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**Analysis of Power Quality Issues in Ethiopia Railway Traction System: The**  
**Case of Awash-Woldia Project**  
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**ADDIS ABABA INSTITUTE OF TECHNOLOGY, AAiT**  
**SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING**  
**DEPARTMENT OF POST GRADUATE ELECTRICAL ENGINEERING**  
**FOR RAILWAY SYSTEMS**

**Analysis of Power Quality Issues in Ethiopia Railway Traction System: The  
Case of Awash-Woldia project**

**By**

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## Declaration

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

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## Abstract

The economic growth of any country depends on the utilization of energy resources. This paper presents the traction system power quality issues and methods of improvement about harmonics current, voltage unbalance, and power factor problems. Power quality issues in power systems have been increased due to nonlinear loads. To compensate these problems direct power compensator (DPC) will be proposed in this paper, in which a capacitive coupled hybrid LLC structure is added. The proposed DPC contains back to back converter by giving out the same dc link power and also connected with the secondary side of 132/27.5kV v/v transformer to provide a voltage balance in transmission line. A dual converter with a compensator is employed together with co-phase traction transformers to reduce the current harmonics, telecommunication disturbance, voltage unbalance and power factor problems.

Reduction in direct power compensator (DPC) 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 direct power compensator (DPC) are being explored. To inject the same compensating currents to the traction power supply system, the DC bus voltage of the direct power compensator (DPC) could be much lower than that of a conventional railway power conditioner (RPC). As a result, the cost of the power quality conditioner is reduced.

Simulation models are built with a direct power compensator (DPC) connected to the secondary side of a 132 kV/27.5 kV V/V transformer. Simulation results shows the direct power compensator (DPC) could compensate reactive power, unbalance voltage and current harmonics simultaneously.

According to this research the system voltage and current harmonic distortion without direct power compensator was 6.71% and 26.46% respectively with power factor value of 0.81. But when DPC is used voltage and current harmonic distortion is changed to 0.82% and 1.28% with power factor value of 0.99. Co-phase traction power supply with proposed direct power compensator (DPC) is therefore, suitable for high-speed traction applications.

*Keywords:* – *Co phase traction power supply system, direct power compensator, V/V transformer, minimum dc operation voltage, voltage unbalance, power factor and current harmonics.*

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## List of Symbols

A	Ampere
AC	Alternate Current
APC	Active power compensator
AT	Autotransformer
BT	Boost transformer
C	Catenary
DC	Direct current
DPC	Direct power compensator
ELV	Extra low voltage
ERC	Ethiopia Railway Corporation
NF	Negative Feeder
HS/HC	High Speed/High Capacity
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
$i_{Lh}$	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
SPC	Static power conditioner
SSs	Substations
T	Track
VA, VB, VC	Voltages at primary side of traction transformer
Vinva	Fundamental frequency component of output voltage of Vac-phase converter
Vinvah	Harmonic component of output voltage of -phase converter
Vinvac, Vinvab	Output voltage of Vac-phase and Vab-phase converter
VLC	Voltage across coupling impedance at -phase
VL	Voltage across coupling impedance at -phase
Vac, Vab	Voltages at secondary side of traction transformer
XL	Coupling impedance between Vac-phase converter and supply system
XLC	Coupling impedance between Vab-phase converter and supply system
$\cos\phi_1$	Displacement power factor of traction load.

## **Chapter One**

### **1 Introduction**

#### **1.1 Background and Motivation**

Electrified transportation systems are non-linear systems representing a reality in continuous evolution. 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 [1].

A railway system is perhaps one of the most critical real systems, from the safety and reliability viewpoint, because it must satisfy numerous requirements and presents complex architectural links among its various subsystems [2].

The ac traction system consumes 25 kV, 50 Hz ac supply from 220/132/110/66 kV Extra High Voltage 3-phase grid system through a traction substation in which step-down transformers are employed. The transformer feeds the electric locomotive through contact line system. The contact line system consists of the contact wire, suspension wire and return wire.

The two most common electrification power supply systems for high speed rail are: 1x25kv and 2 x 25kv systems. Such railway systems are usually fed by specialized traction substations which the main designs of them include the selection of a single phase 25 kV or two phase 2x25 kV systems which feed the train sets through the transformers and autotransformers in the traction substations [3][4].

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 [8] [9] [10].

Moreover, the magnitude of power quality disturbance with respect to traction loads dependent on the path of train travels or route profile, the loading of the train and on the power supply configuration [11][12][13]. To facilitate easy load sharing, each transformer feeds a distance of 30 km to one side. Electric locomotives are connected single phase loads in our power system. They create power quality problems due to their dynamic speed and load conditions. Power quality problem refers to a set of disturbances or conditions that produce undesirable results for equipment, system or a facility [14].

The amount of voltage unbalance and negative-sequence currents depends on the topology of the traction power system, in particular, the type of traction transformers used [5]. Typical transformers used include Scott transformers, Woodbridge transformers, three-phase V/V transformers, single phase transformer, three phase transformer impedance-matching balance transformers, etc., [6]. Scott transformers, Woodbridge 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.

The major power quality problems in traction are system unbalance (voltage unbalance and current unbalance), reactive power, harmonics and resonance, negative sequence currents, rail potential and communication impact, low-frequency voltage fluctuation, power factor problems, flicker, etc [8].

#### 1. System unbalance

When the power supply system is balanced, the three-phase voltages or currents are of the same amplitude and the phase differences are  $120^\circ$  to each other. When the system is unbalanced, the three-phase voltages and currents are unsymmetrical.

The unbalance ratio is usually used to evaluate the severity of the system unbalance. A higher unbalance ratio means a larger unbalance or negative-sequence current injecting into the TPSS. Large unbalanced currents may cause considerable negative currents to impact the electrical devices in utility power system. The negative sequence current, which injects into the stator winding of the generator, will induce a 100 Hz current in the rotor winding and it will increase the temperature of the generator, thereby reducing the life span of the generator. Moreover, the relay protection equipment may malfunction due to the large negative current flow, thus reducing the reliability of the power system.

In the traction power substation (TPSS), the trains are single-phase loads that will cause considerable negative sequence currents [8, 21]. Various transformers with different connection styles are designed to mitigate the voltage unbalance.

#### 2. Reactive power

The reactive power is a measure of the energy exchange between the source and the reactive part

of the load. And the power factor can be used to evaluate the presence of the reactive power. A low power factor indicates a large proportion of the reactive power and a high power factor indicates a small proportion of the reactive power.

In the TPSS, the power factor is also low, so the potential capability of the equipment such as the traction transformer is underused, causing the following harms for the upstream power system [23].

- ✓ The output capacity of the generator set, the power supply capacities of power transmission and transformation equipment, and the efficiency of electrical equipment are reduced, while the cost of electricity generation and transmission is increased.
- ✓ The power losses in transmission network increase.
- ✓ The voltage losses in the power transmission network increase. If the power factor is lower than the specified value, in the case of transmitting the same active power, the apparent power will increase, and the corresponding current will increase so that the voltage losses of power transmission network will increase.

### 3. Rail potential and communication impacts

The rail potential increases during the operation of high speed trains (HSTs) [24]. The reason for the railway potential is that the leakage current exists because of the rail contacting with the ballast bed for insulation. The traction current leaks into the earth from the train through the transverse impedance at the contact point of the train and the rail. And then the leakage current flows back to the substation. Because of the existence of the rail-ground resistance, the leakage current results in the rail potential. On the other hand, the induced current produced by the mutual inductance between the rail and the catenary flows through the rail impedance, which may raise the rail potential. If the rail potential is overly high, it will be dangerous for humans and interfere with the communication system.

### 4. Low-frequency voltage fluctuation

The low-frequency voltage fluctuation (LVF) refers to the amplitude fluctuation of a superimposed voltage with a low frequency below 10 Hz (the rated power frequency is 50 Hz). If the voltage fluctuation amplitude is large enough to cause the rectifier protection action, the locomotives will lose the traction ability to move. More seriously, some studies have pointed out that the low-frequency voltage fluctuations may occur under driving condition, which will lead to serious consequences. Therefore, it is necessary to study the mechanism of the low-frequency

voltage fluctuation. LVF is generated when the frequency of the power grid and that of the TPSS are different.

#### 5. Harmonic and resonance

According to the Fourier theorem, the non-sinusoidal periodic electrical quantities can be expressed as an infinite sum of sine or cosine functions. There will be a series of harmonic components whose frequencies are integral multiples of the fundamental frequency. To evaluate the harmonic content of the network voltages and currents, the total harmonic distortion (THD) is put forward.

The power systems may have harmonic resonance frequency because of the interactions between transmission lines and distributed capacitance. As the rich harmonics in the HSR system, the resonance may occur when the harmonic currents injected by the HSTs match one or more system natural frequencies. The resonance may cause instability of the HST tractive drive system and harm the operations of electrified devices, especially the railroad signalling and communication systems [17]. The resonance further increases the distortions of the voltage and the current, thereby increasing the loss of the power grid. The resonance over-voltage may be applied to the transformer, circuit breaker, arrester, and other equipment, thereby damaging the insulation of the electric equipment [18]. The resonance over-current may cause the distortion of the magnetic field, resulting in large electromagnetic radiation, and interference with the communication system and electromagnetic sensitive facilities [19]. Moreover, the resonance may saturate the transformer core, which will reduce the measurement accuracy.

Those above power quality problems initiate vibrations and torque reduction in machines, overheating, extra line losses in transformers and lines, interference problems with neighboring communication lines and also malfunctioning of relays. So power quality studies are given key importance in traction system.

In this paper, a hybrid device combining active and passive compensators, named as the Direct Power Compensator (DPC), is proposed for compensation in co-phase traction power supply. Direct Power Compensator design procedure and its minimum voltage operation as well as the minimum voltage rating achievable is discussed.

## **1.2 Literature Review**

The new high capacity swift-flying trains require good quality power. So the transformers are designed so as to increase the power quality of system.

The degree of the problem depends on the feeding electric railway traction loads, including train movement, tractive profile of electric locomotives, and power-supply scheme [15]. The current harmonics and power quality aspects are very complicated because of the frequent and strong transient regimes.

Several papers discuss about the major solutions for the power quality problems in traction systems. Consequently, some standards and recommendations have been established in order to avoid the potential problems caused.

The negative sequence current suppression can be done with either using transformer with specific connection to balance load current or feeding from high voltage. The voltage unbalance problems caused by the unbalanced current can be resolved by using the following solutions: distribution of different power supply position, distribution of different phases to balance the load, by feeding high voltage power supply or by implementing balanced devices/equipments.

In 1984, Duncan Glover et al. have done train voltage analysis for modeling of supply system and discussed the use of booster transformers and autotransformers in traction system [16]. In 1985, Kneschke summarized the theory regarding unbalance problems [17]. He initiated the discussions on the use of special winding three phase to two phase transformers such as Scott connected, modified Woodbridge-connected, and Le Blanc connected transformers in traction systems to reduce unbalance which include the typical arrangement for rotary balancing equipment, such as synchronous condensers or induction motors, to remove the negative sequence currents from the three-phase system.

In 1993, Fumi et al. proposed a Static Power Conditioner (SPC) using self-commutated inverters in order to solve the problems of AC electrified railway [18]. This paper concluded that the SPC connected at phase A and phase B of a modified.

Woodbridge connected transformer installed at Substations can control active power, reactive power and harmonic currents. Simplified models of electric railway power-supply substations for three-phase power flow studies have been developed and are introduced by Chen in 1994 [19].

In 1999, Olofsson and Thunberg proposed an Energy Management System (EMS) function for optimal starting and stopping of converter units. The focus was on calculating train positions and

power demands [20]. They also proposed the idea of introducing SCADA in traction systems. At the same time Bhargava concluded the electrical configuration of a traction system depends on the rail system, train load, clearance requirement, technology availability, etc. [21]. Hence the power requirements for different traction systems are different and should be such that it is cost effective economical. It provides reliable and efficient operating system without adverting other power company consumers. The paper summarized the different systems of rails, their power requirements and the main power quality problems in U.S., Sweden and Germany.

Active Filters and Harmonic Compensators were introduced for active, reactive power and harmonic compensation, flicker, voltage distortions, etc. [22–25].

## **1.2 Statement of the Problem**

Electrified Railway Systems are very complex systems in which a variety of components (or subsystems) cooperate to realize the transport service for which the traction power system issues will be designed.

Power quality problem refers to a set of disturbances or conditions that produce undesirable results for equipment, system or a facility. The major power quality problems in traction are voltage unbalance, current harmonics, negative sequence currents, voltage distortion, reactive power problems, power factor problems, impulse current, flicker, etc. These problems initiate vibrations and torque reduction in machines, overheating, extra line losses in transformers and lines, interference problems with neighboring communication lines and also malfunctioning of relays. So power quality issues studies are given key importance in traction system.

## **1.4 Objective**

### **1.4.1 General Objective**

The main goal of this research/thesis is to build up power quality compensator and methods of improvement to current harmonics, voltage unbalance and power factor problems on Awash-Woldia traction substation.

### **1.4.2 Specific Objective**

- ✓ To study and evaluate the existing traction system.

- ✓ To design direct power compensator for reducing harmonic distortion and voltage unbalance.
- ✓ To compare conventional railway power compensator and direct power compensator.
- ✓ To evaluate the voltages and currents unbalance in three phase system.
- ✓ To model and simulate the railway system using MATLAB/SIMULINK.
- ✓ Draw recommendations and conclusions.

## **1.5 Scopes**

The power quality analysis in this work was based on the electrical parameters obtained from the proposed Awash-Woldia traction substation. Even though a power quality problem encompasses a wide range of problems, this paper focuses on studying of voltage unbalance, power factor problems and current unbalance in the supply system due to negative-sequence current injected by the traction load. The voltage unbalance will be identified for all Awash-Woldia traction power substations and a range of solutions will be examined. Finally, proposing an optimal solution to reduce the power quality problems is the scope of this paper.

## **1.6 Expected Results and Significance**

Upon successful completion of this thesis, to expect that the proposed co-phase LLC hybrid structure Direct Power Compensator (DPC) and two single phase vv transformers will be reduce the harmonics, voltage unbalance, negative sequence current and reactive power problems.

## **1.7 Methodology**

The methods and techniques that will be followed for the completion of this thesis; that is, for data collection, analysis and interpretation are:

- ✓ Extensive literature survey
- ✓ Data will be collected from Ethiopian rail way corporation (ERC)
- ✓ Mathematical modeling co phase traction power supply with LLC- DPC configuration of two single phase and conventional railway power compensator.

## **1.8 Organization of the Thesis**

This thesis is organized in six chapters.

**Chapter one**

- ✓ Introduction, which provides comprehensible information about the background of the thesis work, statement of the problem, methodology of the research and literature review of the thesis.

**Chapter two**

- ✓ Discussed about railway electrification system, this section provides clear understanding of AC and DC railway electric feeding system and their advantages
- ✓ Discussed different types of power quality issues and its effect in traction system and also power grid.
- ✓ Comparative analysis of traction transformer
- ✓ Overview of AC electrified traction system Awash- Woldia Railway and traction substation line route.

**Chapter three**

- ✓ Describe power supply system and unbalance voltage factor of Awrash – Woldia traction power, traction substation, transmission line.

**Chapter four**

- ✓ Discussed about conventional and proposed circuit configuration and parameter design procedure for minimum DPC voltage operation as well as the minimum voltage rating achievable is discussed.
- ✓ Comparison of conventional railway power compensator and proposed co phase traction power supply with LLC- DPC.
- ✓ DPC Design of Minimum Operation Voltage for Fundamental Compensation and harmonic compensation

**Chapter five**

- ✓ Discussion of simulation results and discussions about proposed co phase traction power supply with LLC- DPC and without direct power compensator.

**Chapter six**

- ✓ This par contains conclusion, recommendation and future work.

## CHAPTER TWO

### 2 Traction Power Supply System

#### 2.1 Railway Electrification Systems and Power Quality

Railway Electrification Systems supply electrical energy to railway locomotives so they can operate without having an on-board prime mover. There are several different electrification systems in use throughout the world. Railway electrification has many advantages but requires significant capital expenditure for installation.

##### ❖ **Characteristics of electric traction**

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 on board. 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.

##### ❖ **Classification of electric system**

Electrification systems are classified by three main parameters:

##### 1) Voltage

Six of the most commonly used voltages have been selected for European and international standardization. These are independent of the contact system used, so that, for example, 750V DC may be used with either third rail or overhead lines (the latter normally by trams).

There are many other voltage systems used for railway electrification systems around the world, and the list of current systems for electric rail traction covers both standard voltage and non-standard voltage systems.

The permissible range of voltages allowed for the standardised voltages is as stated in standards BS EN 50163 and IEC 60850. These take into account the number of trains drawing current and their distance from the substation[9].

## 2) Current

Early electric systems used low-voltage DC. Electric motors were fed directly from the traction supply and were controlled using a combination of resistors and relays that connected the motors in parallel or series.

The most common DC voltages are 600 V and 750 V for trams and metros and 1,500 V, 650/750 V third rail for the former Southern Region of the UK and 3 kV overhead. The lower voltages are often used with third or fourth rail systems, whereas voltages above 1 kV are normally limited to overhead wiring for safety reasons.

The DC system is quite simple but it requires thick cables and short distances between feeder stations because of the high currents required. There are also significant resistive losses. In the United Kingdom, the maximum current that can be drawn by a train is 6,800 A at 750 V. The feeder stations require constant monitoring and, on many systems, only one train or locomotive is allowed per section. The distance between two feeder stations at 750 V on third-rail systems is about 2.5 km. The distance between two feeder stations at 3 kV is about 25 km [9].

## 3) Contact System

Most electrification systems use overhead wires, but third rail is an option up to about 1,200 V. While use of a third rail does not require the use of DC, in practice, all third-rail systems use DC because it can carry 41% more power than an AC system operating at the same peak voltage. Third rail is more compact than overhead wires and can be used in smaller-diameter tunnels, an important factor for subway systems [9].

Third rail systems can be designed to use top contact, side contact or bottom contact. Top contact is less safe, as the live rail is exposed to people treading on the rail unless an insulating hood is provided. Side- and bottom-contact third rail can easily have safety shields incorporated, carried by the rail itself. Uncovered top-contact third rails are vulnerable to disruption caused by ice, snow and fallen leaves [9].

Multiple electrification systems are used throughout the world; Table 2.1 shows the characteristics of the most used.

Table 2.1 World Railway Electrification System and Electrified Distances [10]

System Type		Distance (km)	Main Countries	
DC	Less than 1.5 kV	5 106	Germany, UK, Switzerland, USA	
	1.5 kV to 3 kV	22 138	France, Spain, Netherlands, Australia	
Single-phase AC	More than 3 kV	78 276	Russia, Poland, Italy, Spain, Belgium	
	50 Hz or 60 Hz	Less than 2 kV	245	France, USA
		20 kV	3 741	
		25 kV	84 376	Russia, France, Portugal, India, China
		50 kV	1 173	USA, Canada, South Africa
	25 Hz – 11 kV to 13 kV	1 469	USA, Austria, Norway	
	16.7 Hz	11 kV	120	Switzerland
15 kV		35 461	Germany, Sweden, Switzerland	
Three-phase AC		43	Switzerland, France	
Unknown		3 668	Kazakhstan, France	
Total		235 186		

Consequently, the existence of certain structures is common in all the systems, to protect the power transmission grid from defects, and assure the quality of the energy provided to the railway locomotives.

**i. Traction Power Supply Systems**

These systems include traction power substations, which are located along the line at planned locations. The substations are connected to the power transmission grid and their purpose is to adapt the proper voltage to supply the electric locomotives, as well as to protect the power transmission grid against faults and other electrical defects.

**ii. Traction Power Distribution Systems**

These systems consist of the overhead contact system, mainly used in AC systems, whilst the DC systems usually operate with the third rail. Both systems are used to feed electrical energy to the locomotives and need transformer substations to convert the voltage to suitable levels. They also have capacitor banks to improve the power factor. Moreover, switching stations and, in some cases, autotransformers are required.

**iii. Traction Power Return Systems**

These system consist of the running rails, impedance bonds, cross-bonds, overhead static wires, return conductors and the ground. They guarantee a safe path, of the current supplied to the

trains, to the substation.

**iv. Loads**

Loads include electrical locomotives and rail buses that receive the electrical energy through the pantograph or the third rail to their motors. The current return path is through the rail, which is connected to the ground, and in some cases also through a feeder rail.

The railway’s electrical substations play an important role in the process of supplying electrical energy to the trains. As stated above, the substations are located along the track and fed from the transmission or distribution grid. The distance between each substation, depends on various factors such as the voltage level, trains, and the surrounding electrical traffic.

Despite the increase of AC railways systems in the last decades due to the improvement of power electronic components, the DC systems are still in use in several countries, such as Italy, Belgium, and Poland.

**Advantages of AC and DC Railway Systems**

Table 2.2 presents the major advantages of both topologies.

<b>AC Railway Systems</b>	<b>DC Railway Systems</b>
Advantages	Advantages
Light Overhead Catenaries – lower current intensity	DC train is lighter and less costly
Larger distance between Substations	DC motors are better suited for frequent and rapid accelerations of heavy trains
Simplicity of substations design – No need of rectifiers or rotary converters in case of the 50 Hz systems	Conductor rail less costly, both initially and in maintenance
Lower cost of Fixed Installations	No electrical interference with overhead communication lines
Higher coefficient of Adhesion <sup>1</sup>	
Higher Start Efficiency - the AC motors offers a more flexible and smooth start	

Due to advantages of speed/torque control of AC engines, the AC locomotives have natural higher efficiency reaching 90% in the modern AC locomotives.

## 2.2 Alternate Current Systems

### 2.2.1 Direct-Fed System

The overhead contact system supplies electricity to the locomotives at 25 kV AC, 50 Hz, from substations which are located at frequent intervals, alongside the track. The feeding substations are supplied with single-phase power from traction substations strategically located 35 to 60 km away from each other depending on several factors such as the intensity of traffic and the load introduced by locomotives. Compared with DC-powered systems, which operate at lower voltages, the AC systems provides the same acceleration to the train with the need of a lower current, therefore, lower losses [26].

To keep the balance in the three phase grid system, phase-to-phase changeover sections are installed in the catenary system to separate sections that operate at different phases, as can be seen in Figure 2.1 Power is provided by the grid system across the different phases at adjacent substations in cyclic order. Moreover, switching stations are needed in case of a substation failure [26].

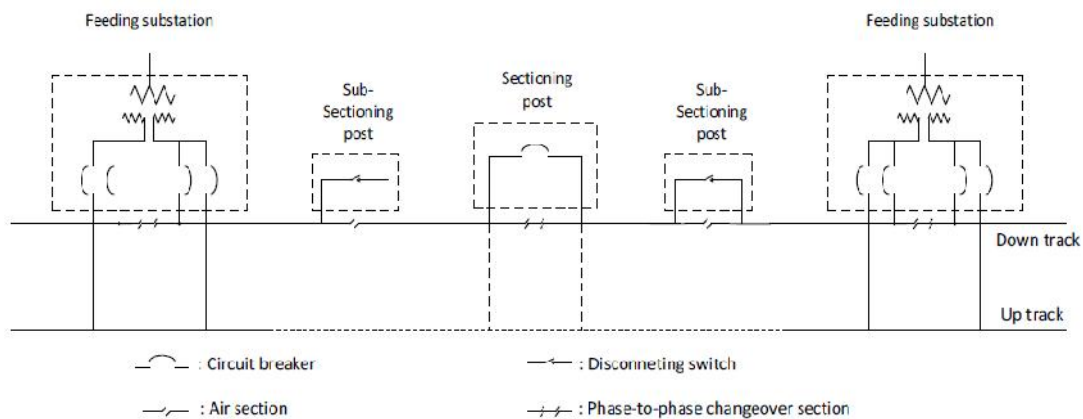


Figure 2.1 Structure of an AC Feeding Railway System [26]

The power transformer in the substations provides 25 kV in the secondary winding, with one of the terminals connected to the catenary system and the other terminal connected to the ground and to the traction return conductor. For this reason, the system is called as 1x25 kV.

Figure 2.2 represents the electrical circuit of the 1x25 kV systems with the representation of the current ( $I_c$ ) that flows in the catenary system and returns ( $I_r$ ) to the substation in the traction return conductor.

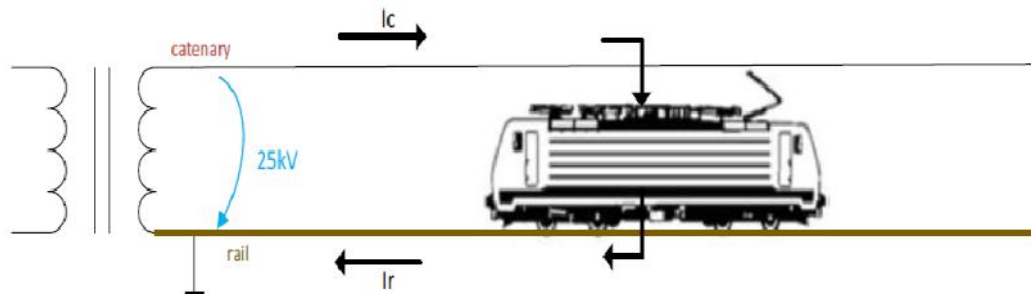


Figure 2.2 1x25 kV Railway Electrification System [26]

### 2.2.2 Autotransformer-Fed System

Similarly to the Direct-fed System, phase breaks, feeding points and switching stations are also installed due to the reasons previously explained. However, the 1x25 kV suffers from voltage drops in the catenary, sometimes reaching the 5 kV, when the distance to the feeding substation is high. Figure 2.3 represents a scheme of the Autotransformer-fed System that aims to solve this issue [26]. In the substation a 50 kV is split into a dual 25 kV supply using a three winding transformer. One winding supplies 25 kV between the catenary and the rails as the 1x 25 kV systems, thus allowing the circulation of 25 kV locomotives in the autotransformer-fed system. The other winding is connected to a feeder cable parallel to the catenary. Since the feeder-to-rail and catenary-to-rail voltages are both 25 kV and in antiphase, the system earned the name 2x25 kV.

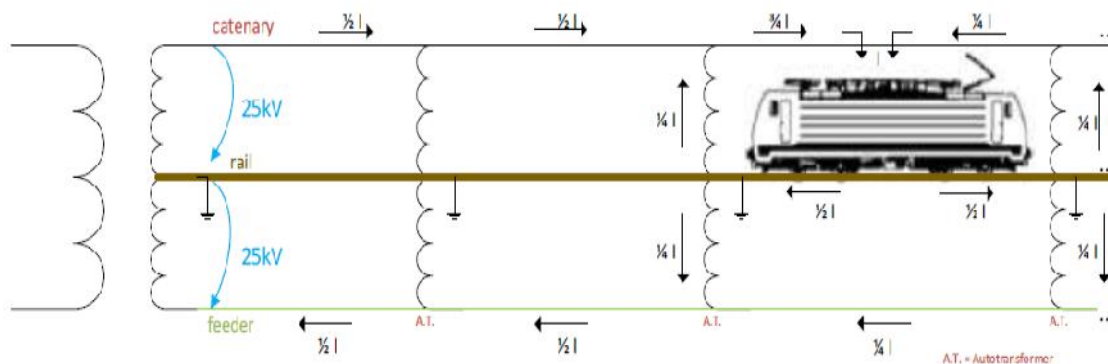


Figure 2.3 2x25 kV Railway Electrification System [26]

As presented in Figure 2.3, if considering that the load current drawn by the train is “T”, then

each phase, catenary and feeder carries half of the load current “ $I/2$ ”. The autotransformer forces an equal distribution of the current along the track, and the currents split and merge only in the section where the train is located. Note that the rails carry less than the full load current in opposite direction of the train, and that it is the only section where the rail carries current. Also, the catenary never conducts the full load current. The feeder provides the cancellation of inductive interference except in the section where the train is located, since it carries a current equal but in opposite to the current in the catenary. The inductive interference, generated by the magnetic field, is present during both normal operating conditions and fault conditions. The inductive interference caused by an energized ac power transmission line is significant in the cases of single phase fault. In normal operating conditions, the balance of the three-phase currents causes no substantial effect. In this cause only a small inductive interference present, due to the geometrical asymmetry of the electromagnetic field. On the other hand the inductive interference generated by ac electric traction line is significant even in normal operating conditions, since these lines are by definition asymmetrical.

Due to the feeder and the autotransformers, there is a substantial reduction of the return current. Therefore, it is possible to provide more power to the locomotives which is an advantage for high speed trains. The 2x25 kV systems additionally allow a higher distance between substations, lower emission of electromagnetic radiation and smaller equivalent impedance when compared to the 1x25 kV systems.

### **2.2.3 15 kV 16.7 Hz Systems**

The 15 kV 16.7 Hz systems are used in several countries in Europe from the time when those countries began high-voltage electrification at 16.7 Hz. In some regions of Germany, Austria and Switzerland the system is supplied by several plants such as nuclear power plants and hydroelectric power plants that are either dedicated to generate 110 kV at 16.7 Hz single phase, or have special generators for this purpose. The neutral is connected to a safety ground through an inductance as is common practice in the distribution power systems. Therefore, the voltage of each conductor with respect to ground is of 15 kV. At the transformer substations, the voltage decreases to 15 kV AC and then supplies the overhead line [26].

### **2.2.4 Direct Current Systems**

Tramways and metropolitan railway systems usually run on Direct Current. In the substations a rectifier is needed for AC-DC conversion, usually a 12 pulse rectifier featuring two sets of 6-pulse rectifiers connected in series or in parallel, thus minimizing the current harmonic distortion. The lower supply voltage of these systems, which consequently draw higher currents; result in thicker and heavier overhead line and pantograph that has to be pressed more firmly against the overhead line; resulting in greater wear. The Metro, which operates with lower voltages, usually 750 V, is supplied through a thick conductor running along the track, called third rail.

Section and tie posts are sometimes used to prevent voltage drops on double tracks where substations are located apart from each other. Due to the higher current in the conductors, the substations in DC Systems are only distanced 3 to 5 km from each other, in the case of heavy suburban traffic supplied with 750 V, and 40 km to 50 km for main lines operating at higher voltages such as 1.5 kV and 3 kV.

### **2.3 Other Systems**

Multi-voltage locomotives are another option to solve the several voltage standards. These locomotives are prepared to operate in AC and DC systems and with different levels of supply voltages.

The well known Train à Grande Vitesse (TGV) Trans Manche Super Train (TMST) operates from Brussels to the south of London, and crosses different electric systems that operate a 25 kV, 50 Hz AC and 3 kV DC, both with overhead lines. For this reason, there is the need to use two pantographs, which are switched on or off when the change of system occurs, and the use of transformers and power electronic converters to adapt the supply to the traction motors [8].

The TGV TMST, working in AC, has a main transformer that is energized and reduces the 25 kV, before sending it to be rectified. At this point, auxiliary inverters acquire sufficient energy for the hotel electric power, and the inverters in the motor block acquire the energy needed for traction. This energy is converted into three phase AC to feed the traction motors.

When the train is running in a DC system (1.5 kV or 3 kV), the DC input is supplied directly via a different main breaker before being filtered, and then the previously mentioned inverters are used to convert the DC system to an adequate AC system, used to feed the traction motors.

There are other types of multi-voltage locomotives that can operate both at 25 kV, 50 Hz AC, or 15 kV, 16.7 Hz AC, from overhead lines. In this case, there is the need to use two transformers for each frequency [8].

The electric battery locomotives are another type that is being introduced in recent years replacing some diesel powered locomotives. This technology has improved but is still far from experiencing great performances, hence this type of locomotives are only being used in industrial environments such as mines, and local deliveries in towns and large industrial plants. This type of trains, with low maintenance and free from smoke, are still very limited due to the small capacity of the batteries.

The major advantage of this technology is the absence of infrastructures along the track to provide energy, as in the conventional AC and DC Systems, thus allowing a considerable reduction of costs.

## **2.4 Power Quality**

### **2.4.1 Introduction**

What exactly is power quality? This is a question with no fully accepted answer, but surely the response involves the waveforms of current and voltage in an ac system, the presence of harmonic signals in bus voltages and load currents, the presence of spikes and momentary low voltages, and other issues of distortion.

Perhaps the best definition of power quality is the provision of voltages and system design so that the user of electric power can utilize electric energy from the distribution system successfully, without interference or interruption. A broad definition of power quality borders on system reliability, dielectric selection on equipment and conductors, long-term outages, voltage unbalance in three-phase systems, power electronics and their interface with the electric power supply, and many other areas. A narrower definition focuses on issues [26].

Why is power quality a concern, and when did the concern begin? In the last 50 years or so, the industrial age led to the need for products to be economically competitive, which meant that electrical machines were becoming smaller and more efficient and were designed without performance margins. At the same time, other factors were coming into play. Increased demands for electricity created extensive power generation and distribution grids. Industries demanded larger and larger shares of the generated power, which, along with the growing use of electricity

in the residential sector, stretched electricity generation to the limit. Today, electrical utilities are no longer independently operated entities; they are part of a large network of utilities tied together in a complex grid. The combination of these factors has created electrical systems requiring power quality [28]. The difficulty in quantifying power quality concerns is explained by the nature of the interaction between power quality and susceptible equipment. What is “good” power for one piece of equipment could be “bad” power for another one.

Two identical devices or pieces of equipment might react in a different way to the same power quality parameters due to differences in their manufacturing or component tolerance. Electrical devices are becoming smaller and more sensitive to power quality aberrations due to the proliferation of electronics. For example, an electronic controller about the size of a shoebox can efficiently control the performance of a 1000-hp motor; while the motor might be somewhat immune to power quality problems, the controller is not. The net effect is that we have a motor system that is very sensitive to power quality. Another factor that makes power quality issues difficult to grasp is that in some instances electrical equipment causes its own power quality problems [28].

The quality of the electric power supply is currently an important issue in relation to public electricity systems. Poor power quality causes unnecessary disturbance leading to malfunction of plant and even loss of load. Therefore commercial pressures to ensure adequate power quality and there are international standards in place to define the maximum permissible disturbance levels. On systems having an open energy market the regulator, who may be perceived to be the ally of the consumer, often sets power quality.

One function of a power quality standard is to fix a target disturbance limit that is acceptable to the equipment user and manufacturer and also the energy supplier. Different conditions exist on private networks which are used by a restricted set of loads. In these systems it is not appropriate to use standards intended for public supplies since many of the normal loads connected to public systems may not be present [19].

Among the important problems taken into account in railway electrification studies, the evaluation of the mutual influence between traction loads and three phase power supply public networks is of a basic importance [18].

The railway electrification load is one of the worst kinds of load for an electrical utility to supply. The only load which gives more challenge to the utility is arc furnace load. The railway

electrification load is highly intermittent, irregular, low load factor and poor power factor. The railway electrification load creates system voltage and current unbalance, generates harmonics and results in voltage flicker.

Because of the above characteristics, the railway electrification load generally requires oversized substation facilities. It stresses the electrical utility equipment more and also causes interference with other customer loads and often complaints from the other utility customers, etc. The railway electrification load is fed on single or two phases of the electrical utility system. This load has always been a challenge to utility engineers and results in increased electrification cost to the railways. Some recently electrified railroads and the utilities are using extremely tight power quality standards to maintain acceptable power quality to other customers. Some of the common power quality characteristics of the loads are discussed in this paper.

With the rapid development of electrical railway, the train speed continuously improving, the electric locomotive traction power also increase exponentially. The electric locomotives in operation, in addition to the absorption of main frequency power from the power grid, also inject the harmonic and negative sequence current into the power grid. Research shows that the harmonic and negative sequence has a negative impact to the power system [8].

At present, the electrification of the rail traction power supply system, recognized with the following characteristics:-

Electric Railway traction power supply system uses two-phase power supply, and produces the negative sequence component in power system.

Using electric traction Rectifier electric locomotive (AC - DC), the locomotive pantograph in the locomotive with frequently speed-level adjustment, switching and sliding flow will generate electric arc due to offline, the system will generating high harmonics mainly based 3, 5, 7 order [27].

Power supply of power supply circuit switching or Electric locomotive through the area without electricity, traction transformer will have a larger inrush current because of the no-load switching.

Therefore, electric railway will have an impact on the power grid system, the main ones are:

- ✓ Power quality decline;
- ✓ Have additional loss, vibration increases large and the heat increase, in the internal of the rotation motors and the transformer .and generators in particular;

- ✓ Increase system power loss, interfere the normal operation of telecommunications equipment;
- ✓ Caused frequent start or lose the lock of the relay protection containing negative sequence components or composite voltage components, may causing the malfunction of phase-difference High-frequency protection and the protection of generator negative sequence current;
- ✓ Harmonics may also trigger system inductors, capacitors resonance, and amplified the resonant, threat the security of power grid [17].

It is well known that a.c. traction loads are fed by single-phase transformer substations. The primary winding of the transformer is connected (phase -to-phase) to a high voltage three-phases network, and then gives rise to the flow of negative sequence currents and therefore to the presence of unbalanced system voltages in three phase network.

There has been for many years an almost universal adoption of transformer tap changers and diode rectifiers bridge (before) and thyristor converters (after) for the traction power units in a.c. locomotives, in order to allow the utilization of direct current traction motors. The currents absorbed by trains flowing in the contact lines and in the primary network branches are then non-sinusoidal and distort the system voltages both in single phase traction system and in three phase network. Phase-angle control of thyristors produces in addition poor power factor during acceleration phase [17].

Modern locomotives, using pulse-width modulation are capable of guaranteeing almost unity power factors through their speed range. The harmonic disturbance is also much more reduced because of the disappearance of low frequency characteristic harmonics. However, even if problems will tend to come down as a consequence of the technological development of the locomotives, we must consider that the lifetime of the locomotives is about 30-40 years, and then the old generation locomotives will be on duty long [17].

The need of predetermining the conducted disturbance in the early design stage, in order to verify the feasibility of a 25 kV single-phase railway electrification, produced in the last 30 years researches and studies, which contributed to the knowledge development in the power quality field .

Less attention has been given in the past to disturbance problems in the d.c. traction system, which form the other main railway electrification typology. The major source of disturbance is

the harmonic distortion caused by the a.c./d.c. converters located in the traction substations. However in the past the problem has not produced special constraints in railway electrifications, mainly because the power demanded by single converter substations was maintained, as a rule, under 5-10 M. The growth of the electric power demand necessary to face the increase both in speed and in weight hauled by single trains, as well the traffic increase along the main lines, made the harmonic pollution aspect more significant than in the past. The constraints imposed by power standards together with the increasing attention given to the power quality aspects have recently determined, for d.c. electrification feasibility studies too, a careful analysis of the technical solutions adequacy as far as concerns disturbances in the public network [28].

Moreover, it is important to underline that the electrification of a d.c. 3kV (or 1.5 kV) line involves, in comparison with an a.c. line, the realization of a higher number of traction substations with a smaller unitary power. Therefore, while the a.c. electrified traction systems are fed, as a general rule, by HV three-phase networks with high short circuit levels, the d.c. systems are often supplied by means of relatively weak HV grids and MV distribution networks as well. It is then evident that the disturbance caused by d.c. electrified traction systems, even if smaller, is much more distributed in the power grid so that not negligible power quality problems can arise in case of modernization and development of existing lines supplied by networks having low short circuit levels. Furthermore for both electrification systems the sudden changes in traction power demand may cause voltage fluctuations and flicker [18].

The growing complexity of the AC and DC traction systems in terms of both new technologies and automation requires a careful control of the Power Quality disturbances they cause.

In particular, the AC traction systems can cause in the three-phase supply network:

Voltage unbalances at fundamental frequency, as a consequence of different active and reactive phase powers absorbed at substation terminals; voltage and current distortions, due to the AC traction locomotives which use controlled converters.

Slow voltage variations, due to the time-varying nature of the phase-powers. The DC traction systems can cause in the three-phase supply network voltage and current distortions, due to the AC/DC static converters of the traction substations.

In addition, inside the traction systems there are voltage and current distortions due to the controlled-converters aboard the locomotives and, in case of DC traction systems, due to the AC/DC substation converters [27].

## **2.5 Power Quality Problems in Electric Railway**

### **2.5.1 Voltage Unbalance**

The most restrictive criteria among voltage unbalance, voltage flicker or harmonics is the voltage and current unbalance. Voltage unbalance in an electrical utility system is caused by unbalanced load or the untransposed transmission system.

Since electrified trains are single phase loads inherently, connection of these time varying (as much as they are high speed) unbalance (as much as they are high power) loads to three phase power system will lead to huge power unbalance [16].

The traction loads are supplied by two phases of the three phase power system through dedicated substations operating at industrial frequency. The degree of voltage and current unbalances depends of the train motion, load condition and power system supply configuration.

The analysis of the problems regarding unbalance covers two aspects:

- ✓ The influence upon the operation characteristics of the plants supplied by unbalanced voltages;
- ✓ The influence on the economical and technical indicators of the transmission and distribution network, as well as on the generator systems.

In the first case, the utility must ensure to the customer the agreement of the voltage unbalance indices within the standardized limits. The customer is interested to monitor the supplying voltage for obtaining the information regarding unbalance and the agreement with the stipulated limits.

In the second case, the customer must ensure the correspondence of the produced disturbances within the allocated limits, established by the utility, as condition for power quality assessment to others customers in the electrical network. The utility is interested to survey the electrical currents of the customer and to verify the correspondence of the unbalance within the allocated limits.

The unbalances affect the operation of the supply system and of various equipments connected to it. The induction motors, fed by an unbalanced system of voltages, present lower efficiency, overheats and increase the real power losses, so a significant loss of the life duration. The voltage unbalance produces also high frequency pulsation torques and consequently vibrations and noises during operation. Moreover, the influence of the voltage unbalance upon the

operation conditions of the generators present in the power system is very important for limiting the overheating of the rotor windings. Voltage unbalance may also cause the undesired tripping of relays, influences converters and PWM drives operation due to the amplitude or phase angle unbalance. The capacitor banks, connected to a power system with unbalanced voltages contribute itself to the aggravation of the unbalance. In fact, on the phase with the smallest phase voltage amplitude, the smallest reactive power is associated and so the smallest improvement of the power factor [15].

Allowing for 1 percent ambient unbalance from other sources, the voltage unbalance from the railway electrification load will have to be limited to 1 percent. Some utilities may allow higher ambient voltage unbalance. Also some utilities have reported consumer complaints when 2 percent imbalance was use. While designing substations and the electrification system for railway electrification, it is always desirable to measure the ambient voltage unbalance over a period of a couple of days. Also the unbalance should be compared with the short circuit duty available to actually calculate the load in the MW causing this ambient voltage unbalance [16].

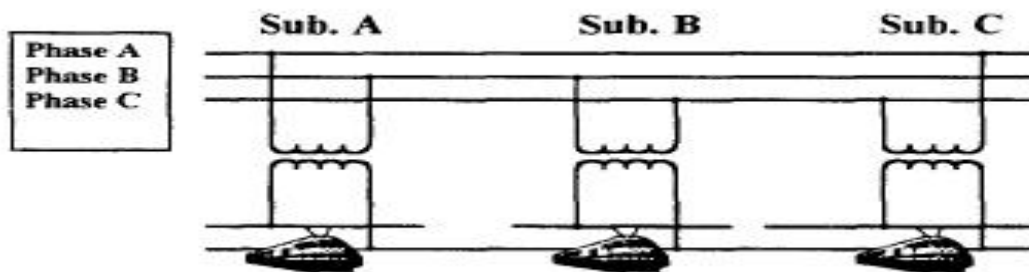


Figure 2.4 Power Distribution System for Adjacent Substation E.R [16]

The typical load fed from a railway electrification substation was estimated to be about 60 - 100 MVA. This would allow about four trains within the substation beat. Assuming that a 100 MVA load has to be fed from two phases of a substation in Figure 2.4 and also assuming that the ambient unbalance is 1 percent, and then the short circuit duty must be more than 10,000 MVA to limit the voltage drop to less than 1 percent imbalance [16].

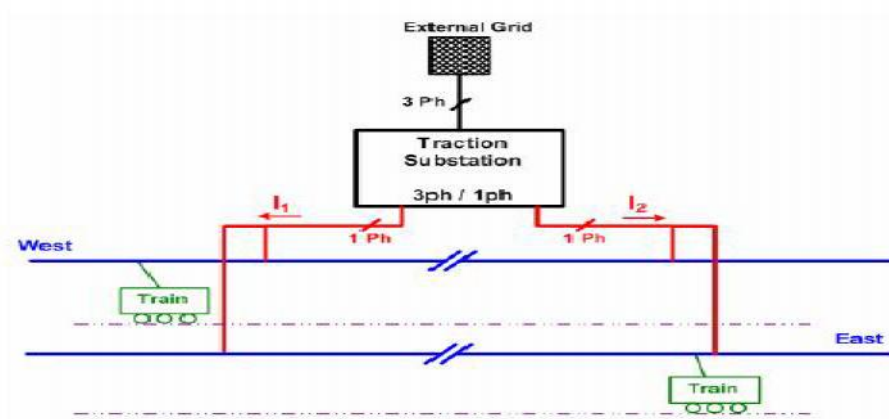


Figure 2.5 AC traction substation feeding two sides of catenary in west and east directions [14]

The simplified well known formula for evaluating the voltage unbalance factor,  $K=P/P_{cc}$  (where  $P$  and  $P_{cc}$  are respectively the power in MVA of the single-phase traction load and the three-phase short circuit capacity at the H.V. terminals) is not in general applicable in cases in which more A.C. traction substations are mutually influenced because of the structure of the power supply network. Three-phase load flows are then usually performed. The traction load values for the unbalance calculations are determined selecting the worst likely loading conditions. These are the instants in which the differences in the power absorbed by the three pair of phases are at a maximum [18].

### 2.5.1.1 Unbalance Limits

In many important ac railway electrification studies a limit of 1-1.5 % for the long duration voltage unbalance and up to 2% for time interval shorter than 10 min has been assumed as acceptable. The above mentioned European Standard requires similar compatibility levels [18].

### 2.5.1.2 Unbalance Factor

The maximum voltage unbalance factor should be calculated at the connection points of the main traction substations to the utility network, which is dependant to the loading characteristics of the traction system. This calculation should be done for controlling and limiting the unbalance magnitude and duration. Most utilities around the world use the voltage unbalance factor as a simple measure to limit the unbalance injections at the connection points of the traction substations. Table 2.3 shows the formula for calculating the voltage unbalance

factor injected from the traction substations to the utility grid for some transformer configurations. Possible changes of network configuration, whether it is the changes within the traction supply system due to load transferring or the daily, weekly or seasonal changes in the utility grid, should be carefully considered in the voltage unbalance calculation [14].

Table 2.3 Voltage unbalance factor injected from the traction system to the grid at the connection point

Transformer Configuration	Voltage Unbalance Factor
Single Phase	$u_u = \frac{S_L}{S_{CC}}$
V-V, Three Phase	$u_u = \frac{S_L}{S_{CC}} \left( 1 + \alpha^2 \frac{S_{L1}}{S_{L2}} \right)$
Scott, Leblanc	$u_u = \frac{S_L}{S_{CC}} \left( 1 - \frac{S_{L1}}{S_{L2}} \right)$

### 2.5.1.3 Unbalance Restricting Solutions

In order to minimize the voltage distortion, traction loads are usually connected to an external grid of 100 kV or higher, however, this also makes them electrically very close to utility generators thereby raising concerns for excessive negative sequence injection into utility generators.

The most applicable and effective solution is the repetitive choosing the feeding phases of the traction substations so that the whole network would be balanced if all the traction substations have the same load at the same time. This procedure is applied for the different transformer arrangements in the traction substations which have been described below [14].

#### 2.5.1.3. (1) Single Phase Transformers

In this arrangement of the traction substations, a single phase transformer is used to feed the traction system which is fed through two phases. One of the two output phases is connected to the catenary feeding the trains along the track and the other is connected to the running rails as the negative return current path. The structure of such an electrification system is shown in Figure 2.6

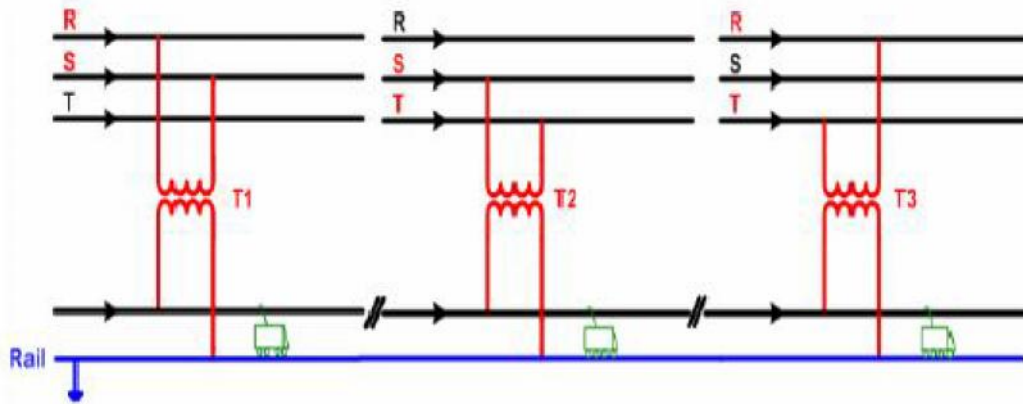


Figure 2.6 Traction electrification systems with single phase transformer arrangement [14]

Studying the different loading schedules for the traction system for this arrangements prove that if the three in after traction substations have almost the same loading, the voltage unbalance can reduce greatly and it might be even zero, but in the worst case, the maximum voltage unbalance of the AC network reaches 12.8% [14].

### 2.5.1.3. (2) Two Single Phase Transformers

The principle of this arrangement is dividing the single phase load between all the three phases resulting in decreasing the voltage unbalance of the AC network. Therefore, two single phase transformers are used as seen in Figure 2.7 which each feeds half of the whole power demand. Studying and calculating the voltage unbalance factors for this transformer arrangement proves a maximum of 6.5% unbalance which is almost half of utilizing a single transformer like the previous and zero, in the case of equal loading of all the transformers [16].

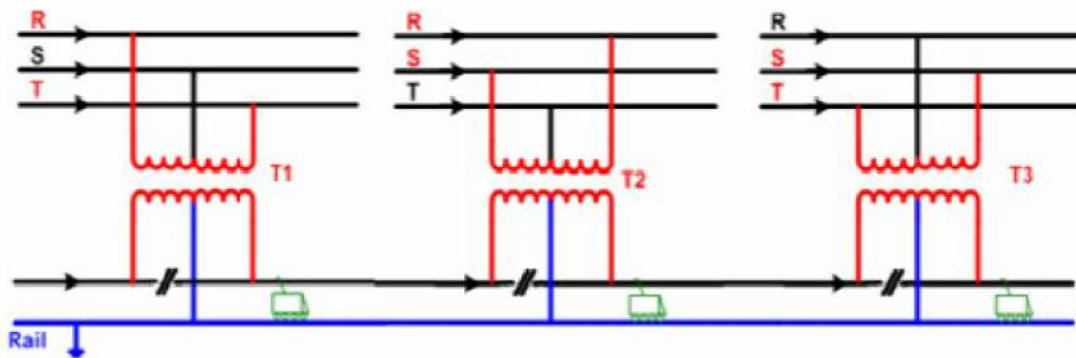


Figure 2.7 Traction electrification systems with Two single-phase transformer arrangement [14].

### 2.5.1.3. (3) Star-Delta Transformer

In such a structure, a three-phase transformer is utilized in the traction substations with the primary winding as Star and the secondary as Delta. The feeding phases of the primary winding are changed respectively so that the whole power network seems balanced. The schematic structure of such an arrangement is shown in Figure 2.8. The maximum voltage unbalance factor of this configuration is about 8.6% but can be reduced to zero in the case of equal loading of all of the transformers [14].

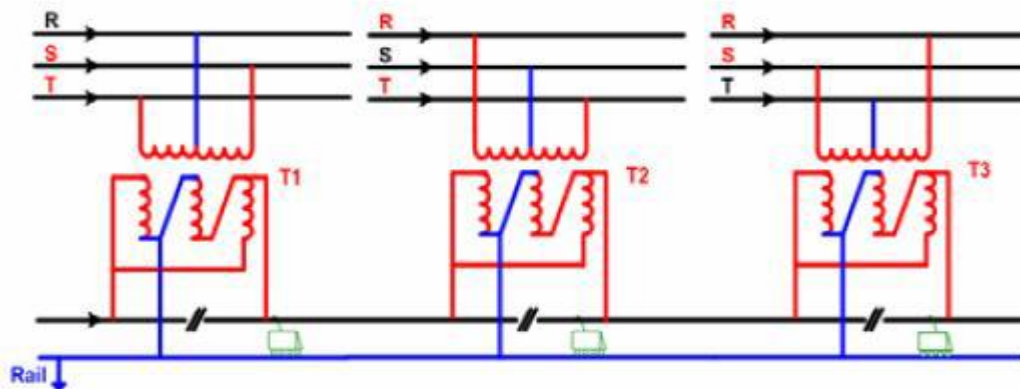


Figure 2.8 Traction electrification systems with three-phase Star-Delta transformer arrangement [14]

### 2.5.1.3. (4) Star-Star Transformer

In this configuration, a three-phase transformer is utilized in the traction substation with a Star-Star winding but the winding of the secondary side is irregular, i.e. the winding on one of the phases on the secondary has twice as many turns as the windings of other phases on that side. This causes a reduction in the voltage unbalance as the highest voltage unbalance factor is equal to 11%. The structure of this configuration is shown in Figure 2.9 [14].

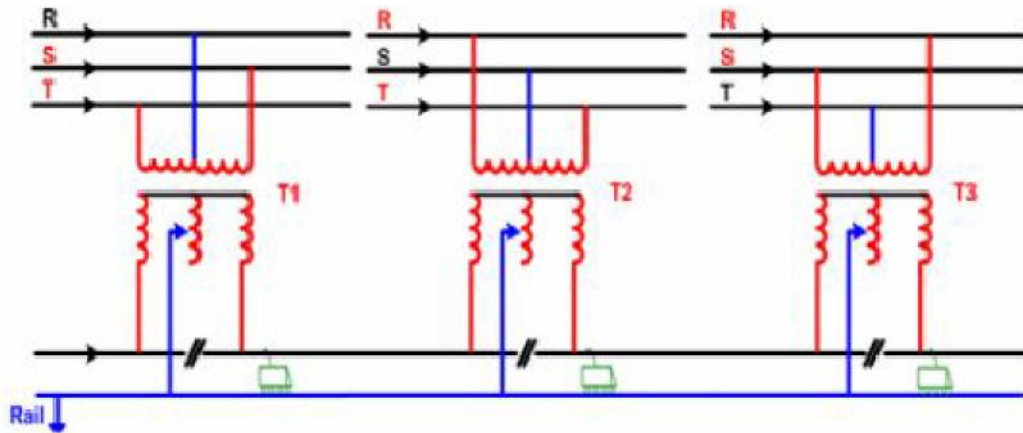


Figure 2.9 Traction electrification system with three-phase Star-Star transformer arrangement [14]

### 2.5.1.3. (5) Scott Transformer

Utilizing Scott transformers is one of the most popular ways of reducing the unbalance problems in traction substations which can transfer the load side balanced two-phase system to the balanced three-phase AC network. The schematic structure of such an arrangement is shown in Figure 2.10. The maximum voltage unbalance factor of this configuration is about 10.24% but can be reduced to zero in the case of equal loading of all of the transformers [14].

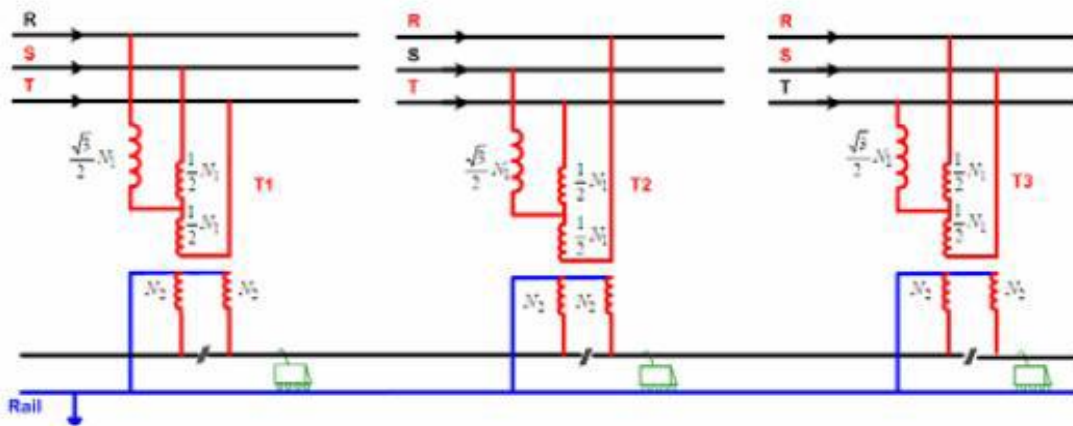


Figure 2.10 Traction electrification system with Scott transformer arrangement [14]

### 2.5.1.3. (6) Leblanc Transformer

Another transformer configuration for reducing the unbalance problems is utilizing Leblanc transformers in traction substations which can transfer the load side balanced two-phase system

to the balanced three-phase AC network. But due to the designing characteristics of Leblanc transformers in comparison with the Scott, Leblanc transformer configuration can be said to be the most utilized system in the world. The schematic structure of such an arrangement is shown in Figure 2.11. The maximum voltage unbalance factor of this configuration is about 6.69% but can be reduced to zero in the case of equal loading of the entire transformer [14].

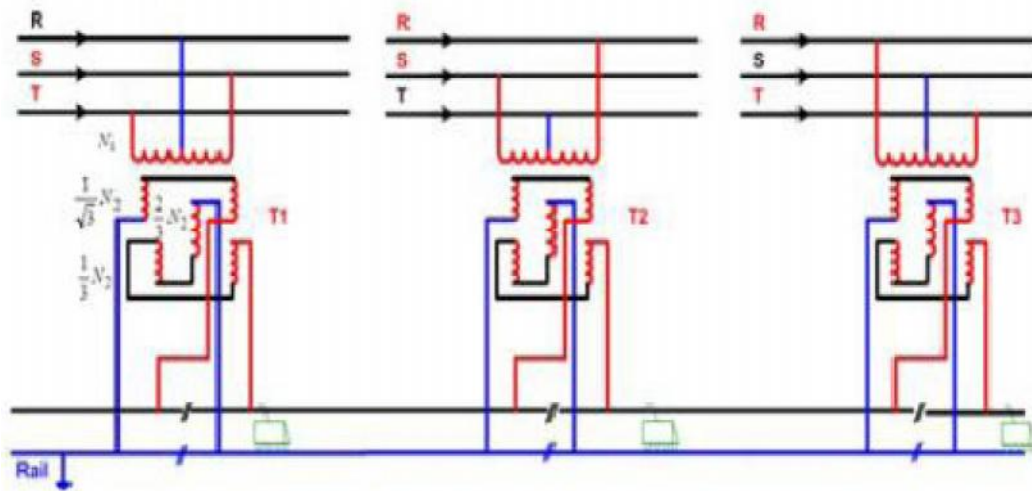


Figure 2.11 Traction electrification system with Leblanc transformer arrangement [14]

#### 2.5.1.4 Choosing Solution of Unbalancing Problem

As a result of this research traditional phase-rotation technique with symmetrical transformer is proved to be the only practicable solution at present for balancing the load among three phases, which splits the overhead feeder into many segments, each of 20-25km long, and a phase insulator about 30m long is used between two segments that belong to difference phase. The balancing effect can get at the equivalent common coupling point of these two systems, when every phase has the same load [16].

But unfortunately it is not enough balance it enough level for public utility system. Because of traction load's distribution and randomness, it is almost impossible to get satisfied balancing effect.

Furthermore, when a train passes the insulator, a serial of operation must be taken and the power supply is interrupted. The existing of phase insulator becomes the main drawback of this method, which limits the trains to exert its rating power and speed, especial in the case of heavy or high-speed transportation.

To achieve better balancing effect, asymmetrical transformers such as the Scott, Leblanc, impedance matching balance transformer, etc, are widely used in railway. When the loads on the two arms that supplied by these transformer are the same (amplitude and phase), the transformer's input current will be balancing.

One leg of this case study balancing of unbalanced power that is why two single phase will be used in proposed method which is one of the symmetrical transformers [14].

### **2.5.2 Voltage Fluctuation**

From instantaneous power demand values voltage dips (in %) can be easily calculated and plotted as a function of the number of occurrences. IEEE Std. 141 indicates for the quantities the border line of flicker irritation. It may be noted that for the new locomotives with choppers or inverters the starting current changes smoothly. In d.c. electrified systems a step change of the current may then occur only for a switching-off of the load current. In normal conditions this event happens when the current is lesser than the maximum current of the locomotive so that the rapid voltage change is not critical. In a.c. electrified systems this disturbance may be more significant due to the passage of trains under line sections fed from different single-phase transformers, which must be insulated because of the phase shifting between the single-phase supply voltages.

The step change of the current may occur when the traction power demanded by a train is at the maximum (the worst case is a train with two locomotives). It can be observed that the disturbance is basically dependent on the short circuit level as for the voltage unbalance [15]. The design criteria adopted for the power supply system to comply with the limits required for the unbalance are usually able to maintain voltage fluctuations below the permitted levels as a natural consequence [18].

When considering the phenomena that affect power quality the effect of particular waveform features on system loads is important. The features may not be the same as those that disturb public electricity supply systems. Traction systems are subject to significant load changes giving rise to frequent voltage fluctuation of up to and beyond 5 per cent. While a frequent 5 per cent voltage fluctuation would be unacceptable to public electricity supplies, traction vehicles are immunized to deal with voltage change and they do not experience significant disturbance. On the other hand the voltage level is well controlled in public electricity supplies. However, to

maximize utilization, voltages within typical 25kV traction systems may be allowed to vary from 29kV to 17.5kV. Without a wide voltage operating range many traction systems would not be economically viable. However the consequence of allowing the voltage to remain at a low level is lower vehicle performance and excessive system power loss. Therefore low system voltage is a more important power quality issue to traction supplies than voltage fluctuation [16].

### **2.5.3 Load Factor**

The railway electrification load factor is dependent on the train frequency and usage. The typical load factor for a substation is about 15-25 percent depending on the, train frequency. Compared to the other utility loads, this is a poor load factor and the energy sales are much lower compared to the peak load demand. This type of load thus results in excessively high investment costs for the utility [16].

### **2.5.4 Voltage Flicker**

The traction power demand on utility system rapidly changes as trains accelerate and decelerate, as they encounter track gradients, and as they enter and leave catenary feeding sections. The quick variation of the traction current results in sudden variation of voltage at the substation connection point and, to a lesser degree, on other utility busbars.

When selecting a utility feed point for supply of traction power substations, the available fault level at the tapping point needs to be determined. As the traction power substations are generally connected to a high voltage utility system, the available fault level will generally be sufficiently high to avoid undesirable effects due to the voltage flicker.

The sudden regulation of the utility voltage may cause objectionable light flicker, disrupt industrial and commercial processes, and adversely affect operation of electronic apparatus, such as computers, instrumentation, and communications equipment. Also, the currents flowing in traction power supply equipment causes pulsating forces which can be of significant magnitude, and therefore, can be potentially harmful to substation equipment.

The light flicker is the most common and noticeable effect of fluctuating loads. Lighting equipment is particularly sensitive to supply voltage variation and people are sensitive, in varying degree, to sudden illumination changes. For example, a voltage change of just 0.25 to 0.5% will cause a noticeable change in the light output of incandescent lamps [15].

### 2.5.5 Harmonic Distortion

Harmonics are sinusoidal voltages or currents having frequencies that are whole multiples of the frequency at which the supply system is designed to operate (e.g., 50 Hz or 60 Hz). An illustration of fifth harmonic distortion is shown in Figure 2.12. When the frequencies of these voltages and currents are not an integer of the fundamental they are termed inter-harmonics.

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

In general, distorting equipment produces harmonic currents that, in turn, cause harmonic voltage drops across the impedances of the network.

■ The main detrimental effects of harmonics are:

- ❖ Maloperation of control devices, main signaling, systems, and protective relays
- ❖ Extra losses in capacitors, transformers, and rotating machines
- ❖ Additional noise from motors and other apparatus
- ❖ Telephone interference
- ❖ The presence of power factor correction capacitors and cable capacitance can cause shunt and series resonances in the network producing voltage amplification even at a remote point from the distorting load [12].

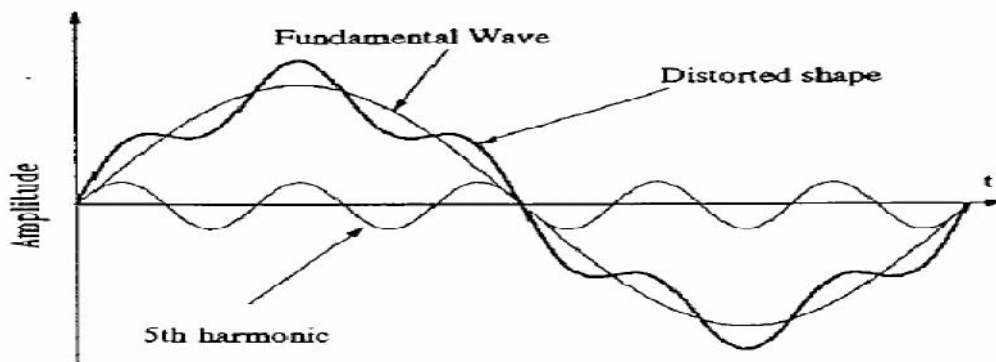


Figure 2.12 Example of a distorted sine wave [12]

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

from large nonlinear loads such as railway system connected to their power system network. Nowadays, there have been considerable developments in industrial processes which rely on controlled rectification for their operation. Railway systems are one of the important users of the technology and consequently they are a large source of harmonic [13].

As we mentioned before there are two system of electrical supply to railway: AC and DC system. Each system has its own harmonic characteristics, which depended on the network components used in the system. In DC systems, chopper and inverter equipment produces harmonic currents and switching transients. In AC systems, the use of converter equipments modifies the nature of the traction current spectrum, generally increasing magnitude of odd harmonics at some values of train speed when compared what is obtained with tap changer equipment [11].

Electric trains having thyristors or pulse width modulation (PWM)-controlled converters inject harmonic currents into the feeding overhead lines. Harmonic currents in the electric train are one of the biggest concerns, and the load current model to represent electric trains is proposed. The current harmonics injected from an ac electric train propagate through power-feeding circuits. Being a distributed RLC circuit, the feeding circuit can experience parallel resonance at a specific frequency. The harmonic current is amplified by the resonance, and the amplified harmonic current usually induces various problems, including interference in adjacent communication lines and the railway signaling system, overheating, and vibration at the power capacitors, and erroneous operation at the protective devices. Therefore, the harmonic current flow must be assessed exactly in the designing and planning stage of the electric traction system. Since the harmonic current flows through the catenary system, it needs to be accurately modeled to analyze and assess the harmonic effect on the power-feeding system [10].

Although the harmonic problem tend to reduce as a consequence of technological development of the inverter fed locomotives , it is important to note that the life time of the locomotives is about 30-40 years ,and then the old generation locomotives will be still in use in the future for some time. Therefore the study of suppressing the harmonic currents in existing type of locomotive types is still very important [10].

Harmonic voltage distortion in traction systems may rise to levels which are 2 or 3 times higher than those normally accepted in public utility systems. There are few recorded problems associated with harmonic voltage distortion in traction systems, one exception being the

presence of harmonic overvoltage. Harmonic overvoltage is a response by parallel resonant paths in the traction supply network to sudden step changes in the locomotive current waveform. Systems in which the phenomenon occurs have voltage waveforms containing a sine wave and a superimposed decaying oscillatory component (Figure 2.14).

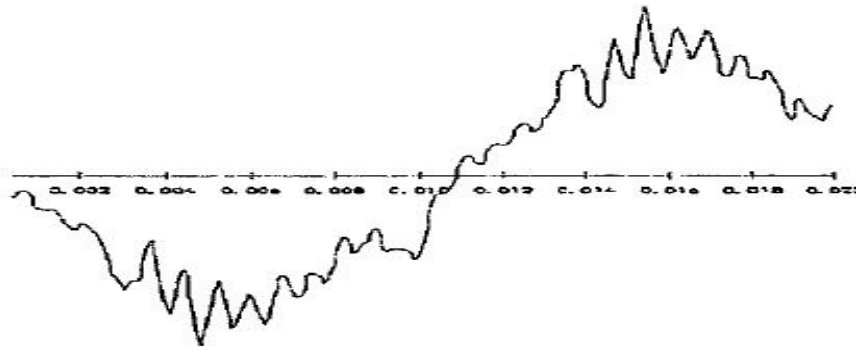


Figure 2.13 Voltage waveform for 25 kV traction feeders [18]

Although the overvoltage is more likely to be generated by phase angle controlled locomotives, once the phenomenon is present the excessive crest voltage is transferred to all other locomotives operating on the same traction feeder. A second waveform feature caused by harmonic distortion is loss of average voltage. Some types of locomotive have rating dependent on average voltage; a raised form factor leads to poor performance irrespective of the levels of RMS voltage. This problem is noticeable on systems having total harmonic voltage distortion in excess of about 10 per cent. Thyristor and diode bridge vehicles are most likely to give rise to loss of average voltage but the effect may pass on to all other loads on the same feeder. The more modern loads having PWM input converters are less likely to cause poor power quality but they may be affected by the problems caused by other types of load [9].

Harmonic produced by traction substations is injected into utility and sum at Point Common Coupling (PCC). Almost each standard deals with summation of multi-harmonic sources. Two kinds of summation law are defined by IEC 61000-3-6 to calculate summation of any kind of harmonic injected into utility. But the character of harmonic produced by electric locomotive is greatly different from other type harmonic because electric locomotive is unsymmetrical load (single phase) and traction load varies quickly and greatly.

- First Summation Law : The first summation law is a simple linear law making use of diversity factors:

$$U_h = U_{ho} + \sum_j k_{hj} U_{hj} \tag{2.1}$$

Where  $U_{ho}$  is the background harmonic voltage of the utility;  $U_{hj}$  is the harmonic voltage of individual load. The magnitude of the diversity factors  $k_{hj}$  depends on conditions that the kind of the appliance considered, the harmonic order  $h$  and the ratio between the rated power of the appliance considered and the short circuit power at PCC. The first summation law is simple to use but the second one is more general.

- The Second Summation Law: The second summation law is more general for both harmonic voltage and current. The law for resulting harmonic voltage of order  $h$  is:

$$U_h = \left( \sum_i (U_{hj})^{\alpha} \right)^{1/\alpha} \tag{2.2}$$

Where:  $U_h$  is the magnitude of the resulting harmonic voltage (order  $h$ );  $U_{hj}$  is the magnitude of the various individual emission level (order  $h$ ) to be combined;  $\alpha$  is an exponent depending mainly upon two factors: the probability for the actual value not to exceed the calculated value and the degree to which individual harmonic voltages vary randomly in terms of magnitude and phase [8].

## 2.6 Hazards of Power Quality Problems

The degraded power quality of rail systems may result in the malfunction of nearby systems. The most important hazard of power quality shortcomings applies to upstream power supply networks that can be harmed seriously as will be discussed hereinafter. Furthermore, it may harm the operation of the signaling and communication systems of the railway.

The impact of low power quality of traction systems on other systems is mentioned in [7]–[19], and the most important ones are as follows.

### ✓ Impacts on Signaling and Communications

Track circuits are designed to work with a special frequency that must not have any interference with the power frequency. However, in the presence of harmonics, communication signals may be affected by harmonic frequencies [17]–[19], resulting in erroneous signals and faulty train positioning, which lead to a disaster.

Communication cables, in turn, usually lie in parallel near the power cables. In the presence of stray currents, the catenary current and return current would be unequal, causing the equivalent magnetic field in communication cables not to be zero.

Therefore, it will induce voltages in communication cables and interfere with communication signals [19]. Moreover, high order harmonics may cause interference between communication and power systems.

✓ **Impacts on Upstream Network**

The impact of power quality problems on upstream supply network investigated in much publication can be categorized to the following three main impacts [7]–[16].

➤ **Decreased Utilization Factor:**

Since the traction load is a large single-phase load, it results in high current NSCs, which will flow in only two phases, and it decreases the utilization factor of the transmission line [8].

➤ **Malfunction of the Protective System:**

Protection relays may operate incorrectly in the presence of harmonics and NSCs of currents and voltages. Traction load injects a large amount of harmonics and NSCs, resulting in the malfunction of the protective system.

➤ **Incorrect Operation of Transmission Line Control Systems:**

Voltage and current sampling is based on the fundamental components of either voltage or current. Every control system in the transmission line would not work appropriately because traction loads inject large amounts of harmonics and NSC current into the transmission lines [9].

## **2.7 Overview of AC Electrified Traction System Awash – Woldia Railway**

### **Project**

The project area starts from Awash 7 kilo and extends in North direction to Woldia via major towns of DebreBirhan, ShoaRobit, Combolcha and Dessie, and further to Mekele and Shire in the next phase. The project area total length is more than 340km and there are 8 traction station located on average every 40km.



Figure 2.14 Layout of Awash- Woldia-Haragebeya railway project and Sebeta-Mieso-Djibouti traction line [11]

### 2.7.1 Main Components of Awash -Woldia Railway Project

The project can be divided in to two main components, namely Transmission lines and Substation construction:

#### 1) Transmission lines

The line route and environmental considerations as accounted for this study is based on, the map of the area and the availability of accesses road for maintenance and construction. The aim of the study has been to assess the technical and economic viability, and environmental acceptability of the line route from 230 kV Combolcha II substation, 400/230 kV Woldia substation, 132 kV Debrebirhan substation, 132 kV Shoarobi substation and 132 kV Kemise substation to newly proposed eight Awash – Woldia rail way project traction stations. In this relation it is expected that different studies of different discipline should address legislation requirements, physical, biological and human environmental considerations, urban development as well as design, construction, maintenance and reliability considerations.

Transmission line routes are mostly selected along roads to facilitate ease of construction and maintenance.

#### 2) Substation

For Awash-Woldia rail way project the scope of the substation is only for extension of existing substations and rehabilitation. The existing substations those are used to interconnect the rail way traction stations are 132 kV DebreBirhan substation, 132 kV ShoaRobit substation, 132 kV Kemise Substation, 230/132 kV Combolcha II substation and newly proposed 400/230 kV Woldia substation and also supply 132 kV Awash Traction station.

### **132 kV DebreBirhan Substation**

132 kV DebreBirhan substation is one of the oldest existing substations and it has a connection from Legetafo and ShoaRobit substations by 132 kV transmission line and it has one two winding 132/15 kV, 6 MVA and one three winding 132/33/15 kV, 20/16/16 MVA transformer but currently only three winding transformer is operational. One 132 kV line bay is extended from this substation to MPS 2 Traction station and there will be one 45 MVar shunt capacitor as per the system study to stable the system.

### **132 kV ShoaRobi Substation**

132 kV ShoaRobi substation has a connection from DebreBirhan and Kemise substations by 132 kV transmission line and it has one two winding 132/15 kV, 6 MVA and one three winding 132/33/15 kV, 16/16/8 MVA transformer. One 132 kV line bay is extended from this substation to MPS 3 Traction station.

### **132 kV Kemise Substation**

132 kV Kemise substation is the new substation it is constructed between ShewaRobit and Combolcha II substations by LILO configuration from the existing 132 kV transmission line. And it has one three winding 132/33/15 kV, 12/12/8 MVA transformer. There is already one free bay for 45 MVar shunt capacitor and One 132 kV line bay is extended from this substation to MPS 5 Traction station line bay.

### **230/132 kV Combolcha II Substation**

230/132 kV Combolcha II substation is connected with Alamata, Semera and Legetafo by 230 kV line and with Combolcha I and Kemise by 132 kV line, it has one three winding 230/132/33 kV, 63/63/23 MVA transformer. One 230 kV line bay is extended from this substation to MPS 6 Traction station. And the existing transformer is not enough for the load around there especially with an addition of these rail way projects so it is recommended to add one 230/132 kV, 125 MVA transformer.

### **400/230/33/15 kV Woldia Substation**

400/230/33/15 kV Woldia substation is under tendering stage it is proposed for the future new demand around Northern area like irrigation and industrial zones, it is expected to come in action before this rail way project is come, this new woldia substation has connection from Bahirdar II and newly proposed Combolcha Industrial zone substation via 400 kV line and by 230 kV transmission line from Alamata to Combolcha line by LILO configuration. It has two 400/230 kV, 250 MVA transformers and two three winding 230/33/15 kV, 63/40/23 MVA transformers. One 230 kV line bay is extended from this substation to MPS 8 Traction station.

### **132 kV Awash Traction Station**

132 kV Awash Traction station is one of the Ethio-Djibouti rail way traction stations and it is under tendering stage. It will have connect from Metehara Traction station and Awash 7 kilo substation via 132 kV single circuit, and it has two winding 132/25 kV, 25 MVA transformer. One 132 kV line bay is extended from this substation to MPS 1 Traction station line bay.

## CHAPTER THREE

### 3. Estimation of Voltage Unbalance and Power System Modeling

#### 3.1 Evaluation of Unbalance Factors Awash- Woldia Traction Substation

The maximum voltage unbalance factor should be calculated at the connection points of the main traction substations to the utility network, which is dependant to the loading characteristics of the traction system. This calculation should be done for controlling and limiting the unbalance magnitude and duration.

In order to determine the unbalance impact of the loads on the utility grid, the unbalance voltage factor is used [9]:

$$U_u [\%] = \frac{|V_2|}{|V_1|} * 100 \quad (3.1)$$

Where  $U_u$  [%] is the unbalance factor,  $V_2$  is the magnitude of the negative-sequence voltage;  $V_1$  is the magnitude of the positive-sequence voltage.

In some cases, especially for the power converters, the information regarding the phase shift  $\psi_u$  between negative and positive sequence voltages is very important.

In these conditions, the determination of the complex voltage unbalance factor  $\bar{u}_u$ , can ensure useful data for analyzing the unbalance perturbations injected in the supplying power system. The complex voltage unbalance factor is [9]:

$$\bar{u}_u = U_u \cdot e^{j\psi_u} \quad (3.3)$$

The exact method for determining the voltage unbalance factor, after measuring the rms values of the line voltages, is [9]:

$$U_u [\%] = \sqrt{\frac{(1 - \sqrt{3 - 6\beta})}{1 + \sqrt{3 - 6\beta}}} * 100 \quad (3.4)$$

$$\beta = \frac{V_{AB}^4 + V_{BC}^4 + V_{CA}^4}{(V_{AB}^2 + V_{BC}^2 + V_{CA}^2)^2} \quad (3.5)$$

Where  $V_{AB}$ ,  $V_{BC}$  and  $V_{CA}$  are the rms line-to-line voltages.

The phase shift  $\psi_u$  is:

$$\psi_u = \tan^{-1} \left( \frac{\sqrt{3} \cdot (V_{AB}^2 - V_{CA}^2)}{V_{AB}^2 + V_{BC}^2 + V_{CB}^2} \right) \quad (3.6)$$

The values of the voltage unbalance factor depend on the voltage level to which the load is connected. In many countries of the European Union the compatibility level on LV is  $u_u \leq 2\%$ .

The planning limits on MV and HV are  $u_u \leq 2\%$  for MV and  $u_u \leq 1\%$  for HV [9].

In France, for the case of high speed trains, new values have been proposed for HV network: respectively  $u_u \leq 1\%$  for periods higher or equal than 15 min and  $u_u \leq 1.5\%$  for periods less than 15 min.

The voltage unbalance factor is defined as the maximum phase voltage deviation from the average value of the three phase voltages, reported to this average value. In this case, for the three phase voltages it is computed an average value  $V_{avg}$  and the deviations  $\delta_A, \delta_B$ , and  $\delta_C$ , [9]:

$$V_{avg} = \frac{V_A + V_B + V_C}{3}$$

$$\delta_A = \frac{V_A - V_{avg}}{V_{avg}}, \delta_B = \frac{V_B - V_{avg}}{V_{avg}}, \delta_C = \frac{V_C - V_{avg}}{V_{avg}}$$

The voltage unbalance is evaluated as follows:

$$u = \max ( |\delta_k| ), k = A, B, C \quad (3.8)$$

The prediction of the voltage unbalance due to single-phase traction loads connected between two of the three-phase lines, at PCC, is [9]:

$$u_u [\%] \cong \frac{S_L}{S_{cc}} * 100 \quad (3.9)$$

Where  $S_L$  - is single phase traction load

Where  $S_L$  the traction is load power and  $S_{cc}$  is the three-phase short circuit level at PCC.

Considering the traction connection schemes and the railway loads  $S_L, S_{L1}$  and  $S_{L2}$ , shown in Figure 3.1, the expression (3.9) can be applied for calculating of the voltage unbalance in any substation configuration represented in Figure 3.1 [7].

Where  $S_{L1}$  - is single phase traction load at transformer one

$S_{L2}$  - is single phase traction load at transformer two

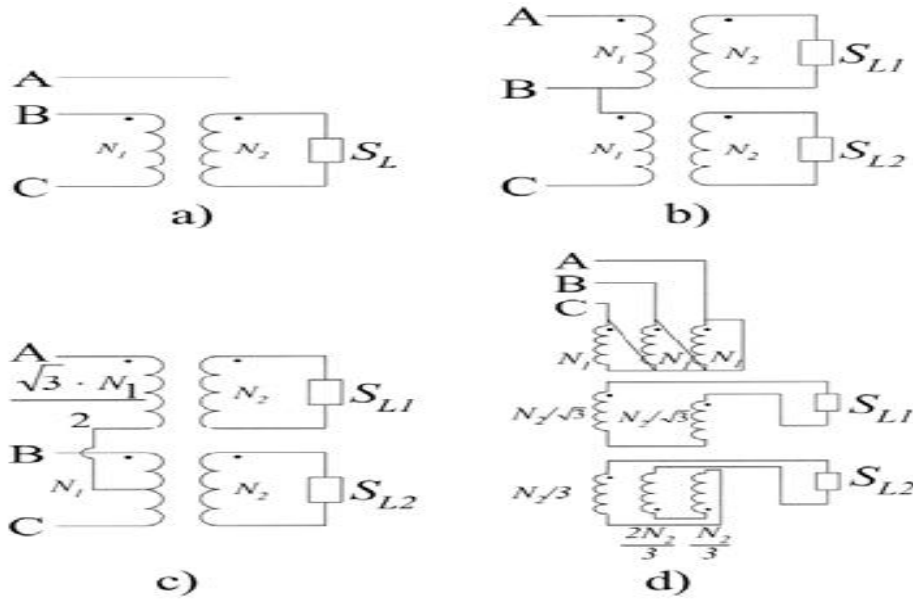


Figure 3.1 Traction connection schemes: a) single-phase connection; b) V-connection; c) Scott connection; d) Le Blanc connection [7]

$$u_u[\%] = \frac{S_L}{S_{cc}} * 100 \quad \text{single phase transformer}$$

$$u_u[\%] = \frac{(S_{L2} + \alpha^2 S_{L1})}{S_{cc}} * 100 \quad \text{v/v transformer} \quad (3.10)$$

$$u_u[\%] = \frac{(S_{L2} - S_{L1})}{S_{cc}} * 100 \quad \text{Scott/ le Blanc transformer}$$

Where  $u_u$  is the unbalance factor in % calculated per transformer

$S_L$ -Is the traction load power either transformer T1 or transformer T2

$S_{cc}$ -Is the three-phase short circuit level at point of common coupling (PCC)

$$\alpha = \exp(2 * \pi * j/3)$$

$$= -0.5 + j\sqrt{3}/2.$$

### 3.2 Assumptions and Basis for Calculation

In our calculations, i.e. for two single phase traction transformer, two V/V traction transformers and three single phase traction transformer the following assumptions have been considered:

- ✓ Traction load cycles remain the same
- ✓ Short circuit parameter of high voltage grid are equal

Based on these assumptions, the voltage unbalance for the three transformer cases can be calculated using values given in table 3.1, 3.2 and 3.3 for traction load power ( normal and degraded) conditions and short circuit power respectively.

**3.2.1 Traction Loads**

There are two operating conditions for the three transformer cases traction load power values i.e. normal and degraded conditions.

Normal Operating Condition (NOC) - It is a status of the power system where all traction supply substations and its devices are in operating as well as the supply network and the wayside equipment; all of the allowed configurations of the power supply system are then possible.

Table 3.1 shows the detail values of traction load power of two single phase traction transformer, two V/V traction transformers and three single phase traction transformer for Normal operating condition (NOC).

Station-Transformer/Normal Operating Condition(NOC)	$S_{L-NOC}$ [MVA] (99% of the time load level, below planed limit)		
	Two single phase transformer	Two V/V transformer	Three single phase transformer
TPS1-T1&T2 / NOC	22.14	22.14	22.14
TPS2-T1&T2 / NOC	21.65	21.65	21.65
TPS3-T1&T2 / NOC	23.17	23.17	23.17
TPS4-T1&T2 / NOC	27.92	27.92	27.92
TPS5-T1&T2 / NOC	25.49	25.49	25.49
TPS6-T1&T2 / NOC	26.09	26.09	26.09
TPS7-T1&T2 / NOC	28.15	28.15	28.15
TPS8-T1&T2 / NOC	27.52	27.52	27.52

Table 3.1 Normal operating condition (NOC) [11]

Where  $S_{L-NOC}$  - is single phase traction load at the time of normal operating condition (NOC)

Degraded Mode Operating Conditions (DEG) – In this operation condition one or more transformers are out of service (outage or maintenance).

Table 3.2 shows the detail values of traction load power of two single phase traction transformer, two V/V traction transformers and three single phase traction transformer for degraded operating condition (DEG).

Station-Transformer/Degraded Operating Condition(DEG)	$S_{L-DEG}$ [MVA] (99% of the time load level, below planed limit)		
	Two single phase transformer	Two V/V transformer	Three single phase transformer
TPS1-T1&T2 / DEG	24.75	24.75	24.75
TPS2-T1&T2 / DEG	34.89	34.89	34.89
TPS3-T1&T2 / DEG	39.06	39.06	39.06
TPS4-T1&T2 / DEG	37.34	37.34	37.34
TPS5-T1&T2 / DEG	38.37	38.37	38.37
TPS6-T1&T2 / DEG	41.63	41.63	41.63
TPS7-T1&T2 / DEG	30.12	30.12	30.12
TPS8-T1&T2 / DEG	41.64	41.64	41.64

Table 3.2 Degraded operating condition (DOC) [11]

$S_{L-DEG}$  - is single phase traction load at the time of degraded operating condition (DEG)

**Further assumptions:**

- For two single phase transformers DEG is considered as a failure of one transformer at the time.
- For two V/V transformers DEG can be considered as failure of one transformer at each station.
- For three single phase transformers DEG can be considered as failure of one transformer at each station.

3.2.2 Short-circuit power

Table 3.3 shows the value of short circuit power for each traction substation. Short circuit parameters of HV grid are also assumed to be equal for each traction transformer i.e. two single phase transformer, V/V and three single phase transformer.

Description	TPS1	TPS2	TPS3	TPS4	TPS5	TPS6	TPS7	TPS8
Voltage [kV]	132	132	132	132	132	132	132	132
Short circuit power [MVA]	760	618	525	462	543	1764	1206	1657

Table 3.3 Short circuit power [11]

### 3.3 Calculations and Results of Unbalance

#### 3.3.1 Formulas used for unbalance calculations

Voltage unbalance in presented substation configuration (shown at Appendix) can be calculated using the following formulas:

- ❖ Single-phase transformer in degraded mode:

$$u_u[\%] = \frac{S_L}{S_{CC}} * 100$$

Where  $u_u$  is the unbalance factor in % calculated per transformer,  $S_L$  is the traction load power either transformer T1 or transformer T2, and  $S_{CC}$  is the three-phase short circuit level at point of common coupling (PCC).

- ❖ All configurations (two single, V/V and three single phase transformer) in normal operating condition (NOC) and V/V and three-single phase transformers in degraded mode operating condition DEG

$$u_u[\%] = \frac{(S_{L2} + \alpha^2 S_{L1})}{S_{CC}} * 100$$

Where  $u_u$  is the unbalance factor in % calculated per transformer,  $S_{L1}$ ,  $S_{L2}$  are the traction load power and  $S_{CC}$  is the three-phase short circuit level at point of common coupling (PCC) and  $\alpha = -0.5 + j\sqrt{3}/2$ .

Table 3.4 Calculations and Results of Unbalance – Normal Operating Conditions

Station-Transformer/Normal Operating Condition(NOC)	$S_L$ [MVA] @ point of	$S_{CC}$ [MVA] @ point of common coupling	Result of unbalance – each transformer		
			Two single phase transformer	Two V/V transformer	Three single phase transformer
TPS1-T1&T2 / NOC	22.14	760	2.91	2.91	2.91
TPS2-T1&T2 / NOC	21.65	618	3.50	3.50	3.50
TPS3-T1&T2 / NOC	23.17	525	4.41	4.41	4.41
TPS4-T1&T2 / NOC	27.92	462	6.04	6.04	6.04
TPS5-T1&T2 / NOC	25.49	543	4.69	4.69	4.69
TPS6-T1&T2 / NOC	26.09	1764	1.48	1.48	1.48
TPS7-T1&T2 / NOC	28.15	1206	2.33	2.33	2.33
TPS8-T1&T2 / NOC	27.52	1657	1.66	1.66	1.66

Table 3.5 Calculations and Results of Unbalance – Degraded Mode Operating Conditions

Station-Transformer/ Degraded Mode Operating Conditions (DEG)	$S_{L-DEG}$ [MVA]	$S_{CC}$ [MVA] @ point of common coupling	Result of unbalance – each transformer		
			Two single phase transformer	Two V/V transformer	Three single phase transformer
TPS1-T1&T2 / DEG	24.75	760	3.26	2.91	2.91
TPS2-T1&T2 / DEG	34.89	618	5.65	3.50	3.50
TPS3-T1&T2 / DEG	39.06	525	7.44	4.41	4.41
TPS4-T1&T2 / DEG	37.34	462	8.08	6.04	6.04
TPS5-T1&T2 / DEG	38.37	543	7.13	4.69	4.69
TPS6-T1&T2 / DEG	41.63	1764	2.36	1.48	1.48
TPS7-T1&T2 / DEG	30.12	1206	2.50	2.33	2.33
TPS8-T1&T2 / DEG	41.64	1657	2.51	1.66	1.66

From the three solutions i.e. two single phase , two V/V and three single transformers have equal unbalance in the HV grid in normal operating conditions, but unbalance factor of two single phase transformer differ from three single phase and two V/V transformers for degraded mode operating condition. Therefore, Two V/V Transformer and Three single phase transformer are preferable than Two single phase transformer in degraded condition

The above calculation indicates that, unbalance is above IEC limit at each station. Therefore balancer device is required to fulfill IEC requirements.

### 3.3 Traction Substation Modeling

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.

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

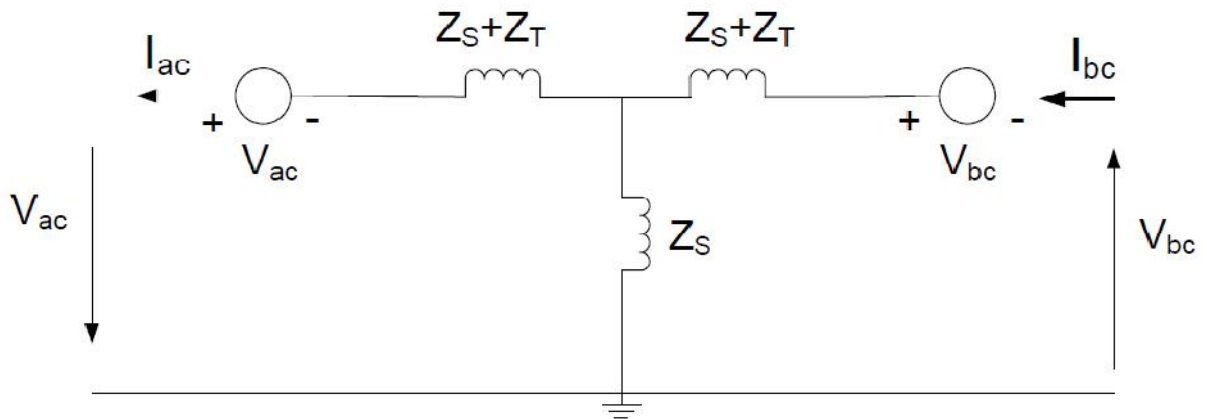


Figure 3.2 V/V connection substation equivalent circuit model

The parameters of these circuits can be easily computed by the following relations

$$\text{The power system impedance, } |Z_S| = X_S = \frac{U^2_{2N}}{S_K} (\Omega) \tag{3.3}$$

$$\text{Transformer short circuit impedance, } |Z_T| \cong X_T = \frac{U_{k\%} U^2_{2N}}{100 S_T} (\Omega) \tag{3.4}$$

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

$S_T$ : Traction transformer capacity (MVA)

$U_{k\%}$ : Short circuit capacity

Traction substation data collected from Awash to Woldia traction substation [11]

$S_K$ : Power system (primary side) short circuit capacity (MVA) = 462MVA

ST traction transformer capacity (MVA) = 22MVA

Secondary side voltage,  $V_s$ (kV) = 27.5kV

Transformer impedance,  $Z\%$  = 10

UK%: short circuit capacity = 10% [reference]

Rated secondary current  $I_s = \frac{22MVA}{\sqrt{3} * 27.5 kV} = 461.88A$

Rated secondary current  $I_{PSC} = \frac{I_s}{Z\%} = 4618.8A$

Short circuit MVA =  $\sqrt{3} * 27.5 * 4618.8 = 219.9MVA$

Short circuit impedance of the network  $Z_{grid} = \frac{V^2}{MVA_{sc}} = 3.437\Omega$

❖ The power system impedance,

$$X_s = \frac{(27.5)^2}{462} (\Omega) = 1.64 \Omega$$

❖ Transformer short circuit impedance

$$X_T = \frac{10\%(27.5)^2}{100 * 22} (\Omega) = 3.44 \Omega$$

There for the substation impedance  $Z_s = Z_T + \frac{Z_{grid}}{a^2} = 3.44 \Omega + \frac{3.437\Omega}{\left(\frac{132}{27.5}\right)^2} = 4.156 \Omega$

The resistive and reactive component of  $Z_s$  can be determined with the value of the X/R ratio

taken from standard  $Z_s = \sqrt{R^2 + X^2}$

These resistive and reactive components with X/R ratio 20 are [Reference]:

$$R = 0.2075 \Omega \quad X = 4.15 \Omega$$

### 3.4 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]. The length of transmission line from the three phase grid substation to the traction substation of

traction power substation four (TPS4) is 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 3.3

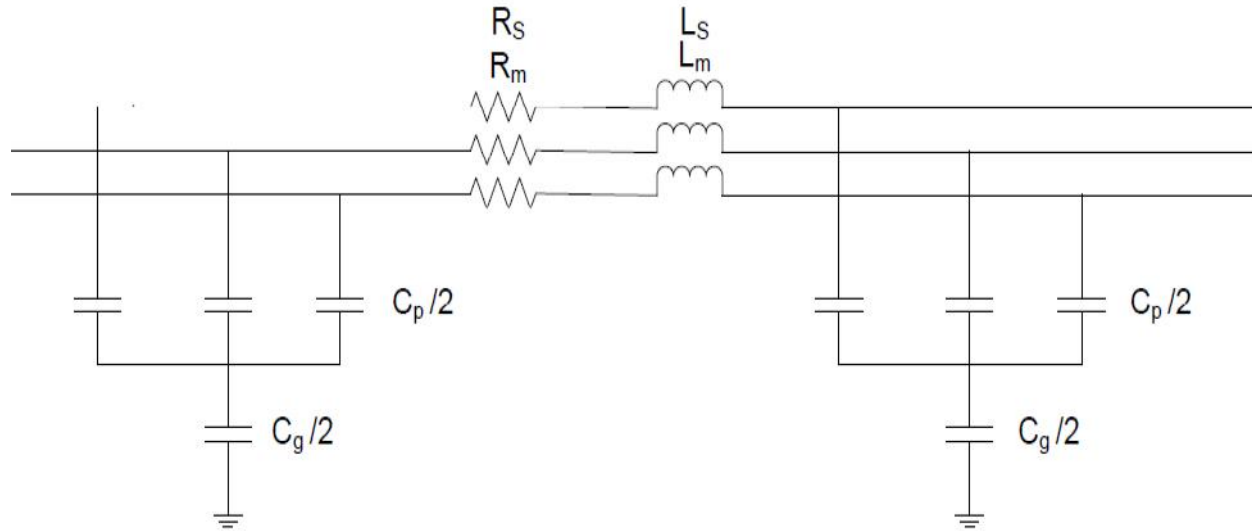


Figure 3.3 Equivalent circuit of three phase pi-circuit model [24]

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. **Line-Line mutual resistances ( $R_m$ )** per-unit length, the default value is 0  $\mu\text{F}/\text{km}$  (no line-line mutual resistance). **Line-ground capacitance** per-unit length, the default value is 0  $\mu\text{F}/\text{km}$  (no line ground capacitance). If the line parameters are defined as follows:

$r_1, r_0$  - positive- and zero-sequence resistances per unit length ( $\Omega/\text{km}$ )

$l_1, l_0$  - positive- and zero-sequence inductances per unit length ( $\text{H}/\text{km}$ )

$c_1, c_0$  - positive- and zero-sequence capacitances per unit length ( $\text{F}/\text{km}$ )

$l_{sec}$  - Line section length (km)

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

$$R_1 = r_1 * l_{sec}$$

$$L_1 = l_1 * l_{sec}$$

$$C_1 = c_1 * l_{sec}$$

$$R_0 = r_0 * l_{sec}$$

$$L_0 = l_0 * l_{sec}$$

$$L_0 = c_0 * l_{sec}$$

❖ Then RLC line section parameters are then computed as follows:

$$R_m = (R_0 - R_1) / 3$$

$$L_m = (L_0 - L_1) / 3$$

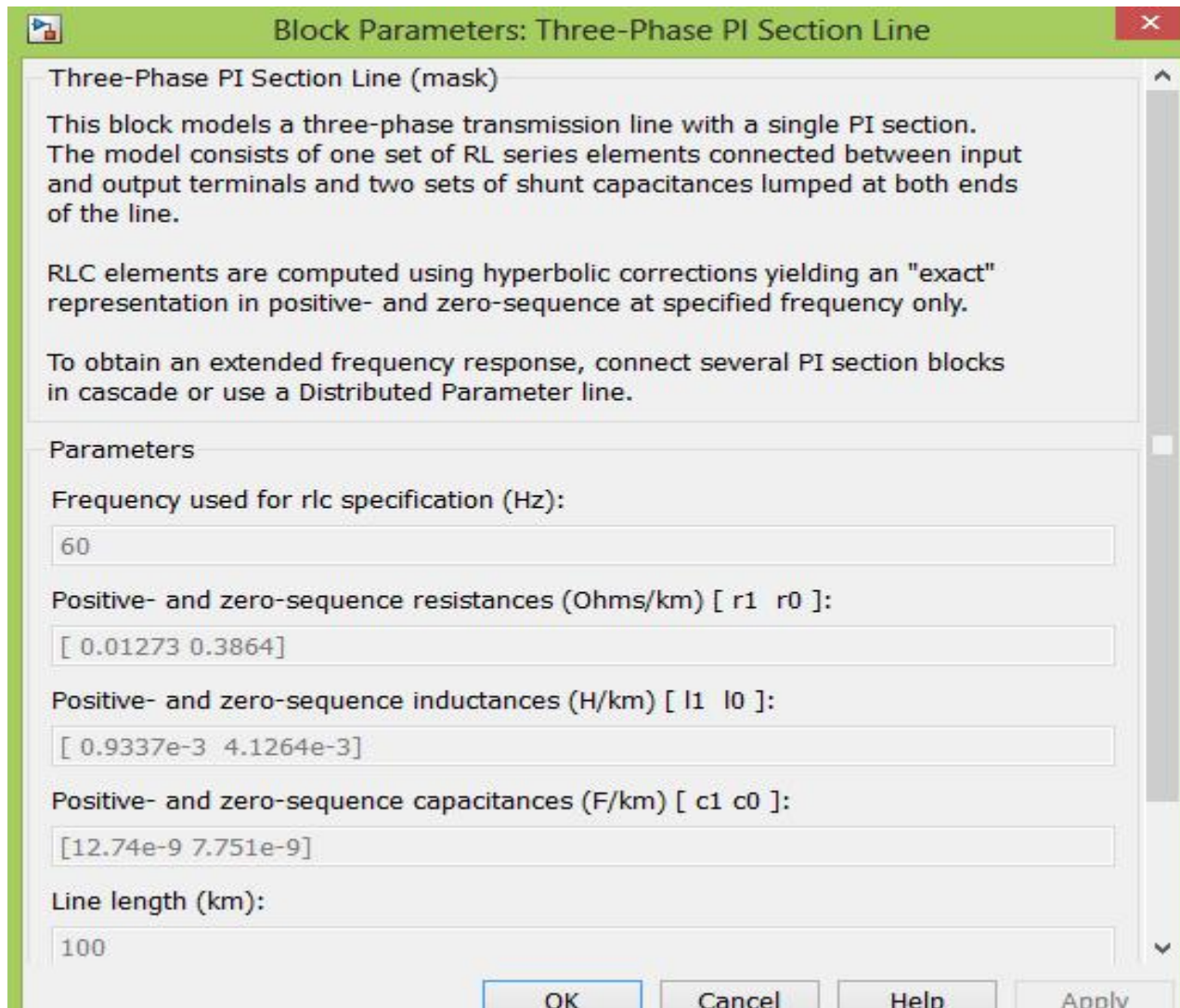
$$C_p = C_1$$

$$R_s = (2R_1 + R_0) / 3$$

$$L_s = (2L_0 + L_1) / 3$$

$$C_g = 3C_1 C_0 / (C_1 - C_0)$$

Dialog box and parameters



The transmission line parameters considered in this thesis are taken from reference [25]. For overhead line 132kV and 200 mm<sup>2</sup> specifications the parameters are X=0.426 /km and R=0.144 /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: 0.4688MS/km+j0.4688GS/km

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

$$X_C = 1/2\pi f C$$

$$C = 1/2\pi f X_C$$

$$X_L = 2\pi f L$$

$$L = X_L / 2\pi f$$

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

Resistance ( /km) -  $r_1 = 0.1019$   $r_0 = 0.6160$

Inductance (H/km) -  $l_1 = 0.0018$   $l_0 = 0.0058$

Capacitance (F/km) -  $c_1 = 6.79 * 10^{-9}$   $c_0 = 6.79 * 10^{-12}$

### 3.5 Loads (Trains)

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

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

Where  $P_m$  is the nominal power of the motor drive in Watt,  $f$  -is frequency

$$P_m = S \cos PF = 5647 \text{ kVA} * 0.85 = 4.8 \text{ MW} \quad \text{where PF is power factor}$$

The desired voltage peak to peak ripple in volt is:

$$V_{P-P} = 5\% V_{dc} = 0.05 * \sqrt{2} * V_{rms} = 700 \text{ V}$$

$$\text{Then the cross pounding ripple is } V_r = \frac{V_{P-P}}{2} = 350 \text{ V}$$

$$\text{Average DC bus voltage } V_{dc} = \frac{2\sqrt{2} * V_{rms}}{\pi} = 8.913 \text{ kV}$$

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

$$\text{Load side (motor) } R = \frac{V_{dc \text{ peak}}}{P_m} = 40 \Omega$$

### 3.5 Overhead Line System (Catenary System) Modeling

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  $0.169 + j0.432 \text{ } \Omega/\text{km}$  at 50 HZ and shunt capacitance of  $0.011 \text{ } \mu\text{F}/\text{km}$  [9] [25] [26].

## CHAPTER FOUR

### 4 Direct Power Compensator (DPC) Design

#### 4.1 Proposed System Circuit Configurations

In this paper, the substation transformer is composed of two single-phase transformers, and is commonly known as the V/V transformer. The three-phase power grid is transformed into two single-phase outputs ( $V_{ac}$  and  $V_{bc}$  phases) through V/V transformer. The locomotive loadings are all connected across the same single phase output ( $V_{ac}$ ), leaving another phase ( $V_{bc}$ ) unloaded.

The DPC consist of back to back converter through a common dc capacitor with a stable dc-link voltage, is connected to the two feeder sections via two steps- down transformers. The two converters are connected to the single-phase step-down transformers via two output inductor  $L_{a1}$ ,  $L_{a2}$ , capacitor  $C_a$  and  $L_b$  respectively.

The two converters can be controlled as current sources to shift a certain amount of active power from one feeder section to the other. These two converters can also provide voltage balance, harmonic suppression and reactive power compensation [9]. Hence, the system can achieve integrated compensation of negative sequence currents, harmonic currents and reactive power.

The circuit configuration of the proposed co phase traction power supply with DPC is shown in Figure 4.1.

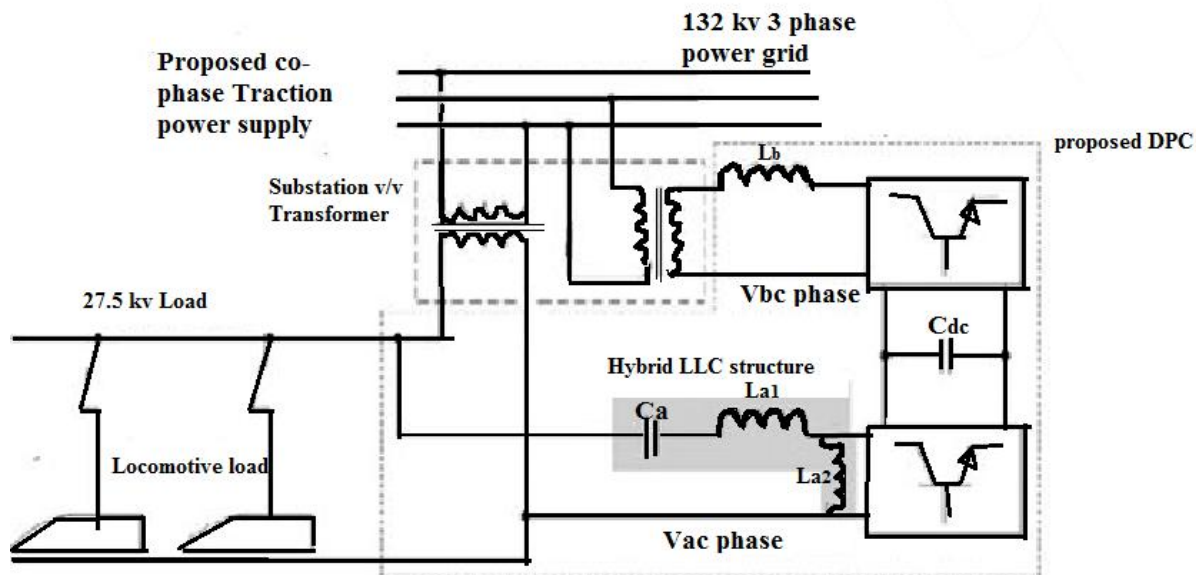


Figure 4.1 Circuit configuration of the proposed co phase traction power supply with DPC

In contrast to conventional structure, the converter is connected to the  $V_{ac}$  phase of the transformer via a capacitive coupled hybrid LLC structure. The circuit configuration of the proposed co phase traction power supply with LLC- DPC is shown in Figure.4.1. To improve the power conversion efficiency of the traction power system. The proposed LLC connected rectifier has the capability to changing the output voltage without increasing the transformer's turn ratio.

The LLC resonant converter is another popular topology because of its outstanding performance such as high-power conversion efficiency, high power density, and over the entire load range. LLC resonant converters have also employing for to reduce the total harmonic distortions and reduce the output ripple current since an interleaved operation for. The converter is connected to the  $V_{ac}$  phase of the transformer via a capacitive coupled hybrid LLC structure. In this paper, a hybrid device combining active and passive compensators, named as the direct power compensator (DPC). It can be observed that with capacitive coupled LLC structure, the amplitude of  $V_{invaLCC}$  in DPC can be less than  $V_{invaL}$  in RPC under the same compensation current [6]. The corresponding mathematical expressions are shown in equation (4.1) and (4.2) [6].

$$|V_{invaL}| = \sqrt{V_{invaL1}^2 + V_{invaLh}^2} \quad , \text{ for the case of railway power conditioner (RPC)}$$

$$= \sqrt{(V_{ac} + |I_{caq}|X_{Lc})^2 + (|I_{cap}|X_{La})^2} \quad (4.1)$$

Where  $V_{invaL}$  - is output voltage of  $V_{ac}$  phase,  $V_{invaL1}$ - fundamental frequency component of output voltage of  $V_{ac}$  phase converter and  $V_{invaLh}$ - harmonic component of output voltage of  $V_{ac}$ -phase converter

$$|V_{invaLC}| = \sqrt{V_{invaLC1}^2 + V_{invaLCh}^2} \quad , \text{ for the case of proposed LLC-DPC}$$

$$= \sqrt{(V_{ac} + |I_{caq}|X_{Lca})^2 + (|I_{cap}|X_{Lca})^2} \quad (4.2)$$

Load current is divided into the fundamental frequency component,  $I_{L1}$ , and the harmonic component,  $I_{Lh}$ ,  $I_L = I_{caq} + I_{cap} + I_{Lh}$

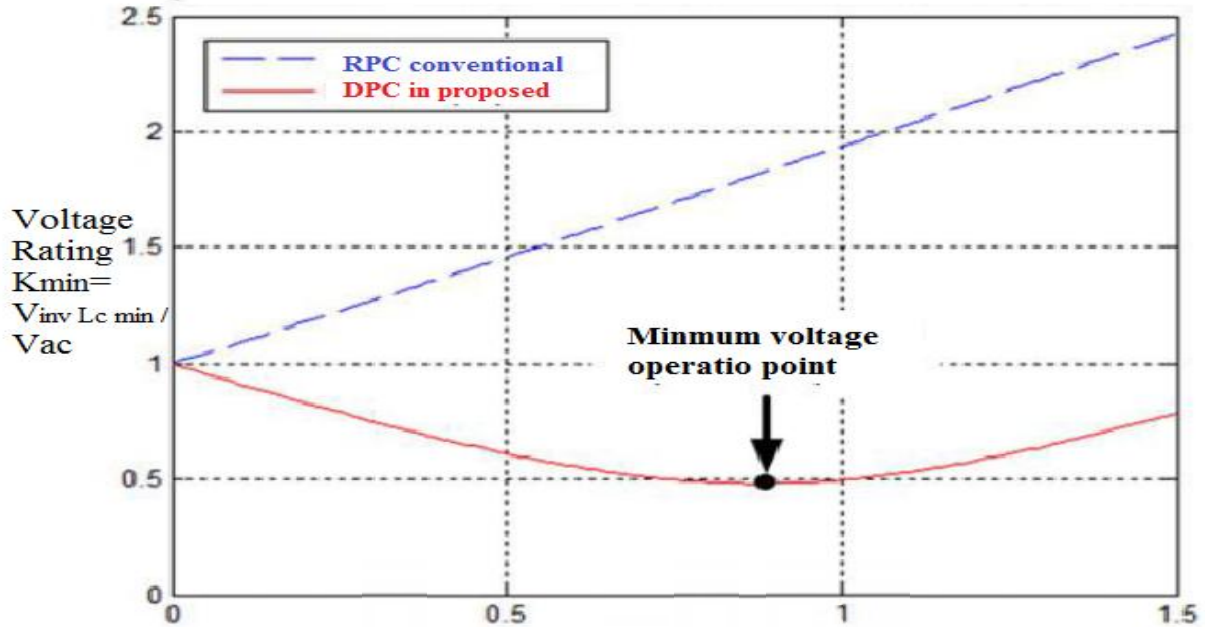
$I_{caq} = I_L * \sin\phi_1$ , where  $I_L$  traction load

$|I_{caq}| = I_L [\frac{1}{2\sqrt{3}}(PF) + \sin(\cos^{-1}(PF))]$ , where  $I_{caq}$  reactive component  $V_{ac}$  phase compensator current

$I_{cap} = I_L * \cos \phi_1$ , where  $\phi_1$ -denotes the phase angle between the supply voltage

$|I_{cap}|=I_L(\frac{1}{2PF})$ , where  $I_{caq}$  active component  $V_{ac}$  phase compensator current

Based on equation (4.1) and (4.2), it can be concluded that with fixed value of  $V_{ac}$ , the values of  $V_{invaL}$  and  $V_{invaLC}$  are highly dependent on the  $V_{ac}$  phase coupled impedance. Variation of conventional RPC and proposed DPC voltage rating (PF=0.85)



$$V_{ac} \text{ Coupled impedance } X_{La} = (V_{ac}/I_a)$$

Figure 4.2 Variation of voltage rating with  $V_{ac}$  phase coupled impedance in RPC of the conventional structure and in DPC of the proposed structure [12].

$V_{ac}$  Coupled impedance in RPC and DPC under load PF of 0.85 are shown graphically in Figure 4.2. The figure shows clearly that under the examined condition, the value of  $V_{invaL}$  in RPC is higher than that of  $V_{invaLLC}$  in DPC.

The operation point can be tuned along the curve by changing the  $V_{ac}$  coupled impedance. Therefore, the DPC operation could be located at the minimum voltage operation point via specific parameter design.

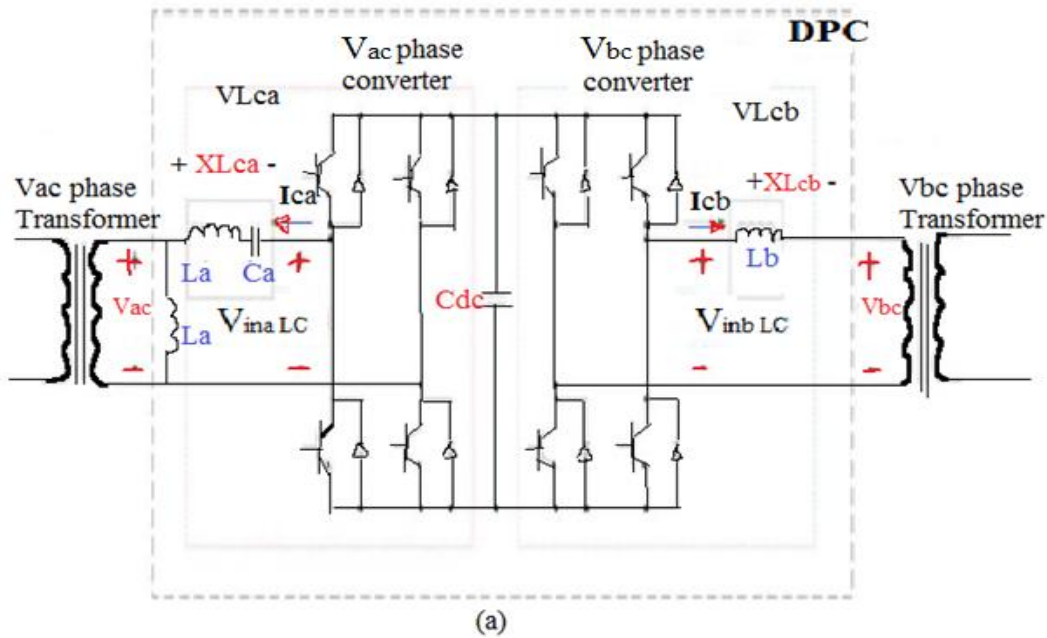


Figure 4.3 Detailed structure and physical definitions of DPC in the proposed co phase traction power.

### 4.2 DPC Parameter Design Based on Minimum Operation Voltage

The usage of DPC operation voltage may be divided according to two purposes: fundamental ( $V_{invaLC1}$ ) and harmonic ( $V_{invaLCch}$ ) compensation.

This idea may be mathematically represented, as shown in (4.3), and the parameters are defined in (4.4) and (4.5). In traction load, fundamental compensation occupies most of the compensation capacity. Here, the comprehensive DPC design will be presented based on the criteria of minimizing the operation voltage for providing these two compensation modes. Thus,

$$V_{invaLC} = \sqrt{V_{invaLC1}^2 + V_{invaLCch}^2} \tag{4.3}$$

$$V_{invaLC1}^2 = (V_{ac} + |I_{caq}|X_{Lca})^2 + (|I_{cap}|X_{Lca})^2 \tag{4.4}$$

$$V_{invaLCch}^2 = \sum_{Lh=2}^{\infty} I_{Lh}^2 X_{Lcah}^2 \tag{4.5}$$

#### DPC Design of Minimum Operation Voltage for Fundamental Compensation

Fundamental compensation in co-phase traction power supply includes basic compensation for system unbalance and reactive power. In short, the operation voltage for fundamental compensation is the required operation voltage to provide power quality compensation (of

system unbalance and reactive power) without harmonic compensation. It dominates the major portion of power quality compensation, as harmonics are usually less significant compared with reactive power and system unbalance in a power system.

The optimum parameter selection of  $V_{ac}$  phase coupled impedance  $X_{Lca}$  may be also determined by taking the derivative of (4.4) with  $X_{Lca}$  and setting it as zero. The process and result are shown in (4.6) and (4.7). It is consistent with the expression in (3.3). Notice that the negative sign in the expression refer to capacitive coupled impedance. Thus,

$$\frac{d(V_{invaLC1}^2)}{d(X_{Lca})} = (V_{ac} |I_{caq1}| + X_{Lca} |I_{caq1}|^2 + |I_{caq1}|^2) = 0 \quad (4.6)$$

$$X_{Lca} = -\frac{V_{ac}(\sin\theta_{ca})}{I_{ca}} \quad (4.7)$$

### **DPC Design of Minimum Operation Voltage for Harmonic Compensation**

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 (9), it can be observed that the discussion relates also to the harmonic impedance that an optimum selection of coupled inductance  $L_a$  and  $C_a$  must be chosen to minimize the harmonic operation voltage  $V_{invaLCh}$ .

Here, the discussion of the DPC design is presented based on the criteria of minimum fundamental operation voltage  $V_{invaLC1}$  in (4.7). In other words, the parameter design for minimum operation voltage during harmonic compensation developed here does not change the fundamental coupled impedance  $X_{Lca}$ .

In DPC, the  $V_{ac}$  phase coupled impedance is formed by the coupled inductance  $L_{a1}$ ,  $L_{a2}$  and capacitance  $C_a$ , whose equivalent impedance can be expressed as (4.8). It is further assumed in the expression that the impedance of coupled inductance  $X_{La}$  and coupled capacitance  $X_{Ca}$  are  $K_L$  and  $K_c$  times of the coupled impedance  $X_{Lca}$ , also shown in the following:

$$X_{Lca} = -(X_{La} + X_{Ca}) = -(K_L + K_c) X_{Lca} \quad (4.8)$$

The relationship between the values of  $K_L$  and  $K_c$  can be then obtained from (4.8), as expressed in the following:

$$-K_L - K_c = 1 \quad (4.9)$$

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

With reference to the expression in (4.9), the impedance at the  $h^{th}$  harmonics can be expressed

$$\text{as } X_{Lcah} = -(X_{Lah} + X_{Lcah}) = -(hK_L + \frac{1}{h} K_c) X_{Lca} \quad (4.10)$$

By substituting (4.9) into (4.10), the expression in (4.11) can be obtained, which is merely important for the analysis that follows, i.e.

$$X_{Lcah} = -\frac{1}{h} [(h^2 - 1)K_{L-1}] X_{Lca} \quad (4.11)$$

Recall from (4.5) that the harmonic compensation voltage  $V_{invaLCh}$  is not only dependent on the harmonic impedance  $X_{Lcah}$  but also on the load harmonic current  $X_{Lh}$ . 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  $V_{ac}$  phase compensation current  $I_{ca}$  and fundamental load current  $I_{11}$ , the load harmonics can be then expressed as (4.12). For simplicity, the denominator is defined as A in the contents that follow. Thus,

$$\begin{aligned} I_{ch} &= r_h I_{L1} = r_h \left( \frac{I_{ca}}{\sqrt{(0.2887PF + \sin(\cos^{-1}(PF)))^2 + (0.5PF)^2}} \right) \\ &= r_h \left( \frac{I_{ca}}{A} \right) \end{aligned} \quad (4.12)$$

Through substituting (4.7), (4.11), and (4.12) into (4.5), the expression for determining the harmonic compensation voltage for DPC can be obtained, as shown in the following:

$$V_{invaLCh}^2 = \sum_2^\infty V_{ac} * \frac{(I_{ca})^2}{A^2} * (\sin ca)^2 * \left\{ \frac{1}{h} [(h^2 - 1)K_L - 1] \right\}^2 \quad (4.13)$$

The value of  $K_L$  for minimum harmonic compensation voltage  $V_{invaLCh}$  can be then determined in a similar manner, by taking the derivative of (4.13) with  $K_L$  and setting it as zero, as shown in the following:

$$\frac{d(V_{invaLCh}^2)}{d(X_{kL})} = \sum_2^\infty \left\{ V_{ac} * \frac{(I_{ca})^2}{A^2} * (\sin ca)^2 * \left[ \frac{(2(h^2 - 1))^2}{h^2} K_L - \frac{(2(h^2 - 1))^2}{h^2} \right] \right\} = 0 \quad (4.14)$$

The expression in (4.15) can be then obtained by further manipulations of (4.14), i.e.

$$K_L = \frac{\sum_2^\infty r_h^2 * \frac{(2(h^2 - 1))}{h^2}}{\sum_2^\infty r_h^2 * \frac{(2(h^2 - 1))^2}{h^2}} \quad (4.15)$$

Furthermore, in co-phase traction power supply system,  $V_{bc}$  phase is unloaded. Ideally, no harmonic compensation is required from the  $V_{bc}$  phase converter. Therefore, the  $V_{bc}$  phase Coupled impedance may be designed according to the minimum operation voltage  $V_{invaLC}$ , as expressed in

$$\begin{aligned}
 X_{Lcb} &= \frac{V_{bc} \sin \theta_{cb} + \sqrt{V_{invaLC}^2 - V_{bc}^2 \cos^2 \theta_{cb}}}{I_{cb}} \\
 &= \frac{V_{bc} \sin \theta_{cb} - \sqrt{V_{invaLC}^2 - V_{bc}^2 \cos^2 \theta_{cb}}}{I_{cb}}
 \end{aligned} \tag{4.16}$$

Assuming that the DPC parameter is designed according to previous discussion for minimum operation voltage [refer to (4.7)], the DPC operation voltage may be determined by substituting (4.4), (4.5), (4.7), and (4.13) into (4.3). The result is given in (4.17).

$$V_{invaLC} = \sqrt{V_{ac}^2 * (\cos \theta_{ca})^2 + \sum_{h=2}^{\infty} V_{ac}^2 * \frac{(rh)^2}{A^2} * (\sin \theta_{ca})^2 * \left\{ \frac{1}{h} [(h^2 - 1)K_L - 1] \right\}^2} \tag{4.17}$$

DPC dc link operation voltage, it may be calculated as square root 2 times of the DPC operation voltage, i.e.,  $V_{invaLC}$ , as expressed in (4.18),

$$\begin{aligned}
 V_{Dc} &= \sqrt{2} * V_{invaLC} = \\
 &\sqrt{2V_{ac}^2 * (\cos \theta_{ca})^2 + 2 \sum_{h=2}^{\infty} V_{ac}^2 * \frac{(rh)^2}{A^2} * (\sin \theta_{ca})^2 * \left\{ \frac{1}{h} [(h^2 - 1)K_L - 1] \right\}^2}
 \end{aligned} \tag{4.18}$$

❖  $V_{ac}$  phase coupled inductance  $L_a$  according to (4.19), which is obtained by substituting (4.7) and (4.15) into (4.8), i.e.

$$L_a = \frac{K_L X_{Lca}}{\omega_1} = \frac{K_L V_{ac} \sin \theta_{ca}}{\omega_1 I_{ca}} \tag{4.19}$$

❖  $V_{ac}$  phase coupled inductance according to (4.20), which is obtained through substituting (4.7) and (4.9), i.e.,

$$C_a = \frac{1}{\omega_1 K_c X_{Lca}} = \frac{1}{\omega_1 (-1 - K_L) X_{Lca}} = - \frac{I_{ca}}{\omega_1 (-1 - K_L) V_{ac} \sin \theta_{ca}} \tag{4.20}$$

❖  $V_{bc}$  phase coupled impedance according to (4.16) and

$$\text{❖ } L_b = \frac{X_{Lb}}{\omega_1} \tag{4.21}$$

The design procedures of  $V_{ac}$  and  $V_{bc}$  phase coupled impedance are introduced, together with the investigations on the minimum DPC dc voltage rating achievable.

### 4.2.1 $V_{ac}$ Phase Coupled Impedance Design

The vector diagram shows the operation of  $V_{ac}$  phase converter in DPC under minimum voltage operation. With constant load PF and capacity, the vector  $I_{ca}$  is fixed. Thus, the vector  $V_{Lca}$  would vary along the line  $I_{L1}$  as the  $V_{ac}$  coupled impedance  $X_{Lca}$  varies. It can be observed that

the amplitude of  $V_{inva LC}$  can be minimized when it is perpendicular to the vector  $V_{LCa}$ . In other words, the minimum amplitude of  $V_{inva LC}$  occurs when the compensation current  $I_{ca}$  is in phase with the voltage  $V_{inva LC}$ .

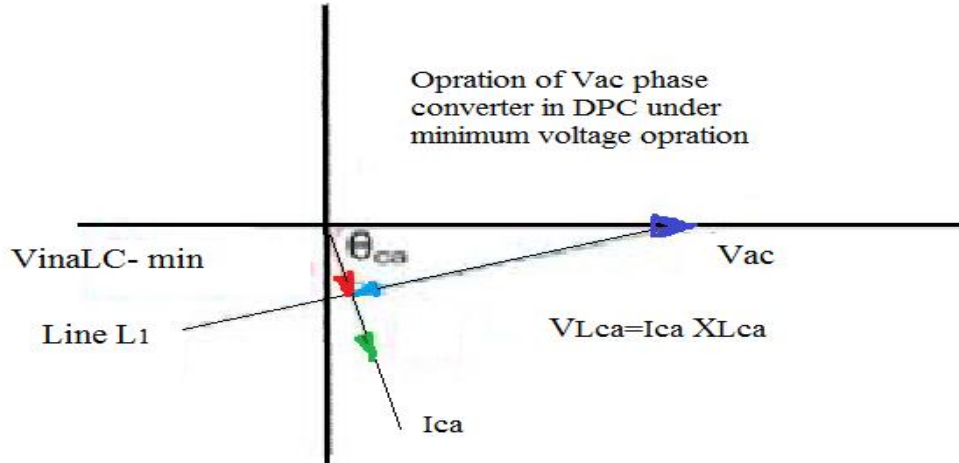


Figure 4.4 Vector diagram showing the operation of  $V_{ac}$  phase

By further defining the power angle of  $I_{ca}$  as  $\theta_{ca}$ , the mathematical relationship in (4.21).

$$V_{LCa} [V_{inva LC-min}] = I_{ca} (X_{LCa}) = V_{ac} \sin \theta_{ca}$$

The corresponding  $V_{ac}$  coupled impedance  $X_{LCa}$  required for minimum  $V_{inva LC}$  can, thus, be determined as shown in

$$X_{LCa} [V_{inva LC-min}] = \frac{V_{ac} (\sin \theta_{ca})}{I_{ca}} \tag{4.22}$$

With the aforementioned analysis, only the  $V_{ac}$  coupled impedance design for minimum DPC voltage operation is determined. However, the ultimate goal of a parameter design is to determine the  $V_{ac}$  phase coupled inductance  $L_a$  and capacitance  $C_a$  for practical application.

The linkage of  $X_{LCa}$  with  $C_a$  and  $L_a$  can be obtained through circuit analysis, as shown in

$$X_{LCa} [V_{inva LC-min}] = \frac{V_{ac} (\sin \theta_{ca})}{I_{ca}} = - \left( \frac{\omega^2 L_a C_a - 1}{\omega C_a} \right) \tag{4.23}$$

Variation of  $V_{ac}$  coupled  $C_a$  and  $L_a$  designed for minimum DPC voltage operation (PF=0.85).

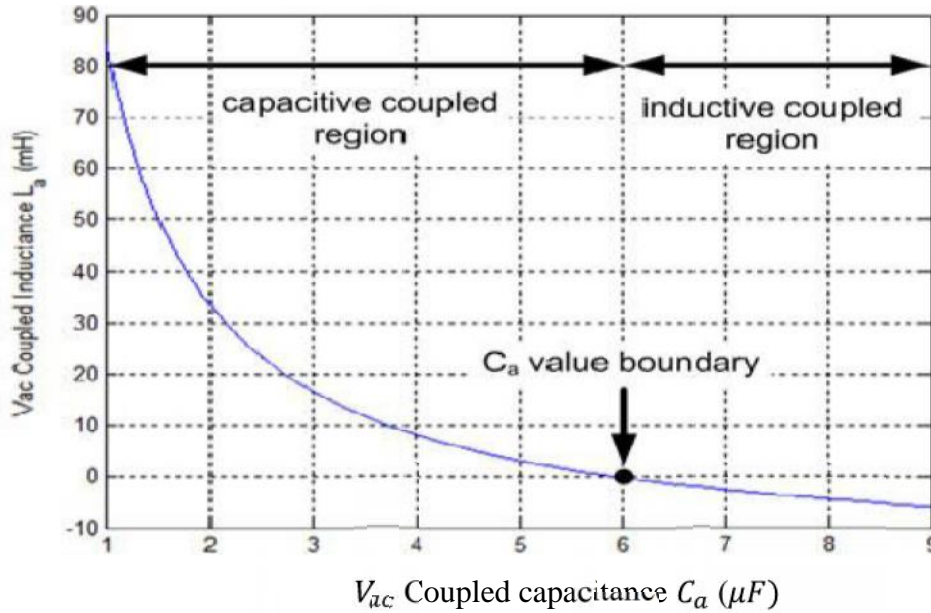


Figure 4.5 Variation of  $L_a$  with  $C_a$  for minimum  $V_{inva}$  LC (PF =0.85, 16MVA)

For example, with  $X_{LCa}$  of 27.5 kV, load PF of 0.85, and capacity of 16 MVA, the variation of  $L_a$  and  $C_a$  which satisfies the relationship in (4.23) is presented. It can be observed that the relationship between  $L_a$  and  $C_a$  for minimum DPC voltage rating is nonlinear. It is more practical for smaller physical size of lower inductance value. Presented in Figure 4.5 it can be observed that the relationship between  $L_a$  and  $C_a$  for minimum DPC voltage rating is nonlinear. Minimum voltage operation in DPC, thus, fails when the value of  $C_a$  is outside this boundary. Furthermore, there is a limitation on the value of  $C_a$ , which is indicated by the large dot. This is also the  $C_a$  value boundary. For a  $C_a$  value exceeding this boundary, the DPC drops into the inductive coupled region, causing the operation similar to RPC. Minimum voltage operation in DPC, thus, fails when the value of  $C_a$  is outside this boundary.

Table 4.1 Data of harmonic current contents substation traction load from simulation result [Table 5.1]

	3 <sup>rd</sup>	5 <sup>th</sup>	7 <sup>th</sup>	9 <sup>th</sup>	11 <sup>th</sup>
Harmonic contents(% of fundamental)	25.12	7.96	4.51	3.04	2.68

❖ Rail system power demand by types of service

Rail Systems	Power Demand
Light Rail	<1MW
Commuter trains	≈3-4 MW
High Speed Inter-city rails	≈4-6 MW
Very Fast Commuter Trains (TGV)	≈8-10 MW
Freight Trains(in Europe)	≈6-10 MW
Freight Trains(in USA)	> 18-24MW

Table 4.2 Power demand of traction system [12]

Considering the traction load with 9.2 MW of co phase traction power supply

$$I_{L1} = 196.79 * 2 = \underline{393.58A}$$

Based on equation (4.12)

$$I_{ch} = r_h I_{L1} = r_h \left( \frac{I_{ca}}{\sqrt{(0.2887 PF_L + \sin(\cos^{-1}(PF_L)))^2 + (0.5 PF_L)^2}} \right)$$

$$\text{Where } I_{L1} = \left( \frac{I_{ca}}{\sqrt{\left(\frac{1}{2\sqrt{3}} PF_L + \sin(\cos^{-1}(PF_L))\right)^2 + (0.5 PF_L)^2}} \right)$$

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

$$= 393.58 \sqrt{(0.2887 * 0.85 + \sin(\cos^{-1}(0.85)))^2 + (0.5(0.85))^2} = 393.58A * (0.8808)$$

$$I_{ca} = \underline{346.66A}$$

❖  $V_{ac}$  phase converter coupled impedance according to equation (4.7)

$$X_{Lca} = \frac{V_{ac}(\sin\theta_{ca})}{I_{ca}} = \frac{27.5 * \sin(\cos^{-1}(0.4824))}{346.66} = \underline{69.48}$$

❖  $V_{ac}$  phase coupled inductance ( $K_L$ ) based on equation (4.15)

$$K_L = \frac{\sum_2^{\infty} r_h^2 * \frac{(2(h^2-1))}{h^2}}{\sum_2^{\infty} r_h^2 * \frac{(2(h^2-1))^2}{h^2}} =$$

$$\frac{\left(\frac{25.12}{393.58}\right)^2 * \left(\frac{3^2-1}{3^2}\right) + \left(\frac{7.96}{393.58}\right)^2 * \left(\frac{5^2-1}{5^2}\right) + \left(\frac{4.51}{393.58}\right)^2 * \left(\frac{7^2-1}{7^2}\right) + \left(\frac{3.04}{393.58}\right)^2 * \left(\frac{9^2-1}{9^2}\right) + \left(\frac{2.68}{393.58}\right)^2 * \left(\frac{11^2-1}{11^2}\right)}{\left(\frac{25.12}{393.58}\right)^2 * \left(\frac{3^2-1}{3^2}\right)^2 + \left(\frac{7.96}{393.58}\right)^2 * \left(\frac{5^2-1}{5^2}\right)^2 + \left(\frac{4.51}{393.58}\right)^2 * \left(\frac{7^2-1}{7^2}\right)^2 + \left(\frac{3.04}{393.58}\right)^2 * \left(\frac{9^2-1}{9^2}\right)^2 + \left(\frac{2.68}{393.58}\right)^2 * \left(\frac{11^2-1}{11^2}\right)^2}$$

$$K_L = 0.0775$$

$$X_{Lca} = -(X_{La} + X_{Ca}) = -(K_L + K_C) X_{Lca}, \quad \text{where } -K_L - K_C = 1$$

Where  $K_L$ - is impedance of coupled inductance  $X_{La}$

❖  $V_{ac}$  phase coupled inductance  $L_a$  according to (4.19)

$$L_a = \frac{K_L X_{Lca}}{\omega_1} = \frac{K_L V_{ac} \sin \theta_{ca}}{\omega_1 I_{ca}} = \frac{K_L V_{ac} \sin(\cos^{-1} 0.4824)}{\omega_1 I_{ca}} = \frac{0.0775 * 27.5 * 0.875951}{2 * 50 * \pi * 346.66} = \frac{1867.01541406}{108906.4509}$$

$$L_a = 0.0171432H = 17.14 \text{ mH}$$

❖  $V_{ac}$  phase coupled capacitance according to (4.20)

$$C_a = \frac{1}{\omega_1 K_c X_{Lca}} = \frac{1}{\omega_1 (-1 - K_L) X_{Lca}} = - \frac{I_{ca}}{\omega_1 (-1 - K_L) V_{ac} \sin \theta_{ca}}$$

$$= - \frac{346.66A}{2\pi(-1-0.0775)*27.5kV \cdot \sin(\cos^{-1} 0.4824)}$$

$$= \frac{346.66A}{8154213.56378221V} = 0.00004251299 \text{ F} = 42.51 \mu F$$

### 4.2.2 $V_{bc}$ Phase Coupled Impedance Design

For the  $V_{bc}$  phase coupled impedance design, it is determined with matching to the minimum voltage  $V_{inva LC-min}$ . The vector diagram showing the operation of  $V_{bc}$  phase converter in DPC in correspondence with the  $V_{inva LC-min}$  is shown in Figure 4.6.

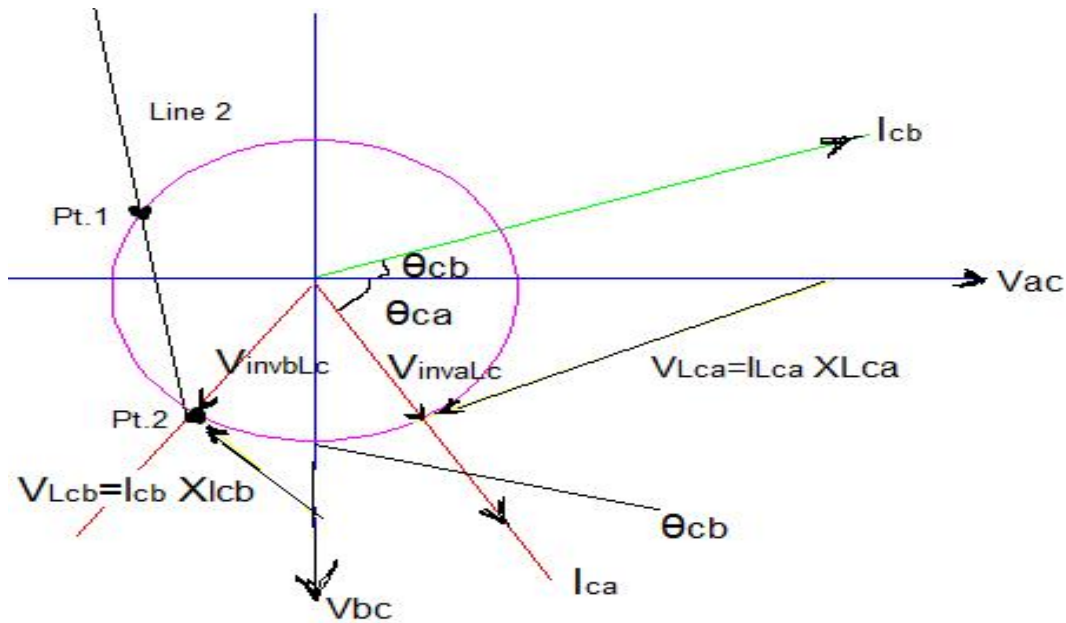


Figure 4.6 Vector diagram showing the operation of DPC in correspondence with minimized  $V_{inva LC}$

The minimum DPC voltage is represented by the circle  $C_{ira}$  with radius  $V_{inva LC-min}$  assuming constant load PF and capacity, the vector  $V_{Lcb}$  varies along the line  $L_2$  with varying  $V_{bc}$  phase

coupled impedance  $X_{LCb}$ . Two intersection points (pt.1 and pt.2) are present between the circle Cira and the line  $L_2$ . These two points are the operation points which satisfy the voltage matching with  $V_{inv LC-min}$ . They may be determined mathematically.

The mathematical expression showing the intersection of circle Cira and the line  $L_2$ . is given in

$$V_{inv LC-min}^2 = (V_{LCb}^2 \sin^2 \theta_{cb} + (V_{bc} - V_{LCb} \cos \theta_{cb})^2) \quad (4.24)$$

The phase angle of the compensating current vector  $I_{cb}$

$$\theta_{cb} = \tan^{-1} \left( \frac{\frac{1}{2} I_{L1p}}{\frac{1}{2\sqrt{3}} I_{L1p}} \right) = \tan^{-1} \left( \frac{0.5}{0.2887} \right) \approx 60^\circ$$

Where  $I_{L1p} = I_{L1} \cos \phi$

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

$$\begin{aligned} (\text{pt.2}) \frac{V_{bc} \cos \theta_{cb} - \sqrt{V_{inv LC-min}^2 - V_{bc}^2 \sin^2 \theta_{cb}}}{I_{cb}} &= X_{LCb} \\ &= \frac{V_{bc} \cos \theta_{cb} + \sqrt{V_{inv LC-min}^2 - V_{bc}^2 \sin^2 \theta_{cb}}}{I_{cb}} (\text{pt.1}) \end{aligned} \quad (4.25)$$

Although both pt.1 and pt.2 may satisfy the voltage matching with  $V_{inv LC-min}$ , operation point at pt.2 is preferred due to the lower impedance of  $X_{LCb}$  and lower power consumptions. Besides the  $V_{bc}$  coupled impedance of  $X_{LCb}$ , there is another issue concerning about the value of  $V_{bc}$ . For the circle Cira to have intersections with the line  $L_2$ , the expression for  $X_{LCb}$  in (4.25) must be real values. Thus, the restrictions in (4.26) can thus be obtained.

$$V_{bc} \leq \frac{V_{inv LC-min}}{\sin \theta_{cb}} \quad (4.26)$$

❖  $V_{bc}$  phase coupled impedance

$$\begin{aligned} I_{cb} &= I_{L1} \sqrt{(0.2887 PF_L)^2 + (0.5 PF_L)^2} = 393.58 \sqrt{(0.2887 \cdot 0.85)^2 + (0.5 \cdot 0.85)^2} \\ &= 393.58 \cdot \sqrt{0.24084} = 193.15 \text{ A} \end{aligned}$$

Where  $V_{bc} = 13.75$ ,  $\theta_{cb} = 60^\circ$

$V_{inv LC-min} = 13.26 \text{ kV}$

$$X_{LCb} = \frac{V_{bc} \sin \theta_{cb} - \sqrt{V_{inv LC-min}^2 - V_{bc}^2 \cos^2 \theta_{cb}}}{I_{cb}} = \frac{13.75 \text{ kV} \cdot \sin(60^\circ) - \sqrt{13.26^2 - 13.75^2 (\cos^2 60^\circ)}}{193.15 \text{ A}} = 10.351381 \Omega$$

$X_{LCb} = 10.35 \Omega$

❖  $V_{bc}$  phase coupled inductance  $L_b$  according to (4.21)

$$L_b = \frac{X_{LCb}}{\omega_1} = \frac{10.35 \Omega}{2 \cdot \pi \cdot 50} = 0.0329 \text{ H} = 32.9 \text{ mH}$$

### 4.2.3 Minimum DPC Voltage Rating Achievable

After investigations of the  $V_{ac}$  and  $V_{bc}$  phase coupled impedance design for the minimum DPC operation voltage, the minimum voltage rating achievable is discussed in this section. The value of  $V_{invaLC-min}$  is a key factor in the minimum DPC voltage rating achievable. By substituting the design of  $V_{ac}$  coupled impedance  $X_{LC}$  in (3.4) into the DPC  $V_{invaLC}$  voltage calculation in (4.2), the minimum value of  $V_{invaLC}$  in DPC ( $V_{invaLC-min}$ ) can be obtained in

$$V_{invLC-min} = (\cos\theta_{ca})V_{ac} \quad (4.27)$$

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

$$K_{min} = \frac{V_{invLC-min}}{V_{ac}} = \cos\theta_{ca} \quad (4.28)$$

Variation of  $K_{min}$  with load power factor (PF) in DPC

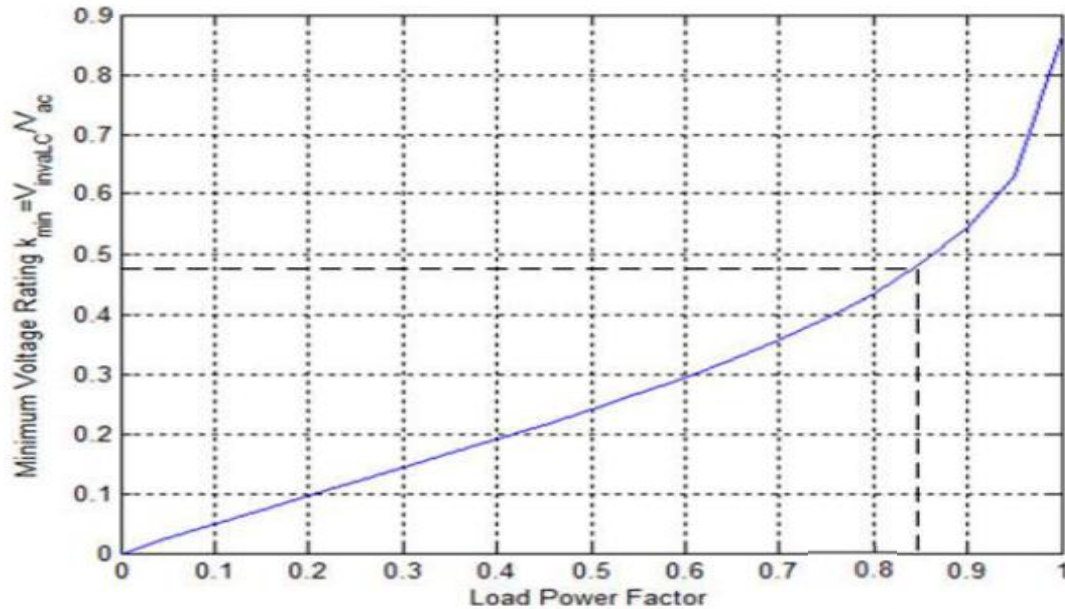


Figure 4.7 Curve showing the variation of DPC minimum voltage rating ( $K_{min}$ ) with load PF [19]

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

$$\theta_{ca} = \tan^{-1} \left( \frac{\frac{1}{2\sqrt{3}} PF + \sin(\cos^{-1}(PF))}{\frac{1}{2} PF} \right) \quad (4.29)$$

Usually traction load power factor range from 0.8 to 0.9, and take the average power factor (PF) = 0.85

$$\theta_{ca} = \tan^{-1} \left( \frac{\frac{1}{2\sqrt{3}} * 0.85 + \sin(\cos^{-1}(0.85))}{\frac{1}{2} * 0.85} \right) = 61.1688$$

❖ The minimum DPC voltage rating is determined by

$$K_{min} = \frac{V_{inv LC-min}}{V_{ac}} = \cos\theta_{ca} = \cos(61.1688)$$

$$\cos\theta_{ca} = 0.4822$$

❖ The minimum value of DPC voltage can be determined by

$$V_{inv LC-min} = (\cos\theta_{ca})V_{ac} = 27.5\text{kv} * 0.4822 = 13.26\text{kV}$$

❖ The peak value of  $V_{ac}$  phase voltage

$$V_{ac} = \sqrt{2}V_{ac} = \sqrt{2} * 27.5\text{kV} = 38.89\text{kV}$$

❖ The minimum dc link voltage

$$V_{dc-link} = \sqrt{2} * 13.26 = 18.75\text{kV}$$

## CHAPTER FIVE

### 5 Simulation Result and Discussion

Simulations using MATLAB are done to verify the aforementioned theoretical studies. The circuit schematic of the system used in simulations is provided in Figure 5.1 and 5.7. The substation V/V transformer is composed of two single-phase transformers, with turning ratios of 132 kV/27.5 kV and 132 kV/13.75 kV. Traction loads are simulated using DC smoothing capacitor and resistor. The compensation device is then connected across the two single-phase outputs of V/V transformer to provide power quality compensation of the system.

Notice that the hybrid LLC structure is included here to filter the ripples and compensate the reactive power introduced by the compensator.

#### 5.1 Co-Phase Traction Power without Compensation

The system performance without compensation is investigated first. Shown in Figure 5.1 are the three-phase source, secondary voltage, and current waveforms for co phase traction power without compensation. It could be observed that the system suffers from unbalance, reactive power and harmonics problem. A traction load of is connected to 132 kVA grid through step down transformer (132kV/27.5kV).

One phase at the secondary side of the traction transformer directly supplies the traction loads. The other phase supplies the loads indirectly via a power conditioner.

❖ Co phase traction power supply system without DPC simulation parameters

➤ Voltage source

Line to-line voltage primary voltage  $V_{ph-ph} = 132kV$

Three phase short circuit (MVA) =462MVA

Frequency (Hz) = 50Hz

Secondary winding (kV) =27.5kV

➤ AC Transmission line

Positive and zero sequence resistance ( /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 inductance (F/km)

$c_1= 6.79 \cdot 10^{-9}$   $c_0= 6.79 \cdot 10^{-12}$



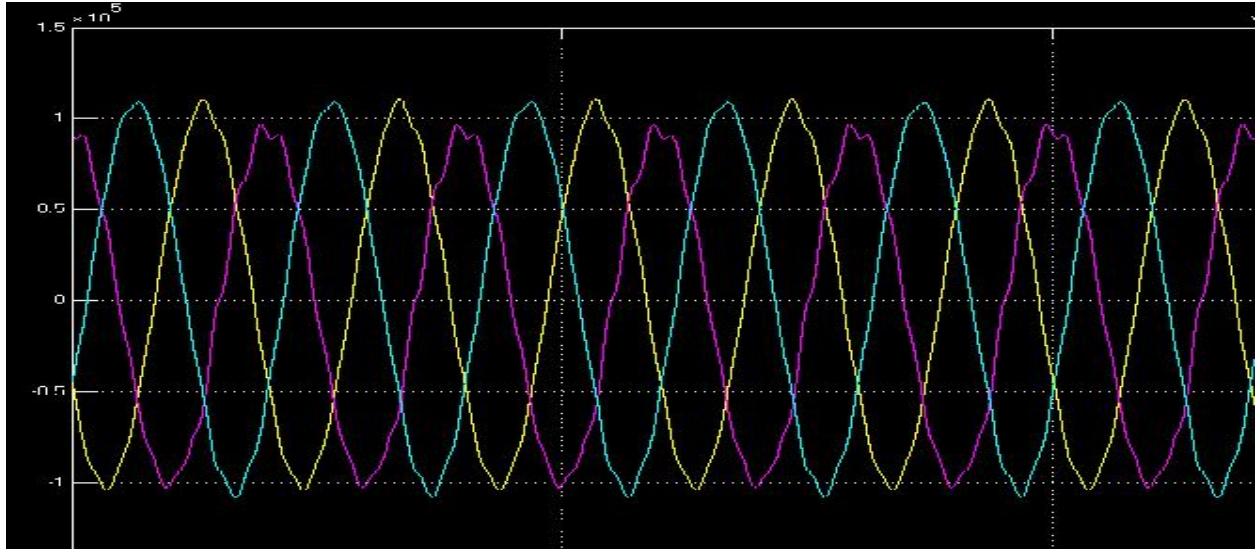


Figure 5.2 Three phase voltage at the grid side of co phase power supply system without DPC when a train is located at 13.52km from TSS.

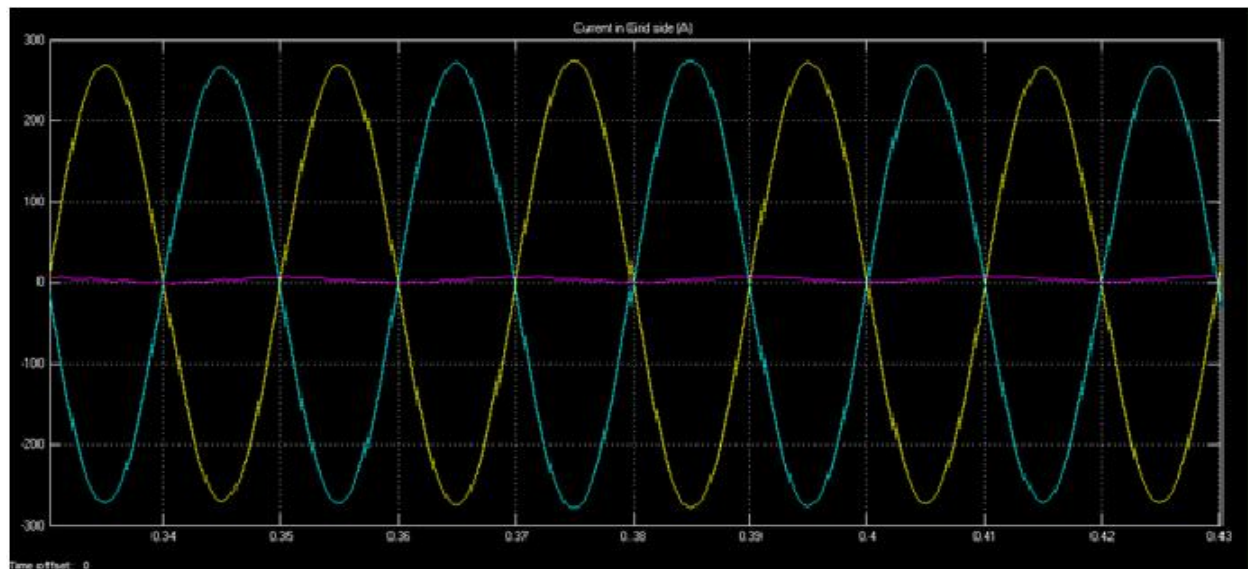


Figure 5.3 Three phase current at the grid side of co phase power supply system without DPC when a train is located at 13.52km from TSS.

Figure 5.3 shows that the three phase grid side current and %THD at phase B is zero since the load is only connected to the  $V_{ac}$ -phase. The three phase source voltage and current waveforms obtained for co phase traction power supply system without DPC are shown in Figure 5.2 and Figure 5.3 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.

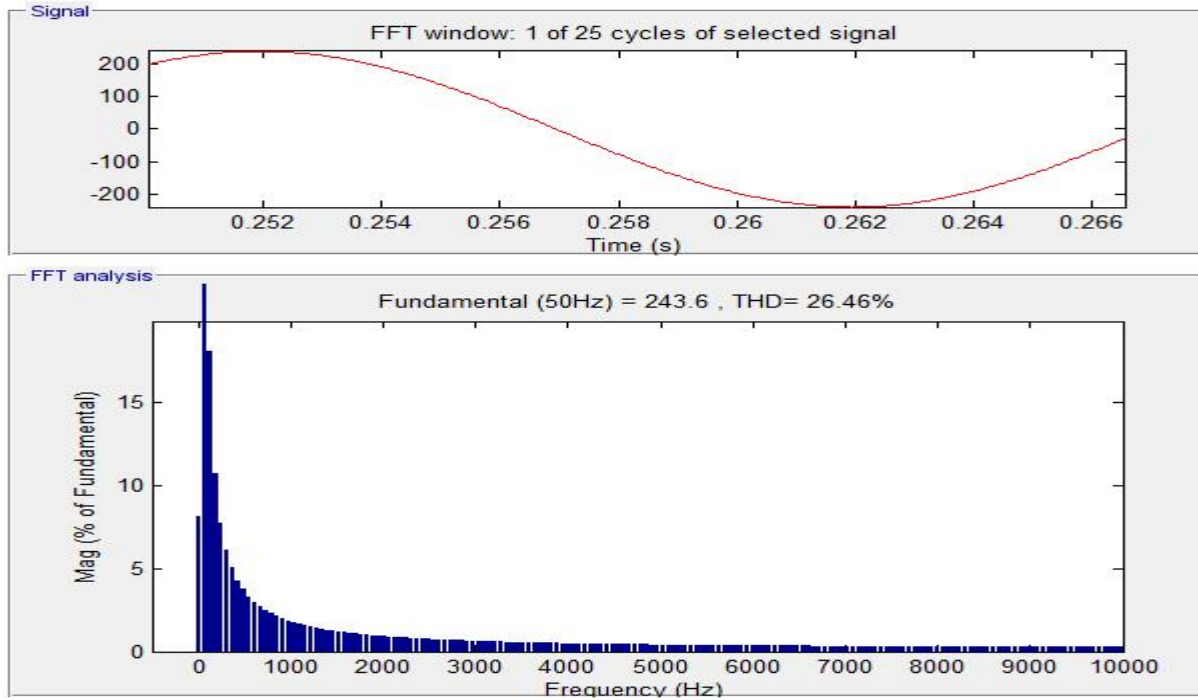


Figure 5.4 Current harmonic spectrum at PCC when a train is located at 13.52 km from TSS (THD=26.46%)

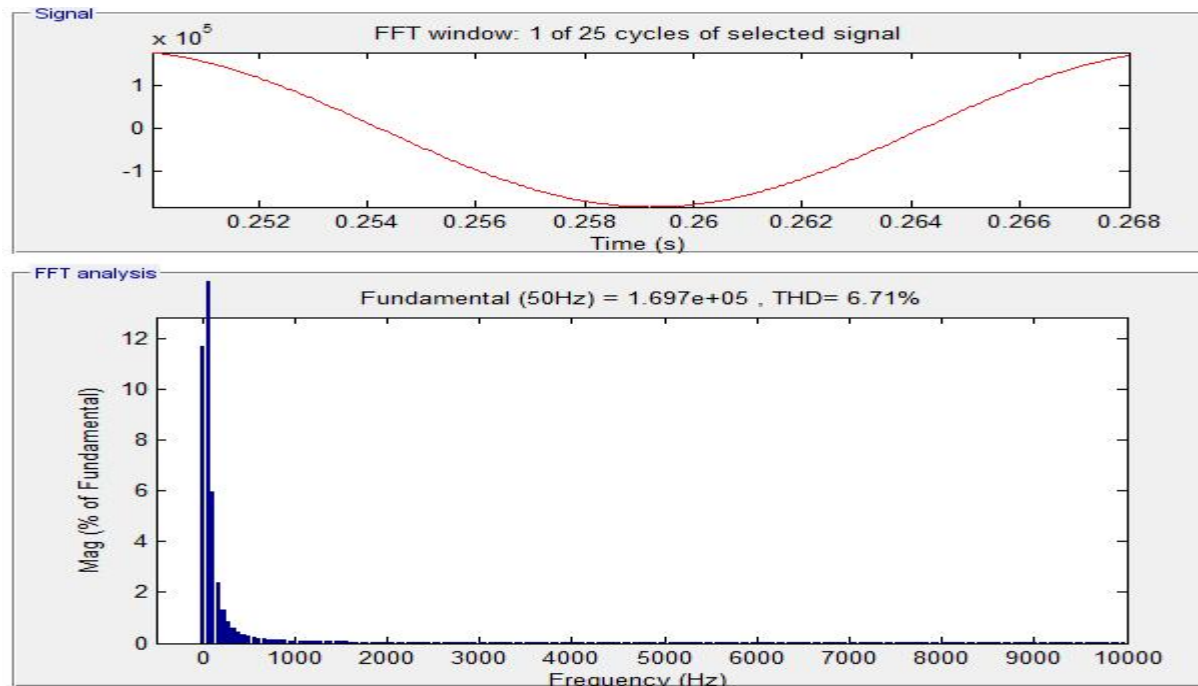


Figure 5.5 Voltage harmonic spectrum at PCC when a train is located at 13.52 km from TSS (THD=6.71%)

### 5.2 Co-Phase Traction Power with DPC Compensation

Table 5.2: System Circuit Parameters Use in the Simulation Verifications

No-	Items	Description
1	$V_{ac}$ coupling inductance	17.14 mH
2	$V_{bc}$ coupling inductance	17.14 mH
3	$V_{ac}$ coupling capacitance	42.51 $\mu$ F
4	DC link capacitance	10000 $\mu$ F
5	$V_{bc}$ coupling inductance	32.9 mH
6	Minimum Dc link voltage (Vdc)	18.75kv

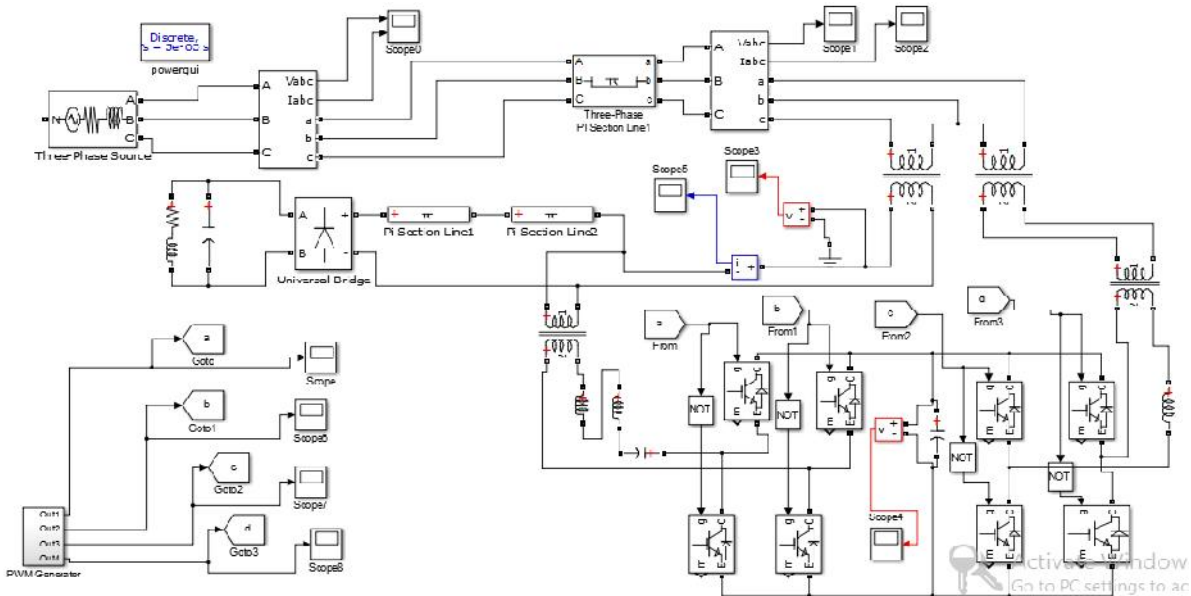


Figure 5.6 Co phase Traction Power with DPC Compensation

DPC is connected with a traction load which is connected to 132 kVA grids through step down transformer (132/27.5kV), to mitigate the voltage, THD and to increase the power factor. Traction load is a time varying load which is represented by rectified with RL load (non-linear load).

$V_{ac}$  and  $V_{bc}$  side traction loads are causes voltage unbalance and it will reduced by compensating voltage by using side transformer. Rectifier with RL load will be the best example of traction load [19].

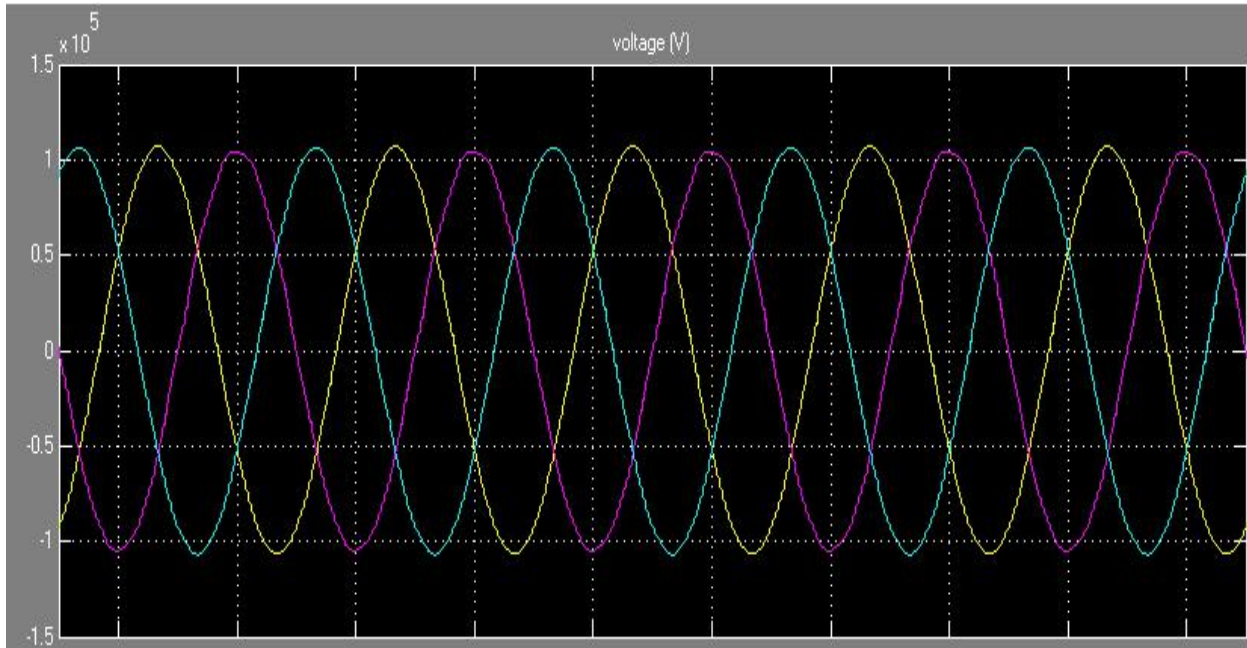


Figure 5.7 Three phase voltage at the grid side of co phase power supply system with DPC when a train is located at 13.52km from TSS.

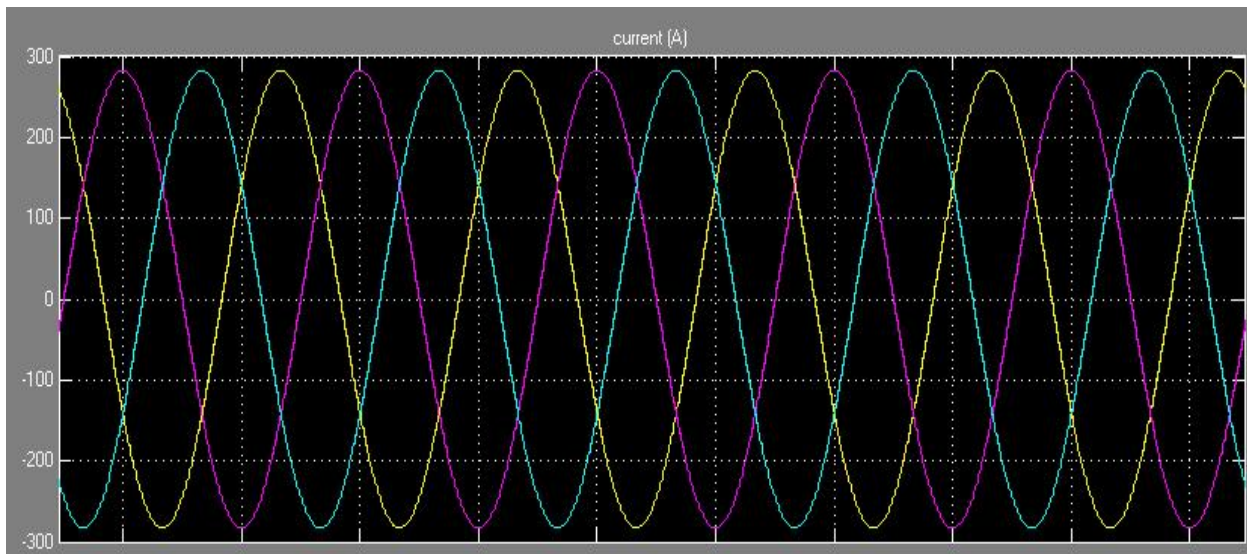


Figure 5.8 Three phase current at the grid side of co phase power supply system with DPC when a train is located at 13.52km from TSS.

As shown the above figure 5.7 and figure 5.8 the three phase voltage and currents are balanced after used direct power compensator.

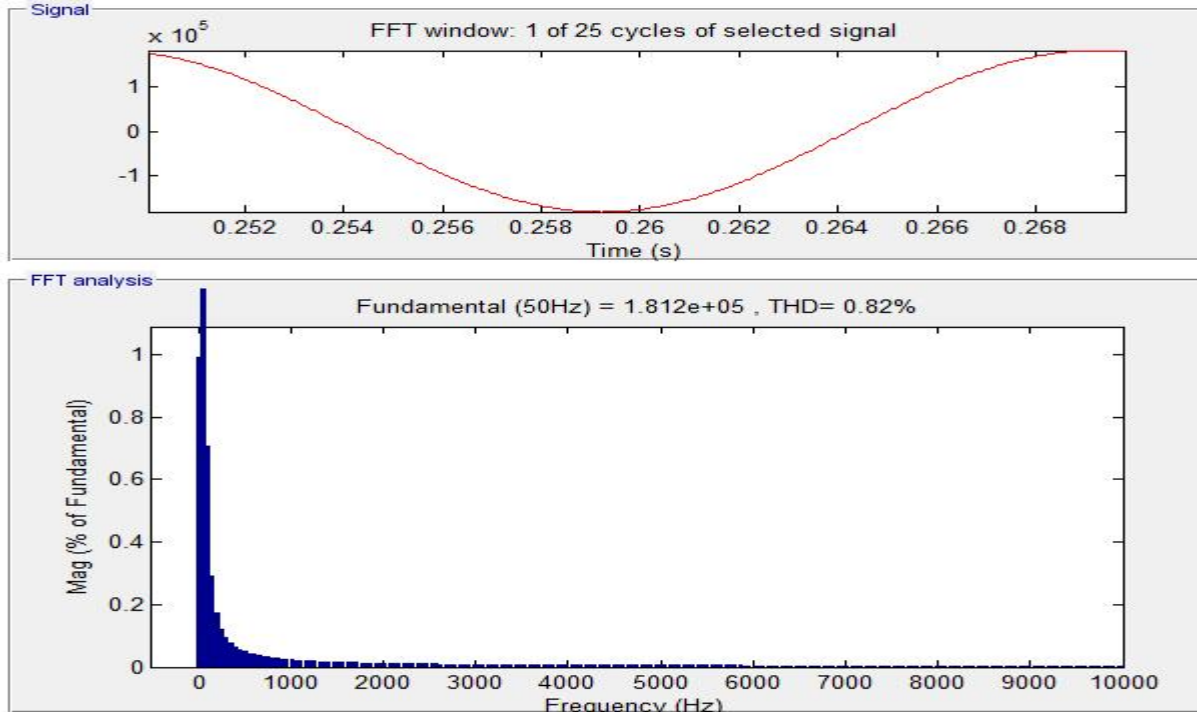


Figure 5.9 Voltage harmonic spectrum at PCC when a train is located at 13.52 km from TSS (THD=0.82%)

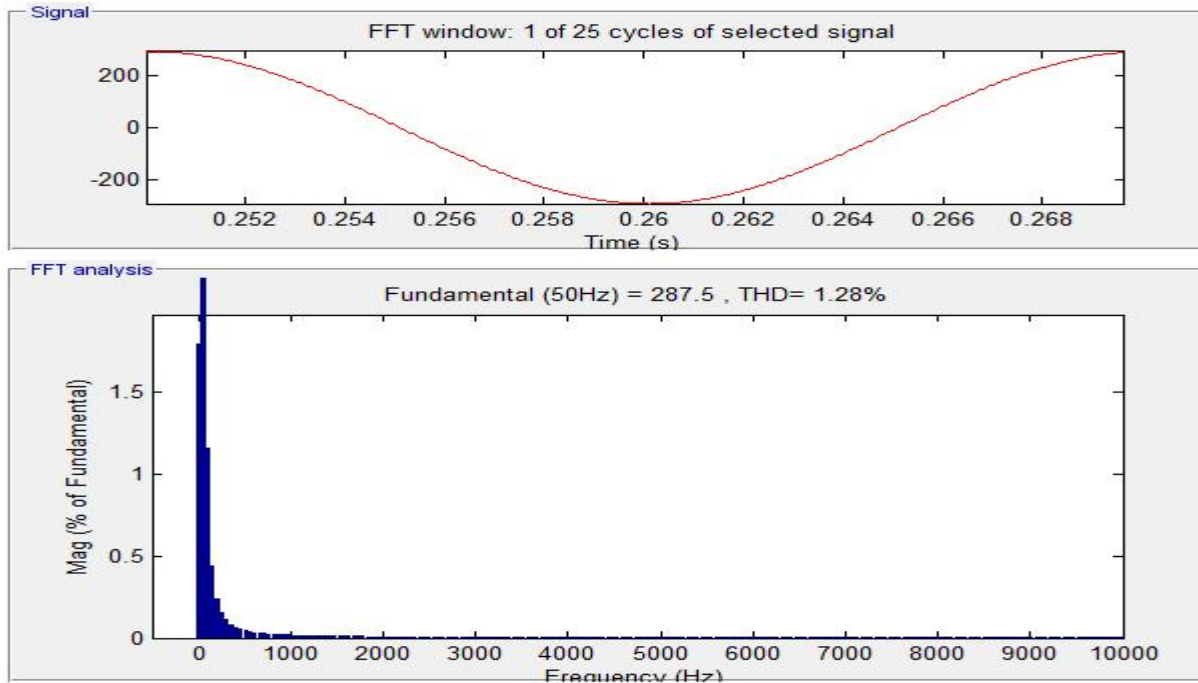


Figure 5.10 Current harmonic spectrum at PCC when a train is located at 13.52 km from TSS (THD=1.28%)

**Simulation Summery**

Configuration	%THD of voltage	%THD of current	Power factor(PF)	Position of analysis
Before compensation	26.46%	6.71%	0.81%	PCC
After compensation using proposed DPC	1.28%	0.82%	0.99%	PCC

Table 5.3 Comparison of %THD current and voltage simulation results at PCC with out and with DPC for mitigation of harmonics of voltage and current compensated Simulation

After plentiful simulations, results depict that, the voltage unbalance and harmonics are above the standard limits. Figure 5.2 shows voltage unbalance and harmonic distortion on the feeding bus. After applying the LLC hybrid filter the current harmonics distortion is reduced highly as shown in Figure 5.7. Moreover, the voltage unbalance factor becomes less than 1% using direct power compensation and current unbalance is further improved as shown in Figure 5.8.

Similarly, the current %THD reduced lower than 2% as depicted on Figure 5.10. Therefore, it is clear that the effectiveness of the LLC-DPC is very high.

## CHAPTER SIX

### 6 Conclusion and Recommendation

#### 6.1 Conclusion

In this work, various power quality issues are discussed and also direct power compensator has been designed. It mainly gives solutions to voltage unbalance; current harmonics distortion and power factor improvement using direct power compensator (DPC), in which a capacitive coupled hybrid LLC structure is added. A comparative analysis for traction system with and without DPC was performed using MATLAB-Simulink. Here, investigations are carried out with and without improvement methods at the point of common coupling.

The system source voltage without power quality compensation is shown in Figure 5.2. The system source voltage total harmonic distortion is 6.71%; this value violates the IEEE Limit of 2.5% at the point of common coupling, with current total harmonic distortions of 26.46%; This value actually violates the IEEE total harmonics distortion current limit of 5%, whereas the three-phase source power factor is 0.81. Obviously, the system source power quality is far from satisfactory. Power quality compensation is thus required.

Based on the simulation result of the total harmonics distortion, the comprehensive design for LLC-DPC mathematically derived. With load PF of 0.85, the minimum DPC voltage rating is 0.48. It is also verified that the LLC-DPC would operate at the minimum voltage with the proposed parameter design, and without increasing the transformer turn's ratio, thus to reach the good power factor at a certain dc link voltage.

According to the data analysis and simulation results, the simulated three-phase source voltage and harmonic distortion are shown in Fig.5.7 and Fig.5.9. It can be observed that the three phase source voltage unbalance and current harmonic distortion are highly reduced. Furthermore, the reactive power is also compensated. This can be verified by its current total harmonic distortions of 1.28%, total harmonic distortion of voltage unbalance of 0.82%, and power factor of 0.99.

## **6.2 Recommendation**

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

## **6.3 Future Work**

Experimental investigations can be done on shunt active power filter by developing a prototype model in the laboratory to verify the simulation results for both PI and fuzzy controllers.

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Appendix A

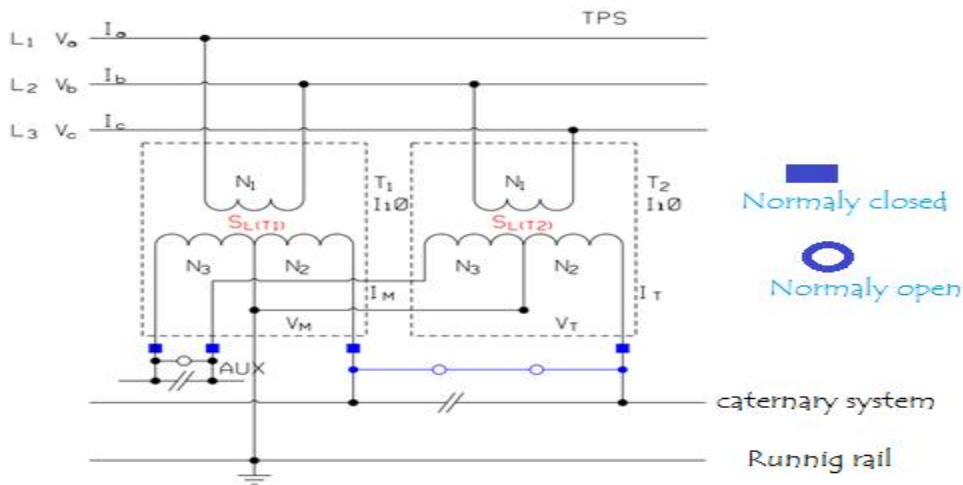


Figure A.1 Two single phase transformer configuration

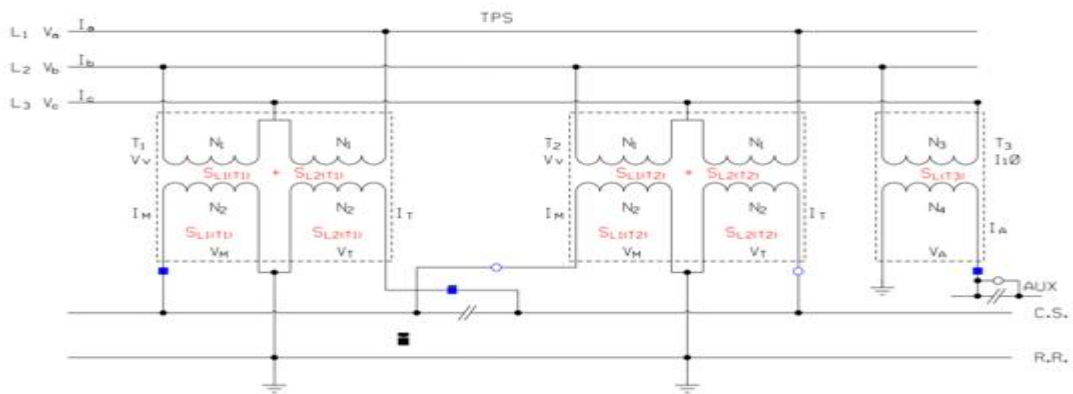


Figure A.2 Two V/V transformer configuration

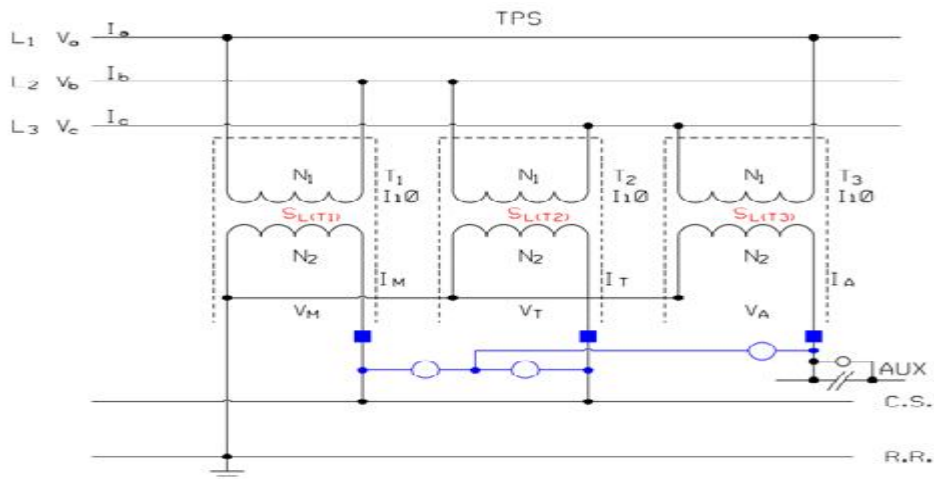


Figure A.3 Three single phase transformer configuration.