points and crossings [9].

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 [9]. 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 [9]. 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 metre-long section of a coal railway near Cologne, between 1940 and 1949 [9].

2.3.3 Standart Frequency 25kV 50Hz Electrification Supply System

Only in the 1950s after development in France did the standart frequency single-phase alternating current system become widespread, despite the simplification of a distribution system which could use the existing power supply network [9].

The first attempts to use standart-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 polyphase 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 [9].

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 [9].

The 25 kV AC 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 [9].

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 [9].

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.

This system is quite economical, but it has its drawbacks: the phases of the external power system are loaded unequally, and there is significant electromagnetic interference generated, not to mention acoustic noise [9].

The practical details of AC power feeding are concerned with maintaining the quality of the supply. On the traction side, catenary feeding systems using booster transformers and auto transformers feeding have been developed to improve transmission efficiency and system regulation and to reduce earth [9].

2.4 External Power Grid for Traction Power Supply System

The single phase 50Hz power supply for railway traction at 25kV is obtained, from 220/132/110kV three phase grid systems through a step up or step down transformer, the primary winding of which is joined to two of the phase of the three phases efficiently earthed transmission line network of the state electricity board. The primary voltage of traction transformer individual: 220kV or 132kV or 110kV and no load secondary voltage being 27.5kV [13]. With the purpose of reduce the imbalance on the three- phase grid system; the two phases of the three phase transmission line are tap, in a cyclic order for feeding the consecutive traction substations [13]. The distance between adjacent traction substations is normally between 50km

and 80km depending upon density of traffic, gradients in the sections and other factors [13]. In Ethiopia every traction substation to the introduction of two independent and reliable 132kV voltage level power supply.

2.5 Overview of AC Electrified Traction System Addis Ababa-Djibouti Railway

Electrified railway systems (RES) 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 [1].

In this system, the traction transformers are supplied from state grid, normally at 132 kV voltage levels. This voltage is further step down to 25kV nominal voltage at traction substation of using 132/27.5kV 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: 25kV; maximum working voltage: 27.5kV, minimum short-time voltage: 29kV, minimum working voltage: 20kV and working voltage under abnormal conditions: 19kV. The electric traction substation with Level-1 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 132kV independent power lines. Power system voltage loss of traction substation is calculated by imputing to the traction substation 132kV of system line side and the minimum short circuit capacity is 400MVA [2].

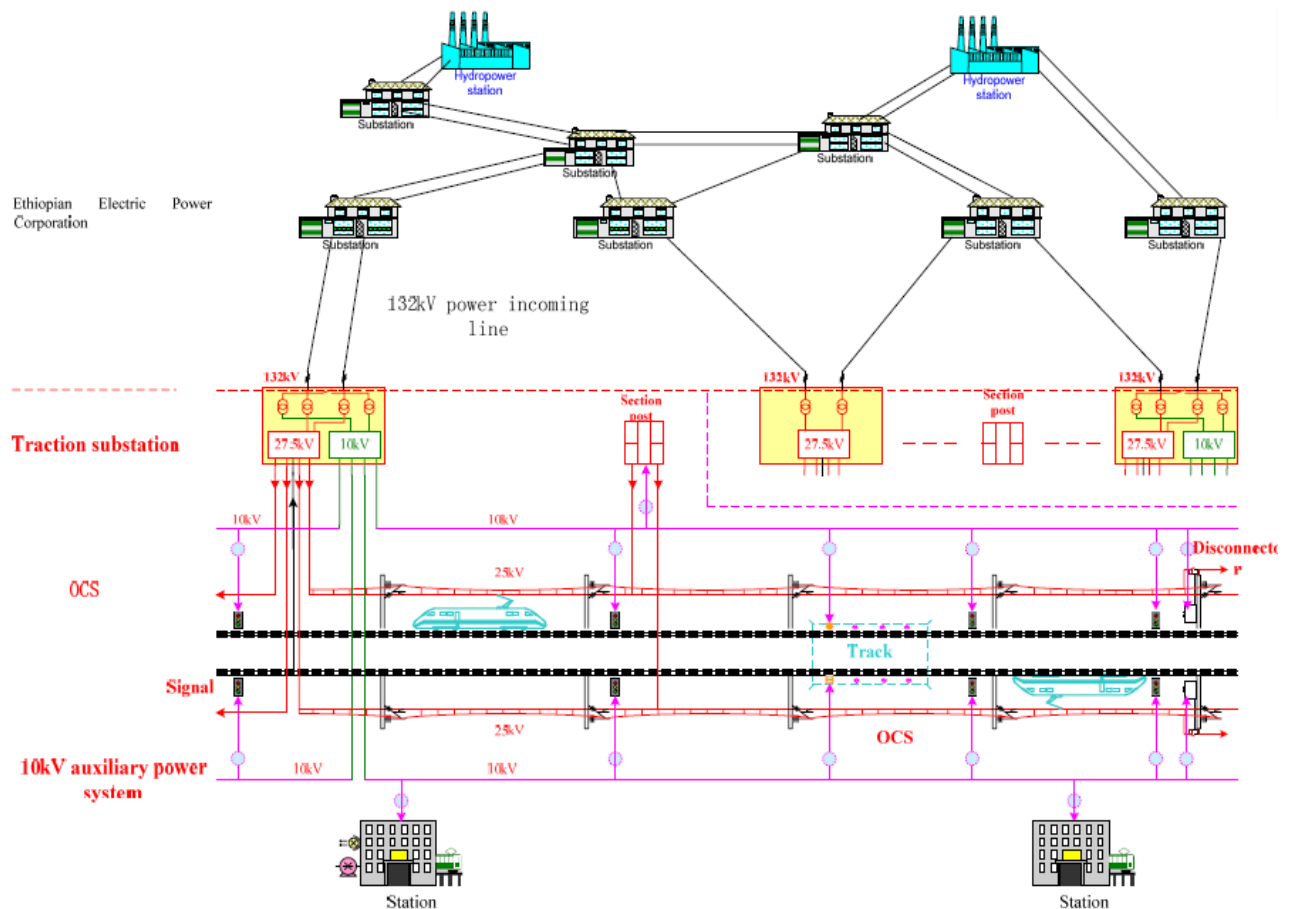


Figure 2.2 The Scheme of the double-track Section[2]

2.6 Power Supply Mode for Traction System

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

2.6.1 Direct Feeding Configuration

Direct connection of the feeding transformer to the overhead catenary and the rails at each substation, in this configuration traction current goes through train and returns to traction substation from rail and earth. Direct feeding configuration is quite simple and it has less investment and maintenance cost. However, there are some disadvantages to this scheme (high impedance of feeders with large losses, high rail-to-earth voltage and the interference to neighboring communication circuits). To reduce those effects, the addition of an extra conductor (Return Conductor) paralleled and tied to the rails at typically 5 or 6 km is needed and this can reduce electromagnetic interference in parallel communication lines by 30%.

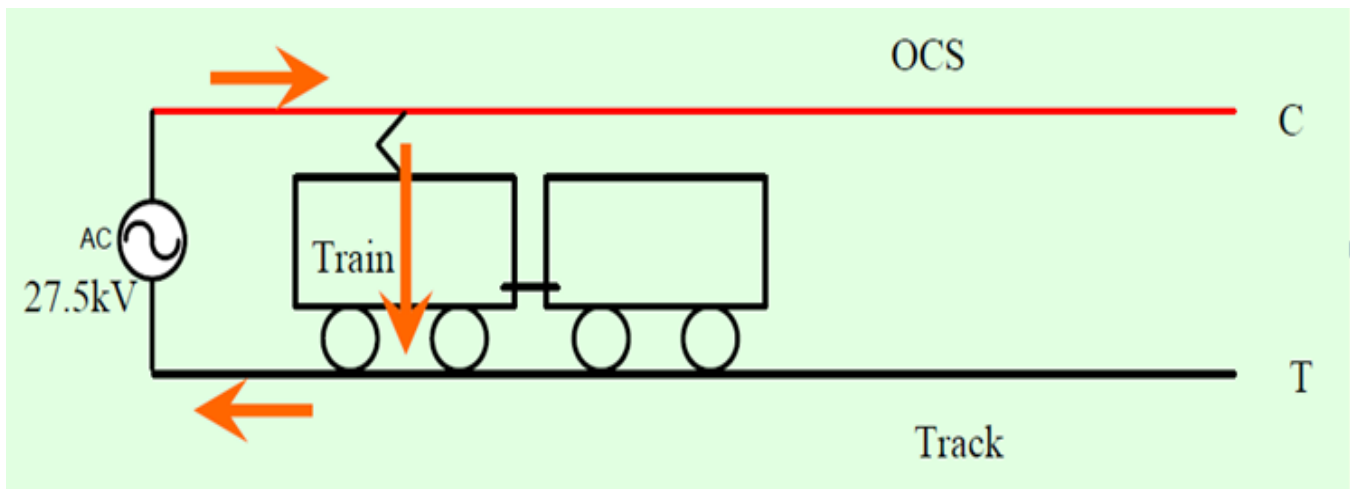


Figure 2.3 Direct feeding configuration[Author]

2.6.2 Booster Transformer Feeding Configuration

In this configuration boost transformer is serial connected between catenary and negative return line. Traction current returns to traction substation through negative return line (N). The flow return current in the return conductor rather than in the rails suppress the magneto-motive force resulting from the catenary current, the turn ratio needs to be unity. Although this feeding

reduces electromagnetic interference with about 0.025 screening factor, the leakage inductance of BTs with a return conductor increases the total feeding impedance by approximately 50% compared with the direct feeding. Thus, the distance of two adjacent feeder substations is reduced because of the voltage drop along the contact wire.

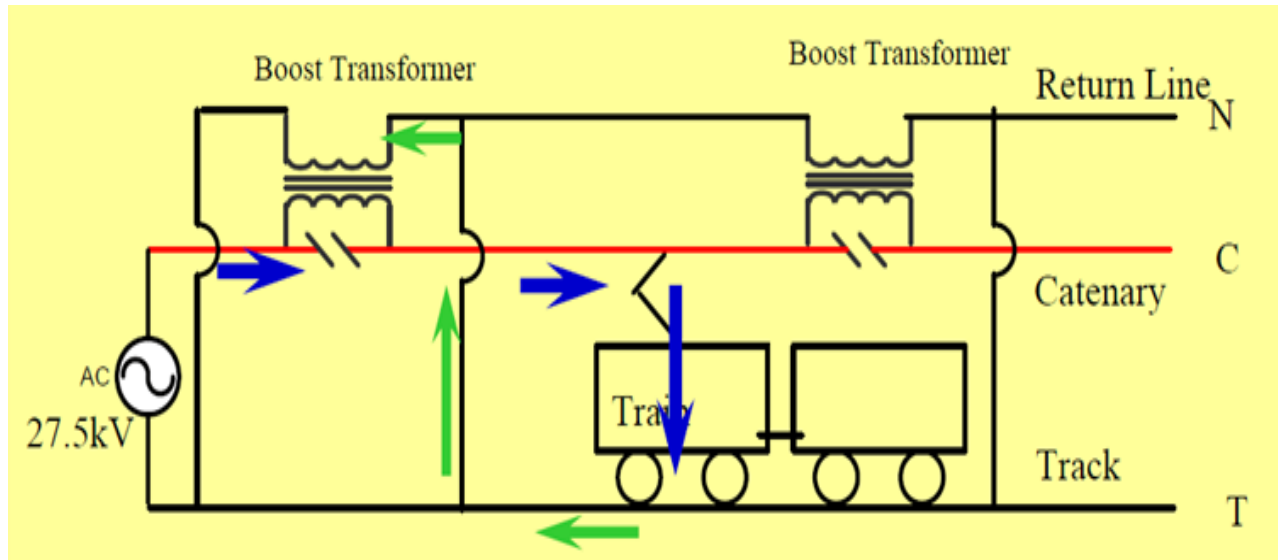


Figure 2.4 Booster transformer feeding configuration[Author]

2.6.3 Direct feeding with return line mode

In this power supply 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.

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.

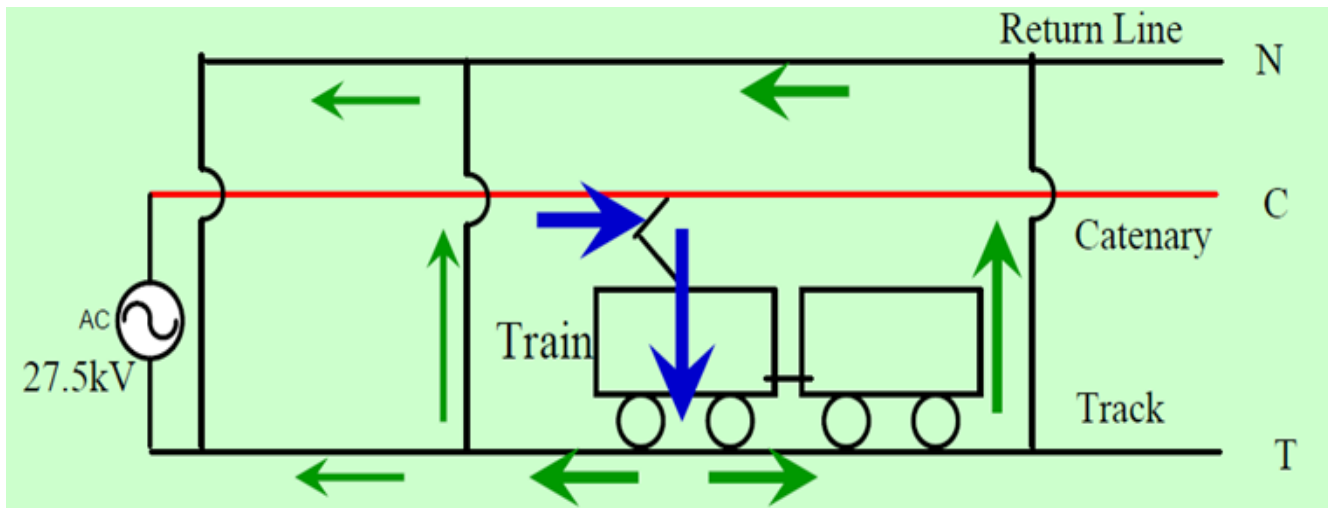


Figure 2.5 Direct feeding with return line mode[Author]

2.6.4 Autotransformer Feeding Configuration

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

Compared with direct power supply configuration, system is voltage is doubled i.e. $2 \times 25\text{kV}$, Voltage drop is reduced to $1/4$. Impedance per unit length is about $1/4$ of direct power supply. Power loss is reduced. And distance between traction substations is increased.

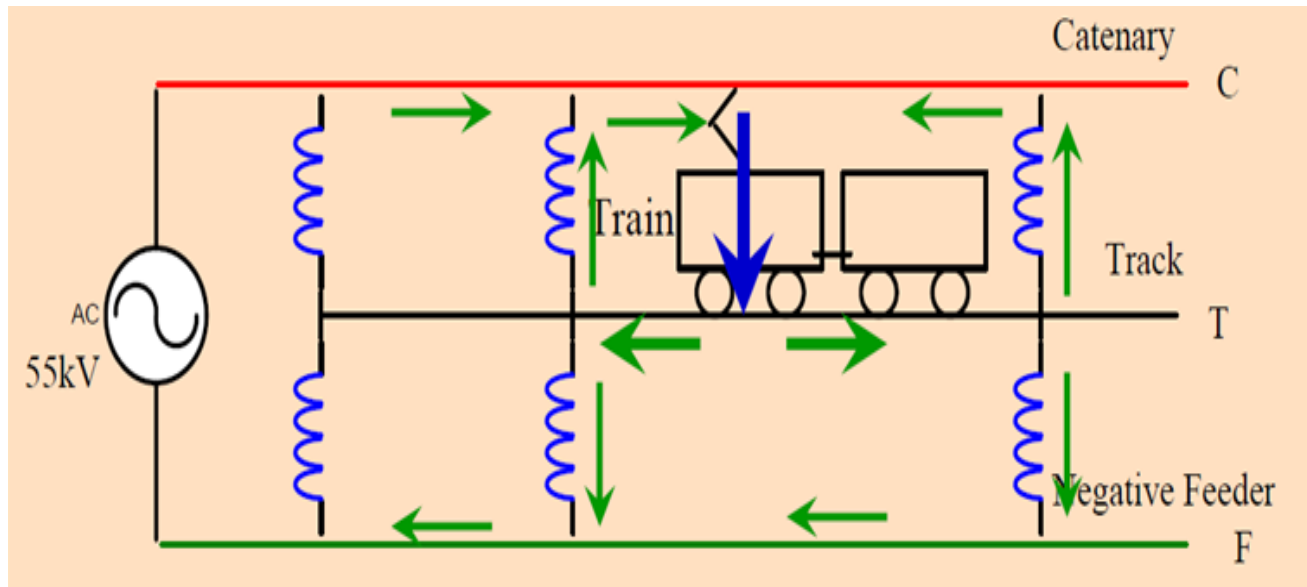


Figure 2.6 Autotransformer feeding configuration[Author]

2.7 Power Quality Issues in Electric Railway System

Both AC and DC electrified systems have been employed to operate for railway traction application based on different engineering and financial considerations as mentioned before. With development of technology over the years, especially the progress of power electronics applications has brought about many technical conveniences and economical profits, but it has simultaneously created new challenges in power system operation. One of the major concerns in this aspect is quality of power for both AC and DC electrified railway power supply system [14]. Power Quality (PQ) is generally used to express the quality of the voltage. This quality signifies the deviation of the voltage magnitude and frequency from the rated values and the deviation of the waveform from a pure sinusoid. That is, disturbance, unbalance, distortion and Voltage Fluctuations and Flicker can be defined as PQ problems [15]. With the wide use of power electronics and non-linear loads, harmonics in traction currents are the most important aspects of PQ. This is because harmonics are steady state, periodic phenomena that produce continuous distortion of voltage and current waveforms unlike transient events that last from a few milliseconds to several cycles. Beside, distortion gives adverse effects to a high-power electrical system such as

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

In addition, the traffic increase of urban railways has made the harmonic pollution aspect of PQ more significant [14]. The adverse effects of harmonics in the railway system and power supply system call for serious concern to both the train operation and power utility companies.

Though to alleviate the problems of harmonic disturbances, special equipment, such as passive filter and active filters are available, the cost of installation and maintenance for such equipment is expensive. Beside, oversize design of filters may results in high cost and should be avoided. The determination of installation as well as the design of the rating and the performance of the equipment requires knowledge about the level of harmonic disturbance. This knowledge is important to both management in decision-making and engineers in technical assessment. Therefore, Harmonic current flow through the contact line system has to be accurately modeled to analyze and assess the harmonic effect on the transmission system [14].

Chapter Three

3 Modeling of Co phase Traction Power Supply System

3.1 Introduction

The single phase 25KV AC system has been adopted in the long-distance electrified railway in many countries. The single-phase traction transformer is widely used in traction substations because of its low cost and simple connection [5][16]. Power quality problems of traction power system, such as power unbalance, harmonics, and reactive power will result in extra line losses, under-voltage at the terminal of contact wire, and unbalanced current of utility grid [4][5]. The degree of the problem depends on the feeding electric railway traction loads, including trains' movement, tractive profile of electric locomotives, and power-supply scheme. These problems present huge impact to the utility grid.

In order to reduce the imbalance caused by the single-phase traction loads, balance feeding transformers are used to replace the single-phase transformer, including Scott transformer, YNvd transformer, Yd11 transformer Woodbridge transformers, three phase V/V transformers, impedance matching balance transformers, etc.[16]. These transformers have different wiring configurations, but basically they are connected to the three phase power grid at the primary side and provide two single phase outputs at the secondary side. Scott transformers, Woodbridge and YNvd transformers are balanced transformers but three-phase V/V transformers are unbalanced. When balanced transformers are used, no negative-sequence current is injected into the public grid when two feeder sections consume the same power. However, for the traction systems with three phase V/V transformers, the negative-sequence current injected into the public grid is half of the positive-sequence current even when two feeder sections consume the same power [17]. The problem with this topology is that a strategy to effectively compensate the negative-sequence and harmonic currents needs to be developed.

Grid-side currents are balanced when the two neighboring sections supplied by one traction transformer have the same loading. Practically, system unbalance still exists because of the uneven load distribution. In addition, reactive power and harmonics from the traction loads make the traction transformer work in the derated mode and increase the system losses [16].

In the traditional supply section at the substation (SS), loads on the two feeders are seldom balanced due to the movement of trains and the power supply scheme. Fundamental balancing is usually provided by connecting different track sections across different phases [4]. This scheme only aimed at balancing the fundamental component while the harmonics remain unbalanced.

There are several disadvantages for traditional traction power supply system. Reactive power, harmonic current and negative sequence current injections will cause poor quality problems. Phase split will also creates speed loss and influence the reliability of the overhead catenary system [18].

As shown in Figure 3.1, a co-phase traction power supply system is constituted by traction transformer and hybrid power quality compensator (HPQC). The phase split in front of traction substation is eliminated. Only single phase current feeds to the traction network. HPQC connects between feeding phase and another phase of traction transformer. The function of HPQC includes active power balancing, reactive power compensation and harmonic filtering.

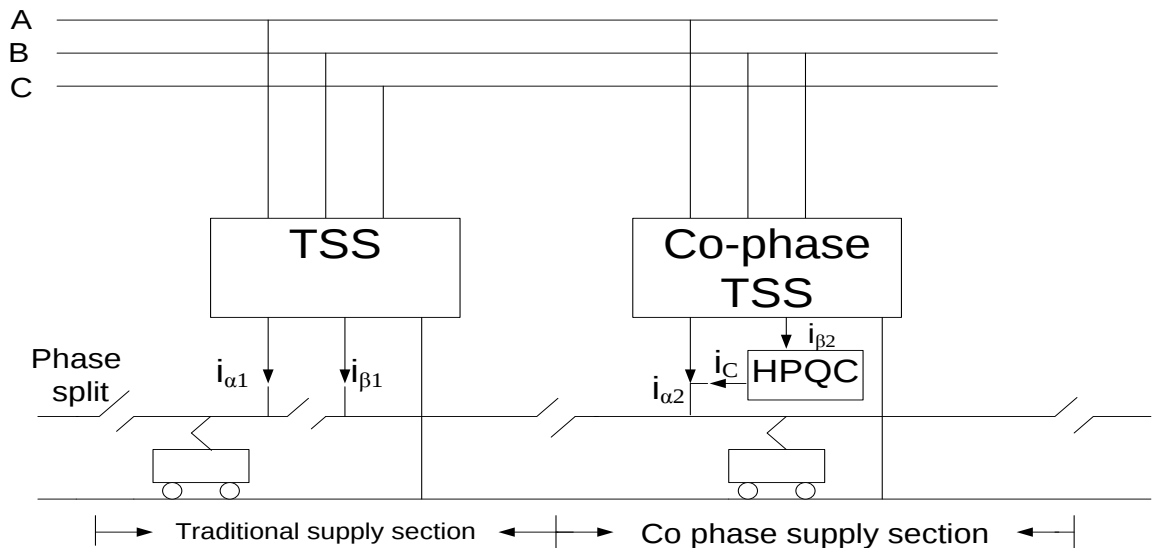


Figure 3.1 Connection scheme for traditional traction power supply system and co-phase traction power supply system[18]

Compared with traditional traction power supply system, half of the phase splits are cut down. The investment is reduced because of neutral sections in front of the traction substation are canceled. The traction performance is improved by reducing power and speed loss in high speed

and heavy load railway. The capacity utilization ratio of traction transformer is increased because of the active power is balanced between secondary windings. The power quality issues to utility grid can be solved comprehensively [18][19].

3.2 Co phase Traction Power Supply System

As shown in Figure 3.2, A co-phase traction power supply system transmits power from power grid to traction network. A traction transformer with V/V connection transfers power from three phases to two phases. The secondary windings of V/V transformer have two phases of 60 degree difference. Phase α supplies the traction load, and phase β is connected with hybrid power quality compensator. A single phase back to back converter is used for active power balancing, reactive power compensation and harmonic filtering. In the connection, only phase α directly connected to the traction network between catenary and track. Therefore, it is a kind of co-phase traction power supply connection scheme.

A co phase system transmits power using only one single-phase distribution line in one traction subsection, while the traditional system adopts two-phase distribution line. Because the two-phase lines in traditional system are out of phase, they must be strictly isolated by inserting a neutral section just as they are fed from different feeder station. The two distribution lines between two adjacent substations adopting co-phase algorithm can transmit power in same phase and be connected together in theory. That is why the system is so-called co-phase traction power supply system. Actually, the two lines should be isolated also in co-phase system because of minor different value and phase of the terminal voltage. Additionally, the co-phase traction power supply system should adopt V/V transformer and hybrid power quality compensator for system power quality.

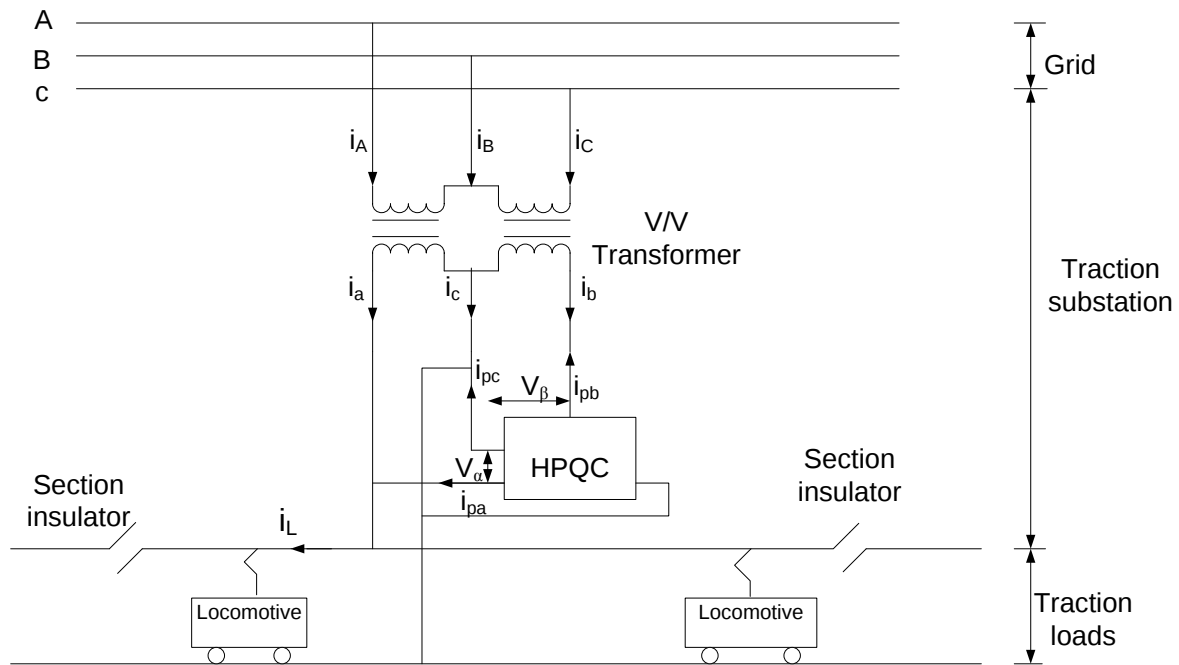


Figure 3.2 Co-phase traction power supply[8]

3.3 Modeling of The Co phase Traction Power Supply without Hybrid Power Quality Compensator (HPQC)

The power quality of the railway power supply system is typically evaluated at the primary side of the traction transformer, that is, the high voltage grid[16][18][19]. The harmonic currents at the secondary side are not able to pass through the traction transformer linearly as the fundamental frequency current does. Harmonics are also better to be compensated at the secondary side to avoid transformer saturation and overheating [16][19]. Hence, it is assumed the harmonics are compensated by HPQC at the secondary side of the traction transformer and are not considered when the performance index is evaluated at the grid side [16].

The system configuration of one substation of the co phase railway power supply is shown in Figure 3.2 in which V/V traction transformer is used. The ratio of turns of the traction

transformer is K. The phasor diagram is shown in Figure 3.3 when HPQC is not installed. The primary side voltages are denoted as V_A , V_B and V_C .

The three-phase voltages at the grid side are expressed as [21]

$$\begin{bmatrix} v_A \\ v_B \\ v_C \end{bmatrix} = \begin{bmatrix} \sqrt{2}V_A \sin \omega t \\ \sqrt{2}V_B \sin(\omega t - 120^\circ) \\ \sqrt{2}V_C \sin(\omega t + 120^\circ) \end{bmatrix} \quad (1)$$

The voltage at the secondary side of the V/V traction transformer is denoted as V_{ac} and V_{bc} and it is expressed in[21], in which v_α directly supplies the electric traction loads

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \begin{bmatrix} v_{ac} \\ v_{bc} \end{bmatrix} = \begin{bmatrix} \sqrt{2}V_{ac} \sin(\omega t - 30^\circ) \\ \sqrt{2}V_{bc} \sin(\omega t - 90^\circ) \end{bmatrix} \quad (2)$$

Without the power flow controller (hybrid power quality compensator) , the load current at the secondary side of the traction transformer is given in[5][21].

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} i_L \\ 0 \\ -i_L \end{bmatrix} \quad (3)$$

Load current is divided into the fundamental frequency component, i_{L1} , and the harmonic component, i_{Lh} , as in [18][21].

$$i_L = i_{L1p} + i_{L1q} + i_{Lh} \quad (4)$$

Where i_{L1p} and i_{L1q} are respectively, the active component and the reactive component of the load current, and could be expressed as[18][21]

$$i_{L1p} = \sqrt{2}I_{L1p} \sin(\omega t - 30^\circ) \quad (5)$$

$$i_{L1q} = \sqrt{2}I_{L1q} \cos(\omega t - 30^\circ) \quad (6)$$

Where

$$I_{L1p} = I_{L1} \cos \varphi_1$$

$$I_{L1q} = I_{L1} \sin \varphi_1$$

Where φ_1 denotes the phase angle between the supply voltage i.e. V_α and the fundamental frequency current of the traction load. The active power consumed by traction load is[21]

$$P_L = V_\alpha I_{L1} \cos \varphi_1 = V_\alpha I_{L1p} \quad (7)$$

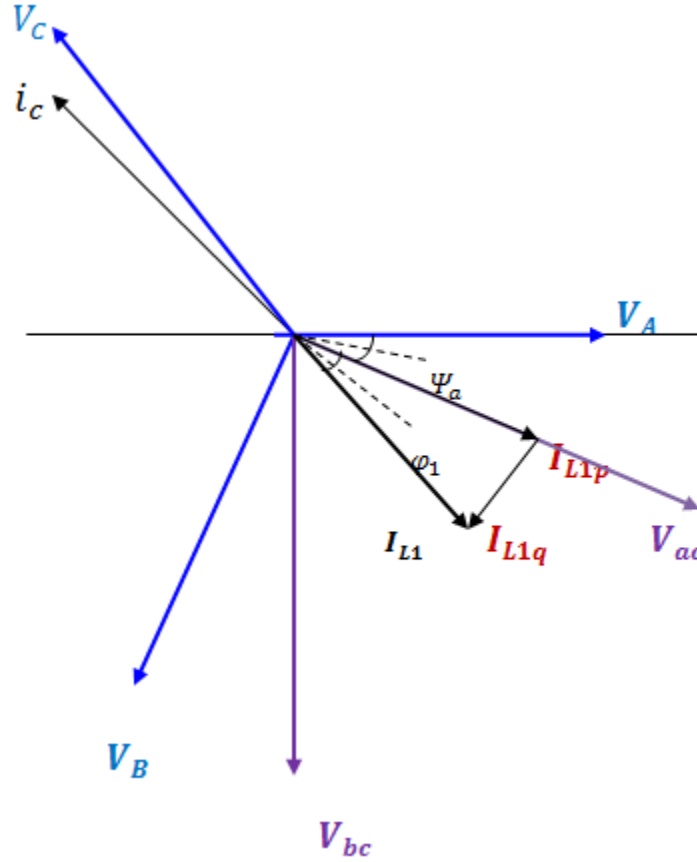


Figure 3.3 vector diagram of the railway power supply system without HPQC[16]

3.4 Modeling of the Co phase Traction Power Supply with Hybrid Power Quality Compensator (HPQC)

A HPQC is installed in the co phase railway power supply, as shown in Figure 3.2, which uses a back to back converter and injects currents to V_{ac} phase and V_{bc} phase, respectively.

The corresponding phasor diagram is shown in Figure 3.4. After the single phase HPQC is installed, the currents at the secondary side of the traction transformer are expressed by (8), in which i_{pa} is the current injecting to the V_{ac} phase and i_{pb} is the current injecting to the V_{bc} phase [5].

When the power quality conditioner works, compensating currents are injected and the currents at the secondary side of the V/V transformer is expressed in[5][19].

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} i_L - i_{pa} \\ -i_{pb} \\ -i_L - i_{pc} \end{bmatrix} \quad (8)$$

The currents at grid side are balanced and with unity power factor, given as in[19]

$$\begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} = \begin{bmatrix} \sqrt{2}I_A \sin \omega t \\ \sqrt{2}I_B \sin(\omega t - 120^\circ) \\ \sqrt{2}I \sin(\omega t + 120^\circ) \end{bmatrix} \quad (9)$$

The three phase grid only provides active power to the traction loads the power is expressed as[19]

$$P_s = 3V_A I_A \quad (10)$$

since the load active power is provided by three phase grid, the power in (7) and (10) should be equivalent, that is,

$P_s = P_L$ in addition $V_\alpha = \sqrt{3}/K * V_A$ where K is the ratio of turns of the traction transformer.

The root mean square (rms) value of the source current could be deduced as expressed in [5][19]

$$I_A = \frac{1}{\sqrt{3}K} * I_{L1p} \quad (11)$$

It is assumed that the current harmonics is compensated at the secondary side of the traction transformer, that is to say, there is no harmonics passing through the traction transformer. The compensating currents of the power compensator are given in[19].

$$\begin{bmatrix} i_{pa} \\ i_{pb} \\ i_{pc} \end{bmatrix} = \begin{bmatrix} i_L \\ 0 \\ -i_L \end{bmatrix} - K \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} \quad (12)$$

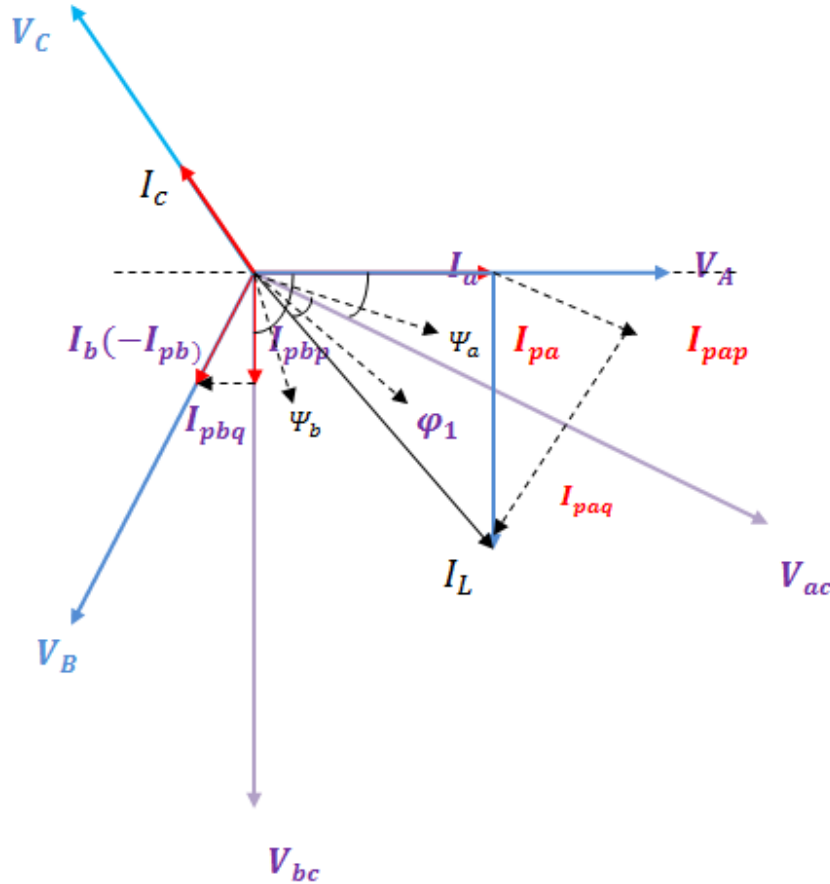


Figure 3.4 vector diagram of the railway power supply system with HPQC[5]

3.5 Calculating the Compensating Currents of the HPQC

The HPQC is designed to balance the three-phase currents at the grid side and compensate load current harmonics and reactive current. In order to achieve these goals, the compensating current of the HPQC is deduced.

By substituting (4)-(6),(9) and (11) into (12), equation (13) which is the required compensating currents are obtained. the compensating currents are constructed by the fundamental frequency component being in phase with the voltage and perpendicular to voltage and harmonics.

The required compensating currents of the HPQC are given in (13) and details are found in [5][19]

$$\begin{bmatrix} i_{pa} \\ i_{pb} \\ i_{pc} \end{bmatrix} = \begin{bmatrix} \frac{1}{2}\sqrt{2}I_{L1p} \sin(\omega t - 30^\circ) - \left(\frac{1}{2\sqrt{3}}I_{L1p} + I_{L1q}\right)\sqrt{2} \cos(\omega t - 30^\circ) + i_{Lh} \\ -\frac{1}{2}\sqrt{2}I_{L1p} \sin(\omega t - 90^\circ) + \frac{1}{2\sqrt{3}}\sqrt{2}I_{L1p} \cos(\omega t - 90^\circ) \\ -i_{pa} - i_{pb} \end{bmatrix} \quad (13)$$

When the hybrid power quality compensator could inject the compensating currents in (13) at the secondary side of the V/V transformer, the reactive current, the unbalance current and the harmonic currents are compensated simultaneously and the grid side currents become balanced with unity power factor.

3.6 Topology of the Hybrid Power Quality Compensator (HPQC)

The topology of the proposed HPQC is shown in Figure 3.5 in which the DC capacitor illustrates the energy exchanged via the DC part. The topology of the DC bus varies according to the converter structure. The α -phase converter is connected in parallel with the traction loads and the β -phase converter is connected to the other phase of the V/V transformer. Coupling transformer is connected at the β -phase, providing more flexibility for the output voltage at the β -phase.

In this work, the HPQC is designed, which could inject the compensating currents with reduced DC voltage. Hence, the total rating of the power converter is reduced.

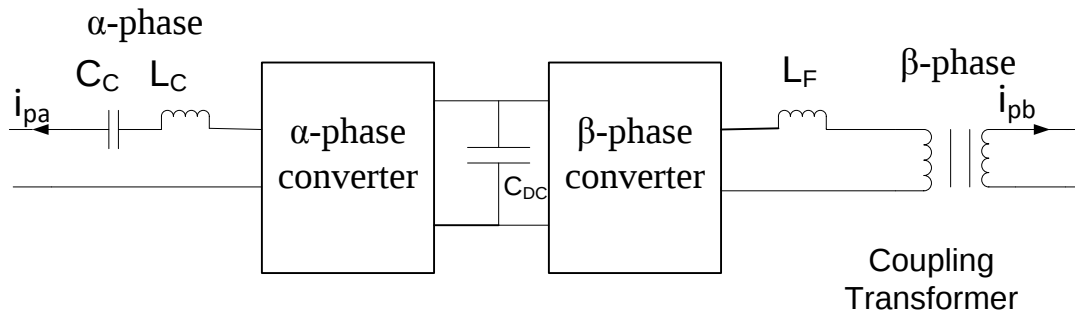


Figure 3.5 Topology of HPQC [19]

3.7 V_{ac} Phase Converter Coupled Impedance Design

First, the ratings of the α -phase converter is analyzed. The α -phase converter is connected to the load side through an L–C branch. According to (13), the α -phase converter needs to inject fundamental frequency current both in phase with the supply voltage and perpendicular to the supply voltage in order to compensate the reactive power and unbalance currents at the grid sides. Harmonic compensation is also achieved by the α -phase converter. Based on the superposition algorithm, the equivalent model of the α -phase is decomposed into fundamental frequency model and harmonics model[19], as shown in Figure 3.6 the required voltage rating is first analyzed in the fundamental frequency model, and then followed by the harmonics compensation.

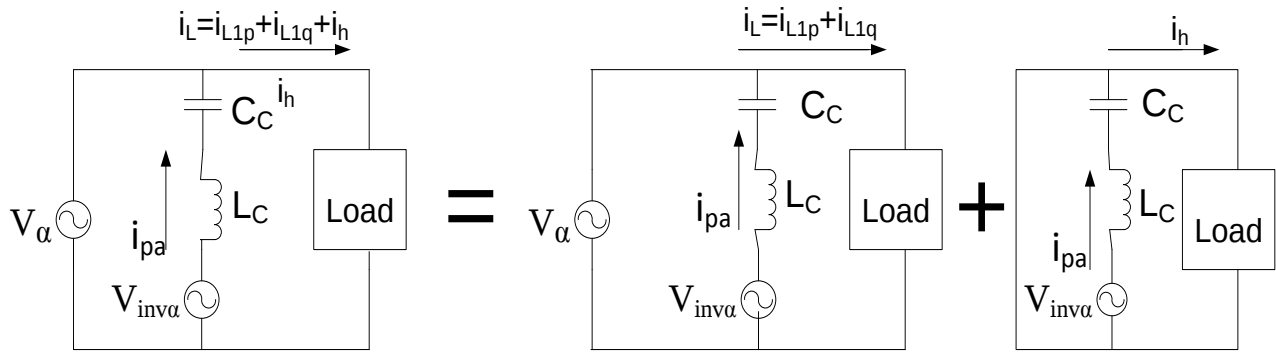


Figure 3.6 Equivalent model of α -phase compensation[19]

3.7.1 Fundamental Frequency Model

In the HPQC, the coupling capacitor is designed for reactive power compensation and the coupling inductor is used for reducing the current ripple. The impedance X_{LC} of the LC branch is capacitive and is given in [20], where ω is the fundamental frequency of the supply system.

$$X_{CL} = \frac{1}{\omega C_c} - \omega L_c \quad (14)$$

The α -phase and the β -phase converter of the HPQC share the same dc bus. As shown in Figure 3.5, a coupling transformer is connected at the β -phase, providing more flexibility for the output voltage at the β -phase. Hence, the dc bus voltage of the HPQC is determined by the required

output voltage at the α -phase. In order to inject compensating current to the α -phase, the fundamental frequency output voltage of the α -phase converter is expressed as [19][20].

$$\vec{V}_{inv\alpha 1} = \vec{V}_{ac} + \vec{V}_{LC} = \vec{V}_{ac} - jX_{LC} \cdot \vec{i}_{pa1} \quad (15)$$

Where $\vec{i}_{pa1}$ is the fundamental frequency compensating current and $\vec{V}_{LC}$ is the voltage across the LC branch.

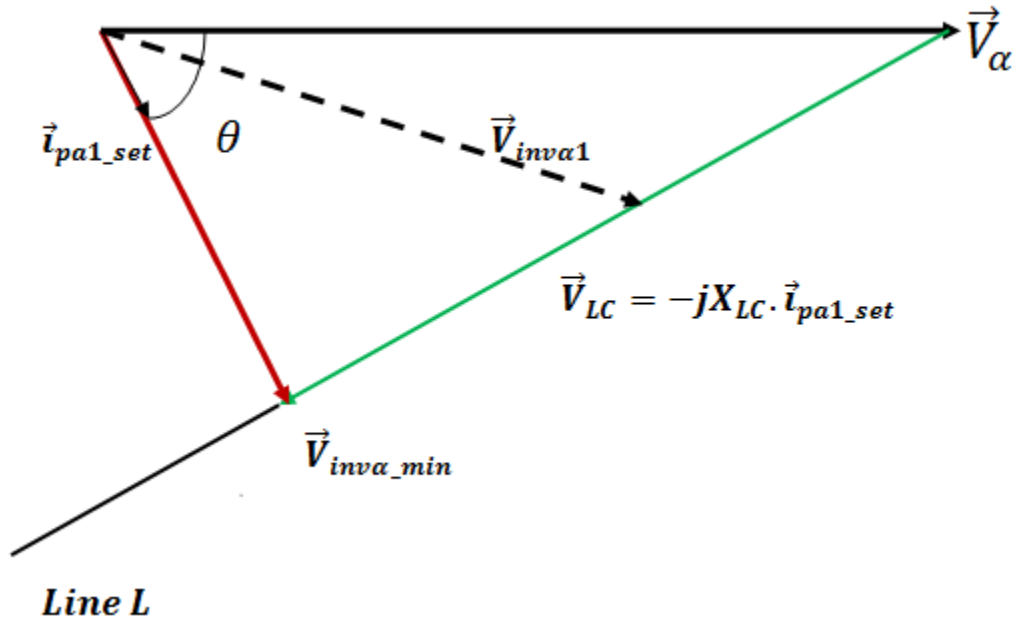
According to (14) X_{CL} is positive. As a result, the $\vec{V}_{LC}$ is obtained by rotating $\vec{i}_{pa1}$ 90 degrees clockwise. The corresponding vector diagram is shown in Figure 3.7. According to (15), the output voltage of the α -phase converter is determined by the coupling impedance X_{LC} and the compensating current i_{pa1} . First, it is assumed that the HPQC is used to compensate a fixed load and the corresponding compensating current is denoted as i_{pa1_set} . Given a fixed i_{pa1_set} the coupling impedance X_{LC} only changes the amplitude of the output voltage of the α -phase converter $V_{inv\alpha 1}$, and it varies along the line L. As shown in Figure 3.7, the voltage reaches the minimum value when the vector $V_{inv\alpha 1}$ is perpendicular to the vector V_{LC} or in phase with vector i_{pa1_set} . In this case, the coupling impedance equals to [5][19][20].

$$X_{LC} = \frac{V_{\alpha} \sin \theta}{I_{pa1_set}} \quad (16)$$

The phase angle of $\vec{i}_{pa1}$ is denoted as θ and is calculated by (17), in which $\tan \varphi_1 = I_{L1q} / I_{L1p}$ and it is the angle between the supply voltage V_{α} and fundamental frequency load current i_{L1} , is determined by the traction load power factor [5][19][20].

$$\begin{aligned} \theta &= \tan^{-1} \left(\frac{\frac{1}{2\sqrt{3}} I_{L1p} + I_{L1q}}{\frac{1}{2} I_{L1p}} \right) \\ &= \tan^{-1} \left(\frac{1}{\sqrt{3}} + 2 \tan \varphi_1 \right) \end{aligned} \quad (17)$$

When the amplitude of the compensating current changes, the voltage vector $\vec{V}_{LC}$ varies along line L in the figure below.


 Figure 3.7 Vector diagram for α -phase converter[5][19][20]

As a result, the minimum output voltage of the α -phase converter is expressed as[19][20]

$$\begin{aligned}
 V_{inv\alpha_min} &= \sqrt{V_{\alpha}^2 - (I_{pa1_set} X_{LC})^2} \\
 &= V_{\alpha} \cos \theta
 \end{aligned} \tag{18}$$

The variation of $\cos \theta$ according to the displacement power factor of the traction loads is shown in Figure 3.8. Since the power factor of traction loads of the electric locomotives widely used normally ranges from 0.80–0.85[19], Figure 3.8 shows that the output voltage of the α -phase converter is much smaller than the system voltage when the HPQC is used since $\cos \theta$ is smaller than one. As a result, a smaller DC bus voltage is required in the designed HPQC. Hence, the power converter of the designed HPQC has a smaller rating, which could reduce the initial cost of the compensators.

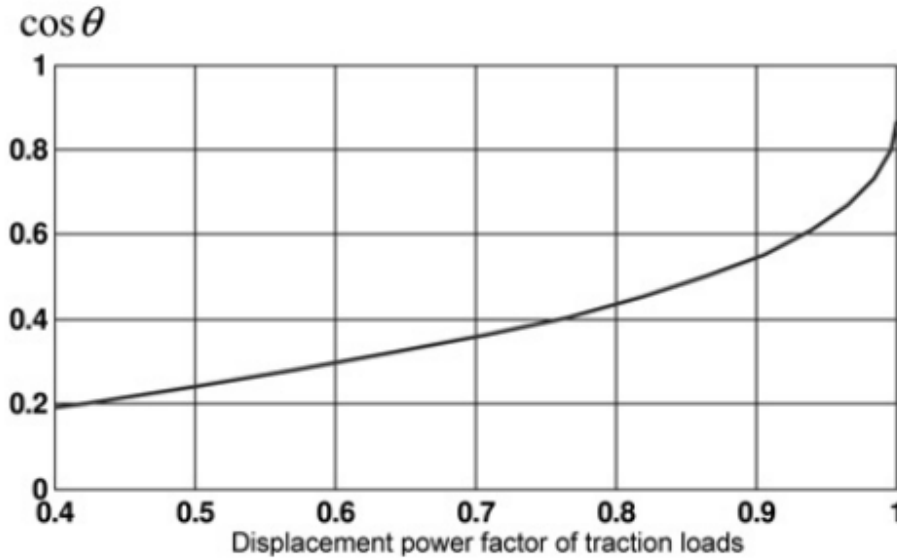


Figure 3.8 Variation of $\cos \theta$ according to the displacement power factor[19]

3.8 V_{bc} Phase Converter Coupled Impedance Design

For the V_{bc} phase coupled impedance design, it is determined with matching to the minimum voltage V_{inva_min} . The vector diagram showing the operation of V_{bc} phase converter in HPQC in correspondence with the V_{inva_min} is shown in Figure 3.9. The minimum HPQC voltage is represented by the circle Cir a with radius V_{inva_min} . Assuming constant load PF and capacity, the vector V_{LC} varies along the line L_2 with varying V_{bc} phase coupled impedance X_L . Two intersection points (pt.1 and pt.2) are present between the circle Cir a and the line L_2 . These two points are the operation points which satisfy the voltage matching with V_{inva_min} . They may be determined mathematically.

The mathematical expression showing the intersection of circle Cir a and the line L_2 is given in[20].

$$V_{inva_min}^2 = V_L^2 \sin^2 \theta b + (V_{bc} - V_L \cos \theta b)^2 \quad (19)$$

By solving the expression, the mathematical expressions for pt.1 and pt.2 can be obtained in[20]

$$X_L = \frac{V_{bc} \sin \theta_b - \sqrt{V_{inv\alpha_min}^2 - V_{bc}^2 \cos^2 \theta_b}}{I_{pb}} \quad \text{at pt.2}$$

$$X_L = \frac{V_{bc} \sin \theta_b + \sqrt{V_{inv\alpha_min}^2 - V_{bc}^2 \cos^2 \theta_b}}{I_{pb}} \quad \text{at pt.1} \quad (20)$$

Although both pt.1 and pt.2 may satisfy the voltage matching with $V_{inv\alpha_min}$, operation point at pt.2 is preferred due to the lower impedance of X_L and lower power consumptions.

Besides the V_{bc} coupled impedance of X_L , there is another issue concerning about the value of V_{bc} . For the circle Cira to have intersections with the line L2, the expression X_L in (20) must be real values. Thus, the restrictions in (21) can thus be obtained

$$V_{bc} \leq \frac{V_{inv\alpha_min}}{\cos \theta_b} \quad (21)$$

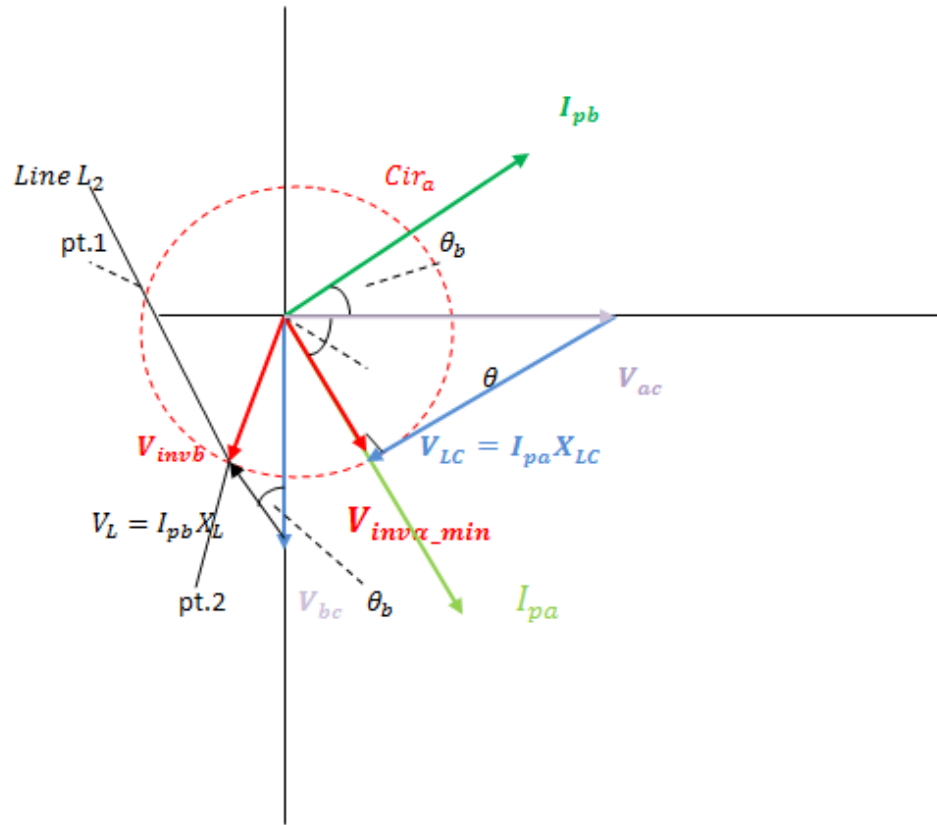


Figure 3.9 Vector diagram showing the operation of HPQC in correspondence with minimized $V_{inv\alpha}$ [20]

According to (13), the compensating current for the β -phase is expressed as

$$i_{pb} = -\frac{1}{2}\sqrt{2}I_{L1p}\sin(\omega t - 90^\circ) + \frac{1}{2\sqrt{3}}\sqrt{2}I_{L1p}\cos(\omega t - 90^\circ)$$

where $I_{L1p} = I_{L1}\cos\varphi_1$.

Unlike the α -phase converter, there is no harmonic compensation requirement for the β -phase. Hence, only the fundamental frequency model is analysed, and the output voltage of the β -phase converter is given by [19]

$$V_{inv\beta} = V_\beta + V_L$$

$$= V_{bc} + jX_L i_{pb} \quad (22)$$

where V_L is the voltage drop across the inductor and $X_L = \omega L_F$. The vector diagram is shown in Figure 3.10

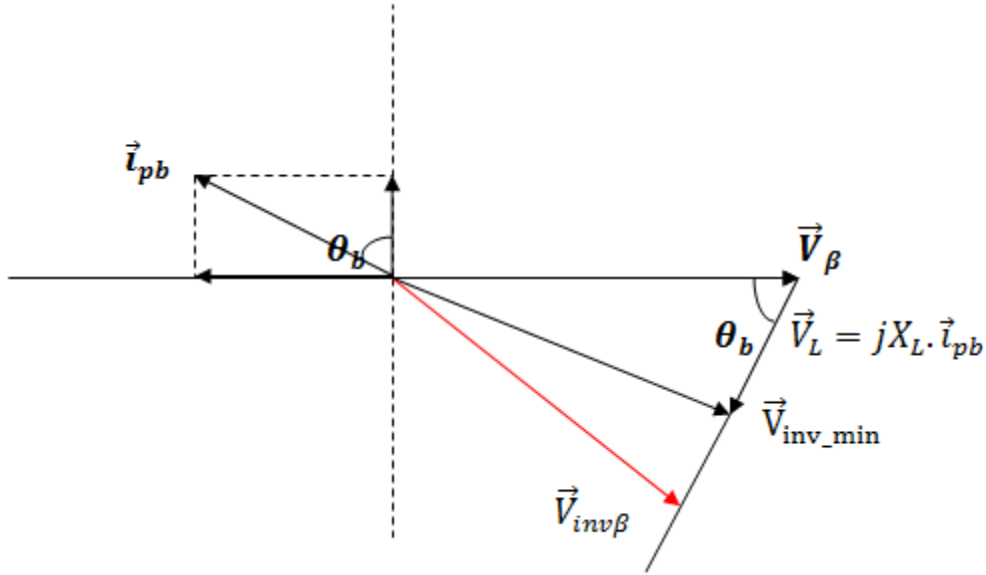


Figure 3.10 Vector diagram for β -phase converter [19]

The phase angle of the compensating current vector i_{pb} is give by[19]

$$\theta_b = \tan^{-1} \left(\frac{1}{2} I_{L1p} / \frac{1}{2\sqrt{3}} I_{L1p} \right) = 60^\circ \quad (23)$$

The direction of voltage vector across the coupling inductor could be obtained by rotating i_{pb} 90° counter-clockwise. The amplitude of the output voltage of the β -phase converter achieves the minimum value when $V_{inv\beta}$ is perpendicular to V_L , as shown in Figure 3.10. Since the phase angle of the β -phase compensating current is a fixed value, the minimum amplitude of $V_{inv\beta}$ equals to $\sqrt{3}V_\beta/2$ that is

$$V_{inv\beta_min} = \sqrt{3}V_{\beta}/2 \quad (24)$$

For a small coupling inductor, the voltage rating of the β -phase converter locates in the range of $\sqrt{3}V_{\beta}/2$ to V_{β} . The α -phase and the β -phase converter share a common DC bus. However, their converter voltage ratings may not match according to the previous analyses. The ratio of turns of the β -phase coupling transformer could adjust the voltage rating of the β -phase converter and therefore solves this problem.

3.9 Minimum HPQC Voltage Rating Achievable

After investigations of the V_{ac} and V_{bc} phase coupled impedance design for the minimum HPQC operation voltage, the minimum voltage rating achievable is discussed in this section. The value of $V_{inv\alpha_min}$ is a key factor in the minimum HPQC voltage rating achievable.

The minimum value of HPQC voltage is obtained by

$$V_{inv\alpha_min} = V_{\alpha} \cos \theta \quad (25)$$

The minimum HPQC dc -link voltage required is

$$V_{dc_link} = \sqrt{2} * V_{inv\alpha_min} \quad (26)$$

Neglecting the effect of V_{ac} phase voltage, the minimum HPQC voltage rating is determined by

$$K_{min} = \frac{V_{inv\alpha_min}}{V_{\alpha}} = \frac{V_{\alpha} \cos \theta}{V_{\alpha}} = \cos \theta \quad (27)$$

It is now obvious that the minimum HPQC voltage rating is dependent only on the power angle of I_{pa1_set} . This again correlates with the load PF, as expressed in

$$\theta = \tan^{-1} \left(\frac{\frac{1}{2\sqrt{3}}PF + \sin(\cos^{-1}(PF))}{\frac{1}{2}PF} \right) \quad (28)$$

Table 3.1 Technical data [2]

Train		SS ₉	HXD3B
Description			
Wire combination 1		JTMH95+CTSH120	
Single-track	Impedance of traction network (Ω/km)	0.127449+j0.416534	
	Power factor	0.85	0.95
	Equivalent impedance of traction network (Ω/km)	0.4042	0.2840
Multiple-track	Impedance of traction network (Ω/km)	0.116155+j0.375627	
	Power factor	0.85	0.95
	Equivalent impedance of traction network (Ω/km)	0.3519	0.2511
Wire combination 2		JTMH95+CTSH120+LBGLJ185	
Single-track	Impedance of traction network (Ω/km)	0.091894+j0.342983	
	Power factor	0.85	0.95
	Equivalent impedance of traction network (Ω/km)	0.2793	0.1945
Multiple-track	Impedance of traction network (Ω/km)	0.080668+j0.303805	
	Power factor	0.85	0.95
	Equivalent impedance of traction network (Ω/km)	0.2468	0.1715

Based on the technical data table 3.1 The phase angle of $\vec{I}_{pa1}$ θ is obtained as follow

$$\theta = \tan^{-1}\left(\frac{\frac{1}{2\sqrt{3}}PF + \sin(\cos^{-1}(PF))}{\frac{1}{2}PF}\right)$$

$$\theta = \tan^{-1}\left(\frac{\frac{1}{2\sqrt{3}} * 0.85 + \sin(\cos^{-1}(0.85))}{\frac{1}{2} * 0.85}\right)$$

$$\theta = 61.1713^\circ$$

The minimum HPQC voltage rating is determined by

$$K_{min} = \frac{V_{inv\alpha_min}}{V_\alpha} = \frac{V_\alpha \cos \theta}{V_\alpha} = \cos \theta$$

$$= \cos 61.1713^\circ$$

$$= 0.4822$$

The minimum value of HPQC voltage is

$$V_{inv\alpha_min} = \sqrt{V_\alpha^2 - (I_{pa1_set} X_{LC})^2}$$

$$= V_\alpha \cos \theta$$

$$= 25KV * 0.4822$$

$$= 12.06KV$$

The peak value of V_α phase voltage is $\sqrt{2} * 25KV = 35.36KV$

The minimum HPQC dc -link voltage required is

$$V_{dc_link} = \sqrt{2} * V_{inv\alpha_min} = \sqrt{2} * KV = 17.06KV$$

The capacitive coupling impedance of V_α required for minimum $V_{inv\alpha_min}$ is

$$X_{LC} = \frac{V_{\alpha} \sin \theta}{I_{pa1_set}}$$

$$X_{LC} = \frac{25KV * \sin(\cos^{-1} 0.4822)}{398.18A}$$

$$X_{LC} = 55\Omega$$

Calculate the V_{bc} phase coupled impedance

$$I_{pb} = 451.76\sqrt{(0.5 * 0.85)^2 + (0.2887 * 0.85)^2}$$

$$I_{pb} = 221.71A$$

$$V_{bc} = 13.75V$$

$$\theta_b = 60^\circ$$

$$V_{inv\alpha_min} = 12.06KV$$

$$X_L = \frac{V_{bc} \sin \theta_b - \sqrt{V_{inv\alpha_min}^2 - V_{bc}^2 * \cos^2 \theta_b}}{I_{pb}}$$

$$X_L = \frac{13.75KV * \sin 60^\circ - \sqrt{(12.06KV)^2 - (13.75KV)^2 * \cos^2 60^\circ}}{221.71A}$$

$$X_L = 9.02\Omega$$

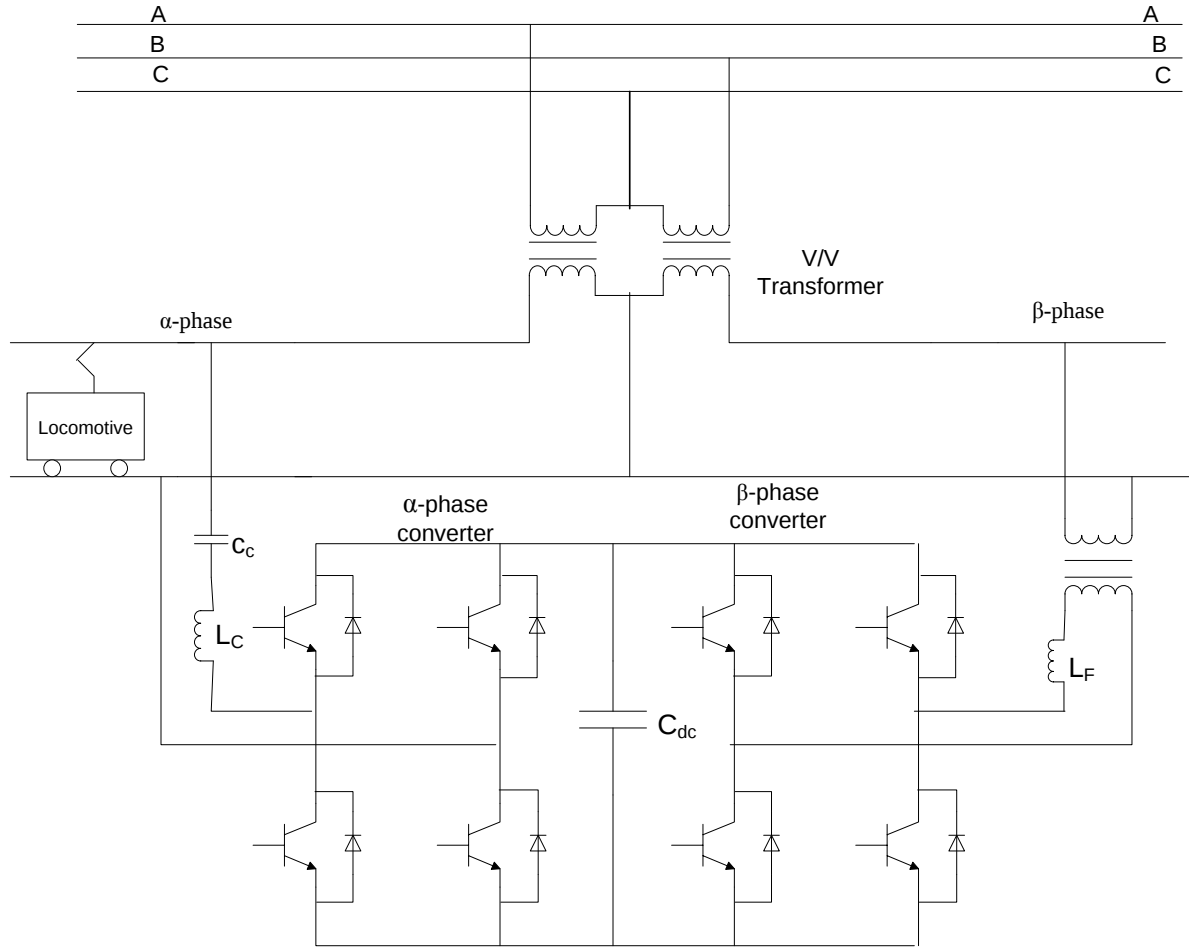


Figure 3.11 System configuration of the co phase power supply system with HPQC[6][19]

3.10 HPQC Parameter Design with Harmonic Consideration

The α -phase converter also works as compensating harmonic currents of the traction loads. it is assumed that the harmonic voltage drop across the coupling impedance is mainly generated by the highly current demand and caused by heavy loading. The effect of voltage distortion caused by power supplier is not considered. The usage of HPQC operation voltage may be divided according to two purposes: fundamental ($V_{inv\alpha 1}$) and harmonic ($V_{inv\alpha h}$) compensation. According to Figure 3.6, the output voltage of the α -phase converter is expressed as in(29), and the parameters are defined in (32) and (33). In traction load, fundamental compensation occupies most of the compensation capacity. Here, the comprehensive HPQC design will be presented

based on the criteria of minimizing the operation voltage for providing these two compensation modes. Thus,

$$V_{inv\alpha} = \sqrt{V_{inv\alpha 1}^2 + V_{inv\alpha h}^2} \quad (29)$$

$$V_{inv\alpha 1}^2 = (V_\alpha + |i_{paq 1}|X_{LC})^2 + (|i_{papi}|X_{LC})^2$$

$$i_{paq 1} = I_{pa 1} \sin \theta$$

$$i_{pap 1} = I_{pa 1} \cos \theta$$

$$X_{LC} = -\frac{V_\alpha \sin \theta}{I_{pa 1}} \quad (30)$$

$$V_{inv\alpha 1}^2 = \left(V_\alpha + |I_{pa 1} \sin \theta| * \frac{V_\alpha \sin \theta}{I_{pa 1}} \right)^2 + \left(|I_{pa 1} \cos \theta| \frac{V_\alpha \sin \theta}{I_{pa 1}} \right)^2$$

$$V_{inv\alpha 1}^2 = (V_\alpha - V_\alpha \sin^2 \theta)^2 + (V_\alpha \cos \theta * \sin \theta)^2$$

$$\text{but } \sin^2 \theta = 1 - \cos^2 \theta$$

$$V_{inv\alpha 1}^2 = (V_\alpha - V_\alpha (1 - \cos^2 \theta))^2 + (V_\alpha \cos \theta * \sin \theta)^2$$

$$V_{inv\alpha 1}^2 = (V_\alpha \cos^2 \theta)^2 + (V_\alpha \cos \theta * \sin \theta)^2$$

$$V_{inv\alpha 1}^2 = V_\alpha^2 \cos^2 \theta (\cos^2 \theta + \sin^2 \theta)$$

$$\text{but } \cos^2 \theta + \sin^2 \theta = 1$$

$$V_{inv\alpha 1}^2 = V_\alpha^2 \cos^2 \theta \quad (31)$$

$$V_{inv\alpha h}^2 = \sum_{h=2}^{\infty} i_{Lh}^2 X_{LCh}^2 \quad (32)$$

In the previous part, X_{CL} denotes the fundamental frequency impedance of the coupling circuit. Actually, X_{CL} is the summation of the impedance of the coupling capacitor and the inductor. The LC branch at the α -phase is designed to be resonant at h^{th} harmonic to eliminate load harmonics.

Although fundamental system unbalance and reactive power compensation occupy the major portion of power quality compensation capacity, harmonic compensation cannot be neglected as it will also add to the overall compensator operation voltage requirement. With reference to (32), it can be observed that the discussion relates also to the harmonic impedance that an optimum selection of coupled inductance L_C and C_C must be chosen to minimize the harmonic operation voltage $V_{inv\alpha h}$. Here, the discussion of the HPQC design is presented based on the criteria of minimum fundamental operation voltage $V_{inv\alpha 1}$ in(30). In other words, the parameter design for minimum operation voltage during harmonic compensation developed here does not alter the fundamental coupled impedance X_{LC} .

In HPQC, the V_α phase coupled impedance is formed by the coupled inductance L_C and capacitance C_C , whose equivalent impedance can be expressed as (33). It is further assumed in the expression that the impedance of coupled inductance X_{LC} and coupled capacitance X_{CC} are k_L and k_C times of the coupled impedance X_{LC} [21], also expressed in the following:

$$X_{LC} = -(X_{LC} + X_{CC}) = -(k_L + k_C) * X_{LC} \quad (33)$$

The relationship between the values of k_L and k_C can be then obtained from (34), as expressed below

$$-k_L - k_C = 1 \quad (34)$$

With harmonic compensation consideration, the effect of harmonic impedance on the operation voltage should be also included.

With reference to the expression in(34), the impedance at the h^{th} harmonics can be expressed as

$$X_{LC h} = -(X_{LC h} + X_{CC h}) = -(hk_L + \frac{1}{h}k_C)X_{LC} \quad (35)$$

By substituting (34) into (35), the expression in (36) can be obtained, which is merely important for the analysis that follows ,i.e.,

$$X_{LC h} = -\frac{1}{h}[(h^2 - 1)k_L - 1]X_{LC} \quad (36)$$

The harmonic compensation voltage $V_{inv\alpha h}$ is not only dependent on the harmonic impedance X_{LCh} but also on the load harmonic current i_{Lh} . Load current harmonics are usually expressed as a percentage of fundamental current. Assuming that the load harmonic current at the h^{th} harmonic is r_h times of fundamental and considering the relationship between V_α phase compensation current I_{pa} and fundamental load current i_{L1} , the load harmonics can be then expressed as [21] and given in (37). For simplicity, the denominator is defined as A in the contents that follow. Thus

$$\begin{aligned} i_{Lh} &= r_h i_{L1} \\ &= r_h \left(\frac{I_{pa}}{\sqrt{(0.2887PF + \sin(\cos^{-1}(PF)))^2 + (0.5PF)^2}} \right) \end{aligned}$$

For simplicity, the denominator is defined as A in the contents that follow. Thus

$$i_{Lh} = r_h \left(\frac{I_{pa}}{A} \right) \quad (37)$$

Through substituting (30), (36), and (37) into (29), the expression for determining the harmonic compensation voltage for HPQC can be obtained, as shown in the following

$$V_{inv\alpha h}^2 = \sum_{h=2}^{\infty} V_\alpha^2 * \frac{(r_h)^2}{A^2} * (\sin \theta)^2 * \left\{ \frac{1}{h} [(h^2 - 1)k_L - 1] \right\}^2 \quad (38)$$

The value of k_L for minimum harmonic compensation voltage $V_{inv\alpha h}$ can be then determined by taking the derivative of (38) with respect to k_L and equating zero [21], as shown in the following,

$$\frac{d(V_{inv\alpha h}^2)}{dk_L} = \sum_{h=2}^{\infty} \left\{ V_\alpha^2 * \frac{(r_h)^2}{A^2} * (\sin \theta)^2 * \left[\frac{2(h^2 - 1)^2}{h^2} k_L - \frac{2(h^2 - 1)}{h^2} \right] \right\} = 0 \quad (39)$$

$$k_L = \frac{\sum_{h=2}^{\infty} (r_h)^2 * \frac{(h^2 - 1)}{h^2}}{\sum_{h=2}^{\infty} (r_h)^2 * \frac{(h^2 - 1)^2}{h^2}} \quad (40)$$

3.11 HPQC Design of Minimum Operation Voltage for Harmonic Compensation

For minimum operation voltage, the HPQC operation voltage is determined by substituting (30), (31), (32) and (38) into (29) is given by [21]

$$V_{inv\alpha_min} = \sqrt{(V_\alpha \cos \theta)^2 + \sum_{h=2}^{\infty} V_\alpha^2 * \frac{(r_h)^2}{A^2} * (\sin \theta)^2 * \left\{ \frac{1}{h} [(h^2 - 1)k_L - 1] \right\}^2} \quad (41)$$

and the HPQC dc link operation voltage is given by

$$V_{dc_link} = \sqrt{2} * V_{inv\alpha}$$

$$V_{dc_link} = \sqrt{2(V_\alpha \cos \theta)^2 + 2 \sum_{h=2}^{\infty} V_\alpha^2 * \frac{(r_h)^2}{A^2} * (\sin \theta)^2 * \left\{ \frac{1}{h} [(h^2 - 1)k_L - 1] \right\}^2} \quad (42)$$

the minimum HPQC voltage rating is determined by

$$K_{min} = \frac{V_{inv\alpha_min}}{V_\alpha}$$

$$K_{min} = \sqrt{(\cos \theta)^2 + \sum_{h=2}^{\infty} \frac{(r_h)^2}{A^2} * (\sin \theta)^2 * \left\{ \frac{1}{h} [(h^2 - 1)k_L - 1] \right\}^2} \quad (43)$$

Comprehensive HPQC Design Procedure

Based on previous discussions and analysis, the detailed procedure for the HPQC parameter design for minimum operation voltage under both fundamental and harmonic compensation is provided in the following.

- i. Select the V_{ac} phase coupled impedance according to (30).
- ii. Calculate the V_{ac} phase coupled inductance L_C according to (44)

$$L_C = -\frac{k_L * X_{LC}}{\omega} = \frac{k_L * V_\alpha * \sin \theta}{\omega * I_{pa}} \quad (44)$$

- iii. Calculate the V_{ac} phase coupled capacitance C_C according to (45)

$$C_C = \frac{1}{\omega * k_C * X_{LC}} = \frac{1}{\omega * (-1 - k_L) X_{LC}}$$

$$= -\frac{I_{pa}}{\omega(-1-k_L)*V_\alpha*\sin \theta} \quad (45)$$

iv. Calculate the V_{bc} phase coupled impedance according to (20)

v. Calculate the V_{bc} phase coupled inductance according to (46)

$$L_F = \frac{X_L}{\omega} \quad (46)$$

vi. Determine the dc link operation voltage in HPQC according to (42) i.e.

$$V_{dc_link} = \sqrt{2(V_\alpha \cos \theta)^2 + 2 \sum_{h=2}^{\infty} V_\alpha^2 * \frac{(r_h)^2}{A^2} * (\sin \theta)^2 * \left\{ \frac{1}{h} [(h^2 - 1)k_L - 1] \right\}^2}$$

Table 3.2 Data of harmonic current contents substation traction load from simulation result [Table 4.2]

	3rd	5th	7th	9th	11th
Harmonic contents (% fundamental)	36.44	7.15	3.73	2.45	1.48

➤ Select the V_{ac} phase coupled impedance

$$I_{pa} = I_{L1} \sqrt{(0.2887PF + \sin(\cos^{-1}(PF)))^2 + (0.5PF)^2}$$

For SS9 passenger locomotive with 4.8MW and PF =0.85

$$P_L = V_{ac} * I_{L1} \cos \varphi_1$$

$$I_{L1} = \frac{4800KW}{25 * 0.85} = 225.88A$$

Considering the traction load with 9.6MW of co phase traction power supply

$$I_{L1} = 225.88A * 2 = 451.76A$$

$$I_{pa} = 451.76 * \sqrt{(0.2887 * 0.85 + \sin(\cos^{-1}(0.85)))^2 + (0.5 * 0.85)^2}$$

$$I_{pa} = 398.18A$$

$$X_{LC} = \frac{V_{\alpha} * \sin \theta}{I_{pa}}$$

$$X_{LC} = \frac{25KV * \sin(\cos^{-1} 0.4824)}{398.18A} = 55\Omega$$

➤ Calculate the V_{ac} phase coupled inductance L_C

$$k_L = \frac{\sum_{h=2}^{\infty} (r_h)^2 * \frac{(h^2 - 1)}{h^2}}{\sum_{h=2}^{\infty} (r_h)^2 * \frac{(h^2 - 1)^2}{h^2}}$$

k_L

$$= \frac{\left(\frac{36.44}{451.76}\right)^2 * \frac{(3^2 - 1)}{3^2} + \left(\frac{7.15}{451.76}\right)^2 * \frac{(5^2 - 1)}{5^2} + \left(\frac{3.73}{451.76}\right)^2 * \frac{(7^2 - 1)}{7^2} + \left(\frac{2.45}{451.76}\right)^2 * \frac{(9^2 - 1)}{9^2} + \left(\frac{1.48}{451.76}\right)^2 * \frac{(11^2 - 1)}{11^2}}{\left(\frac{36.44}{451.76}\right)^2 * \frac{(3^2 - 1)^2}{3^2} + \left(\frac{7.15}{451.76}\right)^2 * \frac{(5^2 - 1)^2}{5^2} + \left(\frac{3.73}{451.76}\right)^2 * \frac{(7^2 - 1)^2}{7^2} + \left(\frac{2.45}{451.76}\right)^2 * \frac{(9^2 - 1)^2}{9^2} + \left(\frac{1.48}{451.76}\right)^2 * \frac{(11^2 - 1)^2}{11^2}}$$

$$k_L = 0.1042$$

$$L_C = -\frac{k_L * X_{LC}}{\omega} = \frac{k_L * V_{\alpha} * \sin \theta}{\omega * I_{pa}}$$

$$L_C = \frac{0.1042 * 25KV * \sin(\cos^{-1} 0.4824)}{2 * 50\pi * 398.18A}$$

$$L_C = 18.24mH$$

➤ Calculate the V_{ac} phase coupled capacitance C_C

$$C_C = \frac{1}{\omega * k_C * X_{LC}} = \frac{1}{\omega(-1 - k_L)X_{LC}}$$

$$= -\frac{I_{pa}}{\omega(-1 - k_L) * V_{\alpha} * \sin \theta}$$

$$C_C = \frac{398.18A}{2\pi * 50 * 1.1042 * 25KV * \sin(\cos^{-1} 0.4824)}$$

$$C_C = 52.42\mu F$$

- Calculate the V_{bc} phase coupled impedance

$$I_{pb} = 451.76\sqrt{(0.5 * 0.85)^2 + (0.2887 * 0.85)^2}$$

$$I_{pb} = 221.71A$$

$$V_{bc} = 13.75V$$

$$\theta_b = 60^\circ$$

$$V_{inv\alpha_min} = 12.06KV$$

$$X_L = \frac{V_{bc} \sin \theta_b - \sqrt{V_{inv\alpha_min}^2 - V_{bc}^2 * \cos^2 \theta_b}}{I_{pb}}$$

$$X_L = \frac{13.75KV * \sin 60^\circ - \sqrt{(12.06KV)^2 - (13.75KV)^2 * \cos^2 60^\circ}}{221.71A}$$

$$X_L = 9.02\Omega$$

- Calculate the V_{bc} phase coupled inductance

$$L_F = \frac{X_L}{\omega}$$

$$L_F = \frac{9.02\Omega}{2 * \pi * 50}$$

$$L_F = 28.71mH$$

- Determine the dc link operation voltage in HPQC

And let $(V_\alpha \cos \theta)^2 = (25KV * 0.4822)^2 = 145.32KV$

$$(V_\alpha \sin \theta)^2 = (25KV * \sin(\cos^{-1} 0.4822))^2 = 479.68KV$$

$$A^2 = (0.2887PF + \sin(\cos^{-1}(PF)))^2 + (0.5PF)^2$$

$$A^2 = (0.2887 * 0.85 + \sin(\cos^{-1}(0.85)))^2 + (0.5 * 0.85)^2 = 0.78$$

$$B = \sum_{h=2}^{\infty} (r_h)^2 * \left\{ \frac{1}{h} [(h^2 - 1)k_L - 1] \right\}^2$$

$$\begin{aligned}
 B &= \left(\frac{36.44}{451.76}\right)^2 * \left\{\frac{1}{3}[(3^2 - 1) * 0.1042 - 1]\right\}^2 + \left(\frac{7.15}{451.76}\right)^2 * \left\{\frac{1}{5}[(5^2 - 1) * 0.1042 - 1]\right\}^2 \\
 &+ \left(\frac{3.73}{451.76}\right)^2 * \left\{\frac{1}{7}[(7^2 - 1) * 0.1042 - 1]\right\}^2 + \left(\frac{2.45}{451.76}\right)^2 \\
 &* \left\{\frac{1}{9}[(9^2 - 1) * 0.1042 - 1]\right\}^2 + \left(\frac{1.48}{451.76}\right)^2 * \left\{\frac{1}{11}[(11^2 - 1) * 0.1042 - 1]\right\}^2 \\
 B &= 9.61 * 10^{-5}
 \end{aligned}$$

Substituting the vales in the following equation

$$V_{inv\alpha_min} = \sqrt{(V_{\alpha} \cos \theta)^2 + \sum_{h=2}^{\infty} V_{\alpha}^2 * \frac{(r_h)^2}{A^2} * (\sin \theta)^2 * \left\{\frac{1}{h}[(h^2 - 1)k_L - 1]\right\}^2}$$

$$V_{inv\alpha_min} = \sqrt{145.32 + \frac{479.68 * 9.61 * 10^{-5}}{0.78}}$$

$$V_{inv\alpha_min} = 12.06KV$$

$$K_{min} = \sqrt{(\cos \theta)^2 + \sum_{h=2}^{\infty} \frac{(r_h)^2}{A^2} * (\sin \theta)^2 * \left\{\frac{1}{h}[(h^2 - 1)k_L - 1]\right\}^2}$$

$$K_{min} = \frac{V_{inv\alpha_min}}{V_{\alpha}}$$

$$K_{min} = \frac{12.06KV}{25KV}$$

$$K_{min} = 0.4824$$

$$V_{dc_link} = \sqrt{2(V_{\alpha} \cos \theta)^2 + 2 \sum_{h=2}^{\infty} V_{\alpha}^2 * \frac{(r_h)^2}{A^2} * (\sin \theta)^2 * \left\{\frac{1}{h}[(h^2 - 1)k_L - 1]\right\}^2}$$

$$V_{dc_link} = \sqrt{2 \left(145.32 + \frac{479.68 * 9.61 * 10^{-5}}{0.78} \right)}$$
$$V_{dc_link} = 17.06KV$$

3.12 Modeling of Traction Substation with V/V Connection

The V/V connection transformer is composed of two single phase transformer, the transformer three phase current from the primary side and supplies two single phase loads on the secondary side[4][5][16][18][20]. The V/V transformers are unbalanced, when balanced transformers are used, no negative-sequence current is injected into the public grid, when two feeder sections consume the same power. However, for the traction systems with three-phase V/V transformers, the negative-sequence current injected into the public grid, and half of the positive sequence current even when two feeder sections consume the same power[1]. The three-phase V/V transformers will bring more negative-sequence current, but they are widely used in the high-speed railway traction system for their advantages high capacity utilization ratio and simple structure [6].

The characteristics of the three-phase V/V traction transformer: it has a maximum power rating utilization ratio of 100%, because no third winding in the primary side flows through negative sequence current in this topology. The power rating operation ratio is an important consideration for selecting traction transformers for the high speed railway traction power supply system, because the high speed locomotives powers are usually very large. Hence, it will decrease the cost to implement traction transformers with a high power rating utilization ratio. The three-phase V/V traction transformers are used in the high speed railway traction power supply system [6]. The traction transformer is connected by two single-phase traction transformers in V/V wiring to form a complete traction transformer.

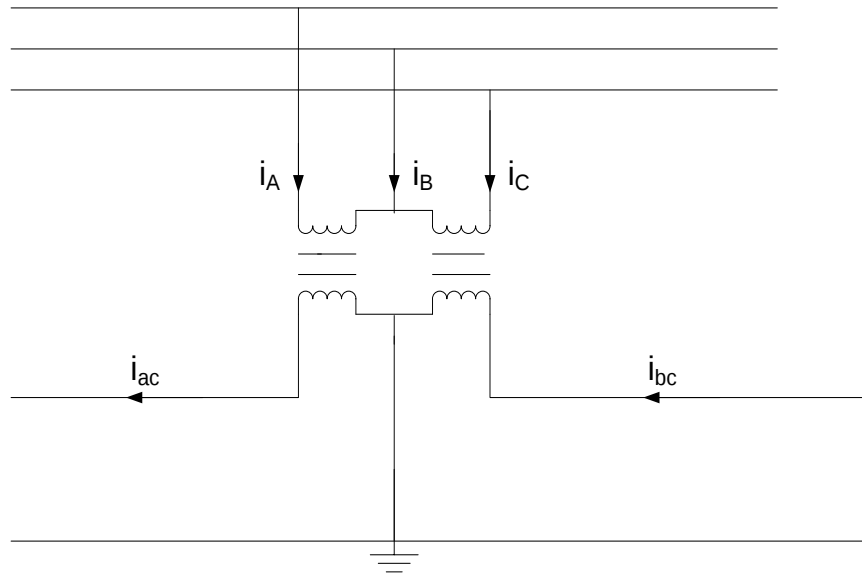


Figure 3.12 V/V transformer connection

Current relationship between primary and secondary side of the traction transformer

$$\begin{bmatrix} i_A \\ i_B \\ i_c \end{bmatrix} = \frac{1}{K} \begin{bmatrix} 1 & 0 \\ -1 & 1 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} i_{ac} \\ i_{bc} \end{bmatrix}$$

The V/V connection substation equivalent circuit model reduced to load side is shown in figure below

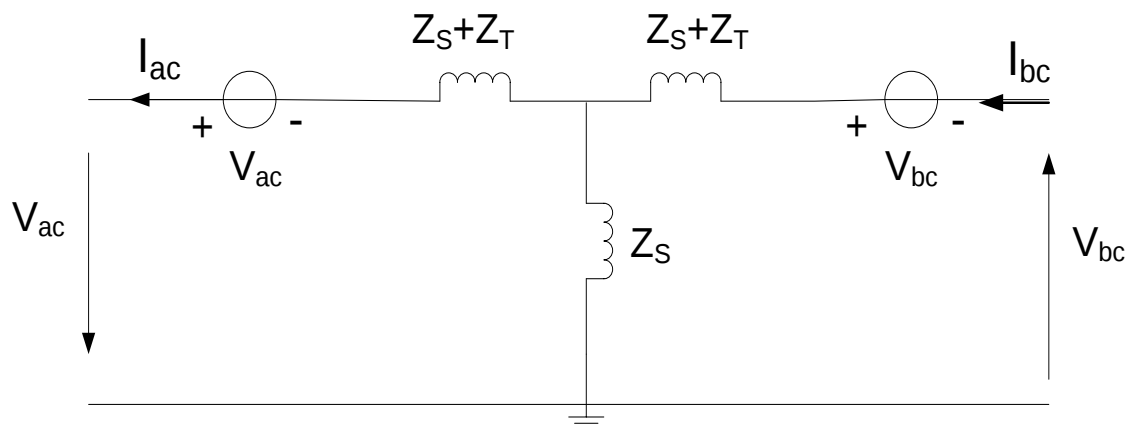


Figure 3.13 V/V connection substation equivalent circuit model

The power system impedance and transformer short circuit impedance calculation of V/V transformers connection respectively given below.

The power system impedance, $|Z_S| = X_S = \frac{U_{2N}^2}{S_K} \Omega$

Transformer short circuit impedance, $|Z_T| = X_T = \frac{U_K \% * U_{2N}^2}{100 * S_T} \Omega$

where S_K : power system (primary side) short circuit capacity (MVA)

S_T traction transformer capacity (MVA)

$U_K\%$: short circuit capacity

Table 3.3 Typical values of short circuit voltage [standard IES60076-5]

Rated apparent power S_n [kVA]	Short - circuit voltage U_K %
≤ 630	4
$630 < S_n \leq 1250$	5
$1250 < S_n \leq 2500$	6
$2500 < S_n \leq 6300$	7
$6300 < S_n \leq 25000$	8

Taking sebeta substation in to consideration the available data is

S_K : power system (primary side) short circuit capacity (MVA) = 400MVA

S_T traction transformer capacity (MVA) =16MVA

$U_K\%$: short circuit capacity = 8% [reference]

$$X_S = \frac{U_{2N}^2}{S_K} \Omega = \frac{(27.5KV)^2}{400MVA} = 1.8906\Omega$$

$$X_T = \frac{U_K\% * U_{2N}^2}{100 * S_T} \Omega = \frac{8 * (27.5KV)^2}{100 * 16MVA} \Omega = 3.7813\Omega$$

3.13 Transmission Line Modeling

AC transmission line transmits electrical power from national grid network to the railway substation. AC lines are modeled using its series resistance, series inductance, shunt capacitance, and shunt conductance. There are three ways in common practice to model power transmission lines. The three models are the short line model, medium line model and the long line models. A line is defined as a short-length if its length is less than 80 km (50 miles), or medium length for the length between 80 km (50 miles) and 240 km (150 miles), and long line for length above 240km [22].

Both short and medium-length lines are approximated by lumped-parameter models [22]. However, if the line is larger than 240 km, the model must consider parameters uniformly distributed along the line [22][23]. Since there is no clear about the length of transmission line from the three phase grid substation to the traction substation of sebeta, assuming the length of the transmission line 40km, it is modeled using the short line model method. Assuming there is a balanced three phase transmission line, the section is modeled using three phase pi circuit with lumped parameters. The equivalent three phase circuit diagram of a three phase pi circuit is given as shown in Figure 3.14

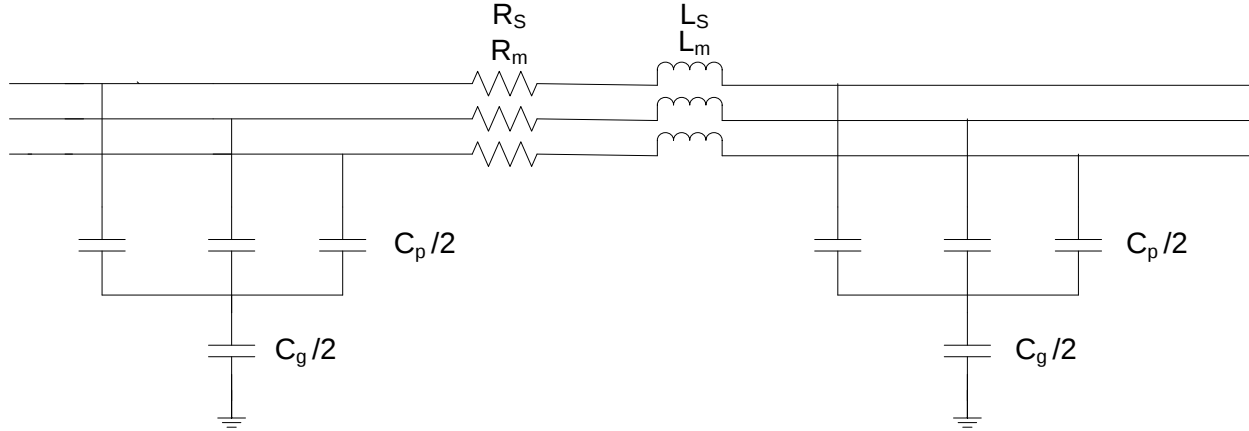


Figure 3.14 Equivalent circuit of three phase pi-circuit model [24]

The line parameters R , L , and C are specified as positive and zero-sequence parameters that take into account the inductive and capacitive couplings between the three phase conductors, as well as the ground parameters. This method of specifying line parameters assumes that the three phases are balanced. The self and mutual resistances (R_s , R_m), self and mutual inductances (L_s , L_m) of the three coupled inductors, as well as phase capacitances C_p and ground capacitances C_g , are deduced from the positive- and zero-sequence RLC parameters as follows. If the line parameters are defined as follows:

r_1, r_0 - positive- and zero-sequence resistances per unit length (Ω/km)

l_1, l_0 - positive- and zero-sequence inductances per unit length (H/km)

c_1, c_0 - positive- and zero-sequence capacitances per unit length (F/km)

l_{sec} - line section length (km)

The total positive and zero-sequence RLC parameters for the short line modeling are evaluated as;

$$R_1 = r_1 * l_{\text{sec}} \quad R_0 = r_0 * l_{\text{sec}}$$

$$L_1 = l_1 * l_{\text{sec}} \quad L_0 = l_0 * l_{\text{sec}}$$

$$C_1 = c_1 * l_{\text{sec}} \quad C_0 = c_0 * l_{\text{sec}}$$

Then RLC line section parameters are then computed as follows:

$$\begin{aligned} R_m &= (R_o - R_1)/3 & R_s &= (2R_1 + R_o)/3 \\ L_m &= (L_o - L_1)/3 & L_s &= (2L_1 + L_o)/3 \\ C_p &= C_1 & C_g &= 3C_1C_o / (C_1 - C_o) \end{aligned}$$

3.14 Traction Power Feeding Section (Catenary System) Model

The feeding section is modeled as series of lumped impedance networks, which is suitable for representing medium and low voltage distribution systems and for balanced harmonic analysis. The average length of the catenary during normal feed conditions is 13.521 km. This feeder is modeled as two 6.76 km pi sections, each having a longitudinal impedance of $0.169 + j0.432 \Omega/\text{km}$ at 50 HZ and shunt capacitance of $0.011 \mu\text{F}/\text{km}$ [9] [25] [26].

In MATLAB/Simulink system the feeding section model obtained by cascading the Pi Section line block.

3.15 Train Model

The other main component is the electric locomotive. The type of electric locomotive that is modeled in this work is SS9 Passenger locomotive with power 4800KW [2][18]. Thus, the locomotive is equipped with main transformer, line side converter, DC-Link, motor side converter and six asynchronous squirrel cage motors. The model that has been used in simulation has been developed by means of only one line side converter and only one motor like it is done in [18].

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

- Basic practical assumptions
 - ✓ The locomotive main transformer includes one primary winding, six

traction winding and one auxiliary winding

- ✓ AC/DC Ideal general purpose diode rectifier with high smoothing capacitor for line side converter

- ✓ In put ac power to the rectifier is equal to the output dc power

➤ Modeling approach:

- ✓ Main transformer rating at 25kV line voltage: [18]
- ✓ Primary winding 25kV, 5647kVA
- ✓ Traction winding 6*1650kV, 5647kVA
- ✓ Traction winding impedance at 25kV, 5647kVA, 8.35%

➤ DC-Link capacitance:

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

$$C \geq \frac{P_m}{12 * f * V_r * V_{dc}}$$

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

$$P_m = S \cos PF = 5647KVA * 0.85 = 4.8MW$$

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

The desired voltage peak to peak ripple in volt is

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

Then the cross pounding ripple is

$$V_r = \frac{V_{p-p}}{2} = 350V$$

Average DC bus voltage

$$V_{dc} = \frac{2\sqrt{2} * V_{rms}}{\pi} = 8.913KV$$

$$C \geq \frac{P_m}{12 * f * V_r * V_{dc}} = \frac{4800}{12 * 50 * 350 * 8.913} = 2.56mF$$

➤ Load side (motor)

$$R = \frac{(V_{dc \text{ peak}})^2}{P_m} = 40\Omega$$

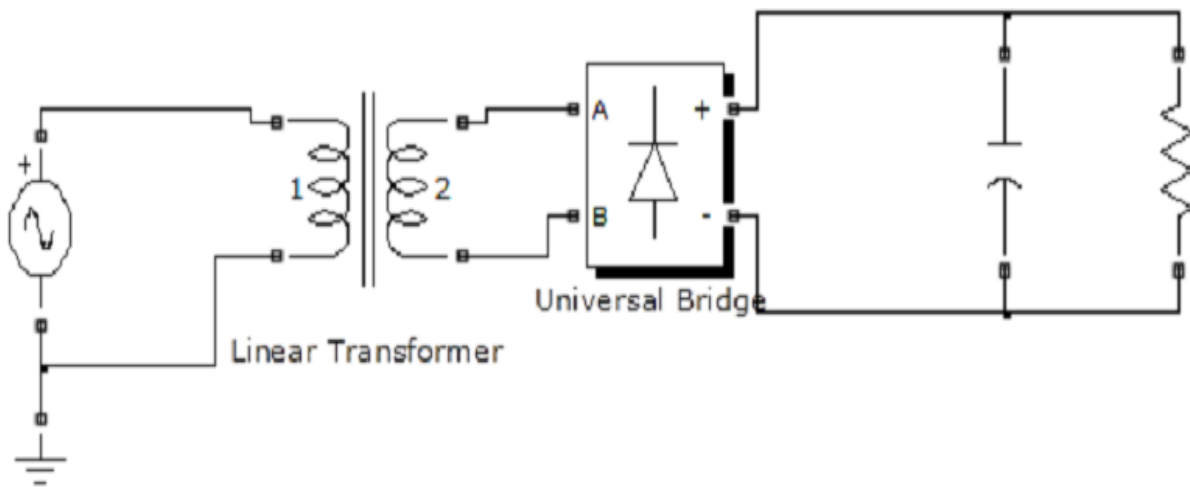


Figure 3.15 Simplified circuit model of DC locomotive

Chapter Four

4 Simulation Results and Discussion

4.1 Introduction

In this chapter, simulation of the traction power system is done using the MATLAB/ Simulink environment. It is a program for simulating dynamic systems. Simulink has the advantages of being capable of complex dynamic system simulations, graphical environment with visual real time programming and broad selection of toolboxes. The program is capable of solving both linear and nonlinear processes so it is suited to simulate co phase traction power supply system.

The first step in simulating a co phase traction supply system is creating a model that represents components of a system by using an existing blocks in the Simulink library or from those created by the user. Then simulation is done for different cases.

First, the simulation is done for the case when there is no HPQC for the existing system. Followed by, simulation with the HPQC.

4.2 Simulation of Co phase Traction Power Supply System without HPQC

In this case simulation is done for the existing system without HPQC. The simulation parameters used in this thesis are based on the actual data obtained from ERC and some approximate calculation. Some methods for determining the parameters through calculation are given in Appendix A. Summary of the simulation parameters is given in the following table.

Table 4.1 Co phase traction power supply system without HPQC simulation parameters

Voltage source	V _{ph-ph}	132kV
	Frequency	50Hz
	3 phase short circuit level	400MVA
	X/R ratio	45
	Positive and zero sequence resistance (Ω/km)	$r_1=0.1019$, $r_0=0.6160$

AC Transmission line	Positive and zero sequence inductance (H/km)	$l_1=0.0018, l_0=0.0058$
	Positive and zero sequence capacitance (F/km)	$c_1=6.79*10^{-9}, c_0=6.79*10^{-12}$
Single phase transformer	Transformer capacity	16MVA
	Winding 1	132KV, $R_{1(pu)}=0.000499, L_{1(pu)}=0.000242$
	Winding 2	27.5KV, $R_{2(pu)}=0.0002495,$ $L_{2(pu)}=0.000121$
Catenary system	longitudinal impedance	$0.169+j0.432\Omega/\text{km}$
	shunt capacitance	$0.011 \mu\text{F}/\text{km}$
	Frequency	50Hz
Traction load (Train)	Dc smoothing Capacitor	2.56mF
	Resistor	40Ω

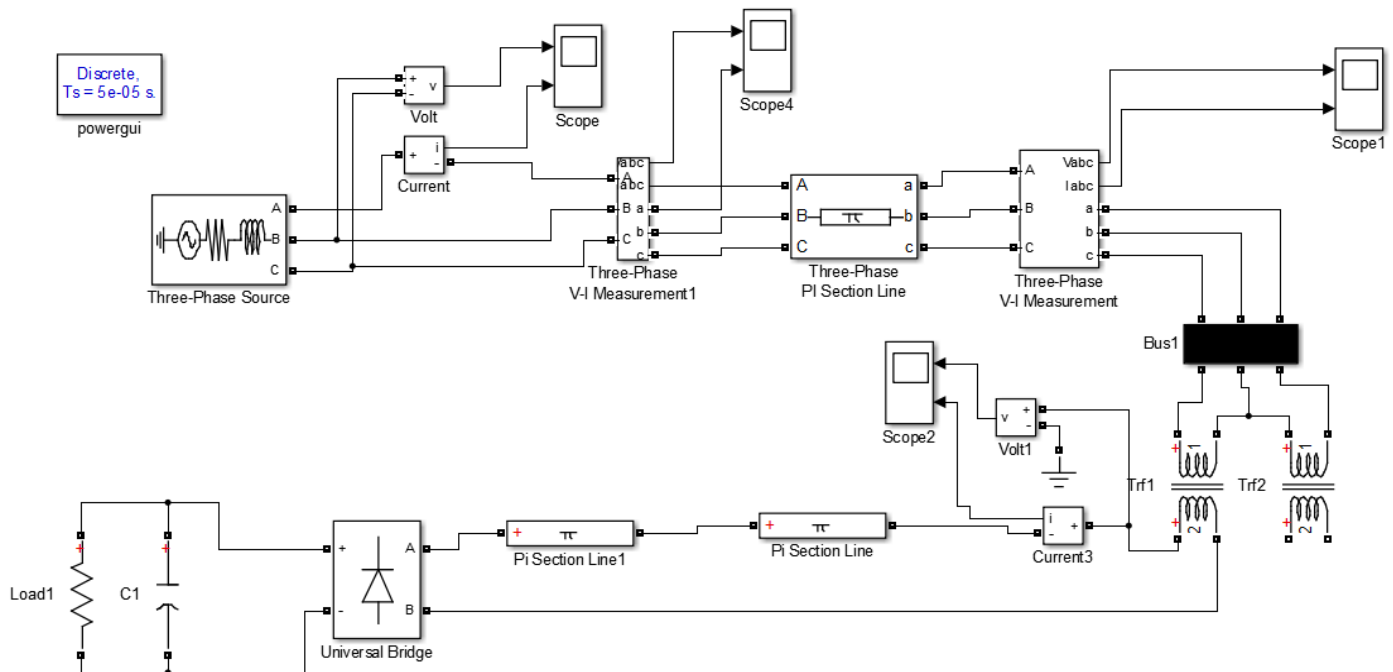


Figure 4.1 Matlab/simulink model of co phase traction supply system without HPQC

Table 4.2 Co phase power supply system without HPQC simulation result of current waveform at the secondary side of the V/V transformer when a train is located 6.76km from TSS

Harmonic Order	Value
3 rd harmonic, %	36.44
5 th harmonic, %	7.15
7 th harmonic, %	3.73
9 th harmonic, %	2.45
11 th harmonic, %	1.48
THD, %	37.54
Position of train	6.76km

Table 4.3 Co phase power supply system without HPQC simulation result of current waveform at the secondary side of the V/V transformer when a train is located 13.52km from TSS

Harmonic Order	Value
3 rd harmonic, %	33.34
5 th harmonic, %	7.44
7 th harmonic, %	3.18

9 th harmonic, %	2.13
11 th harmonic, %	1.50
THD, %	34.47
Position of train	13.52km

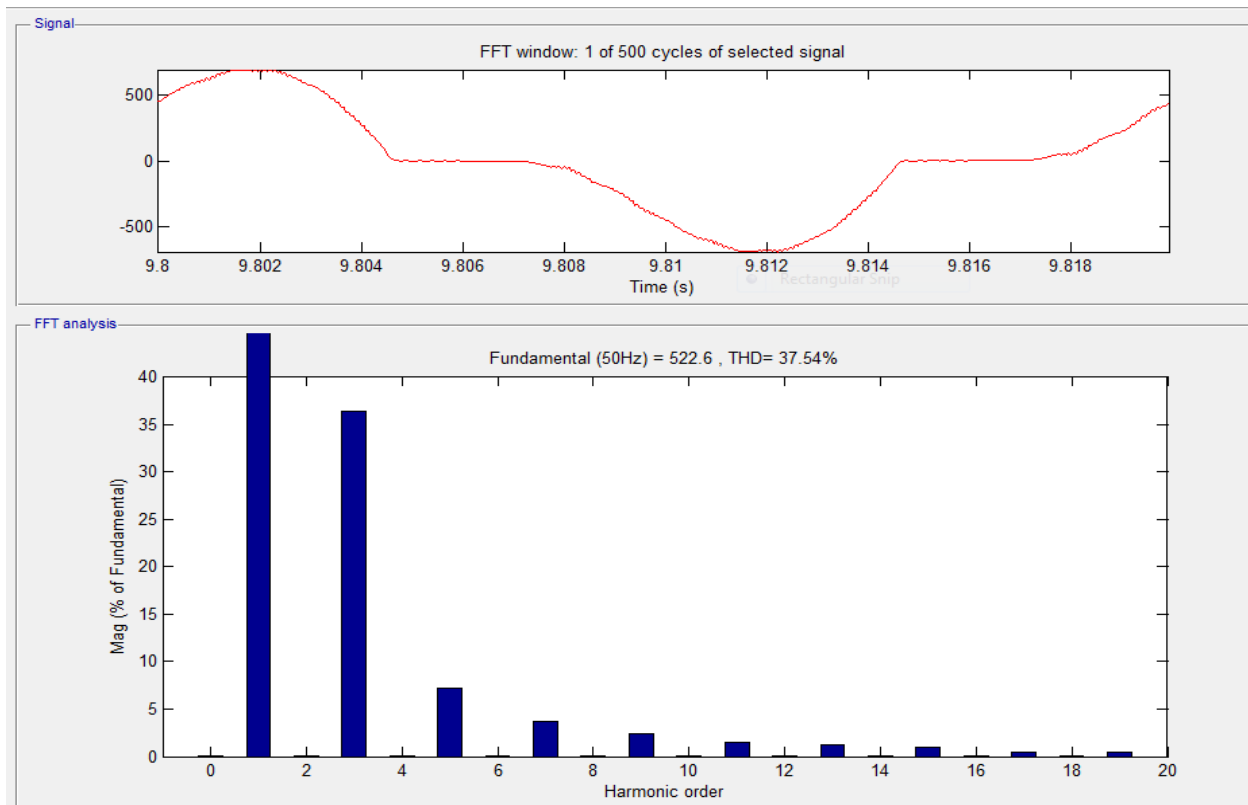


Figure 4.2 Co phase power supply system without HPQC current waveform and its harmonic spectrum at the secondary side of the V/V transformer when a train is located at 6.76km from TSS

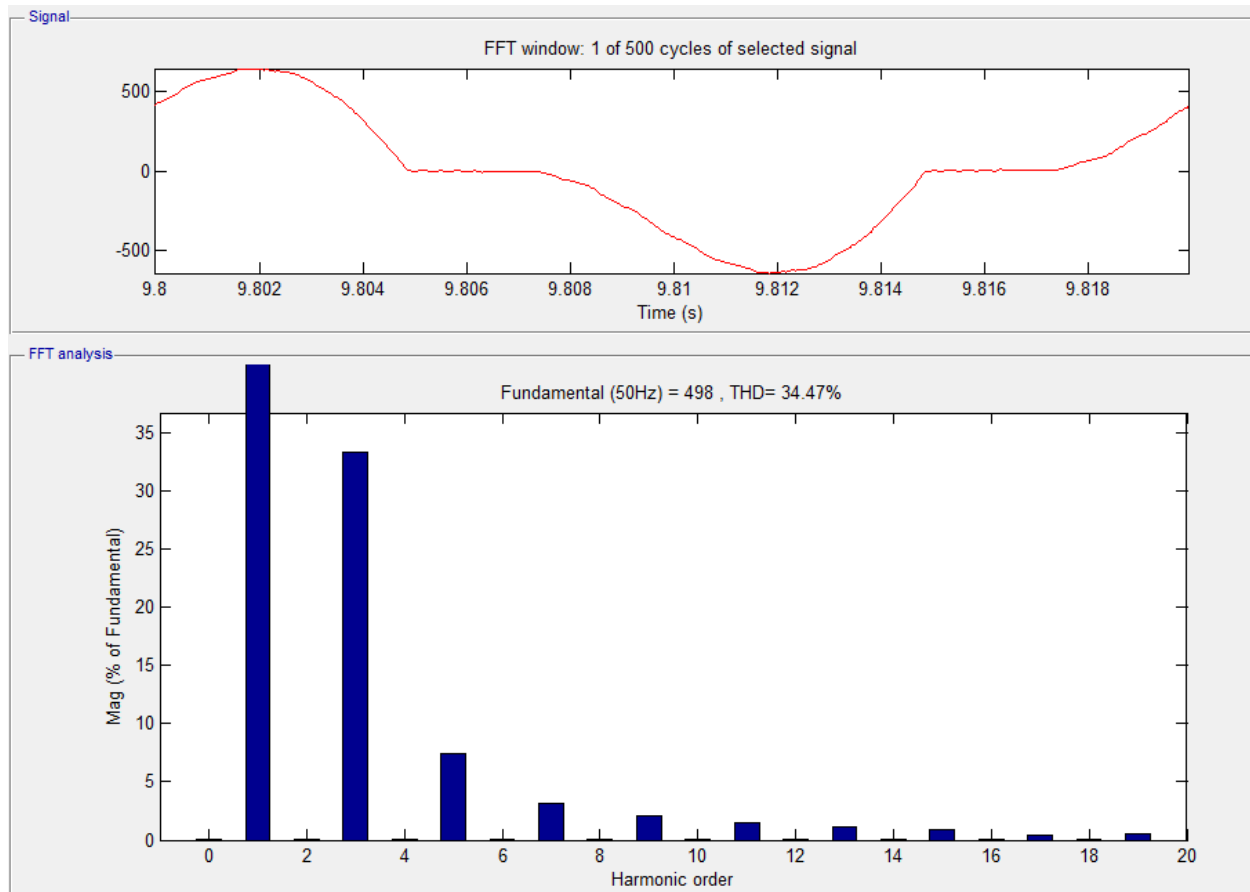


Figure 4.3 Co phase power supply system without HPQC current waveform and its harmonic spectrum at the secondary side of the V/V transformer when a train is located at 13.52km from TSS

Table 4.2 and Table 4.3 show that the THD of traction substation current decreases as the train move away from traction substation. It can also be seen that THD of substation current of a train varied from 34.47% to 37.54% and the highest harmonic value which is 36.44% is seen for 3rd harmonic order.

Table 4.4 Co phase power supply system without HPQC simulation result of the three phase grid currents waveform when a train is located 6.76km from TSS

Currents	A	B	C
Rms current, A	81.28	0	79.77
3 rd harmonic,%	34.40	-	35.09
5 th harmonic,%	6.74	-	6.88
7 th harmonic,%	3.52	-	3.59
9 th harmonic,%	2.31	-	2.36
11 th harmonic,%	1.39	-	1.42
THD,%	35.43	-	36.14
Current unbalance%	100		
Position of train	6.76km		

Table 4.5 Co phase power supply system without HPQC simulation result of the three phase grid currents waveform when a train is located 13.52km from TSS

Currents	A	B	C
Rms current, A	77.74	0	76.15
3 rd harmonic,%	31.35	-	32.04
5 th harmonic,%	6.99	-	7.15
7 th harmonic,%	2.99	-	3.06
9 th harmonic,%	2.00	-	2.04
11 th harmonic,%	1.4	-	1.43
THD,%	32.41	-	33.13
Current unbalance%	100		
Position of train	13.52km		

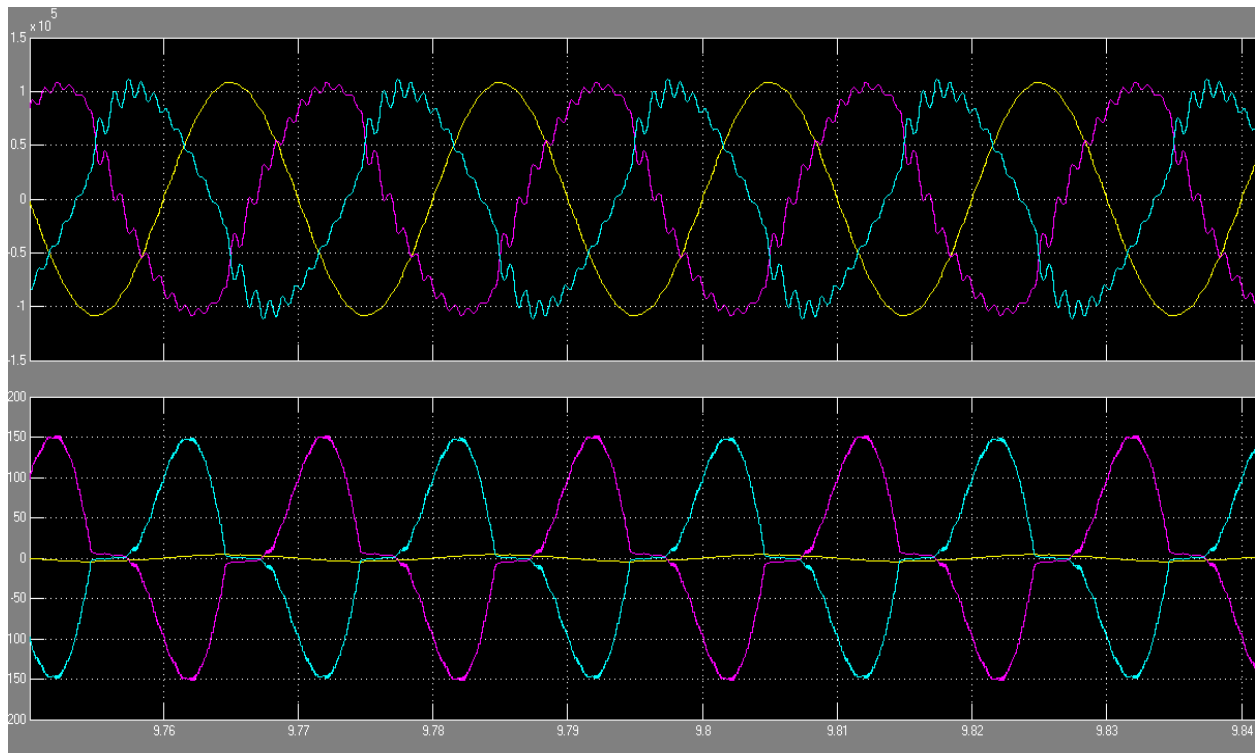


Figure 4.4 Three phase voltages and currents at the grid side co phase power supply system without HPQC when a train is located at 6.76km from TSS.

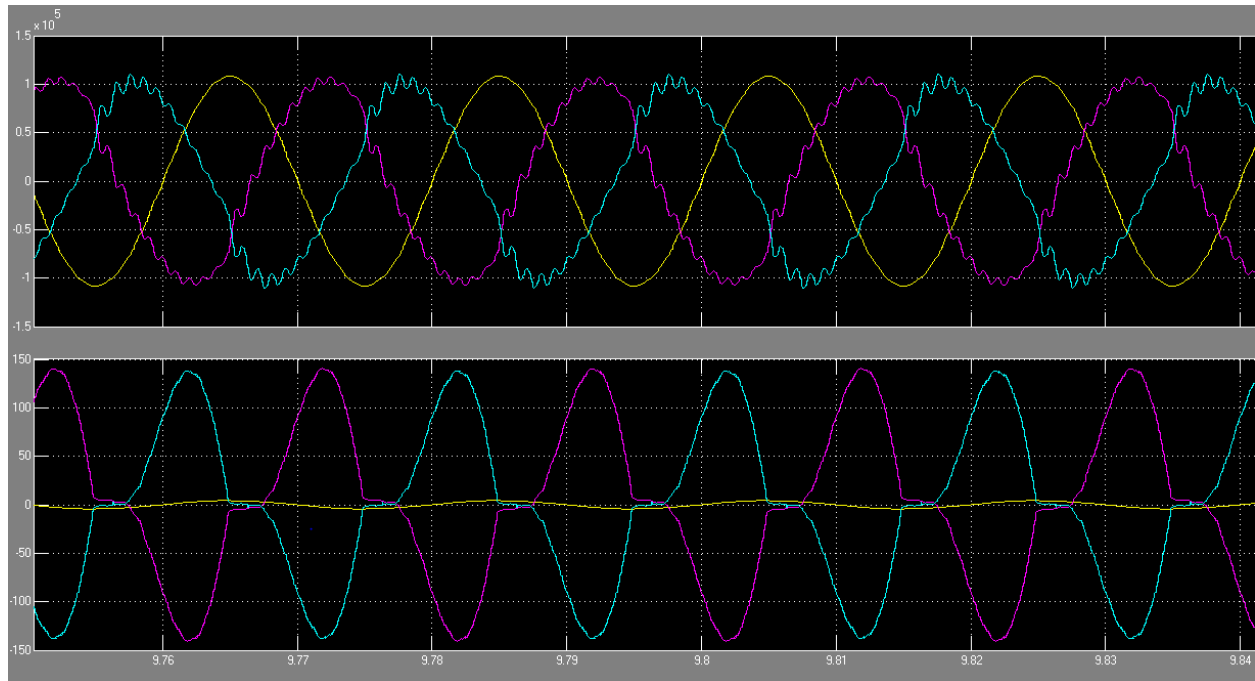


Figure 4.5 Three phase voltages and currents at the grid side of co phase power supply system without HPQC when a train is located at 13.52km from TSS.

Table 4.4 and Table 4.5 show that the current and THD at phase A is varied from 81.28A to 77.74A, 35.43% to 32.45%, the current and THD at phase B is zero since the load is only connected to the α -phase and the current and THD at phase C is varied from 79.77A to 76.15A, 36.14% to 33.13% respectively as the train move away from traction substation. It can also be seen that the three phase current unbalance is 100%. The three phase source voltage and current waveforms obtained for co phase traction power supply system without HPQC are shown in Figure 4.4 and Figure 4.5 as the train move away from traction substation respectively. Obviously the three phase system power quality is far from satisfactory. Power quality compensation is thus required.

4.3 Simulation of Co phase Traction Power Supply System with HPQC

In this case simulation is done for the existing system with HPQC. The simulation parameters used in this thesis are based on the actual data obtained from ERC and the designed parameters

of the hybrid power quality compensator. Summary of the simulation parameters is given in the following table.

Table 4.6 Co phase traction power supply system with HPQC Simulation parameters

Voltage source	V _{ph-ph}	132kV
	Frequency	50Hz
	3 phase short circuit level	400MVA
	X/R ratio	45
AC Transmission line	Positive and zero sequence resistance (Ω/km)	$r_1=0.1019, r_0=0.6160$
	Positive and zero sequence inductance (H/km)	$l_1=0.0018, l_0=0.0058$
	Positive and zero sequence capacitance (F/km)	$c_1=6.79 \times 10^{-9}, c_0=6.79 \times 10^{-12}$
Single phase transformer	Transformer capacity	16MVA
	Winding 1	132KV, $R_{1(pu)}=0.000499, L_{1(pu)}=0.000242$
	Winding 2	27.5KV, $R_{2(pu)}=0.0002495,$ $L_{2(pu)}=0.000121$
Catenary system	longitudinal impedance	$0.169+j0.432\Omega/\text{km}$
	shunt capacitance	$0.011 \mu\text{F}/\text{km}$
	Frequency	50Hz
Traction load (Train)	Dc smoothing Capacitor	2.56mF
	Resistor	40Ω
HPQC Parameters	V_{ac} phase coupled inductance L_C	18.24mH
	V_{ac} phase coupled capacitance C_C	$52.42\mu\text{F}$
	V_{bc} phase coupled inductance L_F	28.71mH
	dc link operation voltage in HPQC	17.06 KV
	dc link Capacitance C_{dc} [From reference]	$10,000\mu\text{F}$

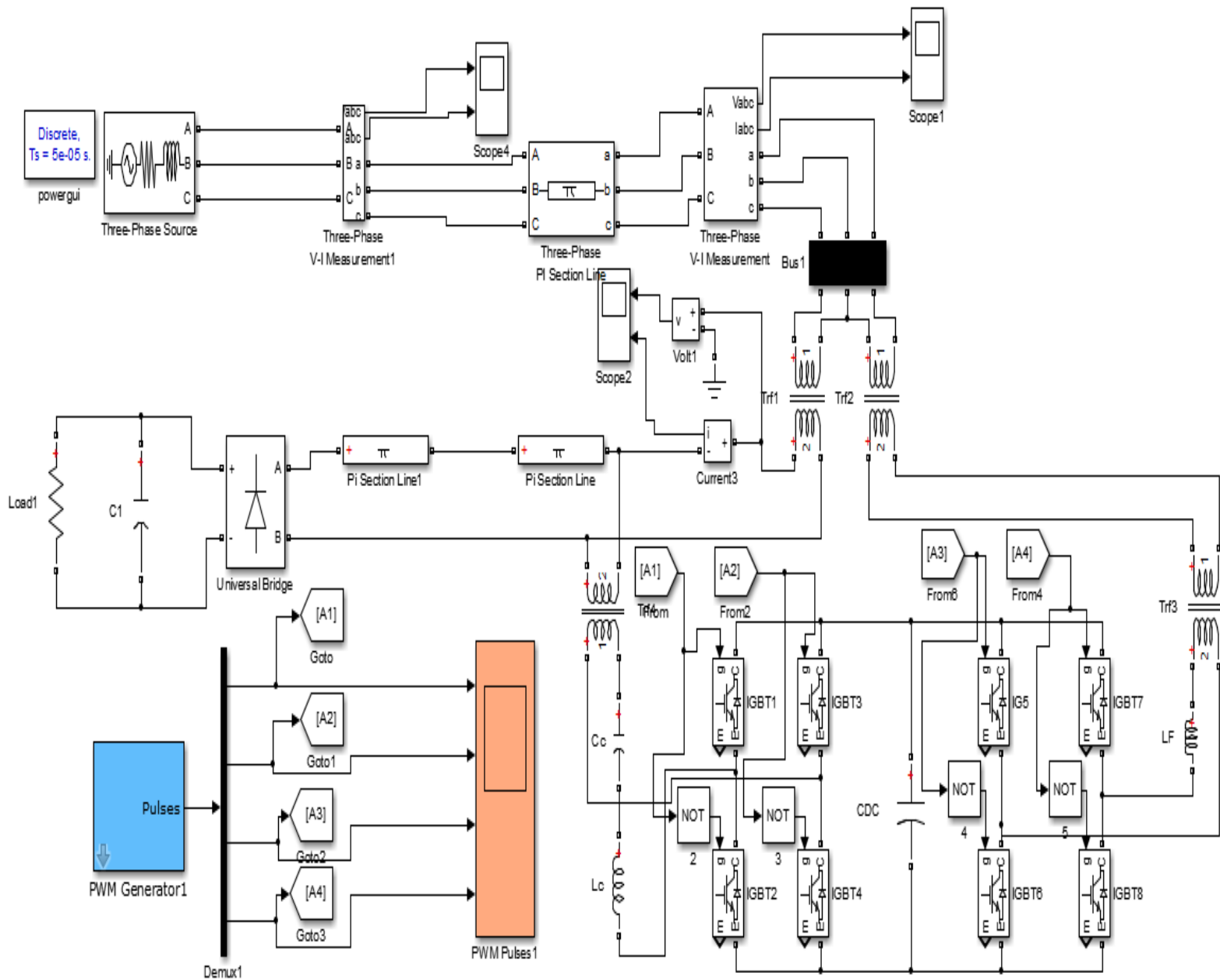


Figure 4.6 Matlab/simulink model of co phase traction supply system with HPQC

Table 4.7 Co phase power supply system without HPQC simulation result of the three phase grid currents waveform when a train is located 6.76km from TSS

Currents	A	B	C
Rms current, A	53.20	52.30	54.70
3 rd harmonic,%	0.54	0.50	0.04
5 th harmonic,%	0.05	0.04	0.01
7 th harmonic,%	0.03	0.02	0
9 th harmonic,%	0.02	0.01	0
11 th harmonic,%	0	0	0
THD,%	0.54	0.51	0.08
Current unbalance%	2.43		
Position of train	6.76km		

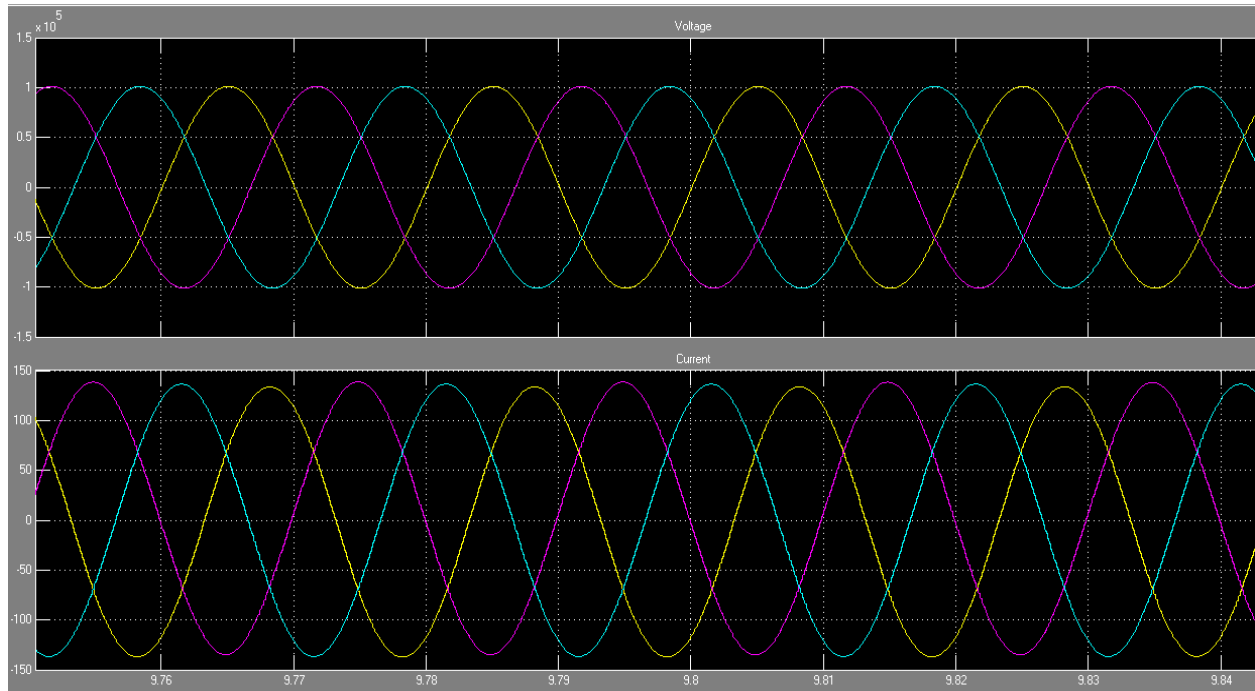


Figure 4.7 Three phase voltages and currents at the grid side of co phase power supply system with HPQC when a train is located at 6.76km from TSS.

Table 4.6 and Figure 4.5 show that the current at phase A is 53.2A, current at phase equals to 52.3A and current at phase C is 54.7A. From this we can observe that the three phase source current harmonics and unbalance are eliminated. This can be verified by its harmonic distortions of 0.54%, 0.51% and 0.08% at phase A, phase B and phase C respectively and unbalance is 2.43%.

Chapter Five

5 Conclusion, Recommendation and Future work

5.1 Conclusion

In this thesis, Hybrid power quality compensator has been designed. Co phase traction power supply system is modeled and simulated using the Matlab /Simulink. First, based on the data from sebeta traction substation and some approximate calculations co phase traction power supply system without hybrid power quality compensator is modeled and simulated using Matlab/ simulink. The simulation result shows the three phase source current suffers harmonic distortions and system unbalance i.e. the THD% of the phase currents of phase A, phase B and phase C is 35.43, 0 and 36.14 respectively. The THD% current of phase B equals to zero since the current at phase B is zero. The three phase source current unbalance is 100%.

Based on the result of simulation hybrid power quality compensator (HPQC) has been designed for the reduction of operational voltage both under fundamental and harmonic compensation. Based on the simulation result of the load harmonics, the comprehensive design for HPQC mathematically derived. The HPQC operation voltage rating is around 0.4824 under comprehensive compensation. This corresponds to a dc link voltage of around 17.06kv. This shows that under comprehensive compensation, with a proper LC parameter design, a lower DC voltage operation can be achieved. This can eventually reduce the initial cost and switching loss.

Co phase traction power supply system with HPQC is modeled and simulated using Matlab/Simulink. The simulation result shows that the three phase source harmonics and unbalance are reduced i.e. almost eliminated. This can be verified by its harmonic distortions of current 0.54%, 0.51% and 0.08% at phase A, phase B and phase C respectively, and unbalance of 2.43%. Since the negative sequence current 12.69 is smaller than the threshold value 34.99 then the system unbalance satisfies the standard.

Finally, from the result obtained it can be concluded that co phase traction power supply with HPQC performed best in solving three phase source unbalance and harmonics filtering.

5.2 Recommendation

To maintain power quality in the proposed Ethiopian single-phase 25kV AC electric traction system, one of the major issues to be addressed should be the issue of three phase source unbalance current and harmonic distortion. In this regard, the Ethiopian railway corporation (ERC) should be in position to take remedial solutions (techniques to overcome the existing problems).

Accordingly, it is possible to reduce adverse effects of three phase source current unbalance and harmonics distortion on the grid and traction equipment.

5.3 Future work

The thesis mainly focused on HPQC parameter design. The design of automatic dynamic closed loop controller i.e. hysteresis and PID controller which responds to the real time will be the future work. Therefore it is opened for further work who have interest on co phase traction power supply system and to design its controller.

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Appendix A Parameter Determination

I) EEPCo Substation Parameters

The EEPCo network that provide supply for railway substations have a transformer with capacity of 40MVA, impedance percentage 10% and 400kV/132kV [2]. Depending on these data the grid short circuit capacity and equivalent impedance are calculated as follows

$$\begin{aligned} \text{Transformer full load current, } I_{FL} &= \frac{\text{Transformer KVA}}{\sqrt{3} * V_{SC}} = \frac{40,000 \text{ KVA}}{\sqrt{3} * 132 \text{ KV}} \\ &= 174.95 \text{ A} \end{aligned}$$

The short circuit current referred to secondary side becomes the ratio of full load current to impedance percentage.

$$I_{SC} = \frac{\text{Full load current}}{\% \text{ impedance}} = \frac{174.95 \text{ A}}{0.1} = 1,749.5 \text{ A}$$

The short circuit capacity MVA,

$$MVA_{SC} = \sqrt{3} * V_{SC} * I_{SC} = \sqrt{3} * 132 \text{ KV} * 1749.5 \text{ A} = 400 \text{ MVA}$$

The equivalent supply impedance referred to the transformer secondary side is given by;

$$Z_S = \frac{V_{SC}^2}{MVA_{SC}} = \frac{(132 \text{ KV})^2}{400 \text{ MVA}_{SC}} = 43.56 \Omega$$

From IEC 60076, the X/R ratio for the transformer capacity of 40MVA is equal to 45. Taking this value for X/R, the equivalent source reactance and resistance will be determined from the equation $Z^2 = R^2 + X^2$ and through calculation $R=0.9678\Omega$ and $X=43.5492\Omega$.

II) Transmission Line Parameters

The transmission line parameters considered in this thesis are taken from reference [27]. For overhead line 132KV and 200mm² specifications the parameters are $X=0.426\Omega/\text{km}$ and $R=0.144\Omega/\text{km}$. And the positive and zero sequence impedances

Positive sequence impedance: $0.1019 + j0.5912$

Zero sequence impedance: $0.6160 + j1.8151$

Zero sequence susceptance: $0.4688\text{MS/km} + j0.4688\text{GS/km}$

Using inductive and capacitive reactance, the values of inductance and capacitance are determined as follows:

$$X_C = \frac{1}{2\pi f C}; C = \frac{1}{2\pi f X_C}$$

$$X_L = 2\pi f L; L = \frac{X_L}{2\pi f}$$

Using frequency of 50Hz and the reactance values of line parameters mentioned above, the following positive and zero parameters are calculated.

- ✓ Resistance (Ω/km) - $r_1=0.1019$ $r_0=0.6160$
- ✓ Inductance (H/km) - $l_1=0.0018$ $l_0=0.0058$
- ✓ Capacitance (F/km) - $c_1=6.79 \times 10^{-9}$ $c_0=6.79 \times 10^{-12}$

III) V/V Traction Transformer (single phase transformer)

In this paper, for MATLAB /simulink model the substation transformer is modeled by two single-phase transformers, and is commonly known as the V/V transformer.

The short circuit and open circuit data of Sebata transformer is given as follows [2]

Table A1 short circuit and open circuit data of Sebata transformer

$V_{OC}=27.5\text{KV}$	$Z_{SC} \%=8.4, \text{PF}=0.9$
$I_{OC}=0.5\%I_n=1.85\text{A}$	Primary Voltage=132kV
Transformer rating=16MVA	Secondary Voltage=25kV

The short circuit parameters, I_{sc} and V_{sc} , can be determined using the rated transformer data and percentage of impedance.

Transformer short circuit current (I_{sc}),

$$I_{sc} = \frac{\text{Transformer full load current}}{\text{Transformer impedance}}$$

Transformer full load current, I_{FL} ;

$$I_{FL} = \frac{16MVA}{\sqrt{3} * 25kv} = 369.51A$$

Then short circuit current will be,

$$I_{sc} = \frac{369.51}{0.084} = 4398.93A$$

The short circuit voltage is,

$$\text{Impedance percentage} = \frac{\text{Impedance voltage}}{\text{Rated voltage}} * 100\%$$

$$Z_{sc} \% = \frac{V_{sc}}{V_p} * 100$$

$$V_{sc} = \frac{V_p * Z_{sc} \%}{100} = \frac{132KV * 8.4}{100} = 11088V$$

The shunt admittance is determined from open circuit data. To evaluate R_m and X_M , we define the conductance of the core-loss resistance and the susceptance of the magnetizing inductor as follows:

$$G_C = \frac{1}{R_m}, B_C = \frac{1}{X_M}$$

Where, G_C is conductance of core-loss resistance

B_m is susceptance of the magnetizing effect

Since both elements are in parallel, their admittances add. Therefore, the total excitation admittance is:

$$Y_E = G_C - jB_C = \frac{1}{R_m} - j \frac{1}{X_M}$$

The magnitude of the excitation admittance in the open-circuit test is given as:

$$Y_E = \frac{I_{OC}}{V_{OC}}$$

From the short-circuit data the magnitude of the series impedance referred to the primary side of the transformer is calculated. The magnitude of the series impedance referred to primary side is given by the equation: primary side of the transformer is calculated. The magnitude of the series impedance referred to primary side is given by the equation:

$$Z_E = \frac{V_{SC}}{I_{SC}}$$

$$Z_E = R_{eq} + jX_{eq}$$

$$Z_E = (R_P + a^2 * R_S) + j(X_P + a^2 * X_S)$$

Using the test data and the above calculated parameters, the linear transformer parameters are estimated as given in the following table.

Table A2 calculated parameters of single phase transformer

$Y_E = 6.7272 \times 10^{-5}$	$R_m = 16516.69 \Omega$	$X_m = 34102.71 \Omega$
$Z_E = 2.5208$	$R_{eq} = 2.2687 \Omega$	$X_{eq} = 1.0988 \Omega$

The per-unit Conversion

This allows us to specify the resistance and inductance of the windings in per unit (pu) value. The values are based on the transformer rated power P_n , in VA, nominal frequency f_n , in Hz,

and nominal voltage V_n , in V_{rms} , of the corresponding winding. The base impedance, base resistance, base reactance, and base inductance are estimated by

$$Z_{Base} = R_{Base} = X_{Base} = \frac{V_n^2}{P_n}$$

$$L_{Base} = \frac{X_{Base}}{2\pi f_n}$$

Given the primary winding rated voltage 132KV, 16MVA and 50Hz, the base parameters will be,

$$Z_{Base} = R_{Base} = X_{Base} = \frac{\left(\frac{132000}{\sqrt{3}}\right)^2}{16000000} = 363\Omega$$

$$L_{Base} = \frac{363}{2\pi * 50} = 1.1555H$$

For each winding, the per unit resistance and inductance are defined as

$$R_{(pu)} = \frac{R(\Omega)}{R_{Base}}, \quad L_{(pu)} = \frac{L(H)}{L_{Base}}$$

Assuming that the two secondary windings are identical and each parameters of the secondary is half of the primary winding, the per unit values are calculated.

Table A3 calculated parameters of single phase transformer in per unit form

$R_{m(pu)}=45.5005$	$L_{m(pu)}=93.9468$
$R_{1(pu)}=0.000499$	$L_{1(pu)}=0.000242$
$R_{2(pu)}=R_{3(pu)}=0.0002495$	$L_{2(pu)}=L_{3(pu)}=0.000121$

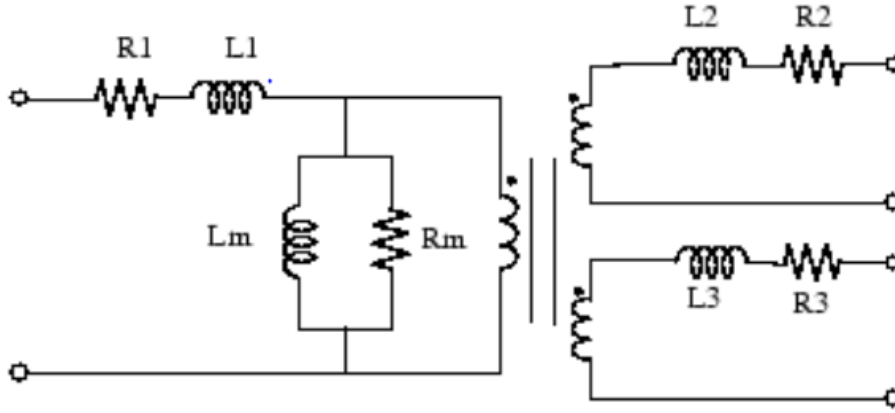


Figure A1 Equivalent circuit of three winding transformer [28]

Appendix B Current Unbalance factor

Without the HPQC the currents at the grid side are given by [16]

$$\begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} = \frac{1}{K} \begin{bmatrix} i_L e^{-j(\psi_a + \varphi_1)} \\ 0 \\ -i_L e^{-j(\psi_a + \varphi_1)} \end{bmatrix}$$

Where $\psi_a = \frac{\pi}{6}$. The zero, positive and negative sequence components may be determined by using the method of symmetrical components.

$$\begin{bmatrix} i^0 \\ i^- \\ i^+ \end{bmatrix} = \frac{1}{K} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} = \frac{i_L}{K} \begin{bmatrix} 0 \\ \sqrt{3} e^{-j(\psi_a + \varphi_1 + 30^\circ)} \\ \sqrt{3} e^{-j(\psi_a + \varphi_1 - 30^\circ)} \end{bmatrix}$$

Where $a = e^{+j120^\circ}$. The unbalance factor of the currents is given by

$$\text{current unbalance factor} = \frac{|i^-|}{|i^+|} * 100\%$$

$$\text{current unbalance factor} = \frac{|i^-|}{|i^+|} * 100\% = 100\% \text{ without HPQC}$$

According to the power quality standard[18],the voltage unbalance is estimated by

$$\varepsilon_U = \frac{\sqrt{3}|I^-|U_L}{S_k} * 100\%$$

in which U_L is the line to line voltage and S_k is the short circuit capacity. In case the value of ε_U does not exceed 2%, the power quality standard is satisfied.

If the negative sequence current is smaller than the threshold value then the system unbalance satisfies the standard.

$$|I^-| \leq \frac{S_k \varepsilon_U}{\sqrt{3} U_L} = \frac{S_k * 2\%}{\sqrt{3} U_L} \text{ is the threshold value equation.}$$

The negative sequence current after compensation can be calculated by

$$|I^-| = \frac{1}{\sqrt{3} K} I_A^2 + I_B^2 + 2 * I_A * I_B \cos(-120^\circ + \varphi_A - \varphi_B)$$

Where I_A and I_B are the primary currents, φ_A and φ_B are the power angles respectively.

$$|I^-| = 12.69 < \frac{400,000,000 * 2\%}{\sqrt{3} * 132000}$$

$|I^-| = 12.69 < 34.99$ the system unbalance satisfies the standard.