DISTRIBUTION NETWORK PERFORMANCE IMPROVEMENT USING LOAD COMPENSATION

BY:

OJO ALABA JAMES

SUPERVISORS:

Mrs K.O. Awodele

Prof. A.B. Sebitosi

This dissertation is submitted in fulfilment of the requirements for the degree of Master of Science in Electrical Engineering

DECEMBER 2022

Department of Electrical Engineering
University of Cape Town
Cape Town, South Africa

Declaration

This MSc research work is my original work and has not been presented for an award of any degree in and out of this University. I know the meaning of plagiarism and declare that all the work in this dissertation, except for that which is properly acknowledged, is my own.

Signed by candidate

……………..

Alaba James, OJO

Dedication

I dedicate this work to Almighty God, the giver of life. May His name continue to be praised.

Acknowledgements

I return all glory, honour and adoration to Almighty God for His infinite mercy He granted me before, during and after the successful completion of this programme. To God be the glory.

I sincerely appreciate the guidance, dedication, financial support and exemplary academic standards of my supervisor, Mrs Kehinde Awodele. I am also indebted to my co-supervisor Professor Adoniya Ben Sebitosi for his counsel, encouragement and financial support.

I would like to appreciate the support of the electrical personnel of the upper campus maintenance department of the University of Cape Town for their support and assistance during the data collection at one of their substations. Also, to the technicians in charge of computer laboratories of the Electrical department.

I equally appreciate my colleagues at the Federal Polytechnic Ado Ekiti, in Nigeria, for their support and encouragement during this programme.

Lastly, I thank my wife (Taiwo), my children (Praise, Favour, Precious), and other members of my family for their enduring love and support throughout this programme. I say thank you so much. May God bless you all.

Abstract

The phenomenal growth in electricity demand due to the population growth and industrialization, as well as the inadequacy of generation, transmission and distribution capacities have affected the quality of power delivery and the overall performance of the entire power system network as witnessed in South Africa since 2008. Even if additional power generating sources are provided, the power generated has to be transferred to the consumers through transmission and distribution networks which would also require additional investment for capacity expansion and this would amount to huge investment and burden for the utilities. To reduce this investment, an option could be, performance enhancement of the existing transmission and distribution system. Since the overall performance of power system networks depends on the loads connected to it, the distribution system is the backbone by which electricity supply is distributed to the customers, therefore, ensuring the economical operation of the distribution network within power quality standards is imperative. The presence of substantial single-phase loads, and large industrial loads such as arc welding, electric furnace, lighting etc. contribute to contribute to system unbalance and harmonic currents and may lead to the pollution of the supply voltages and excessive neutral current in three-phase four-wire networks. In addition, in the recent years, the use of power electronic-based devices/equipment in industrial, commercial and residential sectors due to advancements in technology and the need for energy efficiency measures has increased the power quality problem. Such loads include Adjustable speed drives (ASD), High voltage Direct current (HVDC) system, traction systems, flexibles AC transmission systems (FACTS), heating, ventilation and Air conditioning (HVAC) and loads with switch-mode power supplies. These power electronics-based devices draw non-sinusoidal currents which interact negatively with source at the point of common coupling and have other effects such as current and voltage distortion, errors in metering and malfunctioning of protective equipment, increased heating in conductors and power transformers, poor voltage regulation in the supply's distribution system due to resonance condition.

In this study, a power quality survey of commonly used nonlinear loads and a typical commercial building was initially conducted to evaluate the existing level of power quality issues in the distribution system. Various voltage and current waveforms of some of the commonly used loads and their harmonic spectra were recorded using a power quality Analyzer. In mitigating the above problems due to poor power quality, an effective load compensation is required to improve the performance of the system. This dissertation, therefore, investigates the power quality issues, causes, effects and measurement. It also proposes effective compensation techniques for performance improvement of distribution network considering unbalance, poor power factor and harmonic distortion using passive components and shunt active filter. An innovative load compensation model has been proposed and developed through simulations using MATLAB/Simulink in the Sim Power System toolbox. An analysis of the distribution network with and without load compensation shows an improved power factor of about 38% and an appreciable reduction in the kVA demand of the network while the active method was able to reduce the current harmonic of the load to an acceptable standard. Based on the investigations reported in this dissertation, it may be concluded that various options for load compensations in the distribution system for improving the performance of distribution networks were successfully explored.

Table of Contents

List of Figures

List of Tables

Nomenclature

ANSI -	American National Standards Institute
APF -	Active Power Filter
ASD -	Adjustable Speed Drives
CENELEC -	Comité Européen de Normalisation Électrotechnique (European Committee for Electrotechnical Standardization)
CFL -	Compact Fluorescent Lamp
DSM -	Demand Side Management
DSTATCOM -	Distribution Static Compensator
DVR -	Dynamic Voltage Restorer
FACTS -	Flexibles AC Transmission Systems
FL -	Fluorescent Lamp
HVDC -	High Voltage Direct Current
IEC -	International Electrotechnical Commission
IEEE -	Institute of Electrical and Electronics Engineers
LV	Low Voltage
MATLAB -	Matrix Laboratory
NEMA -	National Electrical Manufacturers Association
PC -	Personal Computer
PCC -	Point of common coupling
PF	Power Factor
p-q -	Active and Reactive power
PQ -	Power Quality
rms	Root Mean Square
SAPF -	Shunt Active Power Filter
SMPS -	Switch-Mode Power Supplies
THD -	Total Harmonic distortion
UPQC -	Unified Power Quality Conditioner

1. Introduction

This chapter introduces a recent trend in electricity demand in South Africa, measures taken to solve it, the trend of power quality issues in distribution networks as the background and the need for load compensation. It also gives the motivation for the research, research objectives and questions to be answered by the research. The chapter then concludes with the outline of the dissertation.

1.1 Background

The electrical power system involves three major blocks Generation, transmission and distribution and the combination is expected to deliver a reliable and efficient power supply to the end-users. However due to population growth, changes in living culture and the need for industrialization, there is an increase in electricity demand as witnessed in South Africa in 2008 [1]. The South African electricity sector is dominated by Eskom, the national utility, a primary electricity supplier that generates 95% of the electricity used in the country while the balance of 5% is supplied by the municipalities and redistributors as illustrated in Figure 1-1 [2] [3].

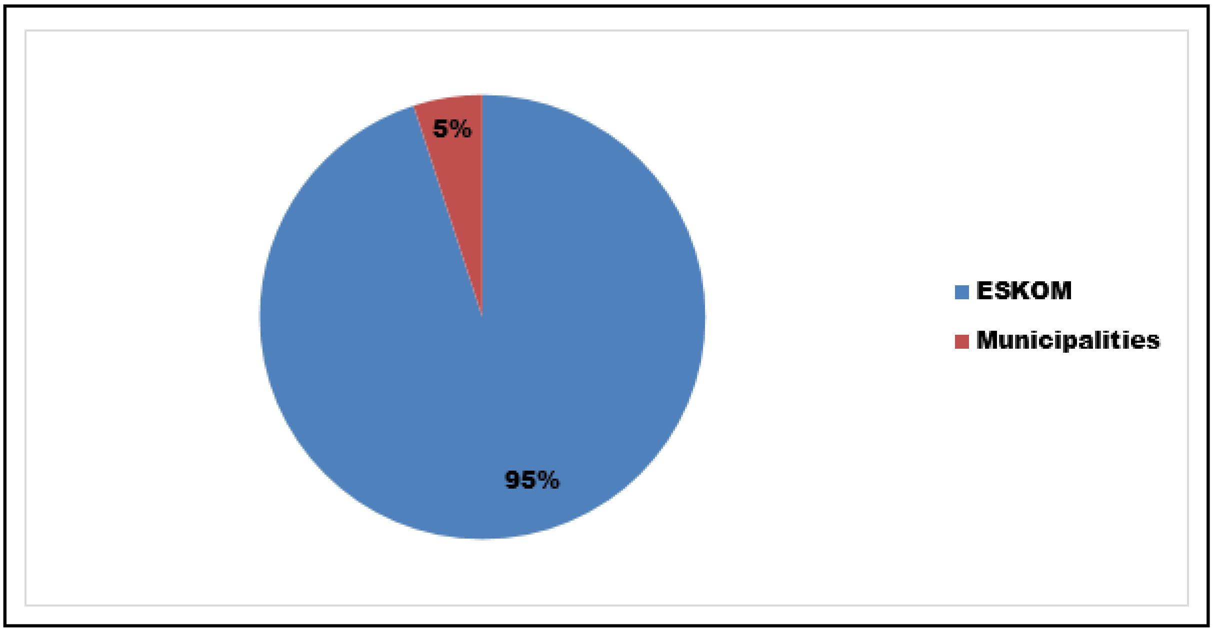


Figure 1-1: Electricity Supply in South Africa [2].

In terms of electricity generation in South Africa, Eskom dominates the production of electricity, with a generation infrastructure comprising coal-fired power stations. Eskom generates, transmits and distributes electricity to industrial, mining, commercial, agricultural and residential customers in South Africa, and to municipalities, who in turn redistribute electricity to businesses and households within their areas. It also purchases electricity from Independent Power Producers (IPPs) in terms of various agreement schemes as well as electricity-generating facilities beyond the country's borders as illustrated in Figure 1-2 [4].

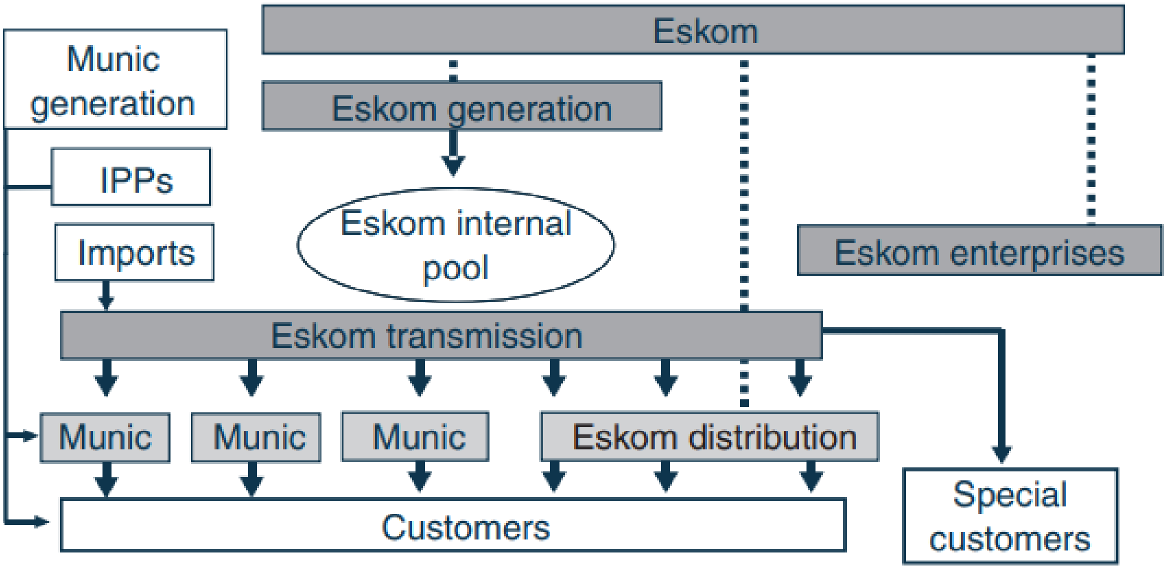


Figure 1-2: Structure of the electricity supply industry in South Africa [4].

The South African supply of electricity supply has been under pressure over recent years due to the state-owned power utility (ESKOM) not having enough capacity to meet the electricity demand as experienced since 2008 [5]. The increased demand poses a challenge to both Eskom and the relevant municipalities to supply these additional loads as efficiently and cheaply as possible [6]. This has led to measures being implemented to ease the pressure on the grid and avoid electricity supply disruptions like load-shedding. Such measures include the contribution of the customers in making the electricity distribution network more efficient using efficient equipment and reducing maximum demand [7]. The programme is demand-side management which was the joint action by the electricity companies and the consumers to improve the consumer load curves thereby leading to energy and cost savings to both the consumer and utility [8]. Load management (LM) involves the control of the demand for power from the grid by reducing the maximum power demand on the grid while Efficiency measures are primarily to reduce the energy used by industrial and commercial machinery and systems which may also reduce the power demand of the network for the same output [9].

Even if additional power generating sources are provided, the generated power would be transferred to the consumers through transmission and distribution networks which would also require additional investment for capacity expansion, and this would amount to another investment and burden for the utilities. To minimise this investment, an option could be, performance enhancement of the existing transmission and distribution system which can be achieved through compensation techniques using either passive or active elements [10].

Load compensation is one of the well-recognized methods for its contribution to the reduction of energy losses, along with other benefits; such as power factor correction, and increase in the transfer and operation capacity of distribution networks. Since the overall performance of power system networks depends on the loads connected to it, the distribution system is the backbone by which electricity supply is distributed to the customers, therefore, ensuring the economical operation of the distribution network within power quality standards is imperative [11].

Nowadays, the distribution systems are being faced with poor power quality problems such as excessive neutral current, increase in reactive power burden, voltage and/or current unbalance and distortion, low power factor, decrease in efficiency and pollution to other consumers connected to the same point of common coupling due to the unbalanced and nonlinear loads. The presence of substantial single-phase loads, and large industrial loads such as arc welding, electric furnace, lighting etc. contribute to the system unbalance and may lead to the pollution of the supply voltages and the recent increase in the use of power electronic-based devices/equipment in industrial, commercial and residential sectors due to advancement in technology and the need for energy efficiency measures [12]. The electronic-based devices/equipment include Adjustable speed drives (ASD), High voltage Direct current (HVDC) systems, traction systems, electric arc furnaces, flexible AC transmission systems (FACTS), heating, ventilation and air conditioning (HVAC), switch-mode power supplies (SMPS) used in Compact Fluorescent lamps (CFL), personal computers (PCs) etc. In addition to the numerous advantages, these power electronics-based devices draw non-sinusoidal currents, increase the reactive power demand from the source and offer highly nonlinear characteristics. Other adverse effects include, errors in metering and malfunctioning of protective equipment, increased heating in conductors and power transformers, poor voltage regulation in the supply's distribution system due to resonance conditions and the reduction in the performance of the entire distribution system [13].

In solving the above power quality issues and improving the performance of the system, an effective load compensation is required and this involves the modification of the system parameters for effective power transfer and these can be achieved at the distribution substation, along the distribution feeder or/and at the load end, but for effective compensation and improvement of the entire power system networks, the compensating techniques have been proved to be more effective at the load end using either passive or active methods of compensation [14], [15]. This research, therefore, investigates the power quality issues concerning unbalance, reactive power burden and harmonics in the distribution systems and the impact of compensation techniques on improving the performance of distribution networks.

1.2 Performance Indices of Distribution System

The performance of an electric distribution network depends on the quality of service and effective service delivery considering voltage, frequency, interruptions, harmonic distortions, percentage of unbalance and other issues relating to power quality [16]. In recent years, Utilities have discovered a tremendous increase in the number of drawbacks caused by deviation in the electric power quality (PQ) and these problems have sharpened because of the increased number of loads which are sensitive to PQ and have become more difficult to solve as the loads themselves also contribute to the degradation of the quality [15], [17], [18].

The term power quality has been used to describe the variation in voltage, current and frequency in the electrical power system networks [19]. Power quality improvement is a major research topic in the modern power distribution system due to the losses associated with poor power quality and which can be solved using a few methods. Two decades ago, the loads used in the industries and by other consumers were mostly linear and passive ones with very few nonlinear loads, but due to advancements in technology and power electronics applications, there is a rapid increase in the usage of nonlinear loads [20], [12]. Electricity distribution networks are the backbone by which electricity supply is distributed to the customers. As such, ensuring the economical operation of the distribution network within acceptable power quality standards is imperative [21]. Load balancing, Reactive power and harmonic compensation at the distribution level are therefore important to maximize the power transfer capacity of the distribution networks without exceeding the thermal limit.

The Distribution network is an important part of the power system components. Since it has direct contact with end-users, and its power supply reliability and power quality has a direct impact on the development of the national economy and people's daily life, it is therefore mandatory to ensure the efficient operation of the distribution network [22]. The X/R ratio for distribution levels is low compared to that of transmission levels and this results in high power losses and a dip in voltage magnitude of radial distribution networks which makes distribution losses account for a higher percentage of the entire power system network losses, thus the effective operation of the distribution network for improved power quality has important significance [23].

1.3 The Need for Load Compensation

Load compensation is the management of reactive power in a system for power quality improvement of the supply. Electrical energy is generated, transmitted, distributed, and utilized as alternating current (AC) which has some disadvantages and one of such is the need for reactive power to be transmitted along with active power [24].

Almost all loads require reactive power for satisfying their magnetic field demands, especially motors. This reactive power is supplied to the loads by the electrical source. Also, the amount of reactive power extracted by the load depends on the load condition [25]**.**

One of the methods in reducing the line losses is the effective management of the reactive power demand in the distribution networks through load compensation. The reactive power demand is due to the reactances of the loads, equipment and line parameters of the power system networks which can either be inductive or capacitive. Meanwhile, most of the loads connected to distribution networks are inductive and must be supplied with lagging reactive power which would also be conveyed by the network together with the active power demand [26]. Therefore, reactive power compensation in the distribution network would not only reduce the reactive power burden on the grid but could also maximize the distribution networks capacity without exceeding the thermal limit. The overall benefits of load compensation depend on different factors, such as size, location and technology used. The following are some of the reasons for reactive power compensation [24].

I. Improvement of Voltage regulation
II. Prevention of Voltage collapse and Voltage sag.
III. Power system stability improvement
IV. Better utilization of machines connected to the network

V. Reduction of losses in the network thereby increasing the network loading capability

1.4 Research Motivation/Justification

There is tremendous growth currently being experienced in South Africa and it manifests itself in the power supply industry as rapid growth in demand on the distribution networks. The increased demand poses a challenge to both Eskom and the relevant municipalities to supply these additional loads as efficiently and cheaply as possible [6].

Due to the integration of new decentralized generations and operations of many non-linear electronic devices in the network, the waveforms of the supply voltages and currents have been affected. As a result, PQ problems are increasing in the electricity network. In some situations, these can have significant technical and financial impacts on the customers as well as the network operators. Therefore economic power delivery and acceptable power quality standards are imperative in the operation of distribution networks.

The primary motivations of the proposed research are as follows:

- The phenomenal increase in electricity demand due to population growth and industrialization with the inadequacy of generation, transmission and distribution capacities to meet the demand
- The changing needs of the electricity customers (mainly industrial customers) because of the increasing use of sensitive (process control) devices and integration of distributed generators in the network.
- The increasing number of power electronic devices connected to the network causes pollution and leads to voltage distortions at the point of common coupling (PCC) thereby increasing the burden on the network
- The higher sensitivity of industrial customers to the loss of production time (due to PQ problems) since they must become more and more efficient and competitive in the marketplace.
- The increasing economic pressure on the network operators due to liberalization, strong regulations by the regulators and the attention to the quality of electricity supply.

1.5 Research Objectives

Power Quality disturbances can be originated in the network as well as at the customer's installation and can propagate to other parts of the network. The PQ level in the network is also highly influenced by the PQ emission behaviours of connected devices and the network characteristics. Inadequate PQ can lead to various technical and financial inconveniences to the customers and network operators.

The followings are the specific objectives of the research:

- To establish the possible causes of poor power quality in Distribution Networks through Monitoring and Assessment
- To establish the extent to which consumer originated incidents and their loading impacts on the grid
- To investigate load compensation methods for solving selected power disturbance problems
- Propose compensation techniques for network improvement considering load balancing, reactive power compensation and harmonic reduction
- To test the developed techniques through simulations using MATLAB/Simulink
- Analysis of the compensation methods through simulation.

1.6 Research Questions

This research intends to give answers to the following questions:

- How does the customer behaviour affect the performance of the Distribution Network?
- What are the impacts of unbalance and increased reactive power burden on the losses of the distribution network?
- What are the impacts of the increased number of nonlinear loads on the distribution network performance?
- How can the Power Quality issues in a typical low voltage distribution network be determined through monitoring and assessment?
- How can the performance of the distribution network be improved using Load compensation?
- How effective are the different load compensation methods?

1.7 Research Methodology

The improvement of the distribution network using load compensation involved the monitoring and assessment of some selected loads and a typical distribution network feeding a commercial building using a power quality analyser.

Mathematical formulation, Design and simulation of compensation techniques for different load combinations are carried out while the performance analysis is based on the measurement of parameters at the supply end before and after compensation.

The design of the test network and modelling of the compensation techniques using passive and active components are considered in this research using MATLAB/SIMULINK software considering three-phase, four-wire configurations for linear and nonlinear loads as indicated in table :

Table 1-1: Cases considered for the simulations

Case	Linear Load		Non-Linear load	
	Balanced	Unbalanced	Balanced	Unbalanced
1	______	✓	______	______
2	✓	______	✓	______
3	______	✓	✓	______
4	✓	______	______	✓
5	______	✓	______	✓

1.8 Scope of the Research

This dissertation covers the design and simulation of load compensation techniques using passive and active components considering load balancing, reactive power compensation and harmonic reduction for performance improvement of power distribution networks. It also covers experimental survey of power quality parameters of some common loads in distribution networks.

1.9 Publications during the Research

First Author Publications

I. **A. Ojo, K. Awodele, A. Sebitosi and M. Mzulwini (2020):** "Application of Active Power Filters for Distribution Network Performance Enhancement," A Paper presented at the 2020 Southern African Universities Power Engineering IEEE Conference. 29th – 31st Jan 2020, Cape Town, South Africa.

II. **A. Ojo, K. Awodele and A. Sebitosi (2019):** "Power Quality Monitoring and Assessment of a Typical Commercial Building," A paper presented at IEEE (AFRICON) conference, 25th -27th Sept 2019, Accra, Ghana

III. **A. Ojo, K. Awodele and A. Sebitosi (2019):** "Load Compensation in a Three-Phase Four-Wire Distribution System Considering Unbalance, Neutral Current Elimination and Power Factor Improvement," Paper presented at the 2019 Southern African Universities Power Engineering IEEE Conference, 28th – 31st Jan 2019, Bloemfontein, South Africa

Co-authored Publications

I. **A. Nyanjowa, K.O. Awodele and Ojo, A.J (2020):** "Comparative Analysis of Load Compensation Techniques in Low-Voltage Distribution Networks Using Passive Components'' Paper presented at the 2020 Southern African Universities Power Engineering IEEE Conference. 29th – 31st Jan 2020, Cape Town, South Africa

II. **T. Mathwai, K.O. Awodele and Ojo, A.J (2020):** "Power Quality Evaluation of Electrical Loads in a Typical Commercial Building'' Paper presented at the 2020 Southern African Universities Power Engineering IEEE Conference. 29th – 31st Jan 2020, Cape Town, South Africa.

1.10 Outline of the dissertation

Chapter 1

This chapter introduces a recent trend in electricity demand in South Africa, the measures taken to improve it, the trend of power quality issues in distribution networks and the need for load compensation. It also gives the motivation for the research, research objectives and questions to be answered by the research. The chapter then concludes with the outline of the dissertation.

Chapter 2

This chapter contains the literature review of power quality issues in the distribution system. It also covers the common power quality issues, causes and their effects. The method of monitoring PQ, Standards used for analysis and mitigation techniques are also reviewed

Chapter 3

In this chapter, the general view of the two types of loads in the distribution systems is reviewed while the methods of load compensation are also reviewed based on techniques and components used.

Chapter 4

This chapter gives the details about the unbalance in power systems, the causes, effects and the mitigation techniques as reviewed from previous works.

Chapter 5

This chapter gives a comprehensive review of harmonics in the power systems in terms of causes, effects and indices for analysis. The common mitigation techniques are also covered in the chapter

Chapter 6

This chapter is mainly devoted to the power quality measurement and evaluation of some selected nonlinear loads in distribution networks and the assessment of a typical distribution network feeding a commercial building. It also gives the mathematical modelling of harmonics of personal computers through measurement.

Chapter 7

This chapter is basically for the mathematical formulation, design and simulation of load compensators for a three-phase four-wire network considering load balancing and reactive power compensation of linear loads using passive components.

Chapter 8

The chapter is devoted to the application of shunt active power filters to deal with power quality issues such as unbalanced load, reactive power compensation and elimination of harmonics in the distribution networks.

Chapter 9

The conclusions are drawn in this chapter based on the discussion and analysis of power quality survey and simulation results of the load compensation techniques. The chapter also gives the benefits of the research and recommendations for future work.

2. Power Quality Problem in Distribution Networks

In this chapter the literature review of power quality issues in the distribution system is presented. It also covers their causes and effects. The method of monitoring Power Quality, Standards used for analysis and mitigation techniques are also reviewed.

2.1 Introduction

The performance of an electricity distribution network is determined by the power quality and quality of service delivery. The parameters commonly used for the performance evaluation are voltage, frequency, interruptions, harmonic distortions and level of unbalance [16]. In recent years, Utilities have discovered a tremendous increase in the number of drawbacks caused by deviation in the electric power quality (PQ) and these problems have sharpened because of the increased number of loads which are sensitive to PQ and have become more difficult to solve as these loads also contribute to the degradation of the power quality [17] [18]. Problem Identification in an electrical network is advisable before any increase in the range of damages occurs for any power system. Monitoring the power quality of the system would enhance the effective operation of the sensitive equipment and serves as a means of identifying the avoidable energy losses that could be caused by poor power quality. With the changing nature of the electricity industry, increased attention is being focused on reliability and improved performance of the distribution networks in terms of power quality. Power providers and users alike are concerned about reliable power, whether the focus is on interruptions, disturbances, harmonic distortion or flicker. Power quality monitoring can help to identify the cause of power system disturbances and even assist to identify the problem before they cause interruptions or disturbances in the network.

Recently, the importance of power quality has increased because of various reasons [27]. There have been some changes as regards to the nature of electrical loads and the characteristics of load have become more complex due to the integration of power electronic equipment, which results in a disturbance of voltage and current. On another hand, several equipment have become more sensitive to variations in power quality.

Due to the worldwide increase in electricity demand and the quest for economic growth, industries are now forced to improve on efficiency to reduce operational costs. Unbalance, poor power factor, increase in reactive power burden and other power quality issues are the major contributing factors which directly influence the operational cost for both supply utilities and consumers of electricity [28] [29].

Nowadays, the distribution systems are being faced with poor power quality problems such as excessive neutral current, increase in reactive power burden, voltage unbalance and distortion, low power factor, decrease in efficiency and pollution to other consumers connected to the same point of common coupling due to the unbalanced and nonlinear loads connected to the distribution network [30], [31].

An unbalanced system condition occurs when the voltages or currents of a three-phase network are not equal in magnitude or/and the phase angle. Unbalance according to IEEE standards can be determined by the ratio of the magnitudes of the negative and positive sequence phasors of the voltage or current at fundamental frequency [32]. The presence of negative and zero sequence currents in unbalanced and harmonic distorted three-phase network give rise to the following problems [33].

I. Increase in kVA demand
II. Excessive neutral current
III. Poor power factor
IV. Increase in total line losses which results in reduced efficiency
V. Excessive heat in machines such as motors and transformers, connected to the system

South Africa's steady economic growth, as well as the increasing focus on industrialisation and a mass electrification programme to take power into deep rural areas, has led to steep increase in the demand for energy [2]. Distribution networks form the bulk of the electricity supply industry infrastructure but don't get the attention enjoyed by the transmission networks or generation infrastructure. The increased electricity demand poses a challenge to both Eskom and the relevant municipalities to supply these additional loads as efficiently and cheaply as possible.

Electricity distribution networks are the backbone by which electricity supply is distributed to the customers. As such, ensuring the economical operation of the distribution network within power quality standards is imperative. Load balancing, reactive power compensation and harmonic compensation at the distribution level are therefore necessary to maximize the power transfer capacity of the distribution networks without exceeding the thermal limit of the entire system [34].

Given the above reasons, the negative and zero sequence currents are undesirable in a power distribution system, especially under three-phase four wire configurations or connections in which the zero sequence currents flow through the neutral conductor. Even for three-phase delta connections where the effects of the zero sequence currents are negligible, the negative sequence current is directly fed back to the supply [35] [36].

In recent years, the use of nonlinear electronic loads such as compact fluorescent lamps (CFLs), computers, televisions, etc. has increased significantly. These nonlinear loads are the main sources of harmonic currents in distribution systems. In a situation where the combination of nonlinear and linear loads is connected to the same network and fed from a sinusoidal supply, the total supply current will contain harmonics. The injected harmonic currents and the resulting harmonic voltages can lead to power quality problems which affect the effective performance of the distribution network and other consumers connected to the same point of common coupling (PCC) [37].

These harmonics are generated to a small extent and at a low distortion level by generation, transmission & distribution equipment and to a larger extent by industrial and commercial loads like induction and arc furnaces, static power converters, PCs and TV receivers. The harmonic currents generally flow towards the supply because the source impedance is low [38]. Traditionally, the saturation of a transformer core using energization is the main source of harmonics in power utility but an increase in the use of FACTS devices will add a further contribution to harmonic distortion [39]. Therefore, it is important for both the utility and consumers to eliminate unbalance and harmonic distortion and their effects; this can be achieved through load compensation.

Reactive power, also known as volt-ampere reactive (VARs), is attributed to the complex impedance of typical ac power system loads and transmission lines. Even though its presence in the power system network is fundamental, it has several undesirable consequences including reduced stability limits (steady-state, dynamic and transient) and decreased power transfer capability. It also leads to increased power losses, the inefficient performance of power system equipment and the potential for the onset of system-wide voltage instability as a result of the change in the reactive power of the loads if not properly compensated and controlled [40]. Therefore, to achieve cost reduction and improve the efficiency of a distribution network, the reactive power to be drawn from the line must be decreased by adequately compensating for the load side from another source [41].

2.2 Power Quality Disturbances and their effects

Power Quality describes the extent of variation in voltage or current waveform from the normal sinusoidal wave. The variation could be in the magnitude, angle or frequency of the voltage or current which affects either the utilities or the consumers. Most authors who have worked on power quality use the term power quality with different meanings. The following set of definitions has been found to be consistent [27] [42] [43]:

Voltage quality is concerned with deviations of the voltage from the ideal. The ideal voltage is a single-frequency sinusoidal wave of constant frequency and constant magnitude. Current quality is concerned with deviations of current from the ideal. The ideal current is again, a single-frequency sinusoidal wave of constant frequency and constant magnitude. Power quality can also be described as the combination of voltage quality and current quality as illustrated in Figure 2-1. It shows the interaction between the utility and the end-user.

Power quality also represents the effective interaction between the power system supply with the connected electrical equipment at the point of connection. The quality of power is termed good if the equipment connected to it operates properly while malfunctioning of the equipment due to power supply means the power quality is poor or deficient. If the power quality of the supply is poor, the asset may suffer excessive heating, accelerated thermal ageing and reduced efficiency. This would result in additional financial costs for both end-users and the network operators in terms payment for energy consumption and reduction in the life span of connected devices or equipment [17], [44], [45].

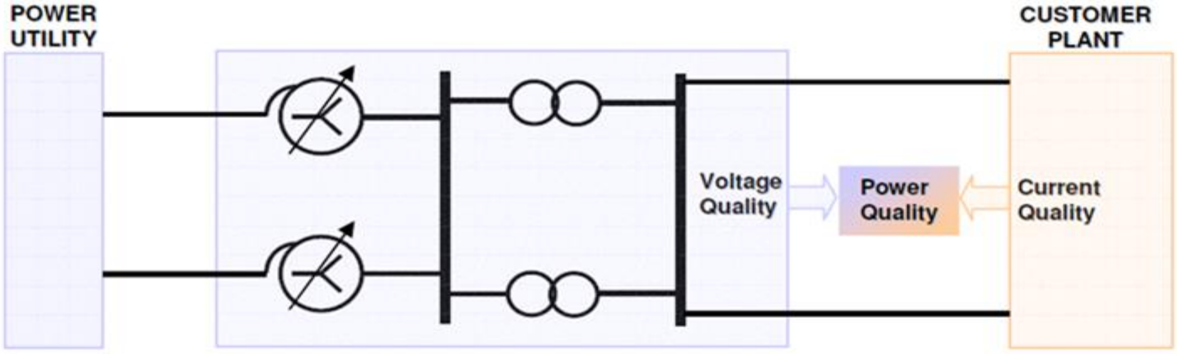


Figure 2-1: Power Quality as the relationship between Voltage & Current Quality [18]

Generally, Power quality issues include many power system problems such as transients, imbalance, notching, harmonics and inter harmonic, voltage swells and sags, and noise as illustrated in Figure 2-2 [46]. In the following sections, these power quality issues, their causes and effects are presented.

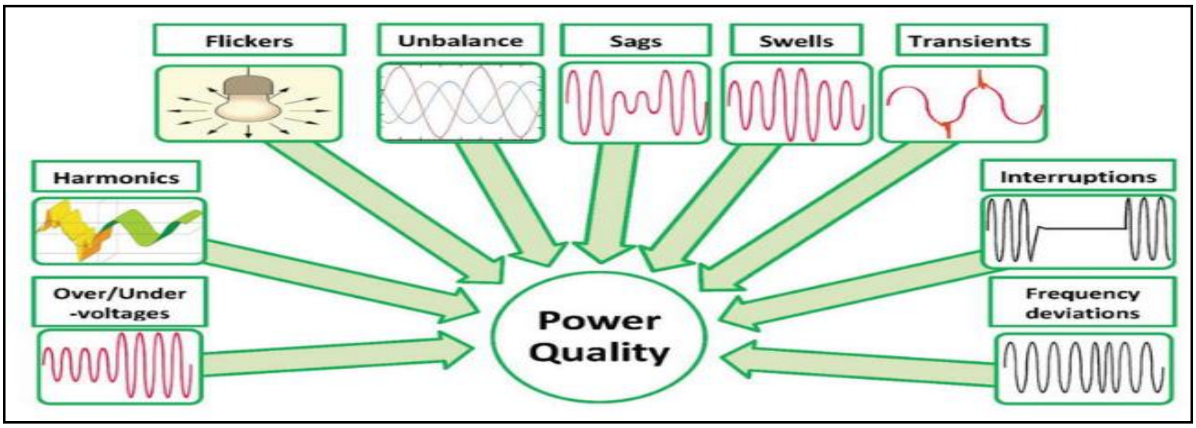


Figure 2-2: The common power quality problems **[46]**.

2.2.1 Voltage Sags (Dips)

Description: According to IEEE-1159 [47], Voltage sag or dip is defined as a decrease of the normal voltage level to between 10 and 90% of the nominal rms voltage at the power frequency as in Figure 2-3, for durations of 0,5 cycle to 1 minute [48]. It can be classified based on duration, as instantaneous, momentary and temporary sag [49].

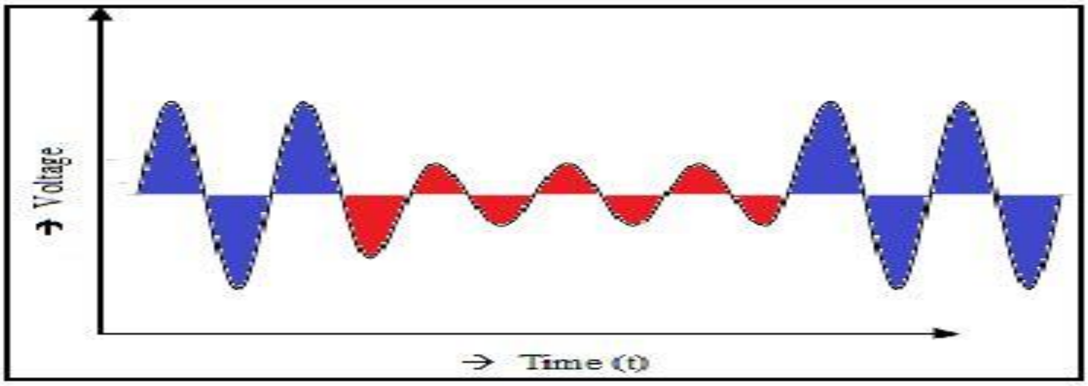


Figure 2-3: Voltage sags waveforms

The severity of voltage sag can be determined using Detroit Edison's sag score equation which is based on the voltage magnitudes in the three phases as in Eqn. 2-1 [50].

$$S = 1 - \frac{V_R + V_Y + V_B}{3} \tag{2.1}$$

where S is the sag score

Causes: Voltage sags or dips can be due to faults on the transmission or distribution network, consumer's installation in terms of connection of heavy loads and start-up of large motors.

Effects: Malfunction of information technology equipment, namely microprocessor-based devices/equipment (PCs, PLCs, ASDs, etc.) that may lead to a process stoppage, and tripping of contactors and electromechanical relays.

2.2.2 Voltage swell

Description: This is a momentary increase of the root mean square (rms) voltage, at the power frequency, outside the normal tolerances as shown in Figure 2-4, with a duration of more than one cycle and typically less than a few seconds [48]. The IEEE Std 1668 [51] identifies a swell as the disturbance where the supply voltage or current reaches 1.1 p.u. to 1.8 p.u. for a duration of 0.5 cycles to 1 minute. According to [52], in South Africa, swells do not usually exceed 1.15 p.u. of the nominal voltage.

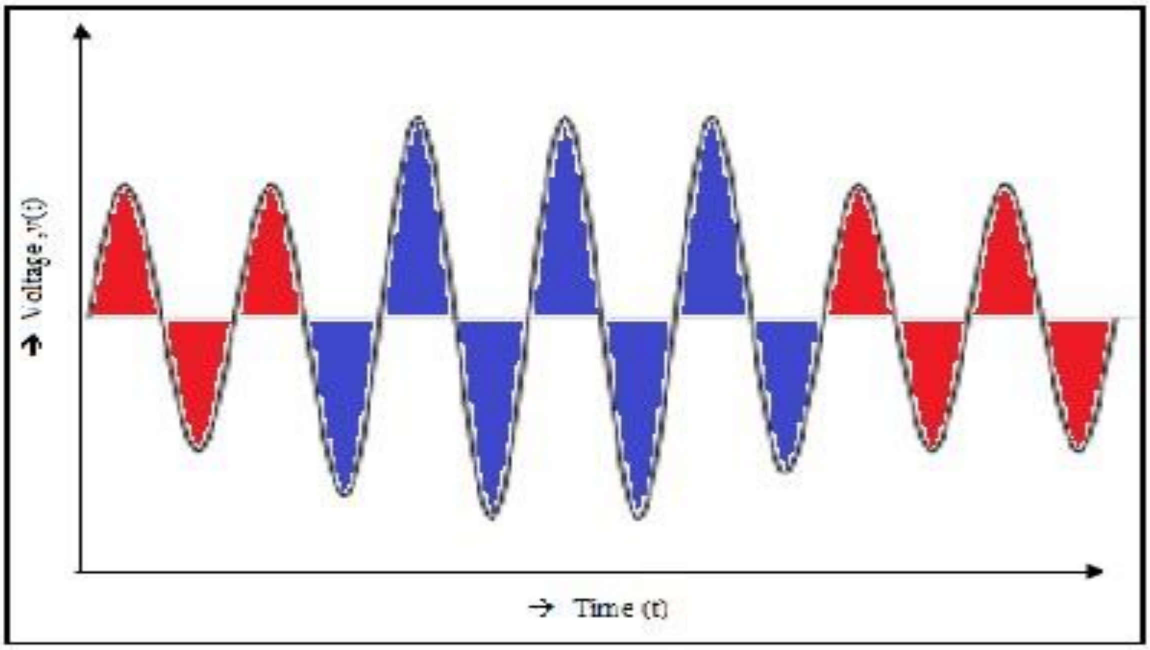


Figure 2-4: Waveform showing a typical voltage swell **[48]**

Causes: Switching on/off of heavy loads, energizing of capacitor banks, badly regulated transformers (mainly during off-peak hours) and changing of loads from one source to another.

Effects: The harmful effects of voltage swell on power system operation include: ageing of electrical connections, data loss, the flickering of lighting and screens, stoppage or damage of sensitive equipment, and insulation breakdown of the affected equipment

2.2.3 Voltage spikes and surges

Description: A voltage spike is a change in voltage magnitude ranging from tens to thousands of volts for a period of nanoseconds to milliseconds while a voltage surge is an increase in the voltage magnitude lasting for a few seconds as in figure 2-5. It is also known as transients.

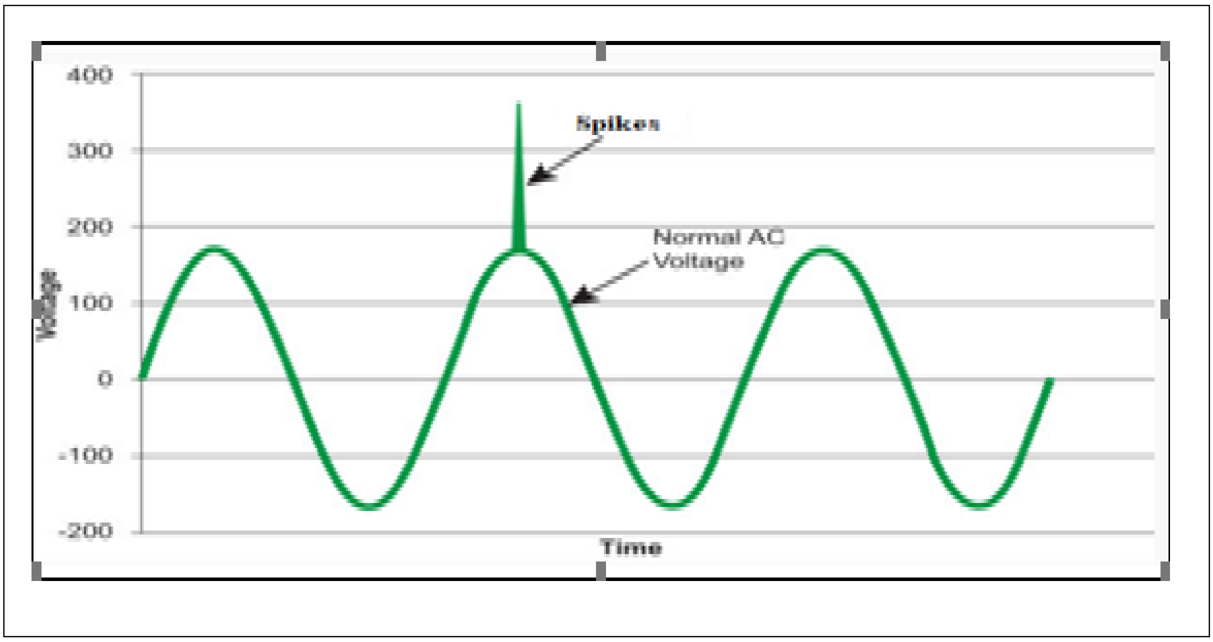


Figure 2-5: Voltage spikes/surges **[53]**

Causes: It can be caused by the operation of utility or consumer equipment. Typically, voltage spikes are the by-products of electrical events such as lightning strikes, short circuits, static discharge, tripped circuit breakers, electromagnetic pulses and other power supply failures while voltage surges are due to switching effects of air conditioners or large electric motors or capacitor switching.

Effects: The most affected equipment are computers and other electronics. The damage caused is usually due to excessive current flow which can exceed the breakdown voltage of the semiconductors.

2.2.4 Interruptions

Description: An interruption occurs when there is a complete loss of voltage for a period. Interruptions are classified as temporary (short) interruptions or sustained (long) interruptions depending on their duration. Total interruption of electrical supply for a duration from a few milliseconds to one or two seconds is termed to be short while an interruption of electrical supply for a duration greater than one to two seconds is regarded as a long interruption [51]. Figure 2-6 shows a typical voltage waveform during an interruption.

The NRS 048 further categorised events that could be considered interruptions by customers into four categories. These are forced interruptions, planned interruptions, voluntary customer load reductions, and involuntary customer load reductions [52]. Forced interruptions may occur as a result of failures while planned interruptions may occur for reasons like maintenance.

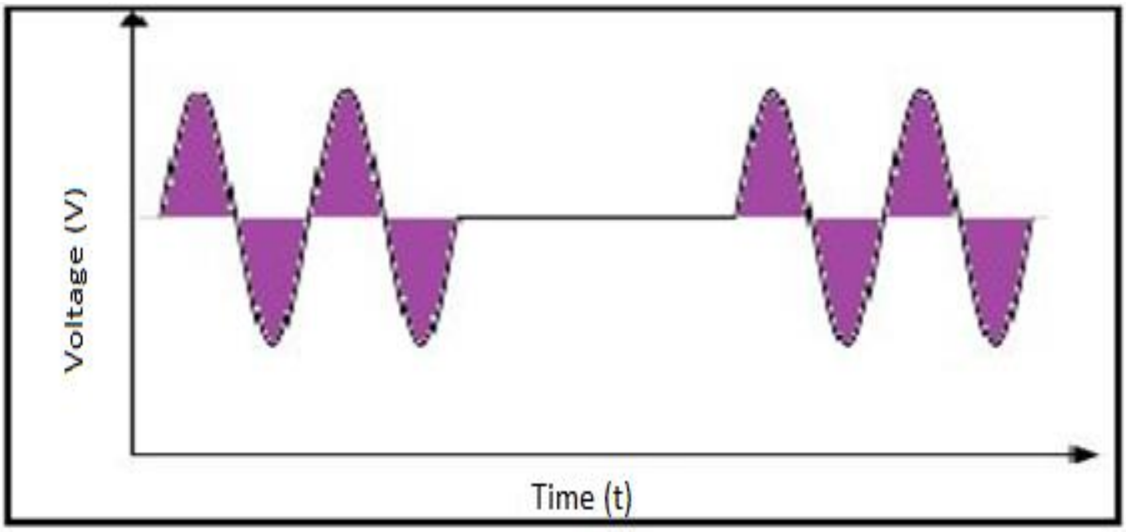


Figure 2-6: A typical waveform of the voltage during an interruption [48].

Causes: Temporary (short) interruptions are mainly due to the opening and automatic reclosure of protection devices to decommission a faulty section of power system networks such as insulation failure, lightning and insulator flashover while long interruption can be caused by equipment failure in the power system network, storms and objects (trees, cars, etc.) striking lines or poles, fire, human error, bad coordination or failure of protection devices [19]

Effects: Tripping of protection devices, loss of information and malfunction of data processing equipment and other sensitive electronic equipment

2.2.5 *Over voltages and under voltages*

Description: over voltages can be defined as any voltage above the nominal or specific operating voltage for a time that exceeds 1 minute while under voltages are defined as any voltage less than the rated voltage for a period of more than 1 minute.

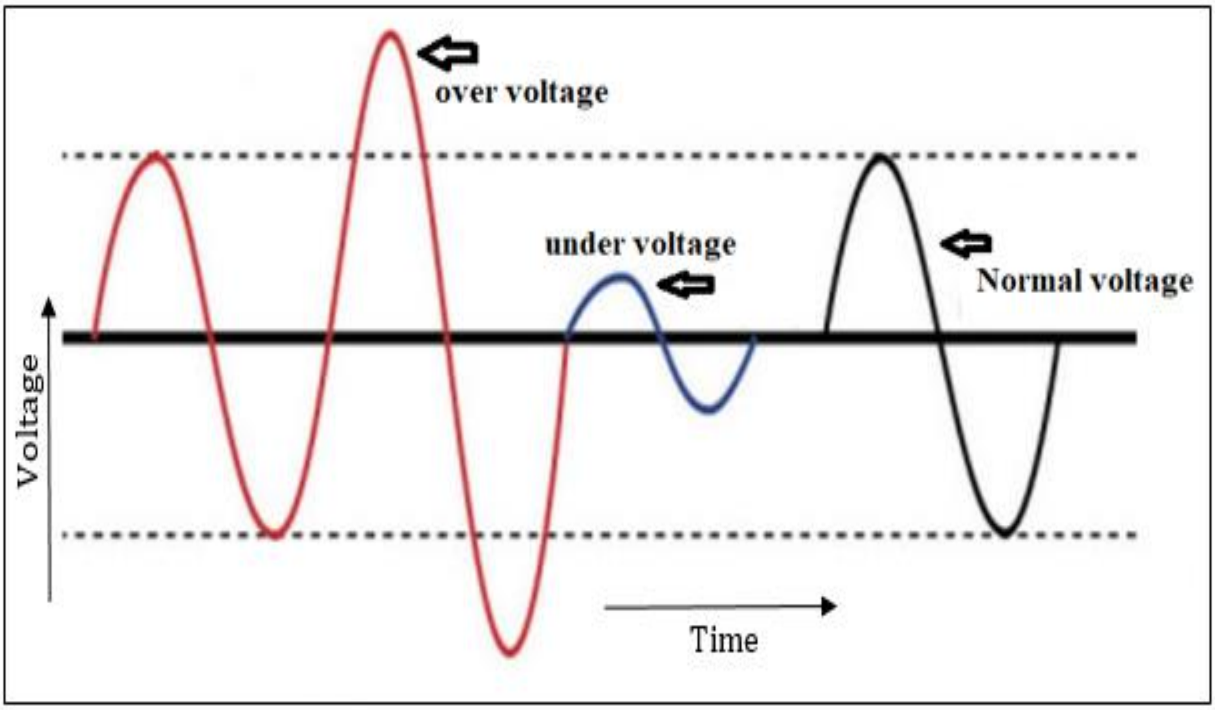


Figure 2-7: Over voltage and under voltage waveforms [53]

Causes: Over voltages are due to sudden injection of loads, harmonic resonance, abrupt line-to-ground faults, poor voltage regulation, overcompensation of reactive power in the network etc. Under voltages are caused by high loading impact, starting of electric motor and traction loads, and improper sizing of cables.

Effects: The impact of over voltage on the electrical equipment includes: insulation breakdown and dielectric failure of protective devices. Under voltages can result in high system losses and stability issues [54].

2.2.6 *Frequency variation*

Description: Frequency variation is the deviation of power frequency from its rated value of 50Hz or 60Hz as in Figure 2-8. It is another power quality disturbance that has negative impacts on the power system performance. Although there could be frequency stability in the utility system with stable and stiff interconnected power system networks but with the application of converters in the power system networks, there is a possibility of frequency deviation due to harmonics emission in the network [55]. Frequency variation can also be defined as the ratio of frequency deviation (RFD) to the rated frequency as follows [46]:

$$RFD = \frac{|f_m - f_r|}{f_r} * 100 \quad (2.2)$$

where f_m and f_r are measured frequency and rated frequency of the system respectively.

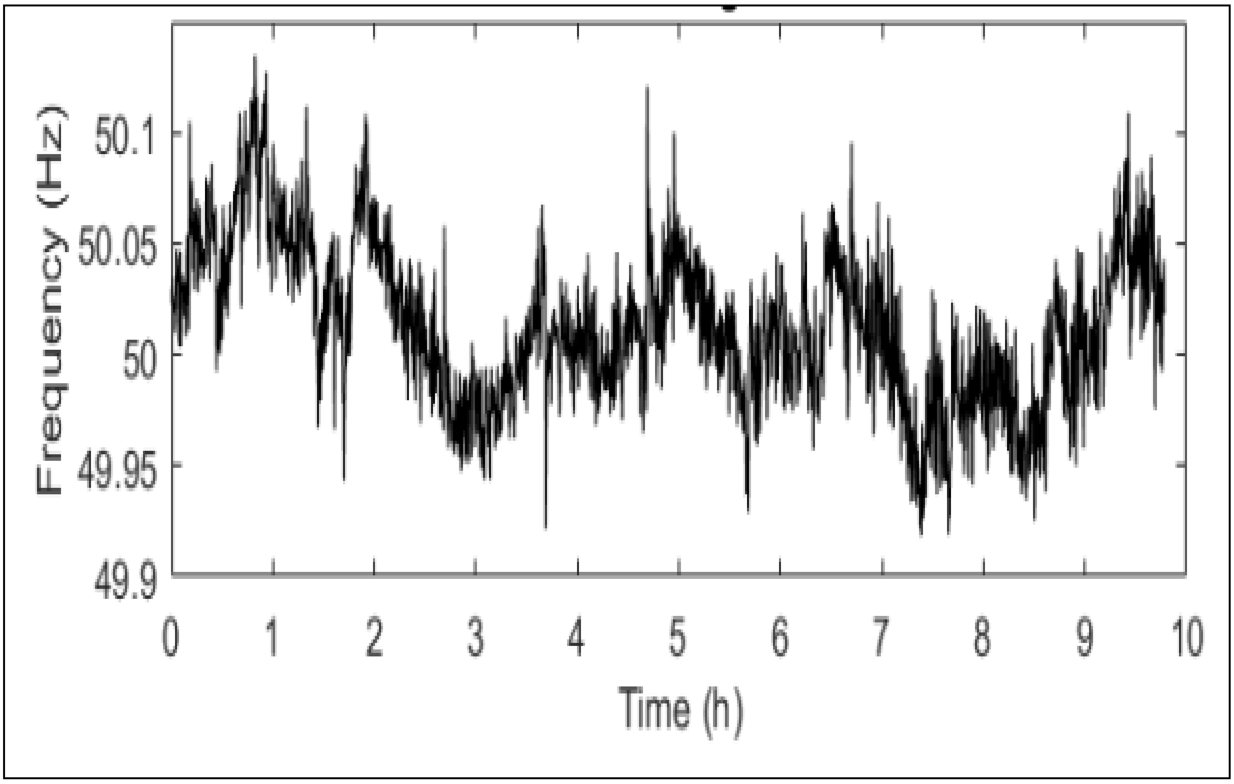


Figure 2-8: Waveform showing Frequency variations **[56]**

Causes: This problem is common in power systems with poor infrastructure and it gets worse if the generator stability is poor especially during sudden addition or removal of loads [57]. Sometimes the load or burden causes the frequency deviation with respect to its zero-loading line [58]. As the load demand increases, the frequency fluctuation increases. Another cause of frequency fluctuation is the poor speed regulation of alternators.

Effects: The impacts include: system collapse and speed variation in electric motors.

2.2.7 Voltage unbalance

Description: According to IEEE 1159 and IEC 61000-4-7, voltage unbalance can be described as a condition in a poly-phase system in which the values of the fundamental component of the line voltages, or the phase angles between consecutive line voltages are unequal [59], [60]. It can also be mathematically defined according to IEEE 112 [61] as the ratio of maximum phase voltage deviation to the average phase voltages known as phase unbalance voltage rate (PVUR) as in equation 2-3 [62].

Equation 2-1

$$\mathrm{PVUR} = \frac{\mathrm{Max}(\,V_{\mathrm{dev}})}{(\,V_{\mathrm{Average}})} * 100 \qquad (2.3)$$

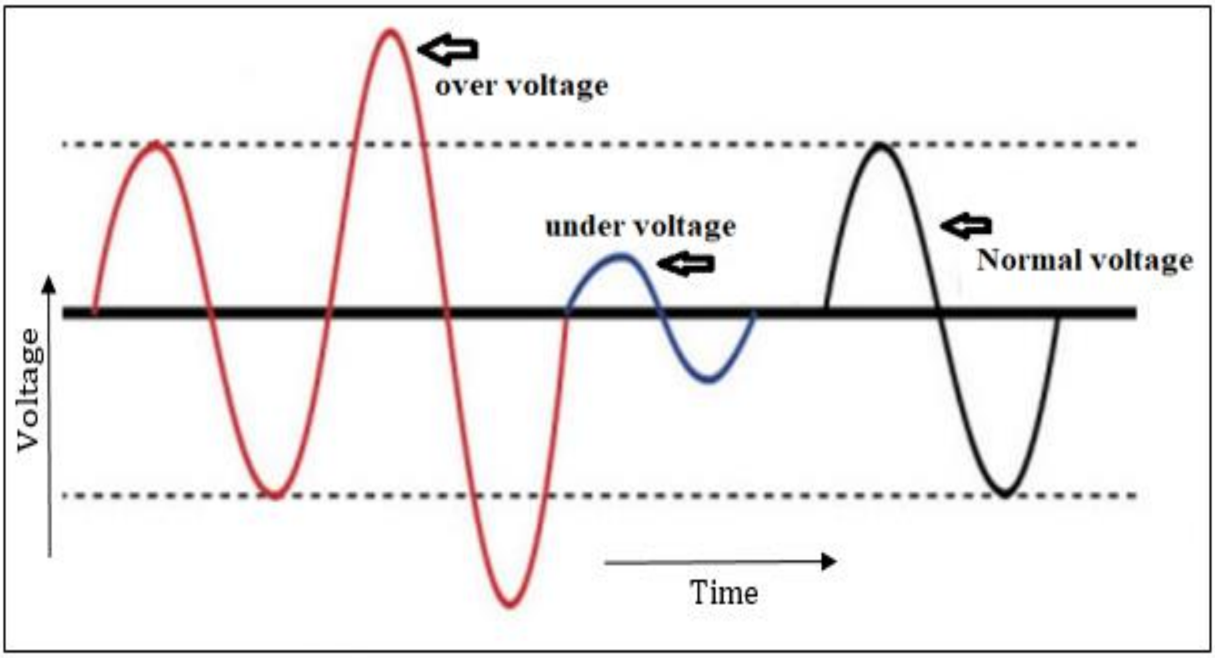


Figure 2-9: Waveform showing voltage unbalance

Causes: Voltage unbalance is most commonly seen concerning unbalanced three-phase loads and uneven distribution of single-phase loads on the phases, especially where large single-phase loads, such as arc furnaces, are in use. It is established that a small unbalance in the voltage can result in a much larger unbalance in the phase currents.

Effects: Unbalanced systems imply the existence of a negative sequence current that is harmful to all three-phase loads such as three-phase induction machines and variable speed drives. In addition, it can also cause heating in transformers and neutral conductors.

2.2.8 Harmonic distortion

Description: Voltage or current waveforms assume a non-sinusoidal shape. The waveform corresponds to the sum of different sine-waves with different magnitudes and phases, having frequencies that are multiples of power-system frequency as shown in Figure 2-9.

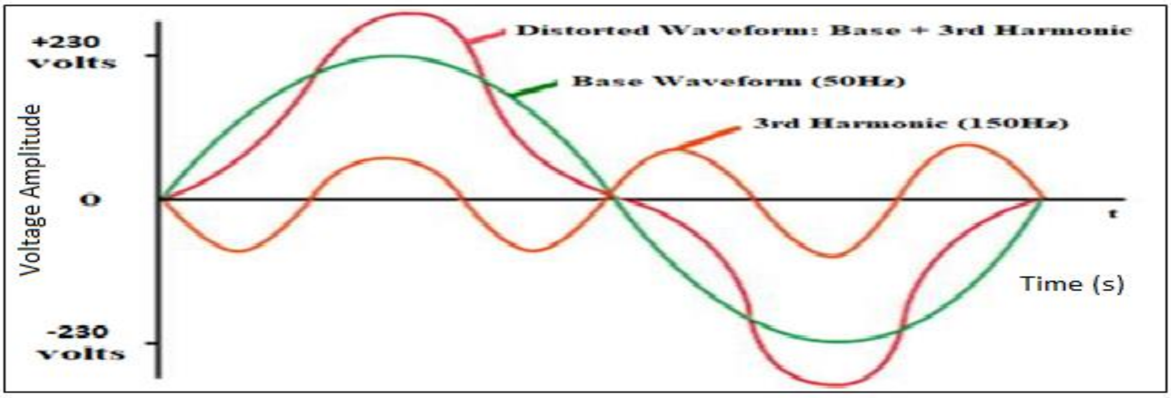


Figure 2-10: Harmonic distortion waveform **[53]**

Causes: *Classic sources*: Arc furnaces, welding machines, rectifiers, and DC brush motors. *Modern sources*: All non-linear loads, such as power electronics equipment including ASDs, switched-mode power supplies, data processing equipment, and high-efficiency lighting.

Effects: Increased probability of the occurrence of resonance, neutral overload in 3- phase systems, overheating of all cables and equipment, loss of efficiency in electric machines, electromagnetic interference with communication systems, errors in measurements when using average reading meters, nuisance tripping of thermal protection and excessive energy loss due to non-sinusoidal currents [63].

2.3 Power Quality Monitoring Methods

PQ monitoring involves the measurement of voltage, current and frequency signals to assess or quantify the performance of power system networks either at the supply end or end-user side. Problems Identification in an electrical network is advisable before any increase in the range of damage occurs for any power system. Monitoring the power quality of the system would lead to accurate operation of the sensitive equipment and serves as a means of identifying the avoidable energy losses caused by poor power quality [59].

2.3.1 *Objectives of PQ monitoring*

The objectives of PQ monitoring are generally categorized into two: proactive approach and reactive approach. A proactive approach is used to characterize the system performance and helps to quantify the performance between utility and customers' needs while a reactive approach is used to characterize a specific problem with the network, especially at the point of common coupling to diagnose incompatibilities between the utility and the consumers. The reactive approach also requires a short time monitoring of specific consumers or loads.

Generally, the procedure for monitoring and investigating power quality requires some steps as illustrated in Figure 2-11 [64].

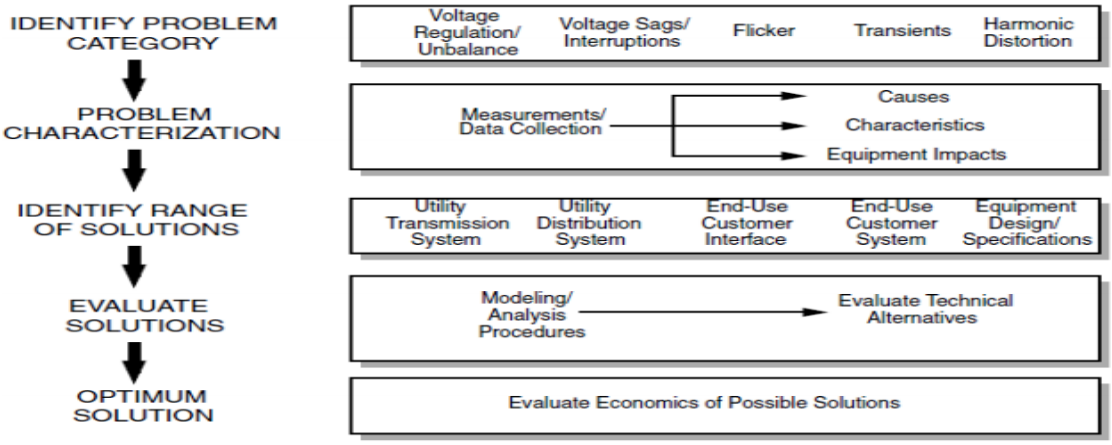


Figure 2-11: Procedural steps for Power Quality Evaluation **[64]**

2.3.2 *Power Quality Monitoring Instruments*

Instruments used to monitor electromagnetic phenomena can range from a simple analogue voltmeter to a sophisticated multiple-site, permanently installed power quality monitoring system. Selection and use of the correct type of instrument require the understanding of the instrument's capabilities and limitations, its responses to power system variations, and the specific reason for such analysis. The portable PQ monitors are used for troubleshooting after an event has taken place while permanent PQ monitors are installed at the strategic place(s) in the network or facility for capturing power quality disturbance as soon as it happened [65]. Generally, the overall architecture of PQ monitors is illustrated in Figure 2-10 [59].

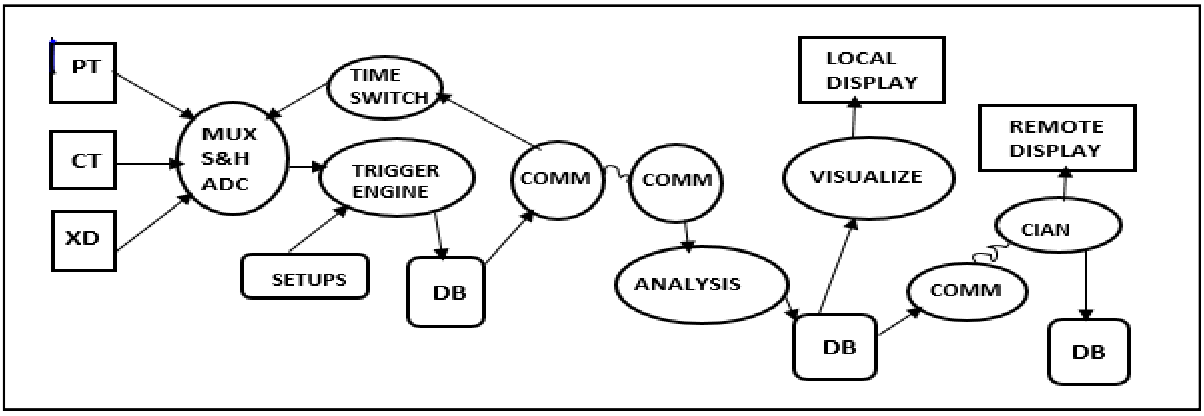


Figure 2-12: Block diagram of Typical Power Quality Monitor **[59]**

2.3.3 Justification for Power Quality Monitoring

There are many reasons and requirements for power quality monitoring. The major reason for monitoring PQ is to avoid the damages that can be caused by PQ events in critical and sensitive equipment at supply and end-users ends. The PQ monitoring may also be used as a tool for ensuring the availability of power to the customers. Other reasons for PQ monitoring as reported by the authors in [66] and [67] include:

- To find out the need for mitigation of PQ problems
- To schedule preventive and predictive maintenance
- To ensure the performance of equipment
- To assess the sensitivity of equipment to PQ disturbances
- To identify power quality events and problems
- To reduce the power losses in the process and distribution system
- To reduce the loss in production and to improve equipment availability and service

2.4 Power Quality Standards and Recommendations

These are the standards developed to ensure the proper operation of utility and consumers' equipment. It also provides measurable limits of deviation of voltage, current or frequency from normal or acceptable levels of service. The purpose is to protect both the utility and the end-user equipment from damage or maloperation that could arise from the deviation of the power quality parameters. The customers should have the level of service corresponding to their devices. Although it is impossible to have a pure voltage waveform with constant amplitude at the consumer terminal, the acceptable or allowed deviation should be specified in the networks at different levels [68]. These acceptable levels are provided by many standards organizations such as the Institute of Electrical and Electronics Engineers (IEEE), International Electrotechnical Commission (IEC), National Electrical Manufacturers Association (NEMA), and American National Standards Institute (ANSI) etc.

The common acceptable Standards Levels in power Quality are discussed below as in [68], [69], [70], [71] [72]:

IEEE Standards 142-1991: Recommended Practice for Grounding of Industrial and Commercial Power Systems. It presents a thorough investigation of the problems of grounding and the methods for solving these problems.

IEEE Standards 141-1993: Recommended Practice for Electric Power Distribution for Industrial Plants. A thorough analysis of the basic electrical-system considerations is presented. Guidance is provided in the design, construction, and continuity of an overall system to achieve safety of life and preservation of property; reliability; the simplicity of operation; voltage regulation in the utilization of equipment within the tolerance limits under all load conditions; care and maintenance; and flexibility to permit development and expansion.

IEEE Standards 242-2001: Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems. It deals with the proper selection, application and coordination of the components which constitute system protection for industrial plants and commercial buildings.

IEEE Standards 446-1995: Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications. It recommends engineering practices for the selection and application of emergency and standby power systems. It provides facility designers, operators and owners with guidelines for assuring uninterrupted power, virtually free of frequency excursions and voltage dips, surges, and transients.

IEEE Standards 519-1992: Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems. This guide applies to all types of static power converters used in industrial and commercial power systems. The problems involved in the harmonic control and reactive power compensation of such converters are addressed, and an application guide is provided. Limits of disturbances to the AC power distribution system that affect other equipment and communications are recommended. This guide is not intended to cover the effect of radio frequency interference.

IEEE Standards 1100-2005: Recommended Practice for Powering and Grounding Sensitive Electronic Equipment. Recommended design, installation, and maintenance practices for electrical power and grounding (including both power-related and signal-related noise control) of sensitive electronic processing equipment used in commercial and industrial applications.

IEEE Standards 1159.3-2003: Recommended practice for the transfer of power quality data. It defines a file format suitable for the exchange of power quality related measurement and simulation data in a vendor independent manner. It also gives the format for all power quality phenomena as stated in IEEE Std 1159 TM -1995, IEEE Recommended Practice on Monitoring Electric Power Quality, other power related measurement data which can also be extended to other types of data.

IEEE Standards 1250-1995: Guide for Service to Equipment Sensitive to Momentary Voltage Disturbances. Computers, computer-like products, and equipment using solid-state power conversion have created entirely new areas of power quality considerations. There is an increasing awareness that much of this new user equipment is not designed to withstand the surges, faults, and reclosing duty present on typical distribution systems. Momentary voltage disturbances occurring in AC power distribution and utilization systems, their potential effects on this new sensitive, user equipment and guidance toward mitigation of these effects are described. Harmonic distortion limits are also discussed.

IEEE Standards 1346-1998: Recommended Practice for Evaluating Electric Power System Compatibility with Electronic Process Equipment. A standards methodology for the technical and financial analysis of voltage sag compatibility between process equipment and electric power systems is recommended. The methodology presented is intended to be used as a planning tool to quantify the voltage sag environment and process sensitivity. It shows how technical and financial alternatives can be evaluated. Performance limits for utility systems, power distribution systems, or electronic process equipment is not included.

IEEE Standards 18-2002: This standard applies to alternating current transmission and distribution systems with the connection of shunt capacitors rated 216V or higher, 2.5 kvar or more, operating at a nominal frequency of 50 or 60 Hz.

IEEE Standards 1453-2004: Recommended Practice for Measurement and Limits of Voltage Fluctuations and Associated Light Flicker on AC Power System.

IEEE Standards 1159-2009: Recommended Practice for Monitoring Electric Power Quality. Monitoring of electric power quality of AC power systems, definitions of power quality terminology, impact of poor power quality on utility and customer equipment, and the measurements of electromagnetic phenomena are covered.

ANSI C84.1-1995: Electric Power Systems and Equipment - Voltage Ratings. Published by NEMA, National Electrical Manufacturers Association, this voluntary standards was first approved in 1954 as a joint effort by the Edison Electric Institute and the NEMA to recommend voltage ratings for both electric systems and equipment to promote compatibility. ANSI standards establishes the steady state voltage delivery window of +/-5% at the point of delivery. It also recommends a tolerance window of +6% and -13% for end use equipment. The standards also establishes a tolerance window for voltage unbalance of +/-3%.

NEMA MG 1-2009: Motors and Generators National Electrical Manufacturers Association [73]. This standards gives technical specifications used by manufacturers. Power quality concerns that can be referenced include voltage and current unbalance tolerance, over and under voltage tolerance, electrical starting characteristics, and insulation values.

EN50160: Indicates Voltage Characteristics of Electricity Supplied by Public Distribution Systems

2.5 Solutions to Power Quality Issues

There are two approaches commonly used in mitigating power quality problems namely: load conditioning and line conditioning systems. In load conditioning method, the equipment is designed to be less sensitive to power disturbances while line conditioning approach involves the installation of conditioning systems that would suppress or counteract the power system disturbances [74].

Generally, power factor improvement, reactive power compensation and other power quality improvement equipment are used in enhancing the power quality and performance of power system networks. These can be summarily classified as passive or active methods. The techniques employed for power quality improvements are different in terms of existing system or equipment from those used in newly designed and developed equipment. These mitigation techniques are further sub classified as consumer based and utility based, since they have different kinds of power quality problems [66].

In solving power quality problems such as poor power factor, unbalanced currents, an excessive neutral current, and harmonic currents, power filters of various types such as (passive, active, and hybrid) in shunt, series, or a hybrid configuration are used depending upon the type of loads connected to the network. However, in many situations, the power quality problems may be other than the above listed as in present distribution systems, custom power devices (CPD) such as dynamic voltage restorers (DVRs), distribution static compensators (DSTATCOMs), and unified power quality conditioners (UPQCs) are used for mitigating the voltage and current related power quality problems respectively.

2.6 Summary

The chapter has summarised the power quality issues in distribution networks, causes and the effects. It also itemised the monitoring procedure, standards for comparative analysis, and the possible solutions to power quality problems. The next chapter is devoted to the review of types of loads and compensation techniques in distribution networks for performance improvement.

3. Types of Loads and Load Compensation in Power System

In this chapter the general overview of the types of loads in the distribution systems are presented while the methods of load compensation are also reviewed based on techniques and components used for compensation.

3.1 Types of Loads

Electrical loads are largely classified into two based on the relationship between the applied voltage and the current flowing through the load.

3.1.1 Linear Loads

A linear load is any load in which the current is proportional to the applied voltage at any time. In addition, it gives sinusoidal current waveform when a sinusoidal voltage waveform is applied across the load (Figure 3.1) [75]. Examples of linear loads include electric motors, resistive loads such as heating element, incandescent light bulbs etc. Linear loads can either be constant current or constant power or constant impedance which comprise passive components namely: resistors, capacitors and inductors whose applied voltage is proportional to the current flowing in the load [76].

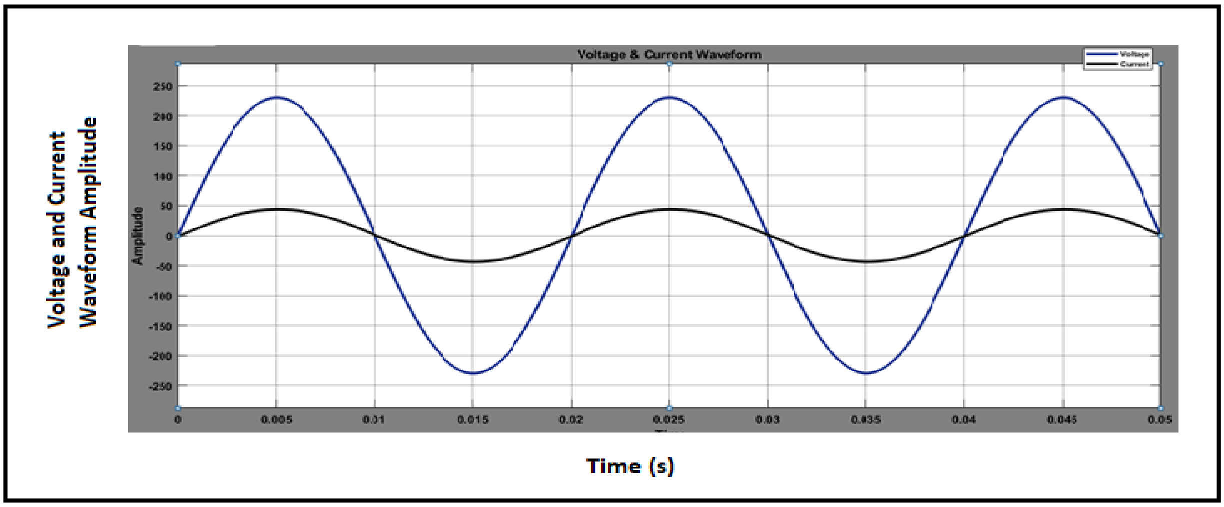


Figure 3-1: A waveform showing the voltage and current relationship of linear loads

The current waveform may either lag or lead the voltage waveform by a phase shift depending on which component (resistor, inductors or capacitors) is the most dominant in the load. However, the resulting waveform remains sinusoidal, nonetheless [77].

The presence of mixed components gives a concept called the Power Triangle which relates apparent power (S), real/active power (P) and reactive power (Q) trigonometrically as illustrated in Figure 3.2 while the power can be determined using equation 3.1 [78].

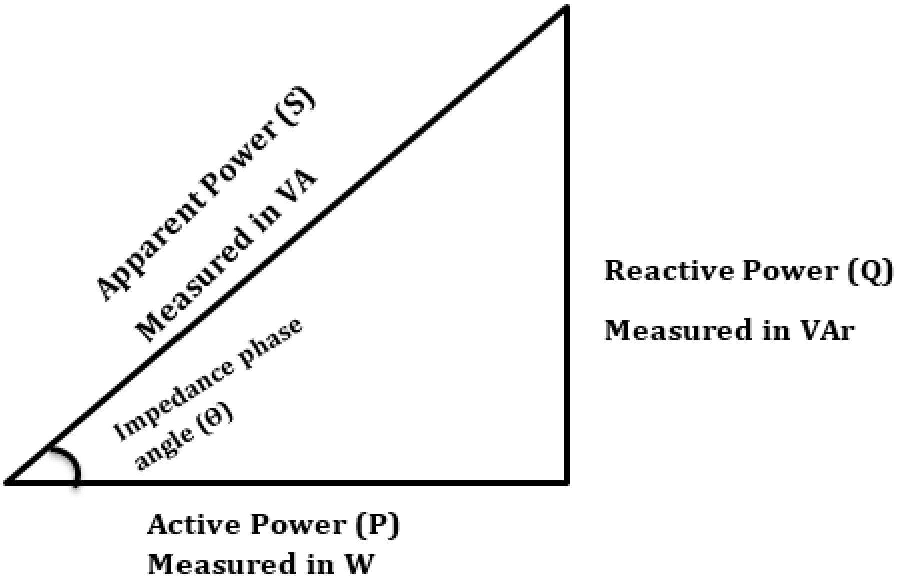


Figure 3-2: The relationship between true, reactive and apparent powers of linear load

Given the phase angle of the load impedance θ, the active, reactive and the apparent power can be calculated using the respective formulae in 3.1.

$$P = VIcos(\theta)$$
$$Q = VIsin(\theta) \tag{3.1}$$
$$S = VI = \sqrt{P^2 + Q^2}$$

The ratio between the active power and the apparent power is called the power factor (PF) of a circuit as in equation 3.2 [78].

$$PF = \frac{Active\ power}{Apparent\ Power} = \frac{P}{S} = \cos(\theta) \tag{3.2}$$

3.1.2 Non-linear Loads

These loads generate current harmonics in the network which leads to distortion of the supply current waveform [79]. Examples of non-linear electrical loads include devices such as personal computers, CFLs, fluorescent light bulbs and electronic power converters. Figure 3.3 shows an example of how a non-linear load can distort current drawn which results in the current's waveform being non-sinusoidal. Under this condition, the voltage waveform is no longer proportional to the current flowing through the load [76] [80].

As a result of the non-linear relationship of the applied voltage and drawn current by non-linear loads, the power equations discussed earlier become inaccurate because of the harmonic distortion caused by the load [81].

The power equations as in equation 3.3 gives the general expression of instantaneous voltage and current while the general power equations can be expressed as (3.4).

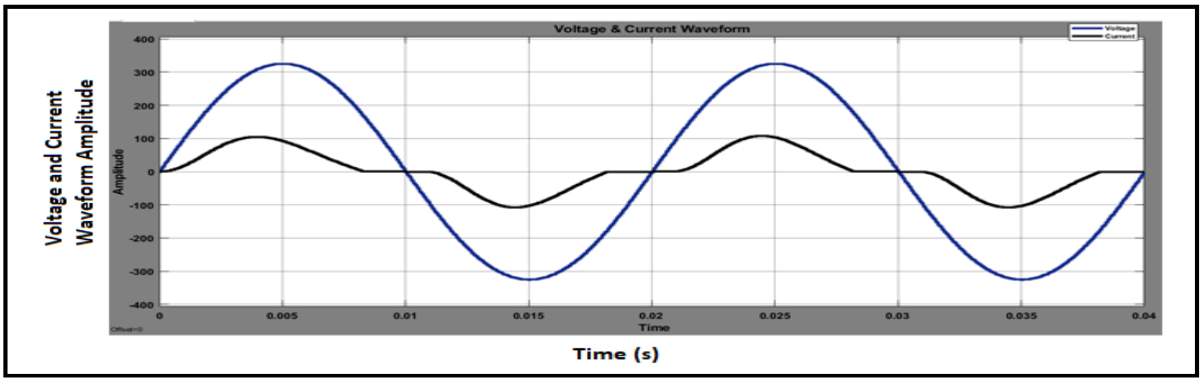


Figure 3-3: Sinusoidal voltage waveform and distorted current waveform of Non-linear load [75]

$$v(t) = \sqrt{2}V cos(\omega t)$$
$$i(t) = \sqrt{2}I cos(\omega t + \varphi) \qquad (3.3)$$

$$P = \frac{1}{T}\int_0^T v(t)i(t)\,dt$$
$$S = \sqrt{\frac{1}{T}\int_0^T v^2(t)\,dt \,.\, \frac{1}{T}\int_0^T i^2(t)\,dt} \qquad (3.4)$$

Classification of nonlinear loads

The nonlinear loads can be categorised based on the load producing harmonics and the type of injected harmonics [82],

I. **Distributed nonlinear loads**: These types mainly consist of small load with rectifiers, SMPS such as PCs, television (TV) sets, CFLs, information technology (IT) equipment and discharge lamps

II. **Large Static nonlinear loads:** These loads are commonly controlled by static power converters. Examples include: single-phase or three-phase rectifiers, 6-pulse or 12-pulse inverters, and cycloconverters.

III. **Large varying nonlinear loads:** These loads are commonly connected to the transmission network. Example of this type is an arc furnace used in metal-melting industry.

Nonlinear loads can also be classified based on the type of harmonics generated or injected to the network as follow [44], [83]:

- **Current harmonic source type:** these loads injects harmonic current into the network during operation. Examples include all loads using current source inverters such as motor drives, renewable energy systems (e.g., wind and solar inverters), and uninterruptible power supplies (UPS)
- **Voltage harmonic source type:** In this type, the loads produces voltage harmonics during operation as in variable speed drives, rectifies with dc capacitor

It is important to note that non-linear voltages and currents include distortions in their waveforms and in order to take these into account when calculating the power equations, the waveforms can be decomposed into fundamental and harmonic contents as $v_1(t)$ and $i_1(t)$ respectively while *n* represents the n^{th} harmonic. V_0 and I_0 are the DC components of the voltage and the current as in (3.5)

$$\begin{aligned} v(t) &= V_0 + v_1(t) + v_2(t) + v_3(t) + \cdots + v_n(t) \\ i(t) &= I_0 + i_1(t) + i_2(t) + i_3(t) + \cdots + i_n(t) \end{aligned} \tag{3.5}$$

Each harmonic component can be expressed in full as in equations (3.6) where V_n and I_n represent the rms voltage and the rms current of the n^{th} harmonic. φ_n Represents the phase shift between the voltage and current components of the n^{th} harmonic.

$$\begin{aligned} v_n(t) &= \sqrt{2}V_n cos(n\omega t) \\ i_n(t) &= \sqrt{2}I_n cos(n\omega t + \varphi_n) \end{aligned} \tag{3.6}$$

The rms of voltage $v(t)$ and the rms of current $i(t)$ are V and I respectively as expressed in (3.7).

$$V = \sqrt{V_0^2 + \sum_{h=1}^{n} \frac{V_h^2}{2}}$$

$$I = \sqrt{I_0^2 + \sum_{h=1}^{n} \frac{I_h^2}{2}} \qquad (3.7)$$

3.2 Load compensation Methods/Techniques

Load compensation involves the modification of the natural parameters of transmission and distribution lines to improve its power transfer capability without violating the overall stability of the system [84]. Reactive power compensation involves two aspects: Load compensation and voltage support, the load compensation involves the balancing of the current drawn from the supply, improvement in power factor, better voltage regulation, etc. of large fluctuating loads while voltage support involves the reduction in voltage fluctuation at a particular point in the transmission network [85]. The compensation in transmission line is broadly classified as follows [86]: Line length compensation, Surge impedance compensation and compensation by sectioning.

Reactive power compensation in a power system can be configured in shunt, series or the hybrid. Shunt compensation is the commonly used configuration and it can be installed at different positions on the network such as the load-end, the distribution substation, along the distribution feeder or in a transmission substation as shown in Figure 3.4 [14], [87]:

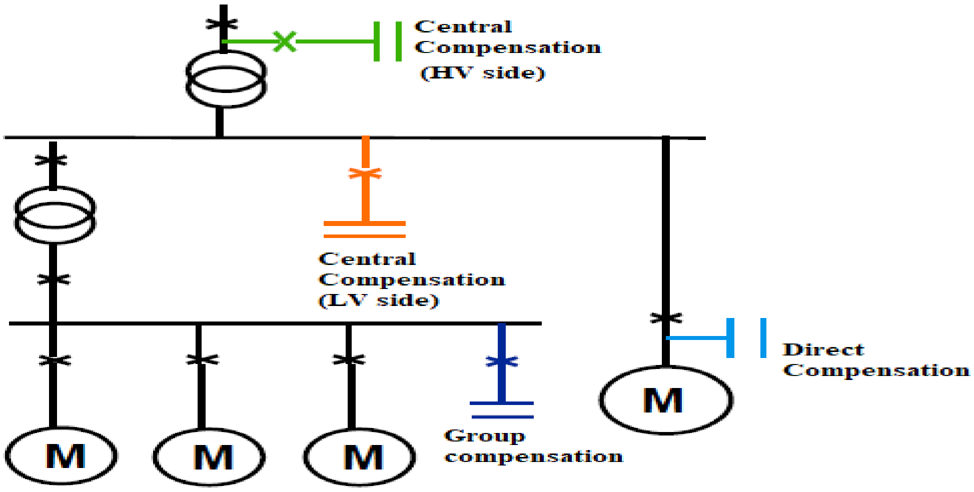


Figure 3-4: Possible Locations of Compensation Device(s) **[14]**

3.3 Classification of load compensation based on Techniques

In general, the loads which have poor power factor, unbalance, harmonics, and dc components require compensation. These loads are arc and induction furnaces, sugar plants, steel rolling mills (adjustable speed drives), power electronics-based loads, large motors with frequent start and stop etc. All these loads can be grouped into three basic categories.

- Unbalanced ac load
- Unbalanced ac + non- linear load
- Unbalanced ac + nonlinear ac + dc component of load.

The dc component is generally caused by the usage of half-wave rectifiers. These loads, particularly nonlinear loads generate harmonics as well as fundamental frequency variations [22].

3.3.1 Compensation by using load admittance

A load compensator can be designed using the actual admittances of the Load in such that the three-phase load connected to a symmetrical line with unbalanced source voltages can be represented by the admittance in delta equivalent formed from the load impedances as shown in figure 3.5 [88].

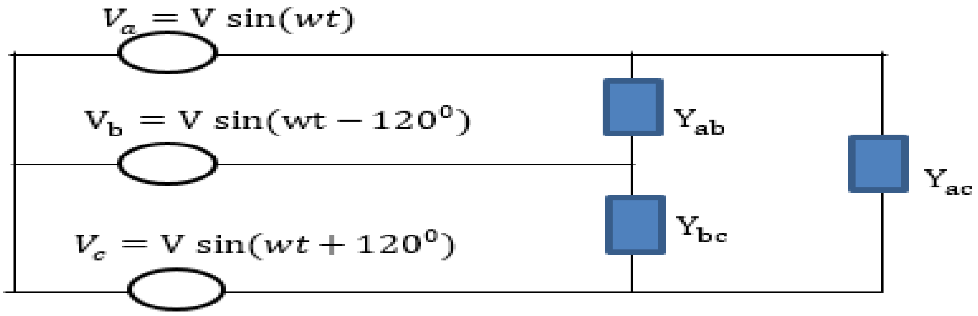


Figure 3-5: Compensation by load admittance **[88]**

The above method assumed the admittance of the load is known or it can be measured, in which neither is possible practically thereby limiting the applications since the admittances could also be a function of the supply voltage and the corresponding current flow.

3.3.2 Balancing compensator

The method used in this type of compensator as proposed by Czarnecki [89] is based on the measurement and computation of the equivalent susceptance and unbalanced admittance of the load as in (3.6). This is achieved through the decomposition of the load vector current to give the active or real, reactive or imaginary and unbalance currents.

Czarnecki [89] , assumed that only the fundamental frequency exists and that the load is fed from a three-phase, three-wire system with sinusoidal and symmetrical supply while the load unbalance and the reactive power compensation were of concern without considering the effects of harmonics in the system.

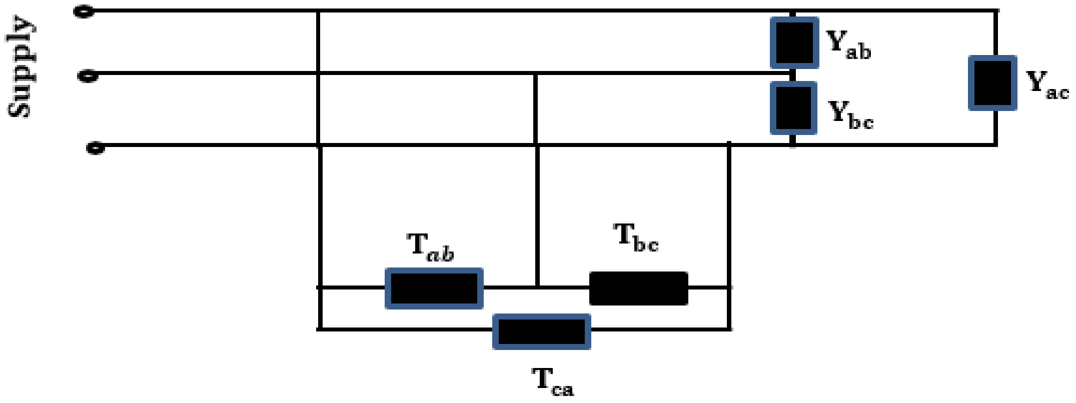


Figure 3-6: Load balancing compensator **[89]**

3.3.3 Instantaneous load compensation methods

The earlier methods can only be used to correct the fundamental reactive power and unbalance of the system in the steady state. However, in a system where harmonics are present, these methods would not provide correct compensation. For the compensation of load that involves unbalance and harmonics, the instantaneous load compensation methods are applied. There are two important theories as applicable to Instantaneous load compensation methods, which are often refer to as p-q theory and Instantaneous Symmetrical Component Theory for load compensation [90].

(a) Instantaneous p-q theory

The p-q Theory is based on a set of instantaneous powers defines in the time domain. No restriction is imposed on the voltage and current waveforms and it can be applied to three-phase system with or without a neutral wire for three phase generic voltage and current waveforms. It can be applied for both steady and transient states [91]

This method involves the algebraic transformation of supply voltages and currents from the **a-b-c** coordinates into **α** and **β** coordinates using Clarke's transformation. The instantaneous real, **p** and reactive, **q** power components can be computed after the transformation.

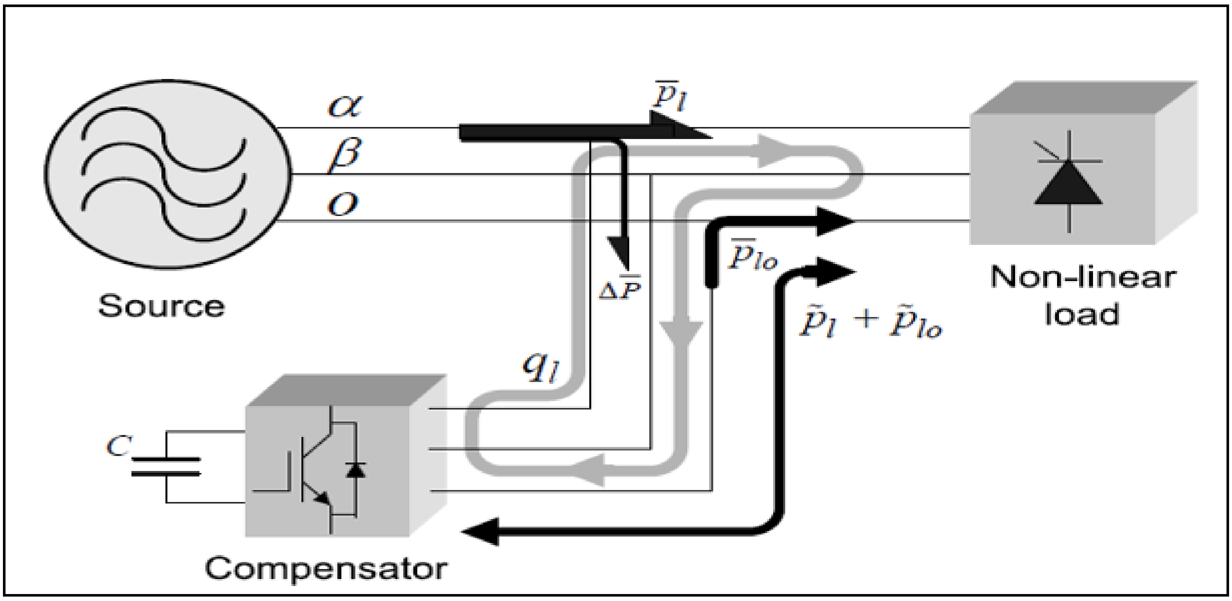


Figure 3-7: Compensation by Instantaneous method [91]

(b) Symmetrical components

Power systems are ideally not designed for unbalance quantities as it makes power system components inefficient and over rated. To understand unbalance in the three-phase systems, a concept of symmetrical components was introduced by C. L. Fortescue in 1918, where he presented that the resolution of an unbalanced system of n-related phasors into n system of balanced phasors, known as symmetrical components of the original phasors [90]. In this context, the unbalanced currents of any three-phase system can be presented in form of positive, negative and zero negative sequence currents to the yield the compensating values in terms of the line voltages and currents [91].

3.4 Load compensation methods based on elements

3.4.1 Passive compensation method

Passive compensation is a technology commonly used for providing reactive power compensation considering power factor correction, voltage regulation, load balancing, and reduction of current flowing through the conductor in three-phase four-wire distribution networks. It has evolved during the past century with the development of different configurations and requirements for power quality disturbance mitigation [92] [93].

Voltage regulation, unbalance improvement, power factor correction, voltage flicker suppression, load balancing and other objectives can be achieved either individually or in combinations which would determine the configurations of the passive components to be used. The current status of the passive compensation technology employing lossless passive components (capacitor and inductor) commonly used in distribution systems by utilities for voltage regulation improvement while most industrial consumers used it for power factor corrections, improvement of efficiency, and overall performance improvement of the entire network [94], [95].

3.4.2 Active compensation method

Load compensation which involves the modification of the system parameters for effective power transfer can be achieved at the distribution substation, along the distribution feeder and at load level but for effective performance, the compensator has been proved to be more effective at the load end using either passive or active methods [15]. Traditionally, the passive method involves the use of passive elements across the load with fixed characteristics. However, they are affected by the changes in the network impedance and other limitations such as large size, high losses at no-load etc. [96]. In overcoming the drawbacks of passive components, the active methods such as active power filters (APF), dynamic voltage restorers (DVR), distribution static compensators (DSTATCOM) and unified power quality conditioners (UPQC) have been developed for an effective mitigation of power disturbances in the distribution networks [97]. Among these, the shunt active power filter (APF) is well established to mitigate power quality problems like current harmonics, reactive power demand, unbalanced load and poor power factor in the electrical power distribution systems [98]. Therefore, in this research the effectiveness of an active power filter for load balancing, reactive power compensation and harmonics reduction in a three-phase four-wire distribution network is tested through simulation using MATLAB/Simulink.

3.5 Summary

In this chapter, the classifications of loads in the distribution networks were well reviewed while the compensation techniques were also identified considering the methods, purpose and compensating elements for effective load compensation in the distribution network as one of *the ways to improve the performance of the entire network. The next chapter shall be devoted on the unbalance in the distribution network, cause and its effects on both the consumer and utility equipment.*

4. Power System Unbalance and Its Impacts

This chapter gives the details about unbalanced in power systems, the causes, effects and the mitigation techniques as reviewed from the works of literature. Unbalance is one of the power quality issues addressed by this research later in the report.

4.1 Introduction

A three-phase power system is termed to be balanced or symmetrical if the voltages and currents have equal magnitudes and angular frequency of 120 degree with respect to each other. The unbalanced or asymmetrical condition occurs if either or both conditions stated above are not met [99]. The voltage and current unbalance interact with each other, and these are serious power quality issues affecting the low voltage distribution systems.

4.2 Unbalance Definitions and its evaluation

The evaluation of unbalance in power systems is based on two different methods: Symmetrical components and Average values methods. In symmetrical method, the unbalanced three-phase system is decomposed into balanced or symmetrical systems known as; positive, negative and zero sequence components. The decomposition can be done in terms of current, voltage and impedance using Fortescue's Theorem as in equation (4.1) or (4.2).

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} \tag{4.1}$$

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{4.2}$$

where $a = e^{j120^0}$

The average method involves the measurement and calculation of the unbalance based on the maximum deviation from the average value of the three-phase values, it can be expressed as a percentage while the calculation is commonly known as unbalance factor [100].

There are five different definitions of unbalance factor based on either sequence components or average value approach. In this report, the voltage unbalance calculation is considered for general calculation of unbalance in power systems.

A. NEMA Definition

The NEMA definition of unbalance which is also known as the line voltage unbalance rate (LVUR) is given by the following equations (4.3) and (4.4) [100].

$$\%LVUR = \frac{Max. Voltage\ deviation\ from\ Average\ Line\ Voltage}{Average\ line\ Volatge} * 100$$

$$\%LVUR = \frac{Max.\left[\left|V_{ab} - V_{L\_average}\right|, \left|V_{bc} - V_{L\_Average}\right|, \left|V_{ca} - V_{L\_Average}\right|\right]}{V_{L\_average}} * 100 \qquad (4.3)$$

$$\%LVUR = \frac{Max.\left[\left|V_{ab} - V_{L\_average}\right|, \left|V_{bc} - V_{L\_Average}\right|, \left|V_{ca} - V_{L\_Average}\right|\right]}{V_{L\_average}} * 100 \qquad (4.4)$$

where average line voltage $V_{L\_average} = \left[\frac{(V_{ab} + V_{bc} + V_{ca})}{3}\right]$ and $Vab, Vbc\ , Vca$ are the line voltages.

B. IEEE Definition

The definition of unbalance factor according to IEEE [101] is the maximum deviation from the average phase voltage referred to the average value of the three-phase voltages. The method is similar to the NEMA method except the phase values are used in IEEE as against the line values used in NEMA.

$$\%PVUR = \frac{Max.Voltage\ deviation\ from\ Average\ Phase\ Voltage}{Average\ Phase\ Volatge} * 100$$

$$\%PVUR = \frac{Max.\left[\left|V_a - V_{ph\_average}\right|, \left|V_b - V_{ph\_Average}\right|, \left|V_c - V_{ph\_Average}\right|\right]}{V_{ph\_average}} * 100 \quad (4.5)$$

Where average phase voltage $V_{ph\_average} = \left[\frac{(V_a + V_b + V_c)}{3}\right]$ and $Va, Vb\ , Vc$ are the phase voltages.

C. CIGRE Definition

In the method recommended by CIGRE [102], the unbalance factor calculation can be determined by the equation (4.6),

$$Unbalance\ factor(\%) = \sqrt{\frac{1 - \sqrt{3 - 6\beta}}{1 + \sqrt{3 - 6\beta}}} \quad (4.6)$$

Where $\beta = \frac{|V_{ab}|^4 + |V_{bc}|^4 + |V_{ca}|^4}{(|V_{ab}|^2 + |V_{bc}|^2 + |V_{ca}|^2)^2}$ and Vab, Vbc, Vca are the line voltages

D. ANSI Definition

The American Standards, ANSI defines unbalance factor as a ratio of the maximum deviation of the line voltage from the average values of the line voltages. This also gives the same definition as applicable to NEMA stated in equations (4.3) and (4.4)

E. True definition/ IEC

This method defines the Voltage/Current Unbalance factor as the ratio of the negative-sequence component to the positive sequence component of the voltage/Current [103], equation (4.7).

$$\%Unbalance\ Factor = \frac{Negative\ Sequence\ Component}{Positive\ Sequence\ Component} * 100$$

$$\%\,VUF = \frac{V_2}{V_1} * 100 \quad (4.7)$$

$$\%\,IUF = \frac{I_2}{I_1} * 100$$

Where V_1 and I_1 represents the positive sequence components of voltage and current while V_2 and I_2 are the negative sequence components of the voltage and current. These components can be obtained using the Fortescue's Theorem, equation (4.1)

4.3 Causes of voltage unbalance

In a three-phase system, the current unbalance is mostly due to load unbalance and it is majorly considered as the cause of voltage unbalance. The responsibility of electricity utilities and distribution network operators is to provide symmetrical voltage supply at the point of common coupling between the distribution grid and consumers while that of current balancing is the joint responsibility of both the electricity suppliers and the customers [104].

One of the major causes of unbalance in a three-phase network is single-phase loading in distribution systems three-phase transformers which can lead to either or both current and voltage imbalance. The performance of power system components can be affected by either voltage or current asymmetry or both. Current unbalance mainly affects the generation and transmission equipment while voltage unbalance affects the customers' equipment [105]. Generally, the voltages at generation power plants are symmetrical based on the construction and operation of synchronous generators used in power networks but the impedance of network in the three phases are not equal due to the position of overhead lines with respect to ground and this leads to an unbalance in the network [106]. However, these differences are negligible and can be reduced by transposition of the line sections [99] [107]. Voltage unbalance can be due to the asymmetry parameters of the power equipment, such as generators, transformers, transmission, and distribution lines. It can also be caused by unequal voltage drops across the impedance of the line due to unbalanced current drawn by the load [108].

Current unbalance is mainly due to unbalanced loading of the network caused by three reasons: uneven distribution of single-phase loads, the connection of large single-phase loads and faults. Under the low voltage (LV) network, especially residential and commercial facilities, the loads are usually single-phase and load symmetry between the phases is not guaranteed. Current unbalance may also occur during transient conditions such as faults, these faults includes: single line to earth fault, line to line faults and two line to earth faults, but this cause temporary unbalance. Thus, although residential and commercial facilities are generally supplied with balanced voltages but due the proliferation of single-phase non-linear loads in the network, there can be a certain level of unbalance at the point of common coupling due to the harmonic's distortion from such loads which leads to zero sequence current flowing through the neutral conductor of the four-wire system and this can affects the overall performance of the system since a small voltage unbalance can result in unreasonable increase in phase currents [107] [109]. Other detailed causes are:

4.3.1 Uneven Distribution of Loads on Distribution Transformers/Lines

Most of the domestic loads and industrial lighting loads are single phase. However, these loads are fed from three phase supply. If the load divisions among different phases are not coordinated, the phase parameters may differ from each other causing unbalanced demand from the supply. The negative or zero sequence voltages in a power system typically result from unbalanced loads causing negative or zero sequence currents to flow [106].

4.3.2 Non-Linear Loads

When a sinusoidal voltage is applied to a certain type of load, and the current drawn by the load is proportional to the voltage and impedance and follows the envelope of the voltage waveform. These loads are referred to as linear loads.

Some loads cause the current to vary disproportionately with the voltage during each half cycle. These loads are classified as nonlinear loads while their current waveforms are non-sinusoidal in nature [110], containing distortions, whereby the 50-Hz waveform has numerous additional waveforms superimposed upon it, creating multiple frequencies in addition to the normal 50-Hz sine wave.

- **Positive sequence harmonics** (harmonic numbers 4, 7, 10, 13, etc.) produce magnetic fields and currents rotating in the same direction as the fundamental frequency harmonic.
- **Negative sequence harmonics** (harmonic numbers 2,5,8,11,14, etc.) develop magnetic fields and currents that rotate in a direction opposite to the positive frequency set.
- **Zero sequence harmonics** (harmonic numbers 3, 9, 15, 21, etc.) do not develop usable torque, but produce additional losses in the machine.

The interaction between the positive and negative sequence magnetic fields and currents produces oscillations of the motor shaft. The permissible limit in terms of percentage of negative phase sequence current over positive sequence current is 1.3% ideally but acceptable up to 2% [111].

4.3.3 Malfunctioning Equipment

The utility can be the source of unbalanced voltages due to malfunctioning equipment, including blown capacitor fuses, open-delta regulators, and open-delta transformers. Open-delta equipment can be more susceptible to voltage unbalance than closed-delta since they only utilize two phases to perform their transformations. The facility housing the motor can also create unbalanced voltages even if the utility supplied voltages are well balanced [112]. Resistive and inductive unbalances within the motor equipment lead to unbalanced voltages and currents [113]. Defects in the power circuit connections, the motor contacts, or the rotor and stator windings, can all cause irregular impedances between phases in the motor that lead to unbalanced conditions [111].

4.3.4 Impact on Generators and Motors

At the customer end, the unbalanced voltage has adverse effects on the efficiency of the equipment connected to the network. For example, in rotating machines, the reverse in the magnetic field due to voltage asymmetry results in extra heating within the windings of the machine and decrease in the efficiency. In [103] and [111], investigation of the impacts of unbalanced voltage on a three-phase induction motor operating at rated load was reported. The reported impacts include increased in losses due to the corresponding increase in windings temperature which results in the reduction in efficiency and life expectancy. Table 4.1 presents the negative effects of voltage asymmetry on a typical induction motor at full load [111]. For example, continuous operation of an electric motor with supply voltage having an unbalance factor of 5% or more will gradually decrease the lifetime of the motor as seen from figure 4.1 and Table 4-1.

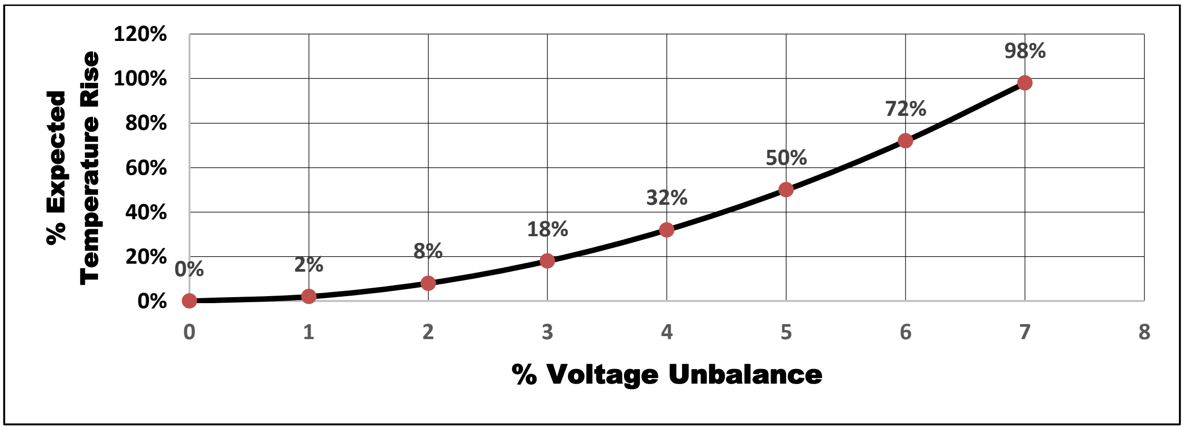


Figure 4-1: Voltage unbalance effect on temperature rise of three-phase machines **[111]**

Table 4-1: Negative Effects of Unbalanced Voltage on Induction Motors

Voltage Unbalance factor	Winding Temperature	I^2R Losses (% total)	Reduction of Motor Efficiency	Motor Lifetime
0%	120^0C	30%	-	20 years
1%	130^0C	33%	0.5%	10years
5%	180^0C	45%	5% or more	1 year

Voltage Unbalance also affects the operation of Variable Speed Drives (VSD). It has been established that three-phase rectifiers and inverters are affected by negative sequence voltage [114]. This unbalanced voltage creates current unbalance from the supply side while the resulting unbalanced current drawn from the supply causes a temperature increase in the rectifier's diodes. Moreover, this unbalanced current could also affect the operation of protective devices. In addition, voltage unbalance can create an increase in the zero-sequence harmonic distortion [103].

4.3.5 Impacts on Transformer

Transformers subjected to negative sequence voltages transform them in the same way as positive-sequence voltages. The behaviour with respect to zero sequence voltages depends on the primary and secondary connections and, more particularly, the presence of a neutral conductor. If, for instance, one side has a three-phase four-wire connection, neutral currents can flow. If at the other side the winding is delta connected, the zero-sequence current is transformed into a circulating (and heat-causing) current in the delta [115]. Transformers offer high reactance to negative phase sequence currents and thus reduces the level of unbalance on the other side of the system. Ideally any distribution transformer gives best performance at 50% loading and every electrical distribution system is designed for it. But in case of unbalance the loading goes over 50% as the equipment draw more current [116].

4.3.6 Impacts on Rectifiers

Power electronic converters serve as the interface for many large electronic loads ranging from three-phase uninterruptible power supplies (UPS's) to motors operating at variable speeds through the use of ASDs. Most of the three phase converters contain diode rectifiers front-end. The characteristic harmonics, for normal operation, in a six-pulse converter are the non triplen odd harmonics, for example, the 5th, 7th, 11th, 13th, etc.: $h=kq \pm 1$ where: k = any integer, q = pulse number [117]. Under the condition of voltage unbalance, the input current harmonics are not restricted to the converter characteristic harmonics, and non-characteristic triplen harmonics can appear such as the 3rd and 9th harmonics [61]. The non-characteristic harmonics magnitudes are proportional to the unbalance magnitude. In [118] an analysis of unbalance magnification effect for an ideal uncontrolled rectifier circuit without ac and dc-side inductors is presented. The conditions of seven distinct operating modes of the rectifier were equally established with respect to the voltage unbalance factor to derive the expressions for symmetrical components of fundamental line currents and current unbalance factor as applicable to three-phase rectifiers.

4.3.7 Impacts on Neutral Current

The unequal distribution of loads between the three phases of the system cause the flow of unbalanced currents in the system, that produce unbalanced voltage drops on the electric lines and increase in neutral current which causes line losses. If the system is balanced phase then Neutral current flow will be less. Money can be saved by reducing the impacts of unbalance on the neutral conductor which can equally improve the performance of the entire three-phase four wire network [119].

4.3.8 Impacts on Power Loss

Voltage unbalance always also results in additional power loss in power system. It implies, the higher the voltage unbalance, the higher the power dissipated which equally translate into higher electricity bills. The imbalance of current will increase the I^2R losses as mathematically shown in equation. An unbalance of 1% is acceptable as it does not affect the cable. But above 1% it increases linearly and at 4% the de-rating is 20%. This means – 20% of the current flowing in the cable will be unproductive and thus the copper losses in the cable will increase by 25% at 4% unbalance [106]. For a three phase system having I_1,I_2 and I_3 as the currents flowing in the phases. The total power loss is given as (4.8).

$$P = I_1^2R + I_2^2R + I_3^2R \tag{4.8}$$

For balance system, $I_1 = I_2 = I_3$, then the total power loss becomes equation (4.9) which would have less value compare to equation (4.8).

$$P = 3.I^2.R \tag{4.9}$$

For instant a system having a total current flow of 120 A but unevenly distributed as I1 = 35 A, I2 = 70 A and I3 =15 A, which is an unbalance factor of 75%. The power loss under this condition is (6350R) watts using equation (4.8) unlike when the current is evenly distributed as 40 A on each phase, the total power loss would be (4800R) watts using equation (4.9) which is 32% loss increase due to 75% unbalance factor.

4.3.9 Impacts on Energy Bill and Maximum Demand

Unbalanced Load increases maximum Demand of Electrical supply which significantly have adverse effects on energy bill. Most utility Company charge residential customers on kW and not on kVA. This means that the charged is based on the “actual” energy consumed and not the “total” energy supplied, therefore, effect of the power factor and Maximum Demand is not pronounced for residential customers unlike Commercial and Industrial consumers who are charged by their maximum demand [120]. Each of the consumers must have been agreed upon with the utility at time of connection. This implies, a penalty is placed on any customer who exceeds the specified or agreed maximum demand as a result of imbalance in the loads [104].

4.4 Mitigation of Unbalance Problem

The presence of negative and zero sequence currents in an unbalanced three-phase four wire system gives rise to the following problems as earlier discussed

i. Increase in kVA demand

ii. Excessive neutral current

iii. Poor power factor

iv. Increase in total line losses which results in reduced efficiency

v. Excessive heat in machines such as motors and transformers, connected to the system

In view of the above reasons, the negative and zero sequence currents are undesirable in power system, although for a three-phase grounded star and delta connections, the effects of the zero-sequence current can be discarded but the negative sequence current is directly fed back to the supply. Therefore, it is necessary for both the utility and consumers to eliminate this unbalance effects through load compensation which is one of the methods used in improving distribution network performance. Some of the well-established techniques of Voltage Unbalance reduction employed by power system networks are examined in this sub-section.

4.4.1 Load Transfer

The electric energy distribution networks are generally unbalanced; this is as a result of even distribution of loads and various numbers of single-phase loads connected to network. Load transfer is one of the measures taken by the utility to solve some power quality disturbances such as balancing loads, electrical losses reduction, and removal of the excessive loads from the network [121]. Load transfer is also applicable to distribution network when there is an overload and under voltage problems to reduce the overall losses in the system. This method of solving unbalance may lead to other problems such as shifting of a switch employed in the breaking process, numerous restrictions and hazards associated with the safety of load transfer system which could also increase substation losses in terms of voltage unbalance amplification in the system [122].

4.4.2 Load Balancing Techniques

In power distribution networks, uneven flow of electric current results in zero-sequence current flow which is sent back to the source through the earthing system and the neutral conductor of the system. The increase in zero sequence current may result in quite a few problems such as increase in negative sequence voltage which may result in overheating of electric motor, voltage drop increase on the distribution line with heavy phase load; increase in ground current; and losses. Balancing of loads on the three phase involves the movement of loads from the phase that is heavily loaded to the phase that is less loaded and this must be carried out with minimum acceptable loss and with voltage unbalance enhancement [123]. The major disadvantage of this method is the use of trial and error for effective application of the method.

4.4.3 Reactive Power Compensation/Capacitor Installation

With the use of correct and appropriate capacitor regulator, joined to the distribution phase that has less than the acceptable per-unit voltage value of 0.95 per-unit, the magnitude of the voltage can be enhanced to be closed to the voltage magnitude of other phases on the distribution network. This will effectively reduce the voltage unbalance factor of the system. Application of capacitors in electrical DNs will help to enhance network stability, correction of power factors and compensation of voltage profile, and equally improve the system capacity through losses reduction [124]. Electric power distribution networks need painstaking system to achieve this reactive power compensation by appropriately installing the capacitors considering sizes and locations. Other advantages of reactive power compensation are: increased line voltages; reduced lagging component of current; reduced losses; increased voltage level at the load end; decrease in capital spending on the network electrical devices; enhanced voltage profiles; and decreased kVA demand where power is purchased [40].

4.5 Summary

As earlier discussed, the main reason for unbalanced low voltage networks is due to unbalanced nature of the connected loads, therefore, in this chapter a general review of voltage unbalance in terms of definitions, causes, effects and mitigation techniques were presented while the next chapter considers harmonics in power systems, its impacts and mitigation methods.

5. Power System Harmonics and Its Analysis

This chapter gives a comprehensive review on harmonics in power system in terms of causes, effects and indices for analysis. The common mitigation techniques are also covered in the chapter.

5.1 Introduction

In recent years, the use of nonlinear electronic loads such as compact fluorescent lamps (CFLs), computers, televisions, etc. has increased significantly and these nonlinear loads are the main sources of harmonic currents injection into distribution systems.

The combination of nonlinear and linear loads connected to the same point of common coupling on the network supplied through the same source could results to harmonic distortion of the total supply current while the injected harmonic currents and the resulted harmonic distortion can propagate into the network and affect the effective performance of other consumers connected the same point of common coupling as shown in figure 5.1 [37].

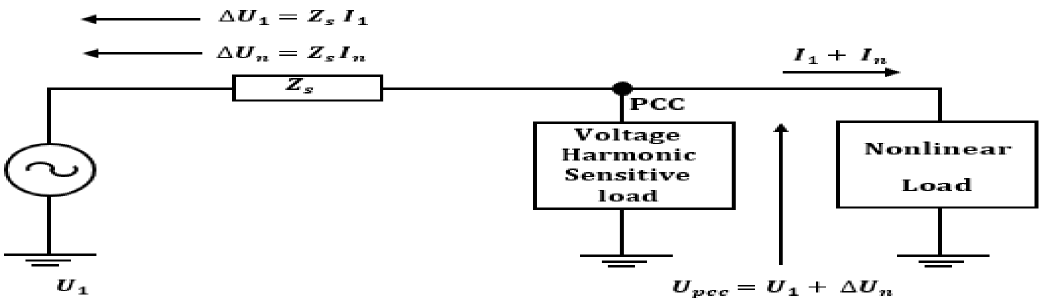


Figure 5-1: Harmonic propagation into a network **[37]**

These harmonics are generated to a small extent and at low distortion level by generation, transmission & distribution equipment and to a larger extent by the industrial & domestic loads like induction & arc furnaces, static power converters, PCs & TV receivers. Other common sources of harmonics in power systems include:

- Electronic ballast
- Switch mode power supplies
- Power electronics based converters

- Photovoltaic systems
- Welding machines
- Uninterruptible power supplies
- Frequency converters

Harmonic currents generally flow towards supply because the source impedance is low. Traditionally, the saturation of transformer core during energization is one of the major sources of harmonics in power utility but the increase in the use of FACTs would further contribute to the level of harmonic distortion [39].

Adverse effects of harmonics include: poor power factor, increased reactive power demand, overheating of distribution transformer, false tripping of protectives devices, increased rms value of current and its associated losses, reduction in the efficiency of power system networks etc. [125], [126], [127].

5.2 Harmonic analysis methods

The waveforms of both voltage and current associated with nonlinear loads can be obtained at the PCC using appropriate meters such as power quality analyser, spectrum analyser etc. [82]. In the year 1822, Jean Baptiste Fourier [128] postulated that any continuous function with a repetitive pattern can be represented by the sum of the fundamental sinusoidal component, DC component and the higher order sinusoidal components at the multiples of the fundamental frequencies. Harmonic analysis involves the act of calculating the magnitudes and phases of the fundamental and higher order harmonics of period waveforms while the resulting series are known as Fourier series which established the time domain and frequency domain functions.

5.3 Fourier Analysis

The common techniques used for Fourier analysis considering the waveform identity, either continuous or discrete signals, are Fourier series, Discrete Fourier Transform and Fast Fourier Transform, these techniques are based on the signals or waveform decomposition or transformation [128].

5.3.1 Fourier series

Any periodic waveform can be decomposed into a Fourier series of DC, fundamental frequency and harmonic terms which contains a sum of simple oscillating functions, namely cosines, sine or complex exponentials.

Considering line current of a waveform represented by a f(t), the decomposition can be done as shown in equation (5.1) [128].

$$f(t) = \frac{A_0}{2} + \sum_{n=1}^{\infty} [\,(A_n \ \cos(n\omega t)) + \ B_n \ \sin(n\omega t)] \tag{5.1}$$

Where n = 1, 2, 3, 4, 5, 6, 7……………………

A_0 = the average value of the function f(t)

A_n and B_n = the coefficients of the series at nth harmonic.

Likewise,

$$A_0 = \frac{1}{T}\int_0^T f(t)dt \tag{5.2}$$

$$A_n = \frac{2}{T}\int_0^T f(t) \ \cos(n\omega t)\, dt \tag{5.3}$$

$$B_n = \frac{2}{T}\int_0^T f(t) \ \sin(n\omega t)\, dt \tag{5.4}$$

The sine and cosine terms in equation (5.1) can be converted into polar form to determine the angle using trigonometric functions as follows in (5.5):

$$\begin{aligned} A_n \ \cos(n\omega t) + \ B_n \ \sin(n\omega t) \\ = \sqrt{A_n^2 + B_n^2} \ * \frac{(A_n \ \cos(n\omega t)) + \ B_n \ \sin(n\omega t)}{\sqrt{A_n^2 + B_n^2}} \\ = \sqrt{A_n^2 + B_n^2} \ * \left[\frac{A_n}{\sqrt{A_n^2 + B_n^2}}\cos(n\omega t) + \frac{B_n}{\sqrt{A_n^2 + B_n^2}}\sin(n\omega t)\right] \ , \\ = \sqrt{A_n^2 + B_n^2} \ * [\sin(\theta_n)\cos(n\omega t) + \ \cos(\theta_n)\sin(n\omega t)] \end{aligned} \tag{5.5}$$

From which trigonometric identity can be applied as follows:

$$\sin(X+Y) = \sin X \cos Y + \cos X \sin Y \tag{5.6}$$

The resulting polar form is as shown in equation (5.7),

$$\sqrt{A_n^2 + B_n^2} * \sin(nwt + \theta_n) \tag{5.7}$$

This implies,

$$\tan(\theta_n) = \frac{\sin(\theta_n)}{\cos(\theta_n)} = \frac{A_n}{B_n} \tag{5.8}$$

5.4 Harmonic Parameters Formulation in Power system

The most commonly used measure for harmonic analysis is the total harmonic distortion which also determines the distortion factor in the system. If the voltage or current signals contain harmonics, the individual harmonic distortion for the signal at any frequency is given as [39]:

$$V_n(\%) = \frac{V_n}{V_1} * 100$$
$$I_n(\%) = \frac{I_n}{I_1} * 100 \tag{5.9}$$

Where V_n and I_n represents the voltage and current harmonics of order 'n' respectively while V_1 and I_1 is the voltage and current at the fundamental frequency respectively.

The total harmonic distortion of both voltage and current signals are:

$$THD_V = \frac{\sqrt{\sum_{n=1}^{\infty} V_n^2}}{V_1}$$
$$THD_I = \frac{\sqrt{\sum_{n=1}^{\infty} I_n^2}}{I_1} \tag{5.10}$$

The rms values of voltage and current can be determined by equations (5.11).

$$V_{rms} = \sqrt{V_1^2 \ * \ (1 + \ THD_V^2)} \qquad (5.11)$$

$$I_{rms} = \sqrt{I_1^2 \ * \ (1 + \ THD_I^2)}$$

The apparent power can be resolved using the separation of the rms current and voltage in fundamental and harmonic terms as shown below [37].

$$S^2 = (V_1^2 \ + V_h^2) * (I_1^2 + I_h^2) = (S_1^2 + S_N^2) \qquad (5.12)$$

Therefore,

$$S_N = \sqrt{(S^2 - S_1^2)} \qquad (5.13)$$

Where S_N is the apparent power due to harmonics which can also be broken into reactive and non-active currents

5.5 Harmonics Classification

Harmonics are classified according to their frequencies which also determines the sequence and effects of each harmonic in a three-phase power system. The classifications are given in Table 5-1 [129].

Table 5-1: Classification of Harmonics and its effects

Harmonics Order	Frequency [Hz)	Sequence	Direction of Rotation	Effects
1, 4, 7, 10, 13, 16, 19..	50,200,350,500...	Positive	Forward	Heating and loss in motors
2, 5, 8, 11, 14, 17, 2 0..	100,250,400,550…	Negative	Backward	Heating and breaking torque in motors
3, 6,9,12,15,18,21…	150,300,450,600…	Zero	Insignificant	Overloading and Heating of neutral conductor

5.6 Harmonic Distortion Limits

IEEE Standards 519-1992 [130] gives the guidelines for acceptable levels of both voltage and current distortions in power systems networks. the current harmonic limits are as shown in Table 5-2 while The acceptable total voltage distortion for voltage level up to 16 kV is limited to below 5% and the individual harmonic should not be more than 3%. Other voltage levels and the harmonic limits are shown in Table 5-3

Table 5-2: Harmonic Current Limits, IEEE Standards 519-1992

Maximum Harmonic Current Distortion, % of I_L						
Vn≤69kV						
I_{sc}/I_L	h <11	11<h<17	17<h<23	23<h<35	35<h	TDD
<20	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0
69kV<Vn≤161						
<20	2.0	1.0	0.75	0.3	0.15	2.5
20<50	3.5	1.75	1.25	0.5	0.25	4.0
50<100	5.0	2.25	2.0	0.75	0.35	6.0
100<1000	6.0	2.75	2.5	1.0	0.5	7.5
>1000	7.5	3.5	3.0	1.25	0.7	10.0
Vn >161kV						
<50	2.0	1.0	0.75	0.30	0.15	2.5
≥ 50	3.0	1.5	1.15	0.45	0.22	3.75
**All power generation equipment is limited to these values of current distortion regardless of actual I_{SC}/I_L						

Table 5-3: Harmonic Voltage Limits, IEEE Standards 519-1992

Voltage level	Maximum Individual harmonic component (%)	Maximum THD (%)
<69 kV	3.0	5.0
69 kV<Vn≤161 kV	1.5	2.5
>161 kV	1	1.5

5.6.1 Impact on Power Factor

Power factor represents the determining factor for the power consumption in power systems network. In a situation where there is a low power factor, it implies poor utilization of the source power there by increasing the demand on the entire network capacity. In an ideal sinusoidal waveform, the power factor is given as [44], [131]:

$$Pf = \frac{V_1 I_1 \cos \varphi_1}{V_1 I_{rms}} = \left(\frac{I_1}{I_{rms}}\right) . \cos \varphi_1 \tag{5.14}$$

Where I_{rms} is the rms value of the source current, I_1 is the current at fundamental frequency while φ_1 is the angle between the current and voltage at the fundamental frequency. It is found that where there is harmonic distortion, it introduces distortion factor such that:

Power Factor = Distortion Factor x Displacement Factor

It implies for a load having distortion factor and displacement factor of 0.637 and 0.988 respectively, the true power would be 0.629 whereas, if the distortion factor is 1, the true power factor is equal to the displacement power factor.

To improve the power factor, the rms value of the source current has to be reduced to minimize the value of the apparent power demand of the supply through load compensation.

5.6.2 Impacts on Transformers

The major effect of harmonic distortion on transformers is the generation of additional heat caused by the harmonic content of the load current. Distribution transformers are most vulnerable to overheating and premature failure. The life of a transformer is dependent upon the life of its insulation. Transformer insulation deteriorates as a function of time and temperature. Transformer temperature, in turn, is related to loading i.e. the winding I^2R losses. No load and load losses are also affected by the presence of harmonics in load currents. The eddy current losses normally is about 10 % of the loss at full load which is directly proportional to the square of harmonic number. Practically, transformer supplying nonlinear loads such as IT equipment and operating at a full load, the losses would be twice as high as for an equivalent linear load and this results in an increase in operating temperature and decrease in life span [44]. Also, the presence of harmonic voltage in the power system network increases the hysteresis and eddy current losses in the laminations as represented by equation 5.15 [132].

$$P_{core\ loss} = K_e \sum_{n \in N} B_{max,n}^2 \, (n.f_1)^2 + K_h \sum_{n \in N} B_{max,n}^{\sigma} \, (n.f_1) \qquad (5.15)$$

where K_e and K_h are constants, $B_{max,n}$ is the maximum flux density corresponding to nth order harmonic, f_1 is the fundamental frequency and $\boldsymbol{\sigma}$ is the Steinmetz coefficient. The copper loss of the transformer may be increased due to additional harmonics current since the loss depends on the rms value of the current flowing through the windings of the transformer. Another effect concern the triplen current harmonics which add up in the neutral conductor while the circulation of the zero-sequence current within the transformer would lead to overloading and thereby causing additional heating of the windings [133].

5.6.3 Impacts on Metering and Measuring Instruments

Metering and instrumentation and metering equipment are equally affected by harmonic distortion in the power distribution networks as a result of high harmonic voltage on the circuits caused by resonant condition produced by harmonics injected by nonlinear loads. The operation of most devices, such as such energy meter and over current relays, designed to monitor fundamental current can give erroneous operation due harmonic distortion. Other measuring devices affected by higher frequency are potential transformers (PTs) / current transformers (CTs) [134].

Measuring instruments which are mostly calibrated on purely sinusoidal voltage and current signals are also greatly affected under distorted supply which makes their measurement prone to errors. These errors are characterised by the order, magnitude and phase of the harmonic distortion [135], [136].

5.6.4 Impacts of Harmonics on Power System Protective Relay

Most power system protective relays are digital and their control algorithms depend on the sample data and zero crossing conditions which makes their operation prone to error in the presence of harmonics [137]. Overcurrent relays are mostly installed to operate with current transformers which may be distorted due to the presence of harmonics causing maloperation of the relays. Also, the response time, operating point and torque of static relays may be affected due to harmonic content of the current as in the case of differential relays which are greatly affected by even harmonics [138].

5.6.5 Impacts of Harmonics on Electronic Equipment

Harmonic distortions also affect Consumers' equipment especially from converter systems which are known to be high sources of harmonic distortions. Consumers' electronic devices are very sensitive to harmonic disturbances due to the fact that some of these equipment use energy in different forms other than the supply frequency and can be affected by external pollutions due to harmonic injection or emission at PCC [139].

Some of the effects of harmonics on electronic equipment are change in picture size and brightness of cathode ray tube, excessive heating of fluorescent and mercury arc lamps. Others are loss of data in computers and printers which are mostly caused by voltage harmonic distortions [140].

5.7 Harmonics Mitigation Techniques

Harmonic currents produced by most nonlinear loads can travel to other locations due to the interconnected structure of power systems networks especially distribution networks which would eventually go back to the sending end of the network. As explained in section 5.7, the overall effects of harmonics are embedded in the harmonic current flow of the nonlinear loads which results in the pollution of the supply voltage and to the underutilization of the entire transmission and distribution networks as a result of the increased losses in form of harmonic power. In order to supply the real power demand with the losses, most equipment are overrated, hence the need for suitable compensation methods for reactive power and harmonics requirement of the harmonic generating loads. The mitigations techniques against harmonics are majorly through passive filters and active filters.

5.7.1 Passive Method of Harmonic Mitigation

Passive harmonic compensation involves the use passive components such resistors, inductors and capacitors in solving harmonic issues in power system networks. Many of these passive techniques such as connection of series line reactors, tuned harmonic filters, and the use of higher pulse number converter circuits are available to reduce the level of harmonic pollution in an electrical network [141], [142]. In these methods, the undesirable harmonic currents may be prevented from flowing into the system by either installing a high series impedance to block their flow or diverting the flow of harmonic currents by means of a low-impedance parallel path, they are mostly connected in parallel with nonlinear loads to remove or reduce the harmonic current injected by the loads. Passive filters are also connected in series or the combination of both but the shunt type are mostly used for the power factor improvement and reactive power compensation in addition to the suppression of the harmonics [143]. The different configurations of passive filters are shown in figure 5.2. Load compensation has traditionally been achieved using passive components. However, passive methods have greatly been affected due to the proliferation of nonlinear loads in the distribution systems, the drawbacks of passive methods include parallel resonance with the impedance of the network, excess compensation of reactive power and being unsuitable for dynamic compensation [144].

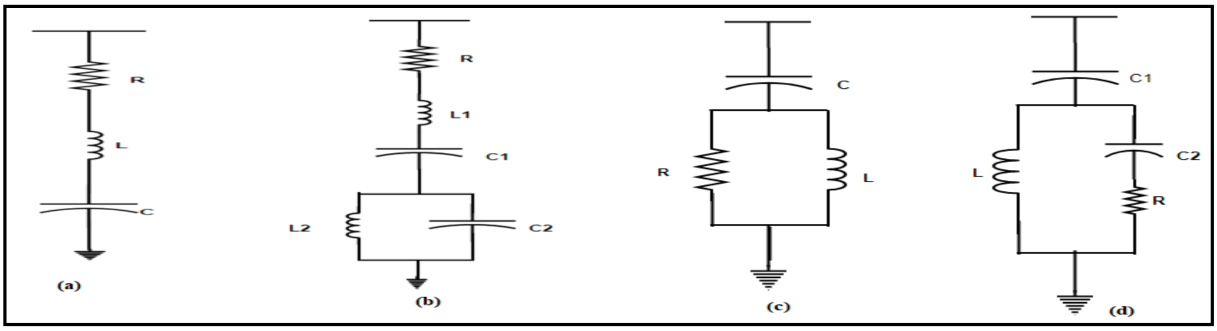


Figure 5-2: (a) Single-tuned, (b) double-tuned, (c) 2nd order high pass (d) 3rd Order high-pass filters [144]

5.7.2 Active Method of Harmonic Mitigation

To overcome the drawbacks of passive components, active methods which involve the use of some advanced equipment that comprises active components have been developed. These include active power filters (APF), dynamic voltage restorers (DVR), distribution static compensators (DSTATCOM) and unified power quality conditioners (UPQC). The active power filter (APF) is well established to mitigate harmonic distortions and other power quality problems such as, reactive power demand, unbalanced load and poor power factor in the electrical power distribution systems [144].

Active Power Filters are classified based on the number of phases, topology, and type of converter. The classification based on the number of phases are two-wire system and three or four-wire systems which are applicable to single-phase, three-phase 3-wire or 4-wire networks. APF configurations can be series, parallel or Hybrid while the type of converter is mainly two types: voltage source inverter (VSI) and current source inverter (CSI) [20], [145]. A typical topology of active filter is shown in figure 5.3.

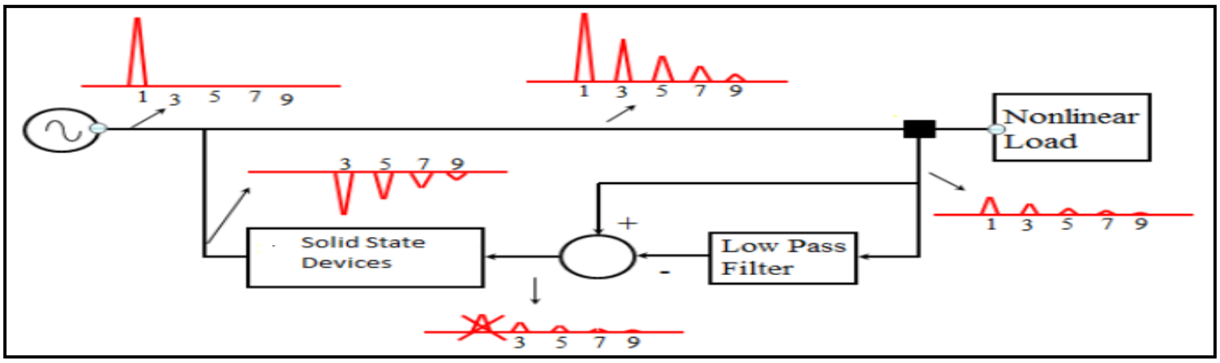


Figure 5-3: Basic concept of control of Active Filters **[145]**

5.8 Summary

In this chapter, brief review of the power systems harmonics, sources, standards and regulations, impacts and mitigation have been presented. The next chapter would be on typical experimental power quality survey of some loads commonly used in residential, commercial sectors while a typical distribution substation is also monitored.

6. Experimental Power Quality Measurement and Evaluation

This chapter is mainly devoted to the power quality measurement and evaluation of some selected residential and commercial loads commonly used in distribution networks and an assessment of a typical distribution network feeding a commercial building is also carried out to evaluate the extent of harmonic pollution in the distribution networks as a result of some of these electrical loads.

6.1 Power Quality Evaluation of Common Residential and commercial Loads

Following the theoretical analysis of harmonics in chapter five, experimental analysis of power quality parameters of some appliances are done in this section to assess the pollution of distribution networks through the use of energy efficient appliances if not well monitored and controlled. This section presents the methodology used for the power quality measurement of some common residential and commercial appliances. In this dissertation, Desktop Computer, Laptop, CFL, standing fan and Filament bulb were considered while voltage and current waveforms, power, Total Harmonic Distortions (THDs), and the power factor of each load were the parameters used for evaluation. All the measurements were carried out using power quality Analysers. The experimental set-up involved the use of three different power quality analysers, the Chauvin Arnoux CA 8334 was used for the measurement of computer laboratory, Dent Power Logger was used for the individual loads while HT Power Quality Analyser was used for the assessment of a typical distribution networks. The connections were done as shown in figure (6.1) by connecting the power Quality Analyzer between the supply and the load considering the expected amount of current from the loads.

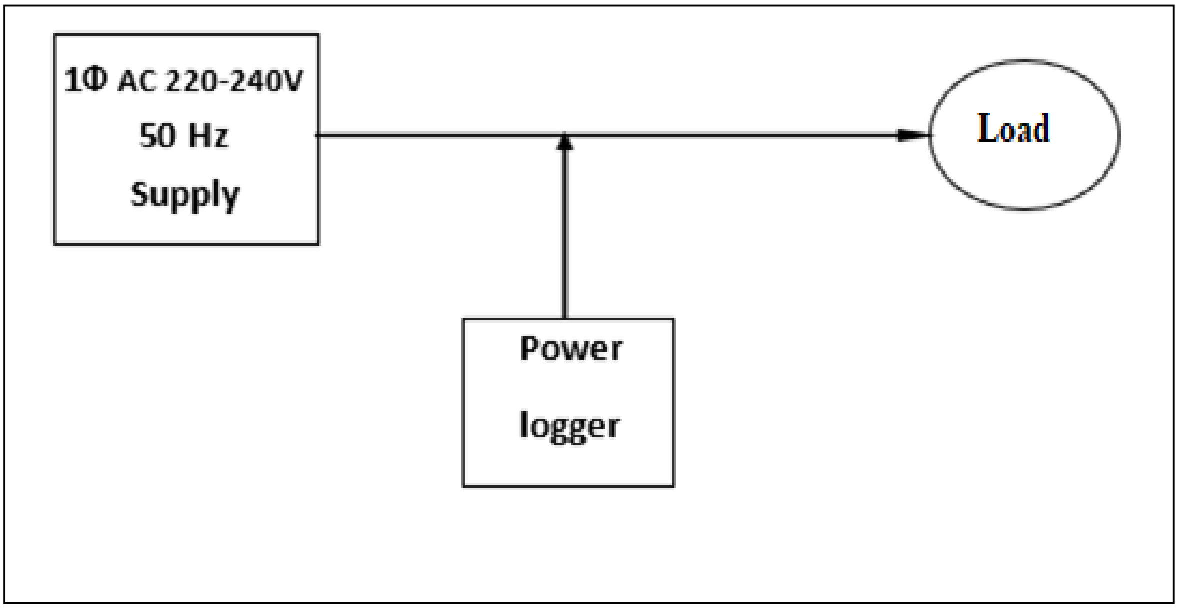


Figure 6-1: Schematic Diagram for the Experimental Setup

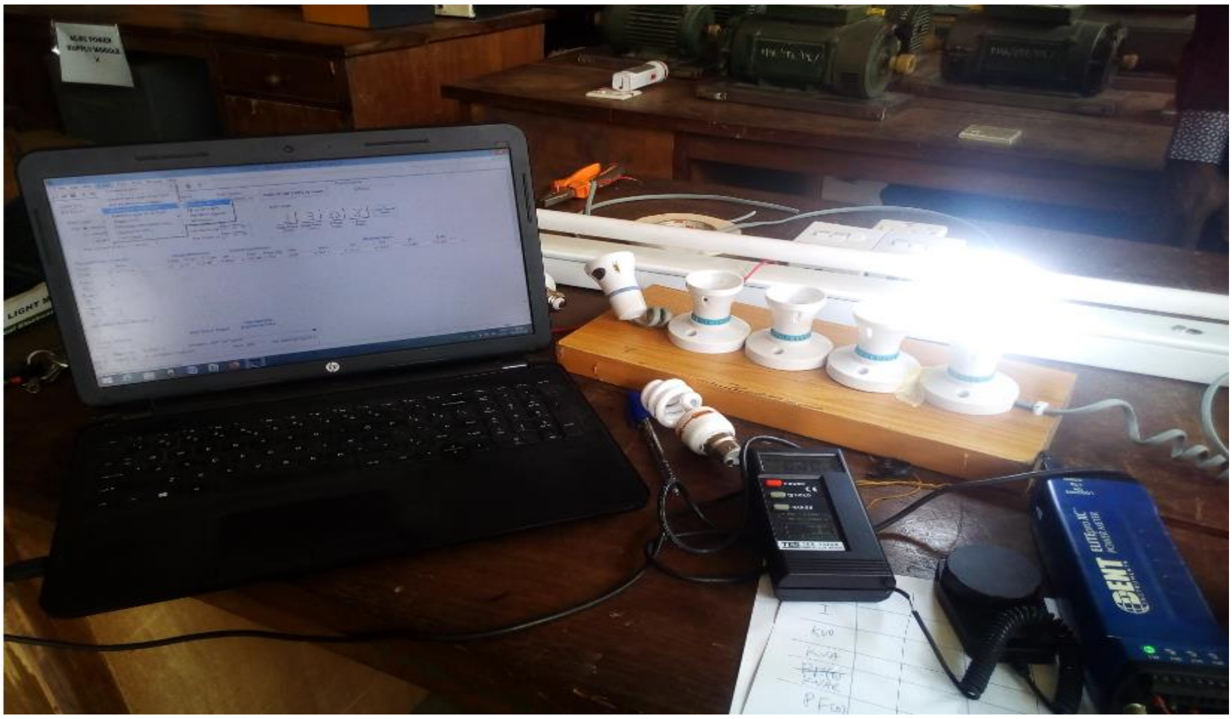


Figure 6-2: Experimental setup for power quality measurement with DENT Power logger

6.1.1 Results and Discussion

The experimental analysis of power quality parameters such as voltage, current, power waveforms, THDs and power factor of a Desktop Computer, Laptop, CFL, standing fan and Filament bulb are presented in this section

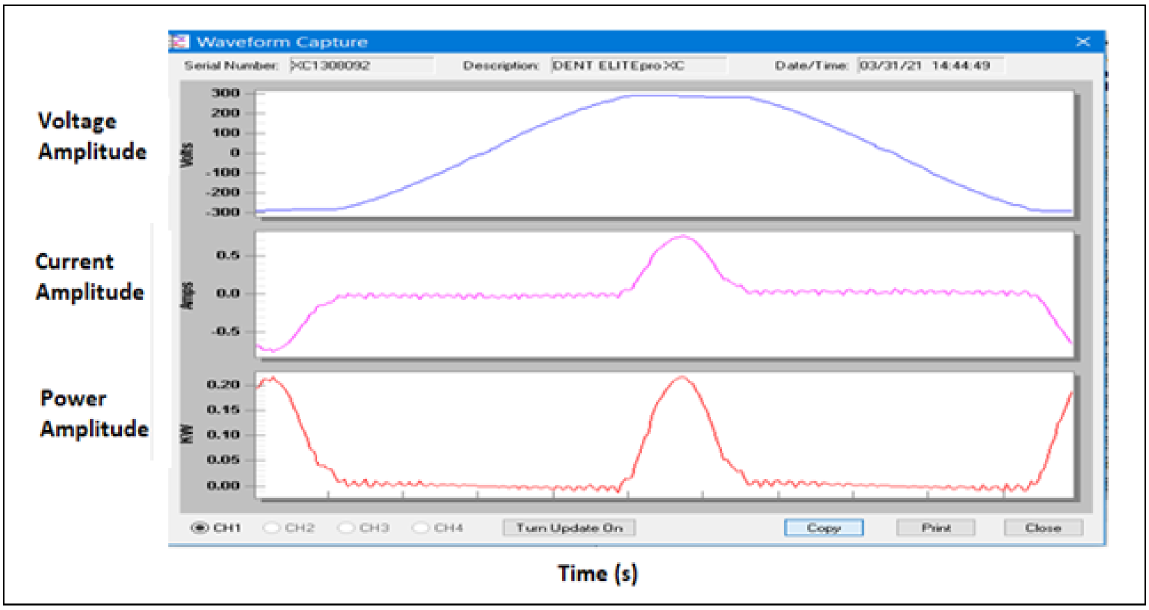

Serial Number: XC1308092 Description: DENT ELITEpro XC Date/Time: 03/31/21 14:44:49

Figure 6-3: Voltage, Current and Active Power Waveforms of Desktop Computer

Desktop Computer: Figure 6.-3 shows voltage and current waveforms of a desktop computer system. It is shown that the current is distorted with corresponding distortion of the voltage and the power waveforms.

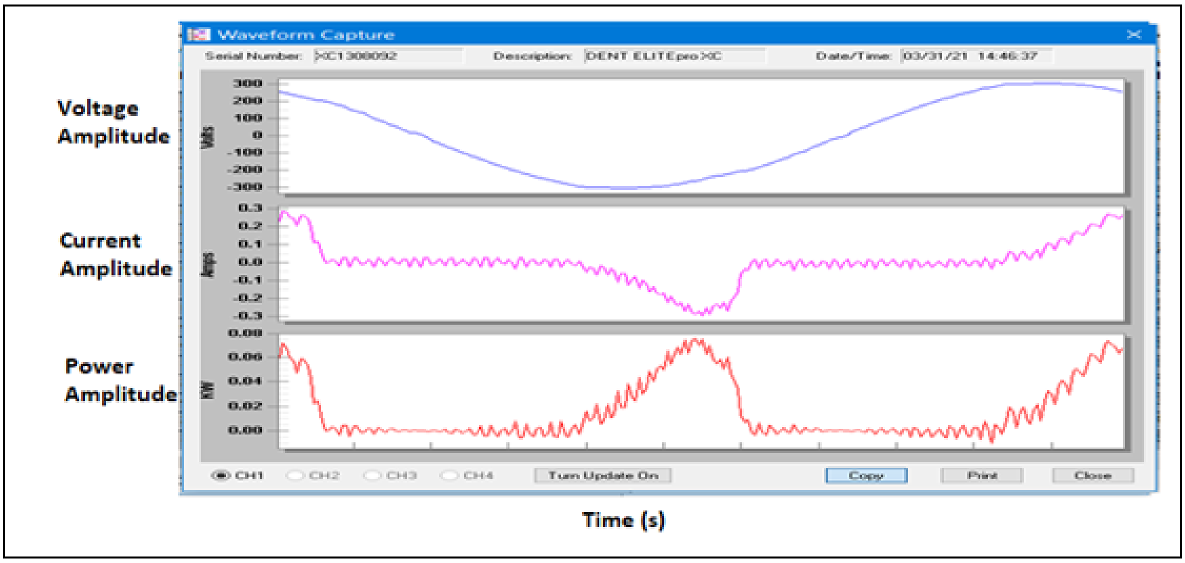

Serial Number: XC1308092 Description: DENT ELITEpro XC Date/Time: 03/31/21 14:46:37

Figure 6-4: Voltage, Current and Active Power Waveforms of CFL_24W

Compact Fluorescent Lamp: In figure 6-4, the level of distortion in CFL is high due to switch mode power supply embedded in the design which depicts high level of harmonic distortion.

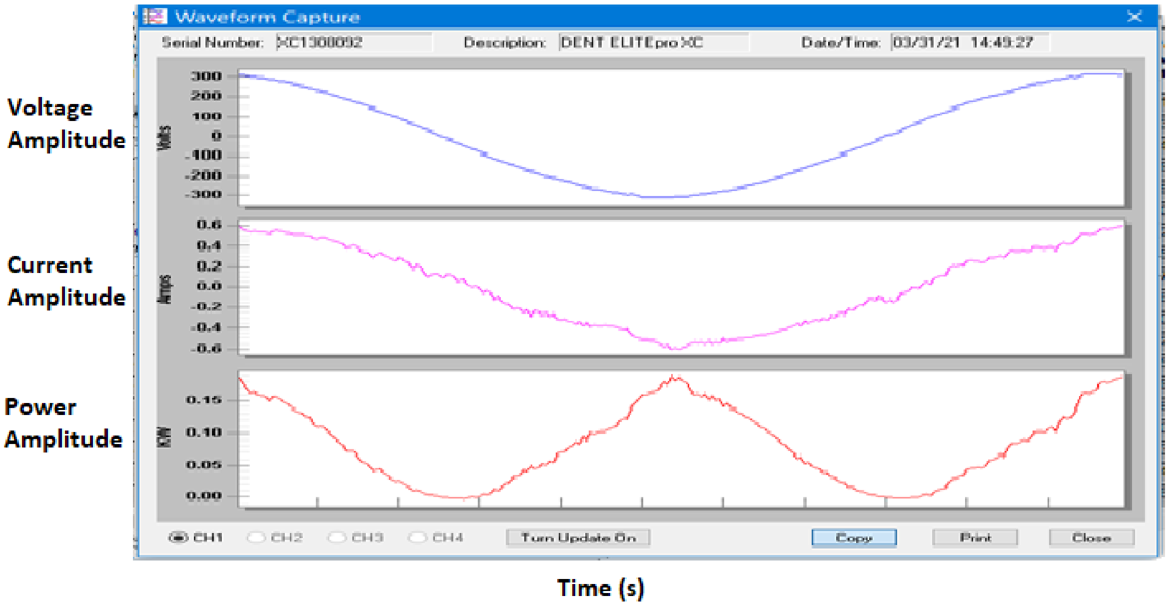

Serial Number: XC1308092 Description: DENT ELITEpro XC Date/Time: 03/31/21 14:49:27

Figure 6-5: Voltage, Current and Active Power Waveforms of 150W_Ox_fan

150W Ox Standing Fan: Considering Figure 6-5, the waveforms of the voltages and currents show an appreciable of ideal waveform. This is due to the linearity nature of an electric fan. It is also shown that the phase shift between the voltage and current tends to zero which indicates close to unity power factor.

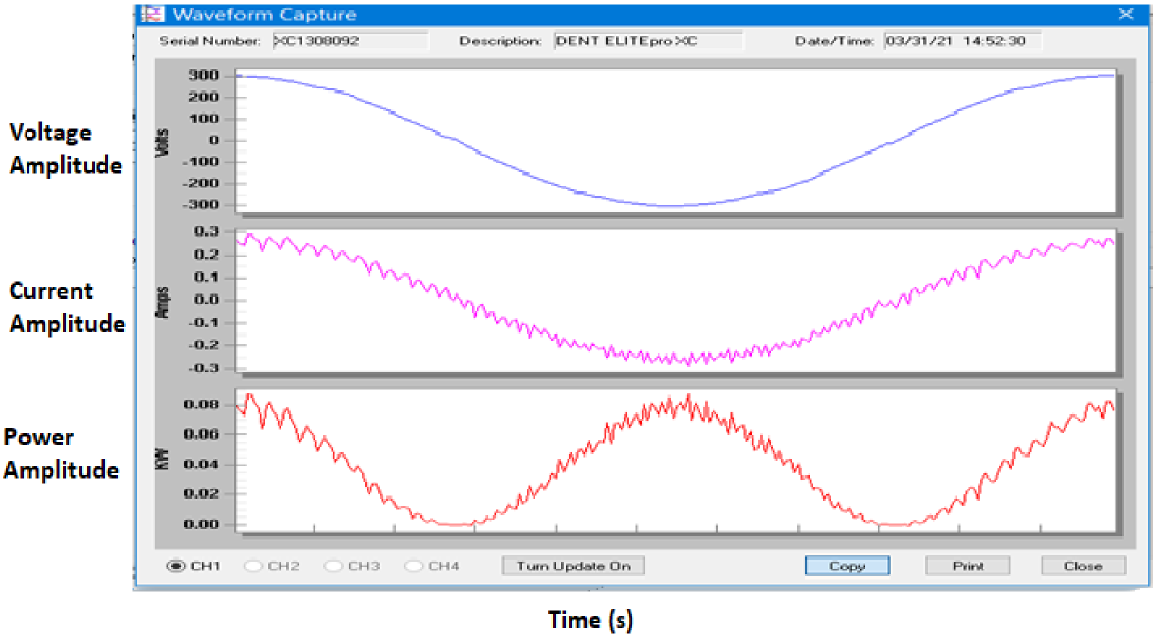

Serial Number: XC1308092 Description: DENT ELITEpro XC Date/Time: 03/31/21 14:52:30

Figure 6-6: Voltage, Current and Active Power Waveforms of 60W_Filament_bulb

Filament Bulb: Because of its purely resistive nature, harmonics in this type of bulb is minimum which is close to zero. The unity power factor of these lamps also indicates its zero harmonics. The waveform in figure 6-6 also depicts that only system frequency is present except for the ripples that could be due to the small value of the current and fluctuation of the supply voltage.

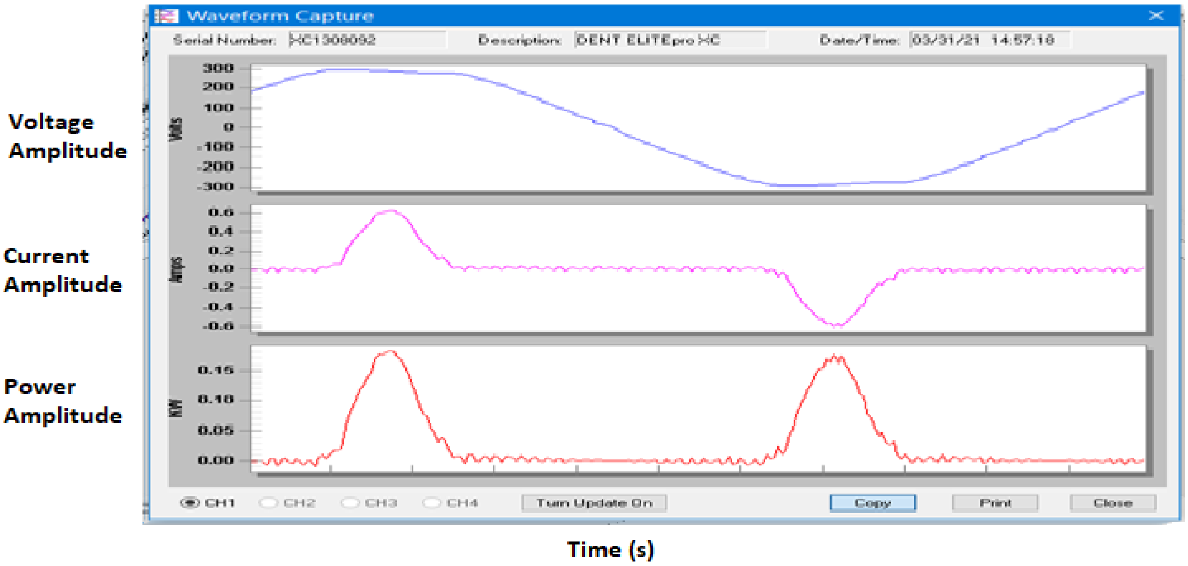

Serial Number: XC1308092
Description: DENT ELITEpro XC
Date/Time: 03/31/21 14:57:18

Figure 6-7: Voltage, Current and Active Power Waveforms of Laptop Computer

Laptop: This is another appliance which contains several power electronic components that injects harmonic currents into the distribution networks. It has resemblance of a desktop computer with higher harmonic distortion as reflected in figure 6-7.

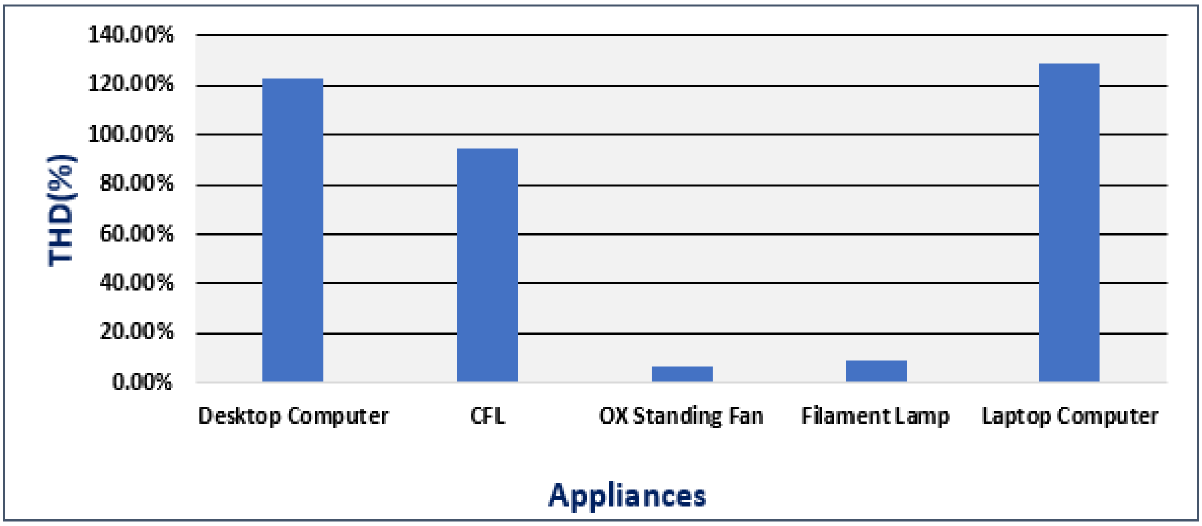


Figure 6-8: THDs of the Appliances

THDs: Figure 6-8 shows the laptops, desktop computer and CFLs have high total harmonic distortions in respective order which means the concentration of such loads would lead to pollution of the entire network thereby increasing the power system losses.

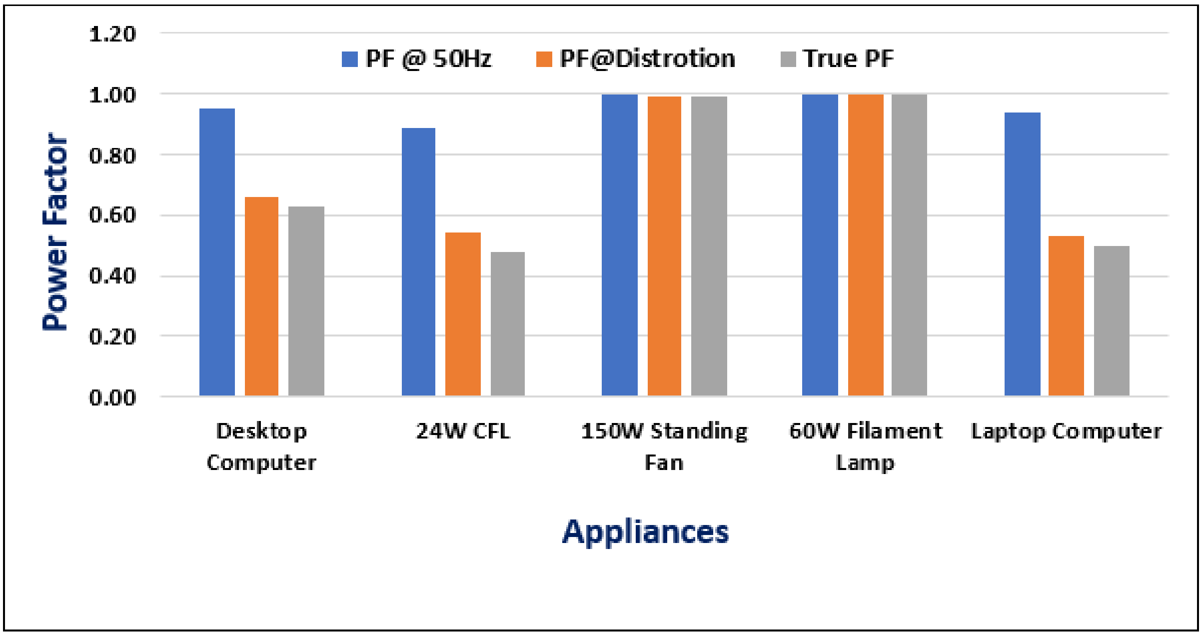


Figure 6-9: Power Factor of the Appliances

Power Factor: Figure 6.9 shows the relationship between the displacement power factor, distortion power factor and the true power factor. In power system analysis, the displacement power factor is the same with true power factor under pure sinusoidal waveforms of voltage and current, filament lamp and electric fan maintained that principle but they differs in other three appliances due to harmonic distortions.

6.2 A Case Study of Harmonic Currents Generated from a Computer Laboratory

Personal computers draw non-sinusoidal current with odd harmonics being more significant. Power Quality of distribution networks is severely affected due to the flow of these generated harmonics during the operation of electronic loads. In this measurement, a computer laboratory having 25 desktop computers was considered while the computers are connected one after the other to know the impact of connecting large numbers of computer on distribution networks. Figure 6.10 shows the practical connection of Chauvin Arnoux CA 8334 Power Quality Analyzer in the computer laboratory.

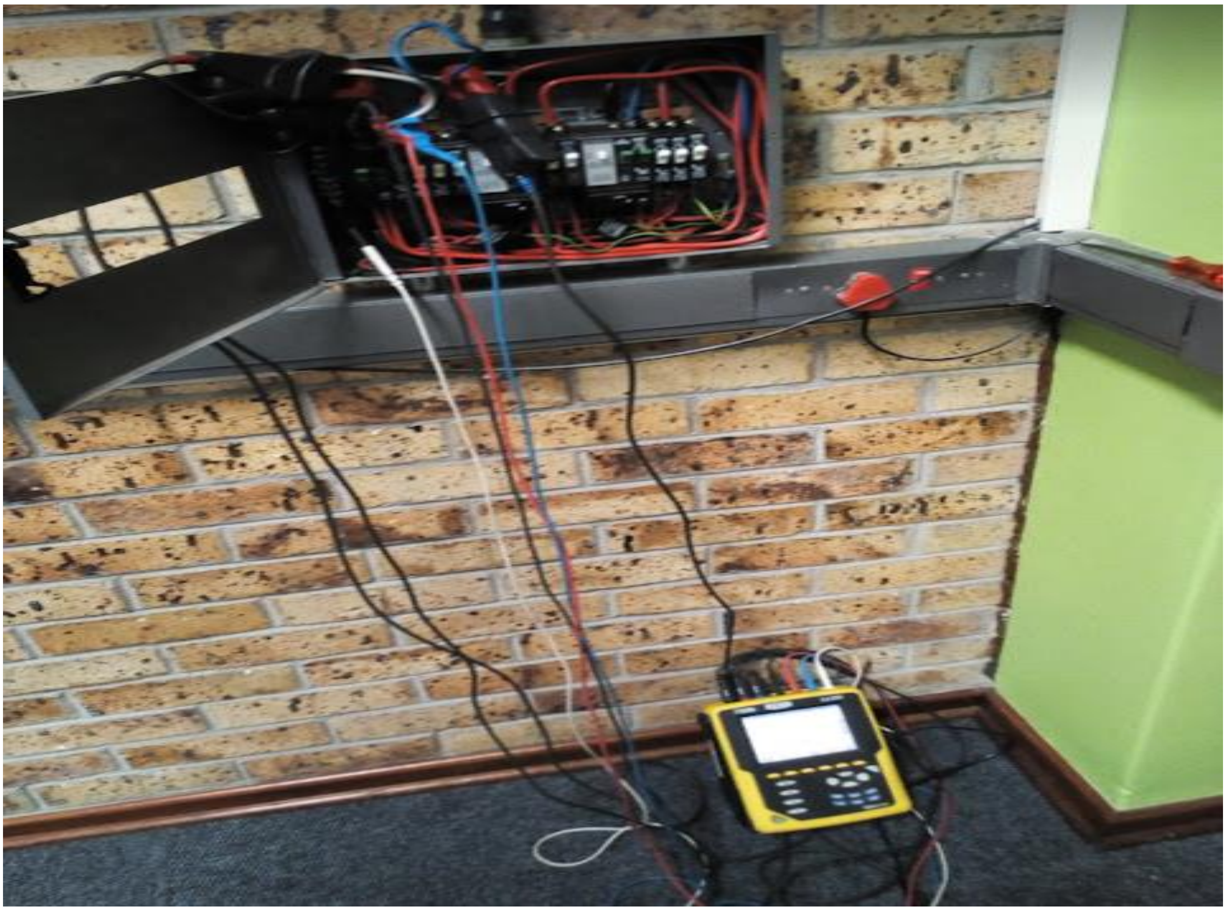


Figure 6-10: Practical Connection PQ Analyzer for the Measurement

6.2.1 Results and Discussion

In order to understand the contribution of this non-linear loads, measurements were made at the distribution board supplying a computer lab with 25 sets of computers at different moment of time on a weekday using the power quality analyzer. The rms voltage and current with the harmonic components and their respective angle were measured using Chauvin Arnoux CA 8334 as shown in Tables 6-1 and 6-2 .

From Table 6.1, the voltage supply is balance with THD ranges from 2.4% - 3.3% which is within the acceptable standard of 5% while the prominent harmonic is 3rd order harmonics.

From Table 6.2 which shows the rms current and individual harmonics of the computer laboratory. The loads are not balanced on the phases with phase C having the highest rms current of 4.35A with 3rd harmonic taking above 50% of the rms current of each phase. The current THD is high due to the nonlinear nature of the computer loads.

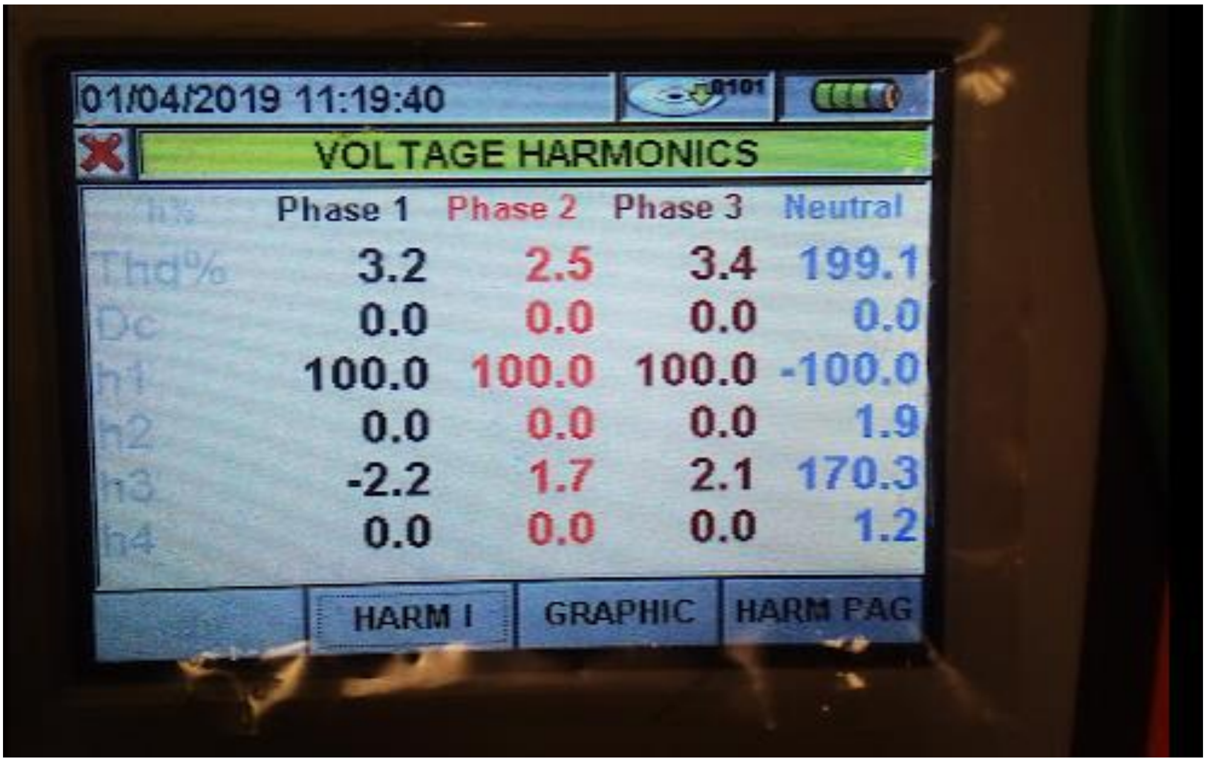
Table 6-1: RMS Voltage of a typical Computer Laboratory

	Phase A		**Phase B**		**Phase C**	
V_rms (V)	227		225		226	
Harmonic components						
	Amplitude	Angle	Amplitude	Angle	Amplitude	Angle
1	226	0	225	-1	226	-5
3	5	49	5	55	4	50
5	2	179	3	-167	1	-168
7	3	49	3	25	2	31
9	3	139	3	133	2	117
11	1	-58	1	-122	2	-110
13	2	11	2	-15	1	-32
THD (%)	3.1		3.3		2.4	
Vn	3.2					

Table 6-2: RMS Current of a typical Computer Laboratory

	Phase A		Phase B		Phase C	
I_rms (A)	2.98		3.38		4.35	
Harmonic components						
	Amplitude	Angle	Amplitude	Angle	Amplitude	Angle
1	2.45	-6	2.14	0	2.61	0
3	1.15	149	1.90	162	2.39	166
5	0.79	-40	1.44	-32	1.89	-25
7	0.58	136	0.92	134	1.34	146
9	0.25	-51	0.44	-64	0.8	-43
11	0.11	96	0.08	77	0.38	142
13	0.07	142	0.14	105	0.14	32
THD (%)	3.1		122.3		133.4	

Waveforms as measured at an instant are as shown in figures (6.11) – (6.13). The waveforms reflect the level of distortions caused by the computer laboratory.



01/04/2019 11:19:40

VOLTAGE HARMONICS

h%	Phase 1	Phase 2	Phase 3	Neutral
Thd%	3.2	2.5	3.4	199.1
Dc	0.0	0.0	0.0	0.0
h1	100.0	100.0	100.0	-100.0
h2	0.0	0.0	0.0	1.9
h3	-2.2	1.7	2.1	170.3
h4	0.0	0.0	0.0	1.2

Figure 6-11: Voltage harmonics of the computer laboratory

01/04/2019 11:18:30

CURRENT HARMONICS

h%	Phase 1	Phase 2	Phase 3	Neutral
Thd%	55.6	122.0	140.1	500.0
Dc	0.0	0.0	0.0	0.0
h1	100.0	100.0	100.0	-100.0
h2	1.5	1.4	0.3	16.9
h3	-41.4	89.7	92.4	1442.8
h4	0.4	0.4	0.6	8.9

Figure 6-12: Current harmonics of the computer laboratory

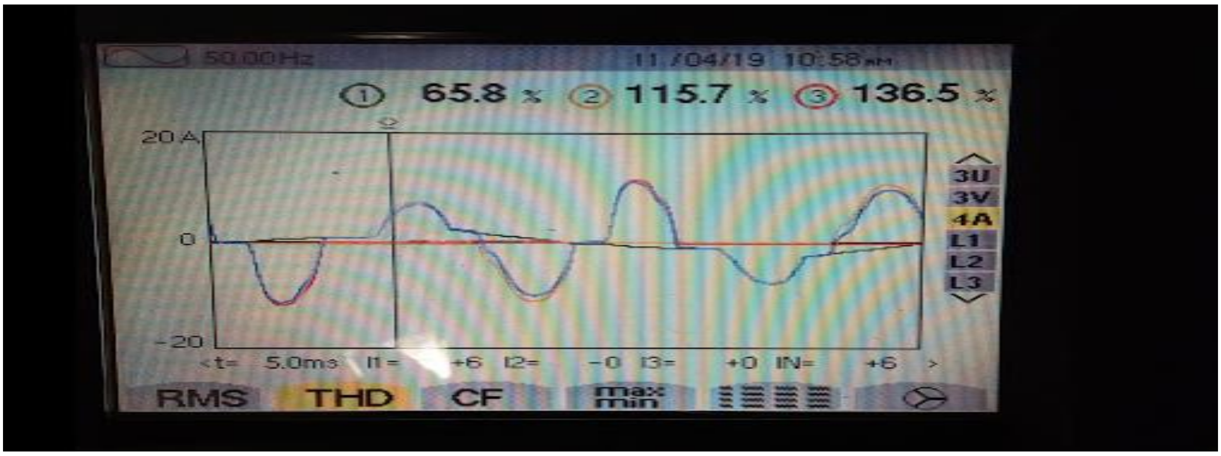


Figure 6-13: Current waveforms at an instant

6.3 Power Quality Measurement and Analysis of a Typical Distribution Substation

The case study considered in this section is the distribution network feeding the Old Engineering Building of the University of Cape Town. The building under investigation is a 6-story building which contains several academic offices, lecture rooms/theatre, some workshops, and two lifts. This building also serves the research offices and computer laboratories with more than 300 computers with 24/7 access to them. The supply to the building is fed from a 750 kVA 11/0.4 kV transformer at the engineering substation. Other loads connected to the network are heating, ventilation, and air-conditioning (HVAC), Compact fluorescent lamps, Fluorescent lamps, printers, and mechanical engineering, electrical engineering, and geomatics laboratories. . The power quality parameters monitored are: voltage and current imbalance, harmonic distortion, and power factor while the detailed measurement was carried out using HT Power Quality Analyzer shown in figure 6-14.

Figure 6-14: Typical connection of HT Power Quality Analyzer for the measurement

6.4 Results and Analysis

Parameters such as current, voltage, active and reactive power, power factor, unbalance factor and harmonic distortions were measured to determine the power quality of the installation. The analysis of the measured data can be used for the evaluation and possible implementation of mitigation techniques. The analysed power quality issues presented in this paper are based on a typical week measurement while all figures presented illustrate the typical working day.

6.4.1 Voltage Analysis

Measured voltages on all phases show some level of fluctuations according to a typical load characteristic of the day and night; such that higher voltage was recorded during the night when demand is low and vice versa as shown in figure 6-15 while figure 6-16 shows the unbalance factor of the voltage calculated using the IEEE method as in equation (4.5). Figure 6-15 shows the voltage variation observed were within the limits of 230V ±6% as stipulated by NRS_048 with the maximum and minimum values of 231.2V and 225.4V respectively while the maximum Voltage unbalances observed were also within the IEEE and NEMA limit of 2% and NRS-048 of 2-3% as illustrated in figure 6-16.

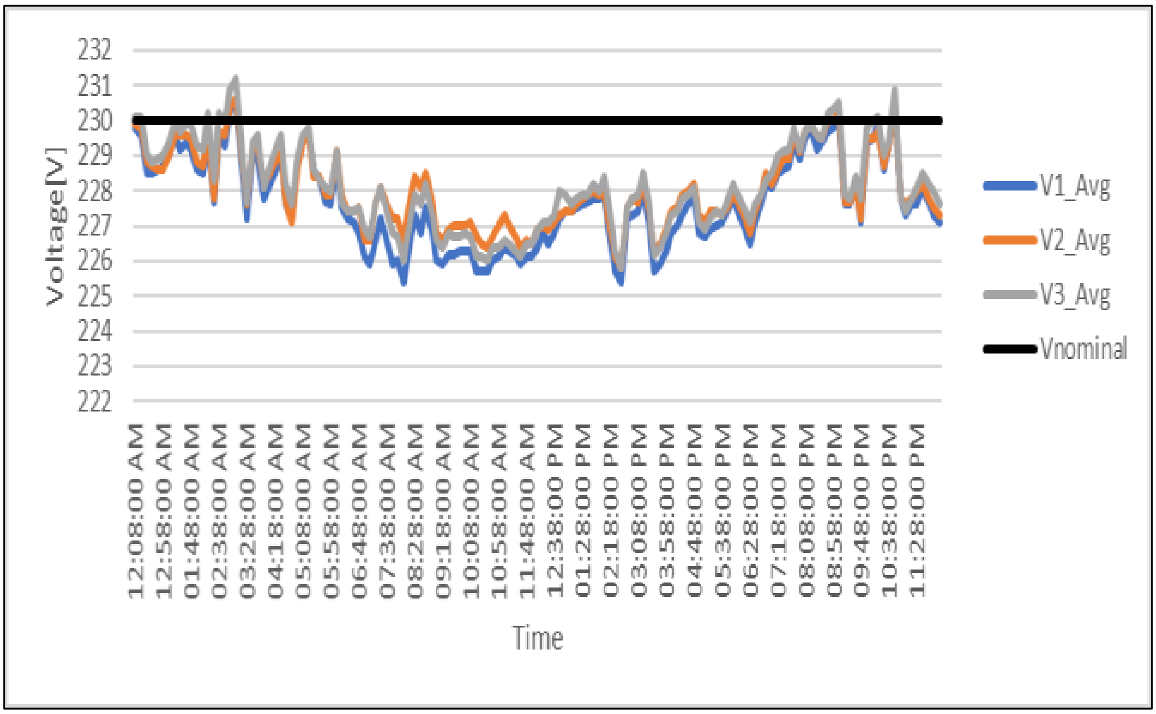


Figure 6-15: Fundamental rms Voltage variation for a day

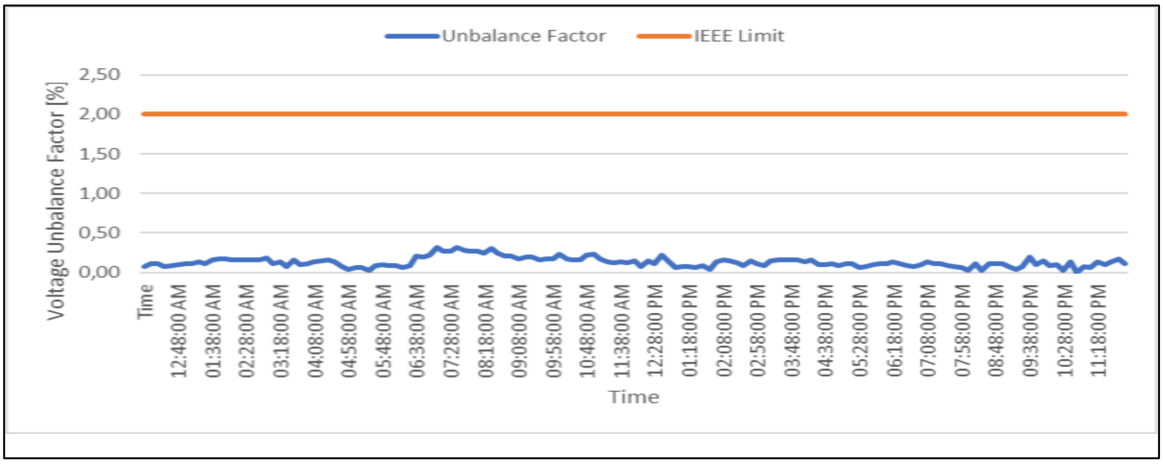


Figure 6-16: Voltage Unbalance Factor in percentage

The distortion in the supply voltage waveform was also observed for the three phases. The maximum total harmonic distortion (THD) value registered over the measurement period was also within the limit, although the value could be above that if more nonlinear loads are added to the network or the aggregated nonlinear loads are not compensated or filtered, the maximum total harmonic distortion of the voltage recorded for the measurement period was 2.98% which is considered to be within the limit of the standards according to IEEE 1459-2010 and NRS-048 of 5% while the dominant harmonic orders are the 3rd, 5th, 7th and 9th harmonics as shown in figure 6-17 and figure 6-18 respectively.

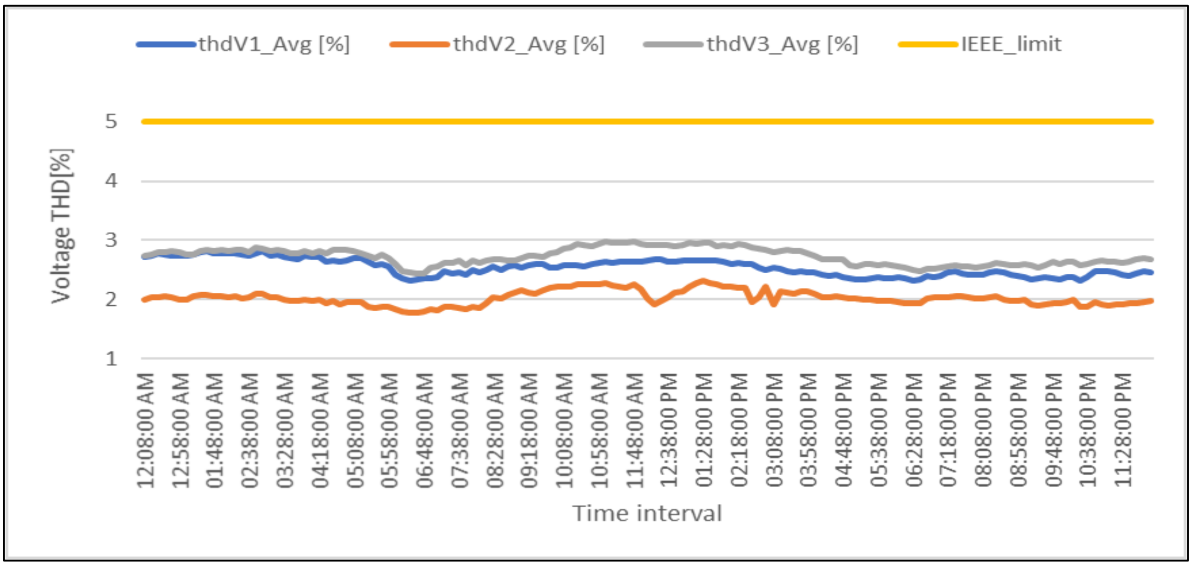


Figure 6-17: Total Harmonic Distortion of the Voltage per phase

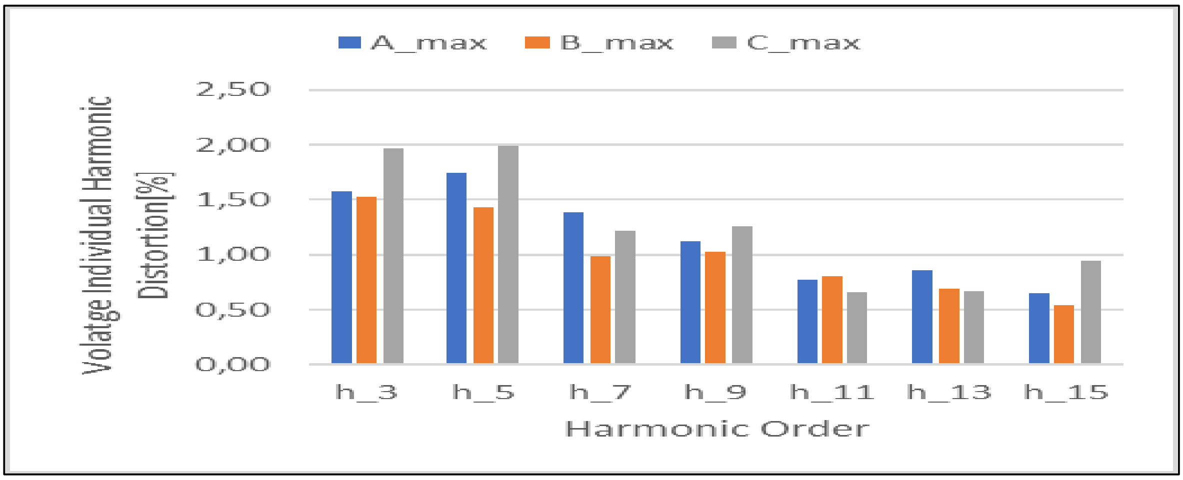


Figure 6-18: Voltage individual harmonic Distortion for one day

6.4.2 *Current Analysis*

Various power quality monitoring include short term or long-term monitoring to solve power quality related issues. Voltage regulation is the responsibility of the utility while the current represents the demand of the consumers from the system. The load demand from the measured values shows the base and peak load demand for the duration of measurement.

The current measured in all the phases during the period also shows the variation according to a typical day and night load characteristics of a commercial building as shown in Fig. 6-19. The neutral current has the minimum and maximum values of 44.54 A and 68.27 A respectively with the mean value of 54.19 A which indicates the degree of unbalanced loading in the phases.

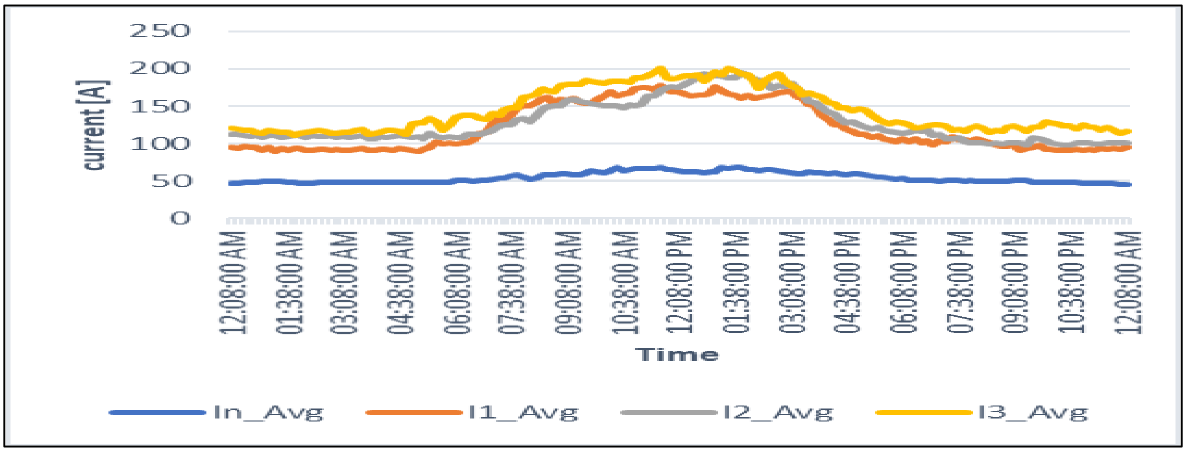


Figure 6-19: Fundamental rms current of each phase and neutral for a day

The current harmonic distortion observed was high. The maximum THDi value registered over the measurement period was 40.5% which is considered according to the IEEE standards as high with phases 1 and 3 having the higher distortions while the third, fifth, seventh and ninth harmonics were dominant as illustrated in figures 6-20 and 6-21.

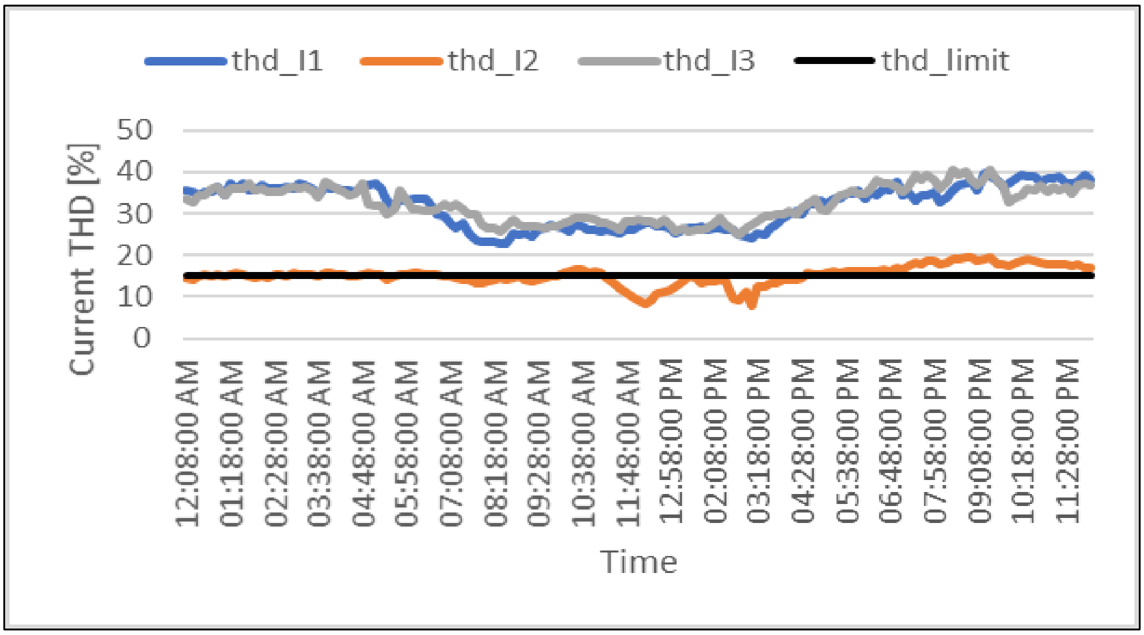


Figure 6-20: Total Harmonic Distortion of the Line Currents for one day

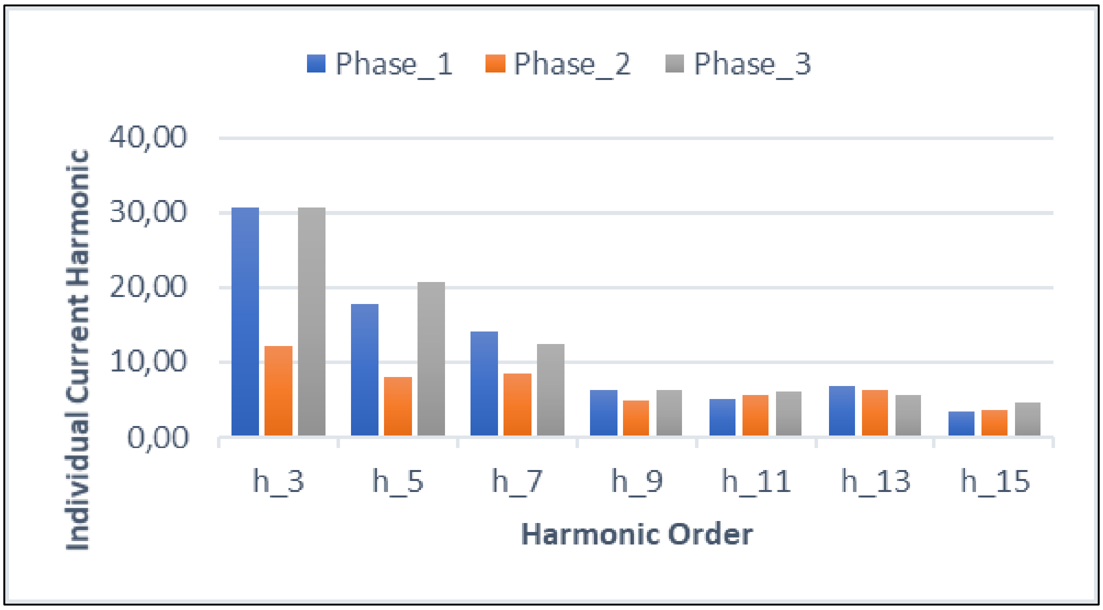


Figure 6-21: Currents individual harmonic distortion for one day

The distortion of the neutral current is high due to the triplen harmonics from the loads which add up into the neutral conductor. Figure 6-22 indicates the maximum and minimum individual distortion of the neutral current odd harmonics as a percentage of the fundamental value with the third harmonic having the highest value followed by other triplen harmonics.

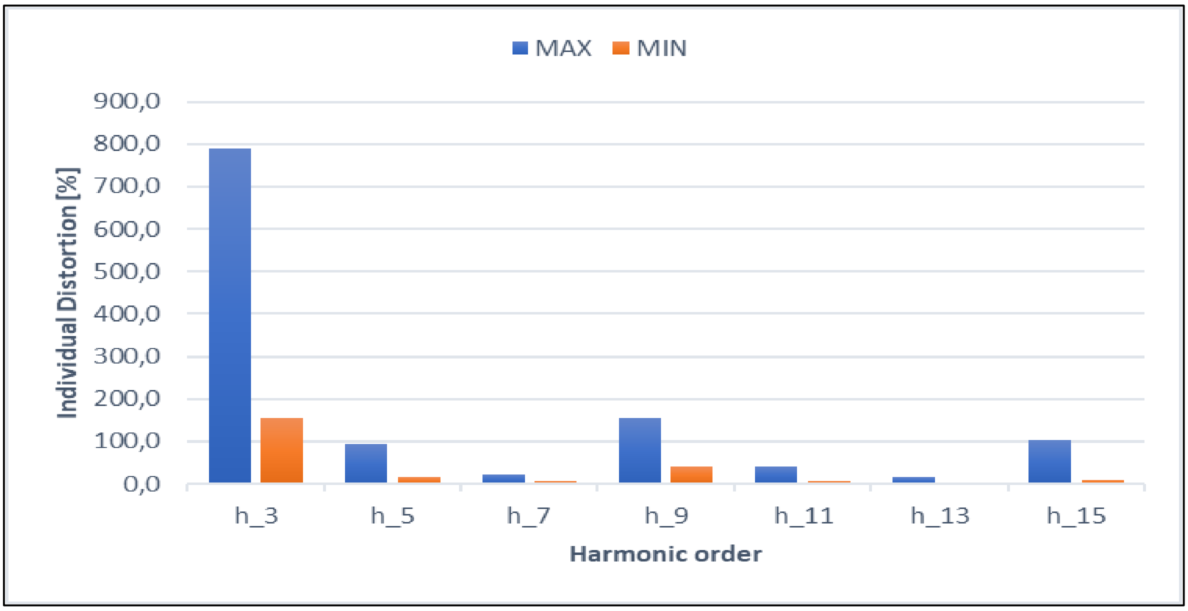


Figure 6-22: Neutral Current maximum and minimum individual harmonic distortion

Generally, the analysis of the data obtained during the monitoring period suggests that the power quality is relatively not very good at the load end compared with the standards. The high current distortion due to the non-linear loads such as CFLs, PCs (especially the computer laboratories), which are considered as sources of power quality disturbances in both residential and commercial buildings. The overall results can be summarised as follow:

- Voltage imbalance does not exceed the 2% specified for low voltage networks as contained in both IEEE and NRS-048 standards
- Voltage variation/deviation does not exceed the ± 6% as specified by both IEEE and NRS_048 standards
- THDv does not exceed the 5% limits specified IEEE standards.
- THDi exceeds the 15% stipulated by IEEE 519 limit.

- The neutral current is highly distorted due to the triplen harmonics present in the network

Referring to the results of power quality monitored from the building and according to available power quality solutions, the mitigation techniques suggested is the installation of filters close to the loads generating the harmonics. In this case, the computer laboratories, since other nonlinear loads are not aggregated like the large number of computers in the computer laboratories.

6.5 Summary

This chapter has shown the power quality measurement of some load commonly used in the low-voltage distribution networks which contribute to the imbalance, increased reactive power burden and harmonic distortion. It also shows the methods and instruments used for typical power quality monitoring and analysis useful for both electricity companies and consumers. The next chapter presents a method to solve the problem of imbalance and poor power factor due to increased reactive power burden through load compensation.

7. Passive Method of Load Compensation

As earlier discussed, the main reason for unbalance in the low voltage networks is the unbalanced nature of the connected loads, therefore, this chapter presents the mathematical formulation and simulation of a load compensator for three-phase four –wire network for load balancing and reactive power compensation using passive components.

7.1 Introduction

The first cause of voltage unbalance during normal operation of the three-phase four-wire networks is the unbalanced structure of the network elements such as transformers, electrical conductors etc. but common corrective measures for this type of unbalance is by transposition of the overhead line conductors to maintain the voltage unbalance within the acceptable limit. Another cause of unbalance in the network are types of loads connected, many of which are single-phase and unevenly distributed on the three phases. Such as welding machines, induction furnaces and traction loads. In order to solve power quality problems mainly caused by unbalanced linear load in a three-phase, four-wire, a method is presented in this section for load balancing and reactive power compensation using passive elements.

The compensator consists of star and delta segments. The star part of the compensator is used for the reactive power compensation while the delta segment determines the redistribution of the active power for load balancing. This method can also improve the power factor and overall performance of LV networks thereby releasing a certain amount of capacity of the distribution grid. The following section is devoted to the mathematical derivation of the model to determine the susceptances for both the star and delta segments of the compensator.

7.2 Formulation of the Mathematical model

In this section, mathematical model based on the symmetrical components theory is being derived for the proposed hybrid compensator for load balancing and reactive power compensation in distribution network. To eliminate the current in the neutral conductor of a three-phase four wire network, the real and the imaginary parts of the zero-sequence current must be removed together with the negative sequence current which determines the unbalance level of the load, through compensation. The real and imaginary components of the load current positive sequence are equal to the real and imaginary parts of the load currents in which the imaginary part must be compensated for power factor improvement.

In this context, the unbalanced currents of any three-phase system can be presented in form of equal positive, equal negative and equal zero negative sequence currents which yields the compensating values in terms of the voltages and currents using the transformation given in equation (7.1) [146].

$$\begin{bmatrix} I_L^+ \\ I_L^- \\ I_L^0 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{7.1}$$

Given that $\alpha = 1 < 120^0 = -\frac{1}{2} + j\,\frac{\sqrt{3}}{2}$

Where $I_L^+, I_L^-\ and\ I_L^0$ are the positive, negative and zero sequence components of the load current using phase 'a' as the reference.

Considering the basic power circuit topology of the proposed compensator applied to three-phase four wire distribution network as shown in figure (7-1), the sizing of the compensator elements are based on four different conditions as stated [92]:

I. Reactive power compensation without considering the unbalance condition of the load

II. Load balancing without considering the power factor improvement

III. Unbalance reduction and power factor correction

IV. Power factor maximization and complete load balancing

In this research, the fourth condition is considered for sizing of the compensating elements since maximum power quality improvement depends on the reactive power and unbalance condition of the network.

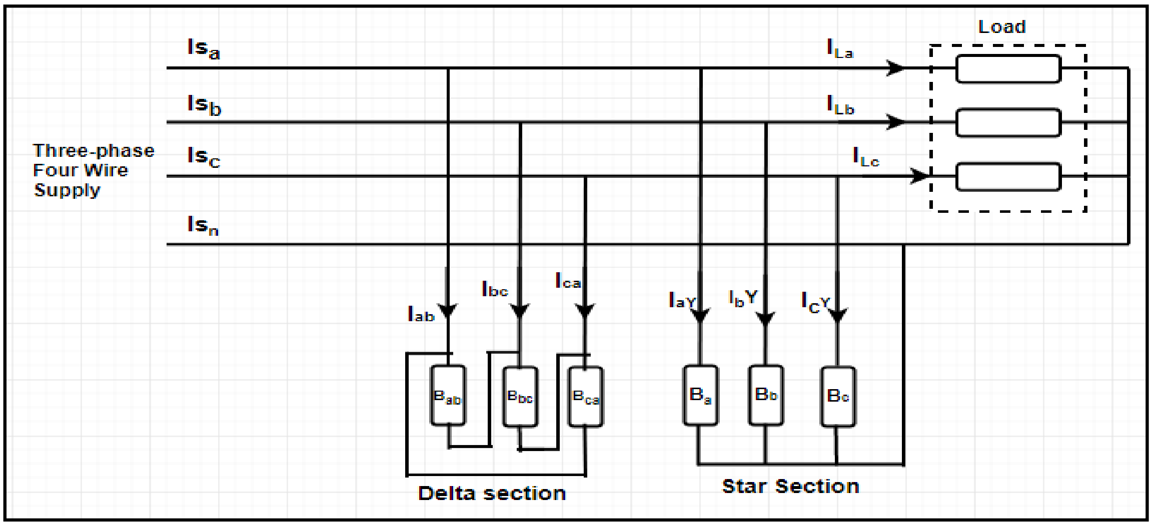


Figure 7-1: Schematic diagram of the Network with the Proposed Compensator

Applying the theory of symmetrical components, the currents flowing through the load and the hybrid compensator currents as shown in figure 7-1 can be decomposed using equation (7.1). The sequence components of the load current, currents through the star and delta sections of the compensator are expressed in terms of the real and imaginary components as in (7.2), (7.3) and (7.4) respectively.

$$\begin{aligned}
I_L^0 &= \frac{1}{3}\left[I_{ar} + I_{br} + I_{cr}\right] - j\frac{1}{3}\left[I_{ai} + I_{bi} + I_{ci}\right] \\
I_L^+ &= \frac{1}{3}\left[I_{ar} - \frac{1}{2}\left(I_{br} + I_{cr}\right) + \frac{\sqrt{3}}{2}\left(I_{ci} - I_{bi}\right)\right] + j\frac{1}{3}\left[I_{ai} - \frac{1}{2}\left(I_{bi} + I_{ci}\right) - \frac{\sqrt{3}}{2}\left(I_{br} - I_{cr}\right)\right] \\
I_L^- &= \frac{1}{3}\left[I_{ar} - \frac{1}{2}\left(I_{br} + I_{cr}\right) + \frac{\sqrt{3}}{2}\left(I_{bi} - I_{ci}\right)\right] + j\frac{1}{3}\left[I_{ai} - \frac{1}{2}\left(I_{bi} + I_{ci}\right) - \frac{\sqrt{3}}{2}\left(I_{br} - I_{cr}\right)\right]
\end{aligned} \qquad (7.2)$$

$$\begin{aligned}
I_Y^0 &= \frac{1}{3}\left[\frac{\sqrt{3}}{2}\left(I_c^Y - I_b^Y\right) + j\frac{1}{2}\left(I_b^Y + I_c^Y - 2 * I_a^Y\right)\right] \\
I_Y^+ &= -j\frac{1}{3}\left(I_a^Y + I_b^Y + I_c^Y\right) \\
I_Y^- &= \frac{1}{3}\left[\frac{\sqrt{3}}{2}\left(I_b^Y - I_c^Y\right) + j\frac{1}{2}\left(I_b^Y + I_c^Y - 2 * I_a^Y\right)\right]
\end{aligned} \qquad (7.3)$$

$$\begin{aligned}
I_D^0 &= 0 \\
I_D^+ &= -j\frac{1}{\sqrt{3}}\left[I_{ab}^D + I_{bc}^D + I_{ca}^D\right] \\
I_D^- &= \frac{1}{2}\left[\left(I_{ab}^D - I_{bc}^D\right) + j\frac{1}{\sqrt{3}}\left(2 * I_{bc}^D - I_{ab}^D - I_{ca}^D\right)\right]
\end{aligned} \qquad (7.4)$$

where a, b, and c correspond to the phases while ‘r’ and ‘i’ represents the real and imaginary components of the load respectively. The **Y** and **D** denotes star and delta configurations respectively.

7.2.1 Determination of compensation currents and susceptances

The full compensation of the positive sequence reactive power is required for maximum power factor improvement and this can be achieved through the cancellation of the imaginary part of positive sequence current in (7.2) while load balancing for a three-phase four-wire network require the cancellation of real and imaginary parts of both negative and zero sequence of the load currents. The proposed compensator would be expected to cancel the components to give the conditions stated in equation (7.5) after compensation.

$$\begin{array}{ll} Imag\ I_s^{+} = 0\,, & ImagI_s^{-} = 0 \\ Real\ I_s^{-} = 0\,, & ImagI_s^{0} = 0 \\ Real\ I_s^{0} = 0\,, & I_{ab}^{D} + I_{bc}^{D} + I_{ca}^{D} = 0 \end{array} \tag{7.5}$$

Applying the KCL to the schematic diagram in figure (7.1) will result to equation (7.6). Where IS represents the source current after compensation.

$$\begin{bmatrix} I_s^0 \\ I_s^+ \\ I_s^- \end{bmatrix} = \begin{bmatrix} I_L^0 \\ I_L^+ \\ I_L^- \end{bmatrix} + \begin{bmatrix} I_D^0 \\ I_D^+ \\ I_D^- \end{bmatrix} + \begin{bmatrix} I_Y^0 \\ I_Y^0 \\ I_Y^0 \end{bmatrix} \tag{7.6}$$

Substituting the equations (7.2) - (7.4) in (7.6) and considering the six conditions stated in (7.5) yields equation (7.7) expressed in matrix form. (see Appendix B)

$$\begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \\ X_6 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 1 & 1 & 1 \\ -2 & 1 & 1 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 & 0 & 0 \\ -1 & -1 & -1 & -\sqrt{3} & -\sqrt{3} & -\sqrt{3} \\ -2 & 1 & 1 & -\sqrt{3} & 2\sqrt{3} & -\sqrt{3} \\ 0 & 1 & -1 & \sqrt{3} & 0 & -\sqrt{3} \end{bmatrix} \begin{bmatrix} I_a^Y \\ I_b^Y \\ I_c^Y \\ I_{ab}^D \\ I_{bc}^D \\ I_{ca}^D \end{bmatrix} \tag{7.7}$$

Where the values of $X_1 - X_6$, are determined based on the load current before compensation using either sequence components or the phase components of the currents as stated in equation (7.8) and (7.9) respectively.

$$\begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \\ X_6 \end{bmatrix} = \begin{bmatrix} 0 \\ -6 * Imag(I_L^0) \\ -2\sqrt{3}\, Real\ I_L^0) \\ 3 * Imag(I_L^+) \\ -6 * Imag(I_L^-) \\ -2\sqrt{3}\, Real\ I_L^-) \end{bmatrix} \tag{7.8}$$

$$\begin{aligned} X_1 &= 0 \\ X_2 &= 2 * I_{ai} - I_{bi} - I_{ci} + \sqrt{3}\,(I_{br} - I_{cr}) \\ X_3 &= I_{bi} - I_{ci} + \frac{1}{\sqrt{3}}(-2 * I_{ar} + I_{br} + I_{cr}) \\ X_4 &= -(I_{ai} + I_{bi} + I_{ci}) \\ X_5 &= (2 * I_{ai} - I_{bi} - I_{ci}) + \sqrt{3}\,(I_{cr} - I_{br}) \\ X_6 &= I_{ci} - I_{bi} + \frac{1}{\sqrt{3}}\,(I_{br} + I_{cr} - 2 * I_{ar}) \end{aligned} \tag{7.9}$$

Solving equation (7.8) by substituting the expression for X_1 -X_6, the currents flowing through the hybrid compensator are obtained and the corresponding susceptances can be determined using equations (7.10) and (7.11) respectively.

$$\begin{aligned} I_{ab}^D &= \tfrac{2}{3}\,(I_{br} - I_{ai}) \\ I_{bc}^D &= \tfrac{2}{3}\,(I_{cr} - I_{bi}) \\ I_{ca}^D &= \tfrac{2}{3}\,(I_{ar} - I_{ci}) \\ I_a^Y &= \frac{1}{\sqrt{3}}\left(I_{cr} - I_{br} - \sqrt{3} * I_{ai}\right) \\ I_b^Y &= \frac{1}{\sqrt{3}}\left(I_{ar} - I_{cr} - \sqrt{3} * I_{bi}\right) \\ I_c^Y &= \frac{1}{\sqrt{3}}\left(I_{br} - I_{ar} - \sqrt{3} * I_{ci}\right) \end{aligned} \tag{7.10}$$

$$
\begin{aligned}
B_{ab}^{D} &= \frac{I_{ab}^{D}}{V_{L-L}} = \frac{1}{V_{L-L}}\left[\frac{2}{3}\,(I_{br} - I_{ai})\right] \\
B_{bc}^{D} &= \frac{I_{bc}^{D}}{V_{L-L}} = \frac{1}{V_{L-L}}\left[\frac{2}{3}\,(I_{cr} - I_{bi})\right] \\
B_{ca}^{D} &= \frac{I_{ca}^{D}}{V_{L-L}} = \frac{1}{V_{L-L}}\left[\frac{2}{3}\,(I_{ar} - I_{ci})\right] \\
B_{a}^{Y} &= \frac{I_{a}^{Y}}{V_{ph}} = \frac{1}{V_{ph}}\left[\frac{1}{\sqrt{3}}\left(I_{cr} - I_{br} - \sqrt{3} * I_{ai}\right)\right] \\
B_{b}^{Y} &= \frac{I_{b}^{Y}}{V_{ph}} = \frac{1}{V_{ph}}\left[\frac{1}{\sqrt{3}}\left(I_{ar} - I_{cr} - \sqrt{3} * I_{bi}\right)\right] \\
B_{c}^{Y} &= \frac{I_{c}^{Y}}{V_{ph}} = \frac{1}{V_{ph}}\left[\frac{1}{\sqrt{3}}\left(I_{br} - I_{ar} - \sqrt{3} * I_{ci}\right)\right]
\end{aligned}
\tag{7.11}
$$

Where V_{L-L} and V_{ph} are the line and phase values of the voltages at the point of common coupling and B is the susceptance while other symbols are as follow

Y = star connection

D = delta connection

a,b.c = the notation for each phase of the three phase

r = real value

i = imaginary value

The values of the sizing elements are determined based on the calculated susceptances which can either be inductive or capacitive using equations (7.12) and (7.13) respectively. The element is inductive when the susceptance is positive and capacitive when the susceptance is negative.

$$L = \frac{1}{2\pi f * B} \tag{7.12}$$

$$C = \frac{B}{2\pi f} \tag{7.13}$$

The following section shows the implementation of the above method of calculating the values of the passive elements in MATLAB/Simulink environment.

7.3 MATLAB/Simulink for an Online Calculator of the Compensating Elements

The proposed hybrid compensator requires the voltage and current measurements at the Point of Common coupling to determine the sizing of the compensating elements as derived from the previous section. Since the active and reactive power rating of the load are not known, a model is required to determine the sizing of the compensating elements which will be able to consider both voltage and current measurement at PCC.

Modelling and Simulation in MATLAB®/Simulink® Environment

MATLAB® which means Matrix Laboratory is an advanced mathematical software which is extensively used by academia and industry because it can solve numerical computations and data visualization using highly respected algorithms with valid and trusted results. It provides a Simulink environment, a powerful software, and it offers the opportunity to design and model, and understand the dynamic behaviour any modelled network and it contains power library editor of tools which can be used to build the input/output devices for implementing the compensating elements calculator which can work on both discrete and continuous models needed for the load compensation of any three-phase four wire network feeding linear loads [147]. Figure (7-2) shows the Simulink library page from which the modelling and simulations of the system are being done.

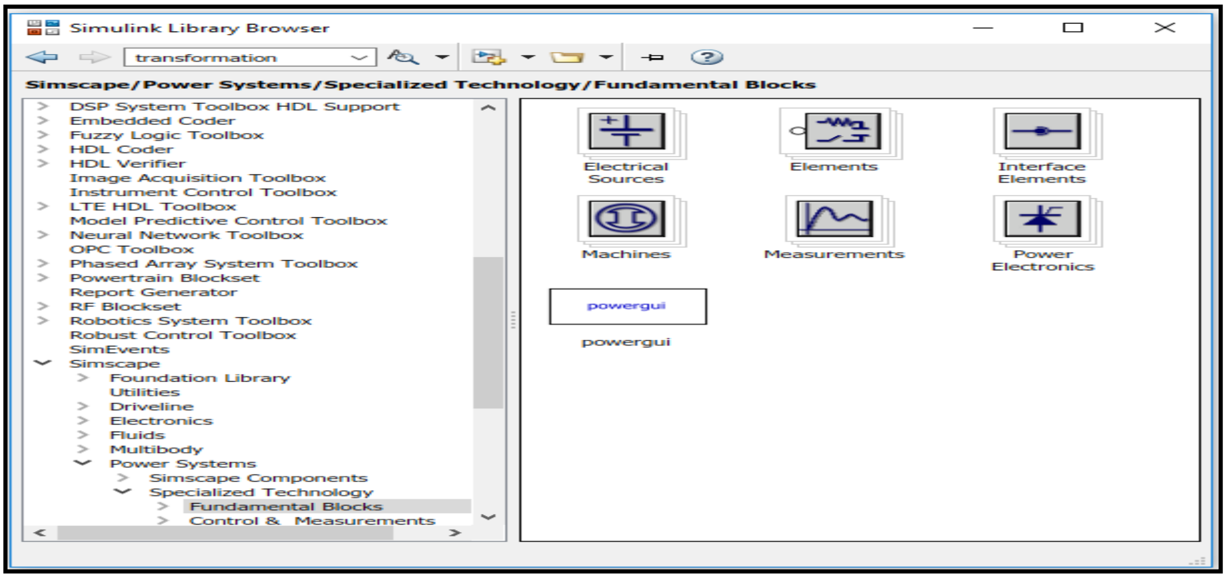


Figure 7-2: MATLAB/Simulink Software Library Page

The proposed hybrid compensator requires the voltage and current measurements at the Point of Common coupling to determine the sizing of the compensating elements as derived from the previous section. Since the active and reactive power rating of the load are not always known, a model is required to determine the sizing of the compensating elements which will be able to consider both voltage and current measurement at PCC

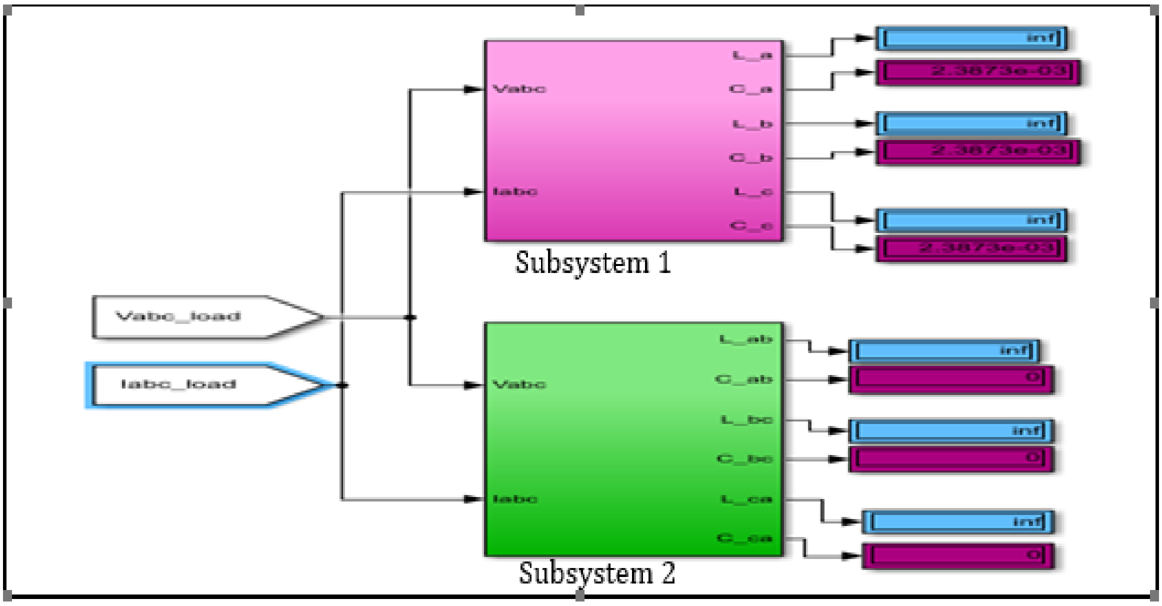


Figure-7-3: Simulink model for compensating elements calculation

In achieving the model, the input to the model is the measured voltage and current at the PCC as shown in Figure (7.3). This is instantaneously used to calculate the active and reactive power of each phase and subsequently determines the active and reactive components of the load currents required for the derivation of the susceptances for both star and delta sections of the proposed compensator as illustrated in Figure (7.4) and (7.5) respectively.

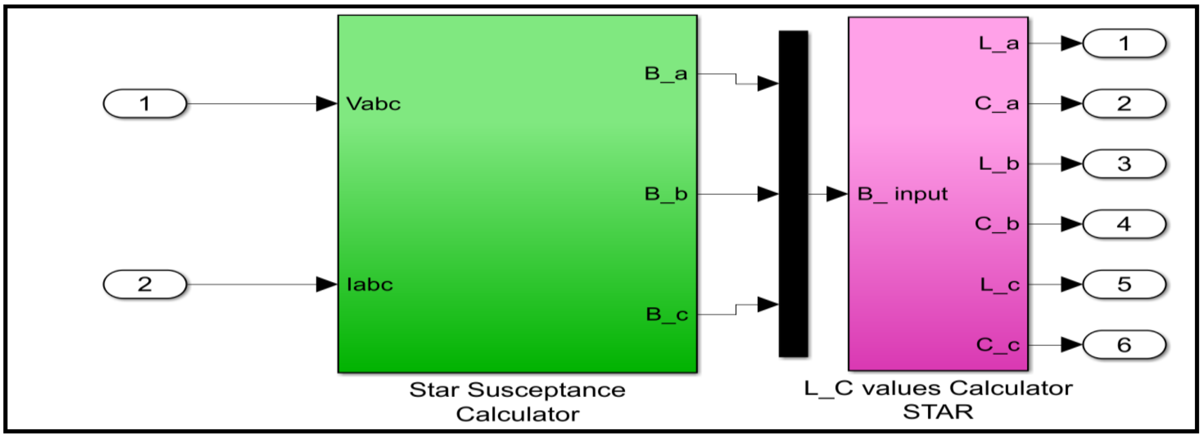


Figure 7-4: Simulink Subsystem for Susceptance Calculator [Star-segment]

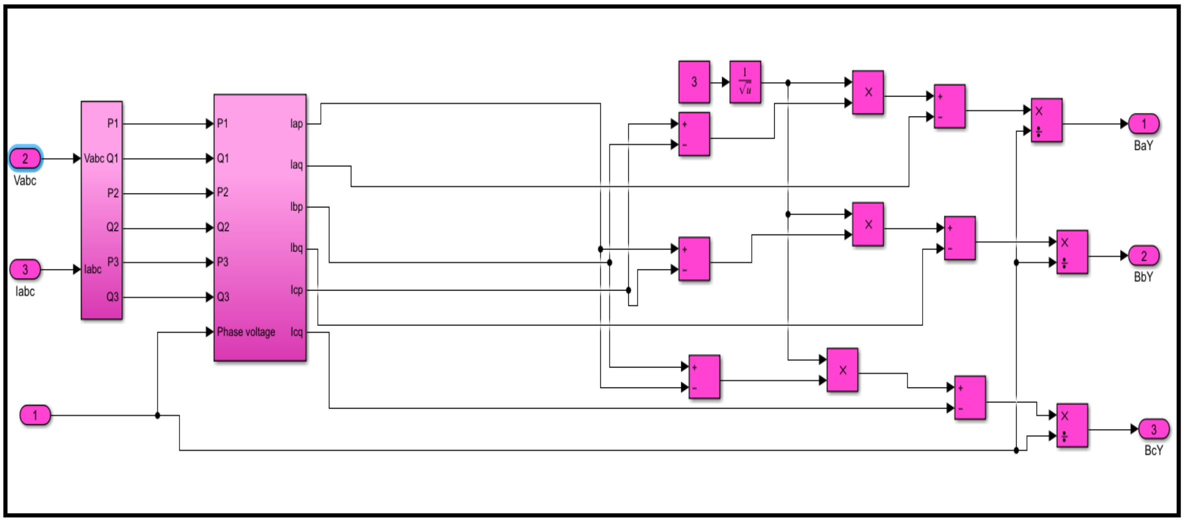


Figure 7-5: Model used for the determination of the Star Susceptances

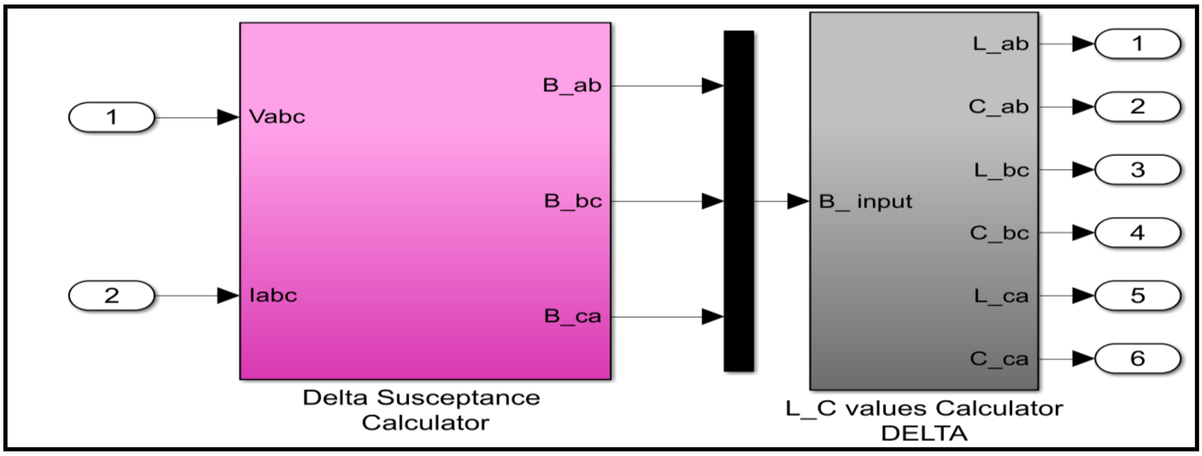


Figure 7-6: Simulink Subsystem for Susceptance Calculator [Delta segment]

The Star and delta susceptances are achieved using the model in Figure (7.7) and respectively while the model for calculating the passive elements are illustrated in Figure (7.8).

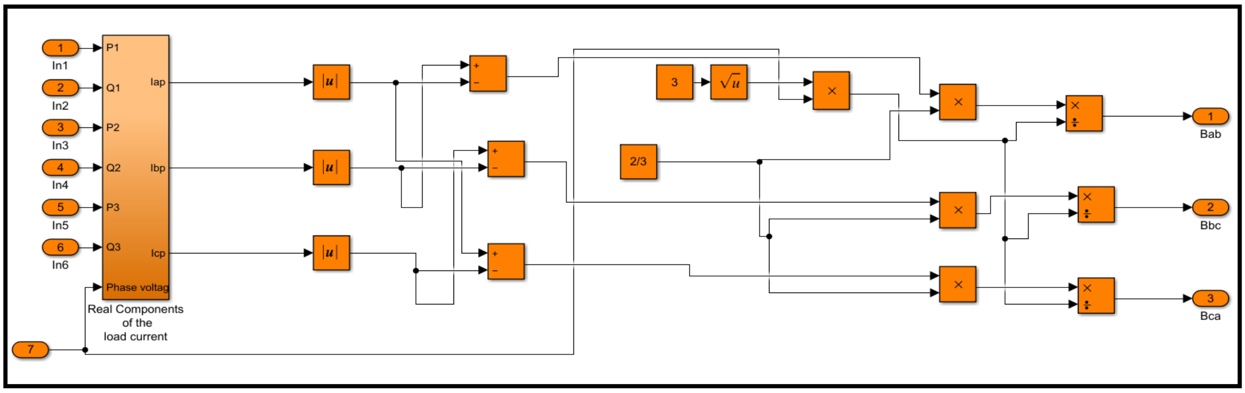


Figure 7-7: Model used for the determination of the Delta Susceptances

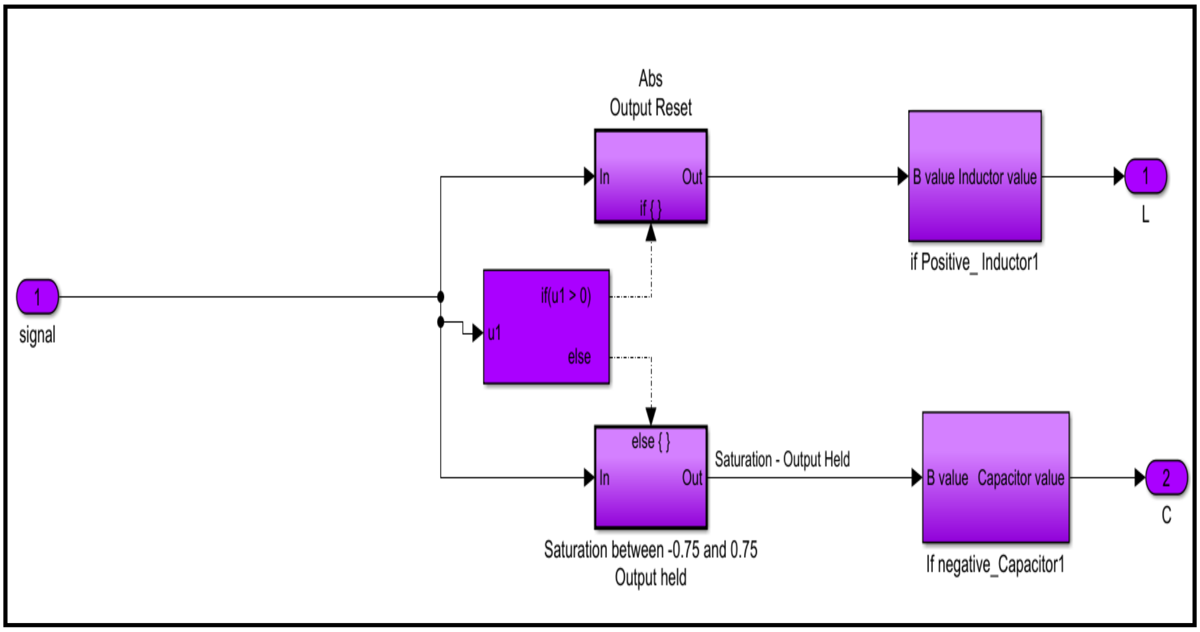


Figure 7-8: Simulink Model for calculating the passive components [L or C]

7.4 Simulation for model verification of the compensating elements calculator

In this section the performance of the compensating elements calculator is evaluated using the load parameters in Table 7-1 considering unbalanced and balanced three phase loads while the compensating elements as determined using manual calculation and the developed Simulink online calculator are illustrated in Tables 7-2 and 7-3 respectively.

Table 7-1: Three phase Balanced and unbalanced Linear Loads Used for model verification

S/N	Load Type	Parameter		
		Phase	Active power (kW)	Reactive Power (kVAr)
1	Unbalanced Load	Red	36	28
		Yellow	27	18
		Blue	60	48
2	Balanced Load	Red	36	28
		Yellow	36	28
		Blue	36	28

Table 7-2: Calculation of the Passive elements Using Manual and Online Methods for Unbalanced linear Loads

Compensator Configuration	Phase/Between phases	Passive Elements (C or L)	Passive Elements (C or L)	% error
		(manual)	(online)	
Star	Red	534.01 μF	533.97 μF	0.0075
	Yellow	1901.29 μF	1901.21 μF	0.0047
	Blue	3174.91 μF	3174.80 μF	0.0035
Delta	Red-Yellow	206.75 μF	206.74 μF	0.0048
	Yellow-Blue	13.36mH	13.37mH	0.00075
	Blue-Red	551.33 μF	551.32 μF	0.0018

Table 7-3: Calculation of the Passive elements Using Manual and Online Methods for balanced linear Loads

Compensator Configuration	Phase/Between phases	Passive Elements (C or L)	Passive Elements (C or L)	%error
		(manual)	(online)	
Star	Red	1671.13	1671.06	0.0042
	Yellow	1671.13	1671.06	0.0042
	Blue	1671.13	1671.06	0.0042
Delta	Red-Yellow	0.00	0.00	-
	Yellow-Blue	0.00	0.00	-
	Blue-Red	0.00	0.00	-

7.5 Verification and performance Evaluation of the Proposed Compensator

The verification and performance evaluation of the mathematical model was done by MATLAB Simulink simulation. The presented electrical distribution network is modelled using elements from the Library Browser like: three-phase balanced source for electrical system modelling, R-L block for the line resistance and inductance, and three-phase loads modelled in an unbalanced condition.

7.5.1 *Network and Load Modelling*

A low voltage distribution network is considered for the unbalanced load investigation and testing of the designed load compensator as one of the methods to solve problems of load balancing and reactive power compensation.

The network comprises 11/0.400 kV transformer, the loads connected to the phases are assumed to be unbalanced and modelled in MATLAB/Simulink as shown in Figure 7.9. The parameter of the network and the load parameters are given in Table 7.4, while the values of the six passive elements used for the hybrid compensator, as measured using the designed Simulink calculator are given Table 7.5.

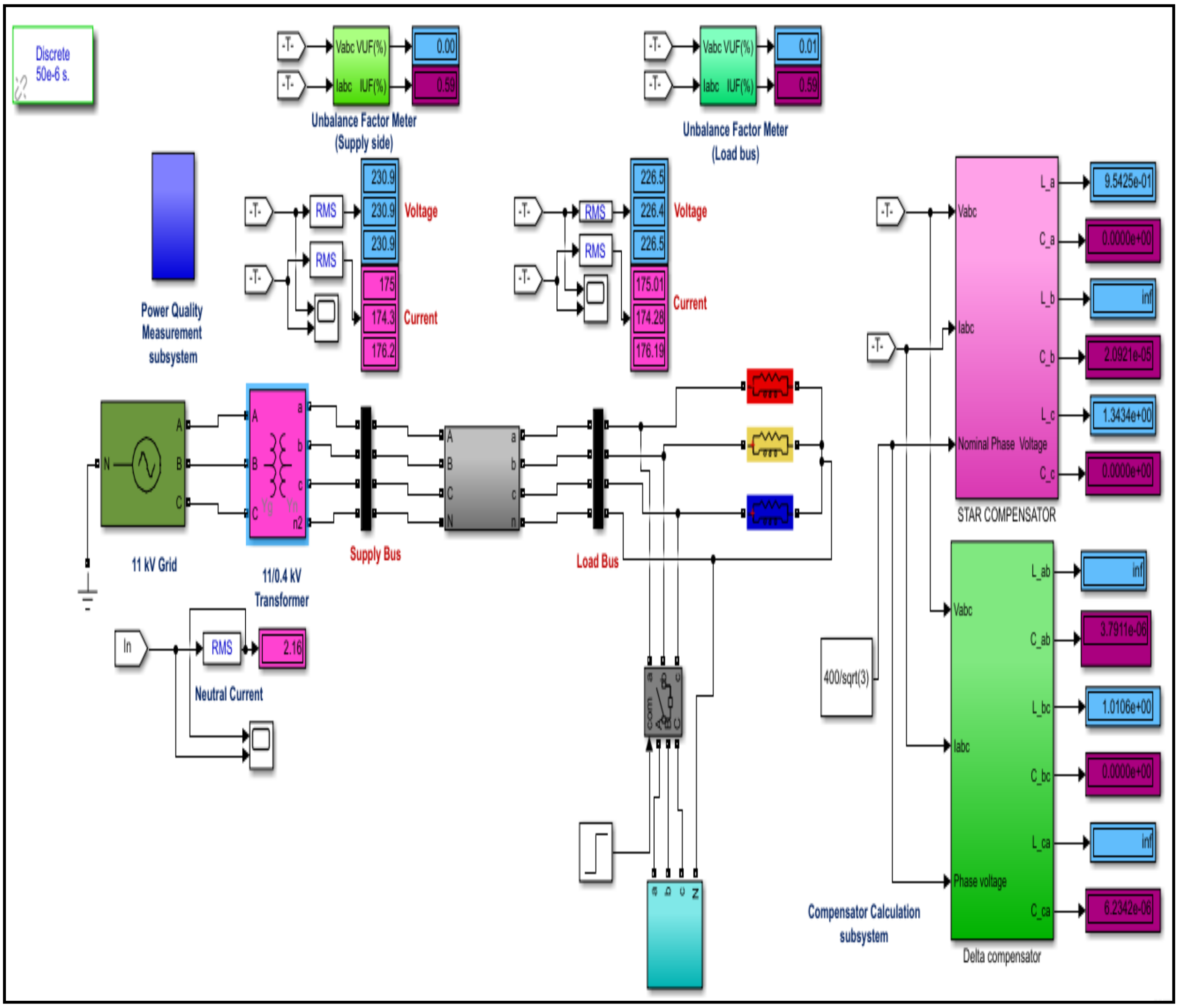


Figure 7-9: Simulink model of the test system

Table 7-4: System parameters for simulation

Phase	**Active power (kW)**	**Reactive power (kVAr)**	**Power factor**
A	36	28	0.7894
B	27	18	0.8321
C	60	48	0.7809
	123	**94**	**0.7945**
Source parameters	400V (L-L), Line impedance = (0.025+j0.04)Ω		

Table 7-5: Compensating Elements

Compensator	**Phase**	**Elements**
Star components	A	533.97μF
	B	1901.2μF
	C	3174.8μF
Delta components	AB	206.74μF
	BC	13.366mH
	CA	551.32μF

7.5.2 Simulation Results and Discussion

Simulation results of the three-phase unbalanced load and the application of a load compensator in a distribution network are as shown in Figure 7.1, for improved performance and efficiency considering the voltage unbalance factor and power factor before and after compensation.

Table 7-6 shows the quality of voltage and current at the secondary terminal of the transformer before and after the load compensation was introduced at 2s with voltage unbalance factor of 1.63% before compensation while the current flowing through the neutral conductor is higher than the current flowing through the yellow phase of the network which can lead to neutral failure and degradation of the transformer due to overheating. An improved power quality in term of power factor was also achieved after compensation from a poor value of 0.794 to 0.987 with reduction of 38.55% in the line loses as shown in Table 7-6.

Table 7-6: Simulation results before and after compensation at 0.2s

Parameter	**Before Compensation**				**After Compensation**			
Phase	A	B	C	n	A	B	C	n
Current (A)	192.5	139.2	304.3	135.43	175.01	174.28	176.19	2.16
Voltage (V)	222.4	225.1	217.5	-	226.5	226.4	226.5	-
Parameter	**Before Compensation**				**After Compensation**			
	A	B	C	Total	A	B	C	Total
Active Power (kW)	34.05	26.93	54.10	115.07	40.39	40.22	40.68	121.29
Reactive Power (kVAr)	28.59	17.54	44.85	90.99	1.28	1.39	1.00	3.67
Apparent Power (kVA)	44.46	32.14	70.27	146.70	40.41	40.24	40.70	121.35
Power Factor	0.766	0.838	0.770		0.982	0.981	0.984	0.987

The simulation time of 5seconds was considered for the performance evaluation of the entire network while proposed load compensator was introduced at 2 seconds of the simulation time to show its effectiveness.

Figures 7.10 and 7.11 represent the instantaneous values and rms values of voltage and current respectively with an improvement of the unbalance voltage factor from 1.87% to 0.05% while the rms values of the voltage also increased from 216.9V to 227.5 V which enables more active power transfer, reduction in the reactive power demand of the load and quality of the load current at the secondary terminal of the transformer before and after compensation. The improved power quality in term of power factor was also achieved after compensation from a poor value of 0.794 to 0.987 with reduction of 38.55% in the line loses as shown in figure 7.12.

Figures 7.13 and 7.14 show the power contribution from the proposed load compensator which established that star segment is responsible for the load balancing while the delta segment is used for the reactive power compensation as earlier stated in the mathematical formulations.

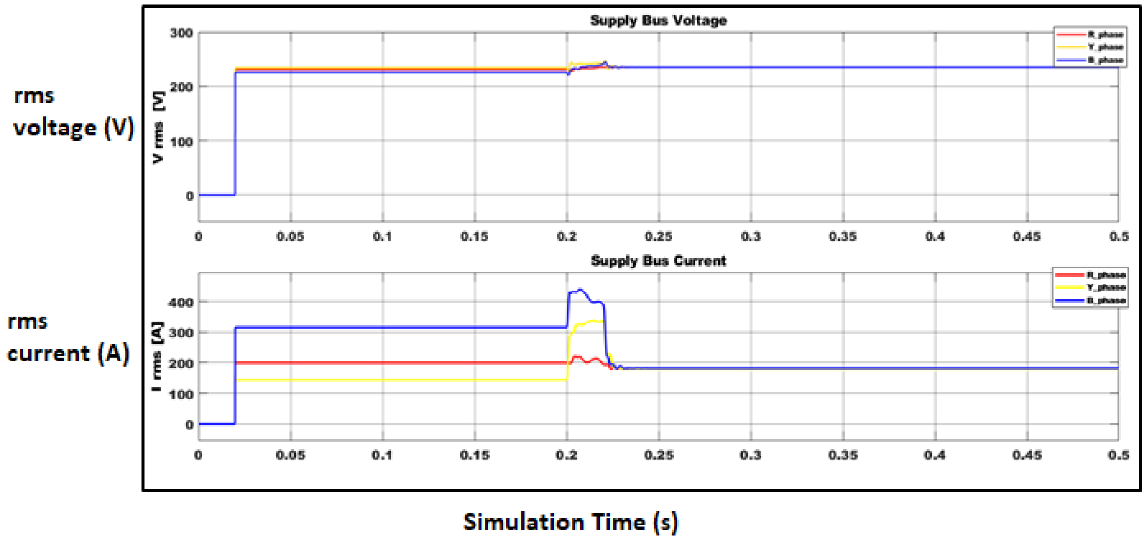


Figure 7-10: rms value of load Voltage and Current before and after compensation

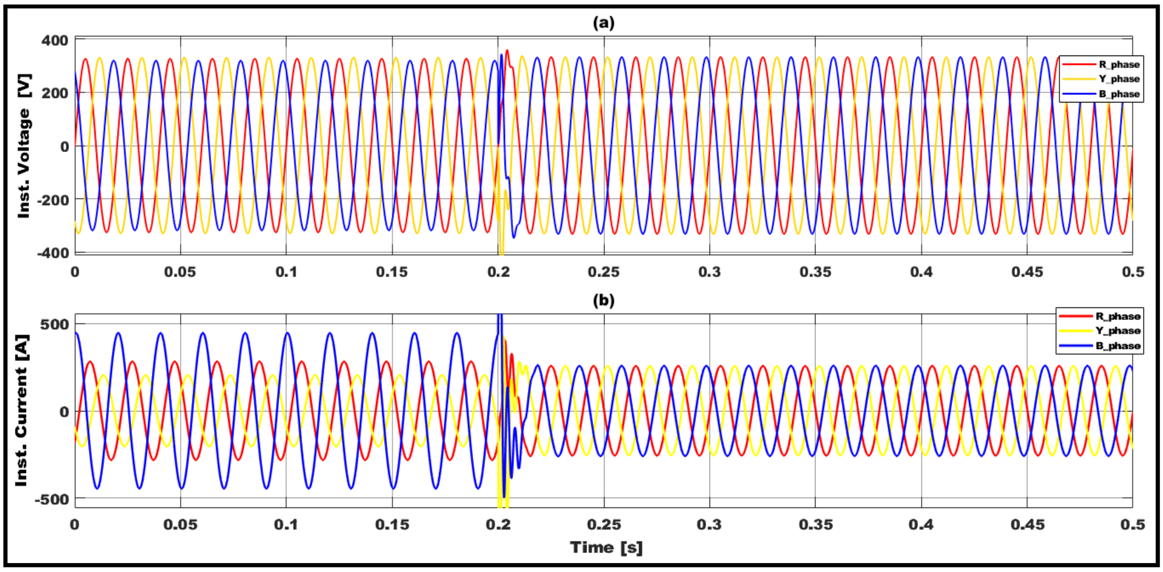


Figure 7-11:(a) Voltage (b) Current waveforms before and after Compensation

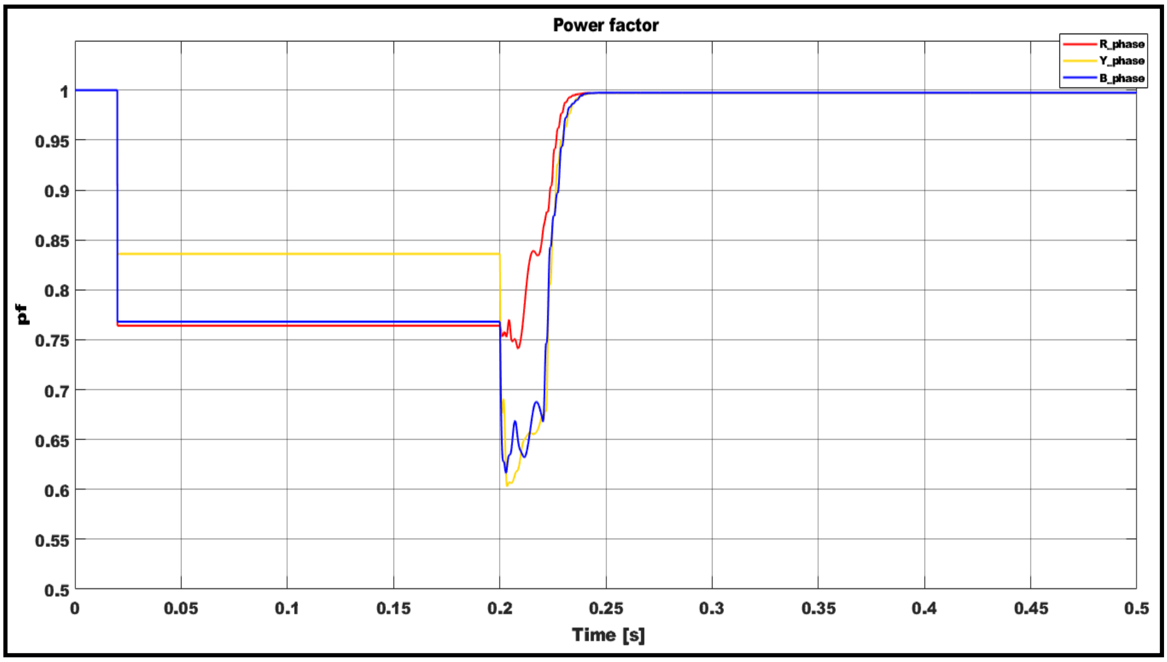


Figure 7-12: Power Factor before and after compensation

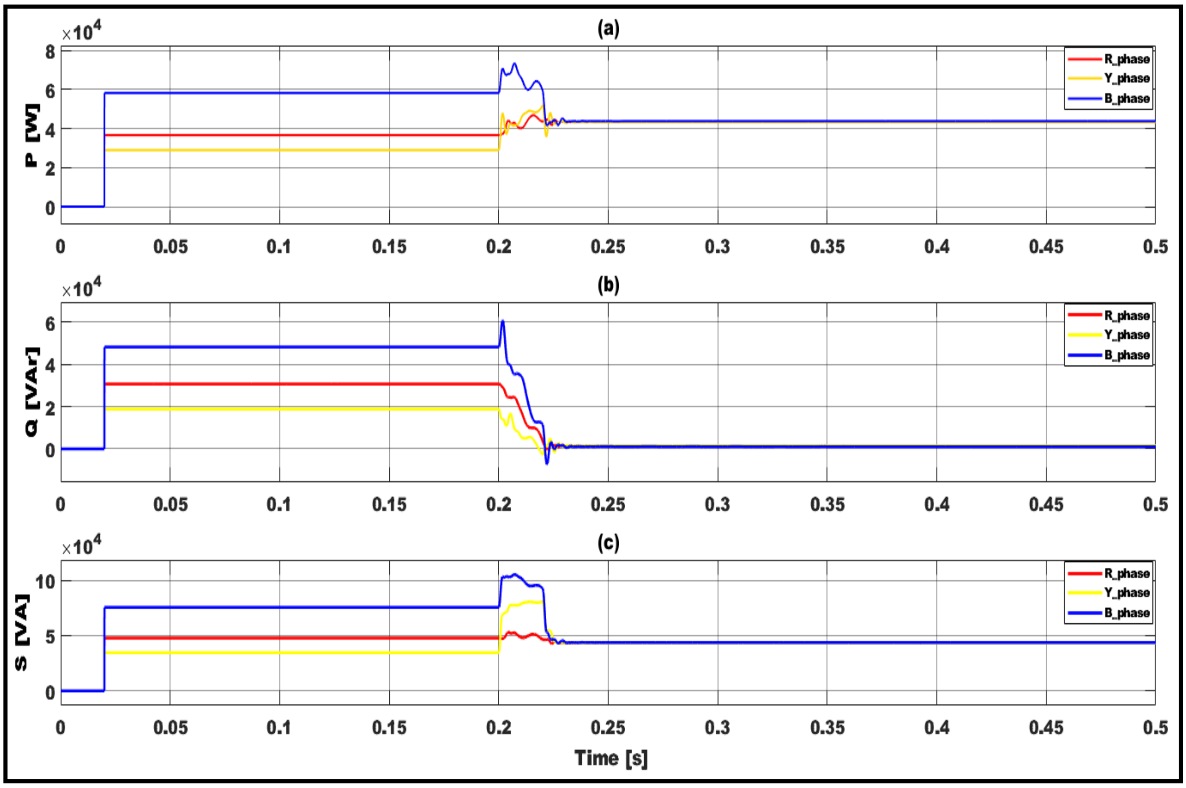


Figure 7-13: (a) Active (b) Reactive (c) Apparent Power before and after compensation

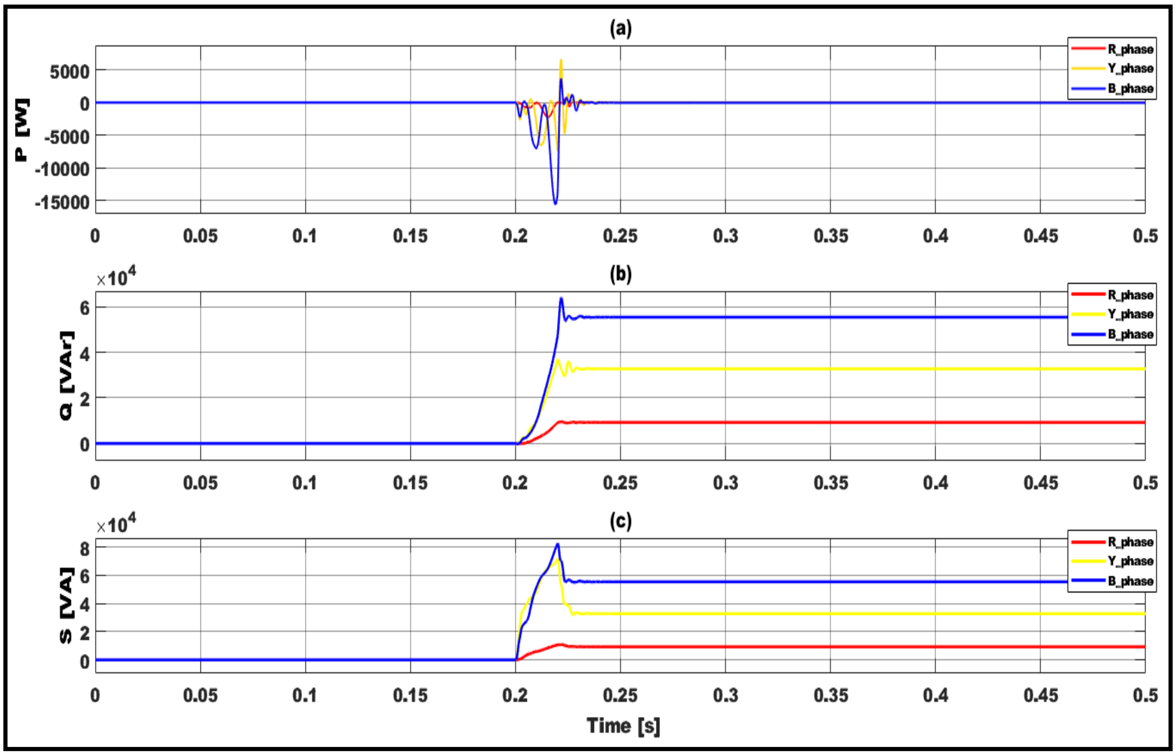


Figure 7-14: (a) Active Power (b) Reactive Power and (c) Apparent Power Contributed by the Compensator {Star Section}

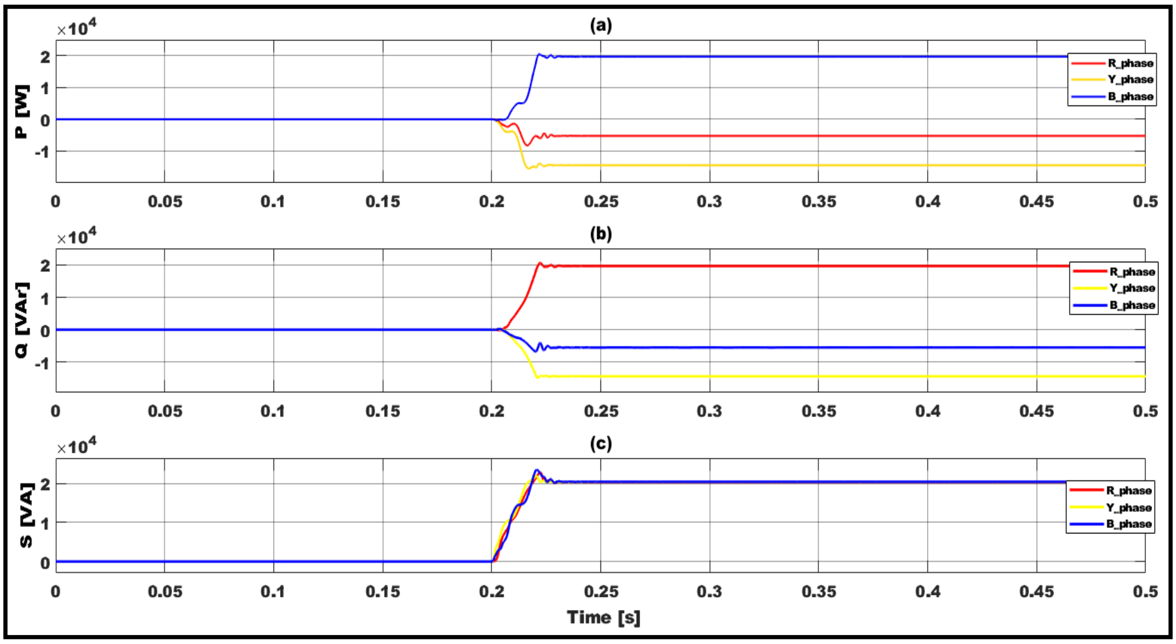


Figure 7-15:(a) Active Power (b) Reactive Power and (c) Apparent Power Contributed by the Compensator {Delta Section}

In this section, design and modelling of an effective and simple load compensator for load balancing, reactive power compensation and power factor improvement using MATLAB/Simulink in Sim Power System tool box was presented. The design of a load compensator and its performance analysis for an effective mitigation against effects of unbalanced load and excessive reactive power demand in a three-phase four wire distribution networks. The simulation results established that the proposed load compensator satisfies the required objective. It is obvious that the compensator has the capability of compensating for load unbalance and reactive power demand in a LV distribution network. It has also been shown that the voltage unbalance in distribution networks is majorly due to unbalanced loads and this is one of the major reason for increase in losses, poor power factor, increased voltage unbalance factor and malfunctioning of three-phase devices. Consequently, the simulation results have shown that the presented load compensator can effectively balance the supply voltage and improve the performance of the entire distribution network using passive components. In order to improve the performance of the distribution networks, it therefore recommended that: Distribution companies must ensure even distribution of loads on their transformers through installation of the presented load compensator at distribution sub-stations to avoid neutral conductor break-down while commercial and industrial consumers such as tertiary institutions, hospitals, Industries, can also reduce cost of electricity consumption through load compensation at their end.

7.6 Summary

As earlier discussed, the main reason for unbalance in low voltage networks is due to unbalanced nature of the connected loads, therefore, this chapter has presented the mathematical formulation and simulation of a load compensator for three-phase four –wire network for load balancing and reactive power compensation using passive components while the next chapter is expected to cover the active method of distribution network performance improvement through load compensation.

8. Active Method of Load Compensation

This chapter is devoted to the application of shunt active power filters to deal with power quality issues as regards load balancing, reactive power compensation and elimination of harmonics in currents.

8.1 Introduction

Load compensation has traditionally been achieved using passive components. However, passive methods have greatly been affected due to the proliferation of nonlinear load in the distribution systems. The problem include: parallel resonance with the impedance of the network, excess compensation of reactive power and unsuitable for the compensation of dynamic loads [96]. The increase in power quality problem severity and concern in power systems has necessitated the development of dynamic and flexible solutions to power quality problems using active power filters (APF) which can be used to compensate both voltage and current harmonics, reactive power and zero sequence currents as summarized in Figure 8-1 [148]. Another advantage of APF is the ability to automatically adapt to the dynamic nature of the network and load variation [149], [150].

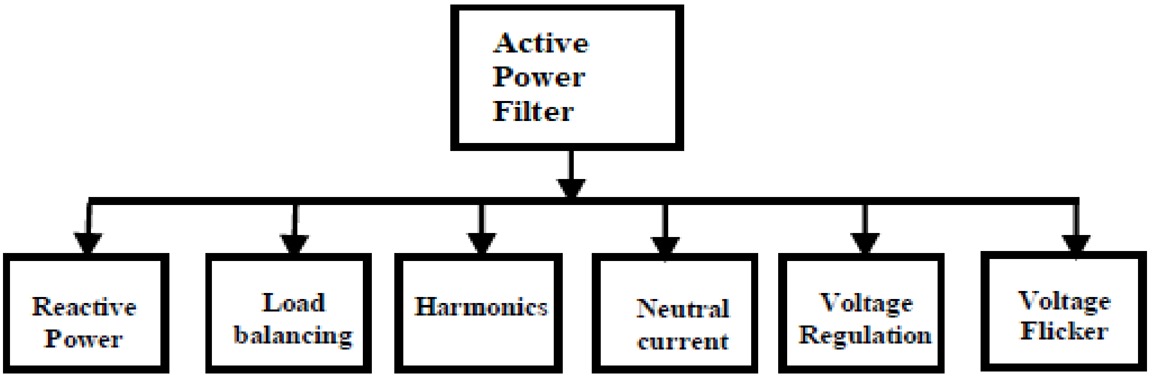


Figure 8-1: Compensation applications of Shunt Active Power Filter [148]

8.2 Classification of Active Filters

Active Power Filters are classified based on number of phases, topology, and type of converter. The classification based on number of phases are two wire systems and three or four wire systems which are applicable to single phase, three-phase 3-wire or 4-wire networks. APF configurations can be series, parallel or hybrid while the type of converter is mainly two types: Voltage source Inverter (VSI) and Current Source Inverter [21] [151]. The focus of this section is on load balancing, reactive power compensation and harmonic reduction, so we consider only the shunt active filters with VSI converter type as illustrated in Figure 8-2 [152].

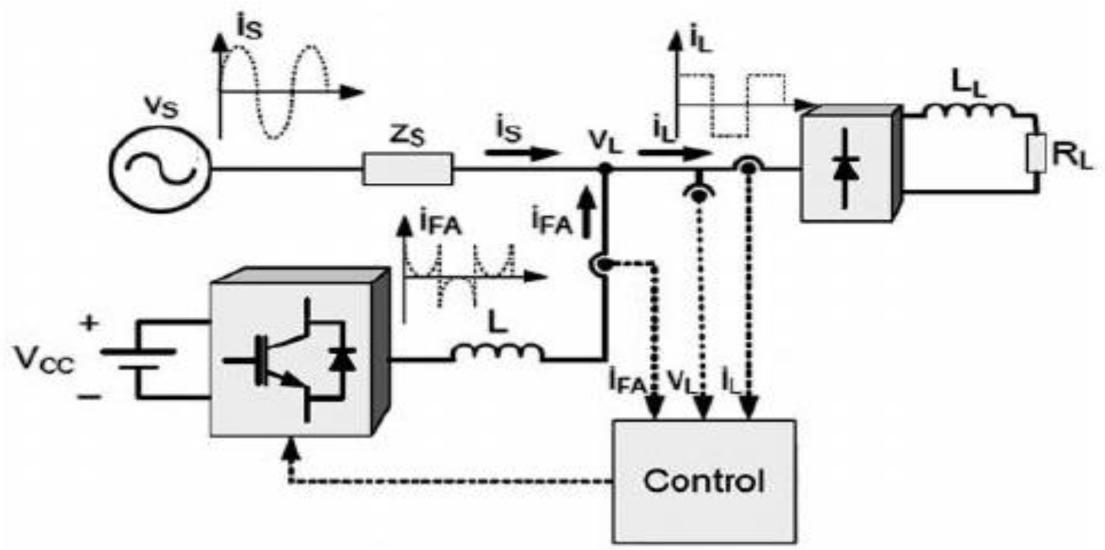


Figure 8-2: Basic scheme of Shunt Active Power Filters

8.3 Control Strategies

The control techniques of APF involve three stages. The first stage is the measurement of supply voltage and load current signals using potential and current Transformers respectively. The extraction of the compensating currents can be achieved based on either frequency-domain or time-domain techniques. However, the frequency-domain is deficient in handling varying load as a result of time delay introduced by the method while the time-domain involves the derivation of the compensating signals instantaneously from the harmonic signals of the voltage and current using any of these methods: Instantaneous p-q theory, synchronous reference frame, synchronous detection method and P-I controller. The final stage of the control is the generation of the gating signals or switching pulses which can be achieved using the followings: PWM, deadbeat, Hysteresis, multi-resonant controller, space vector modulation, sliding mode, fuzzy logic. In this work, the p-q theory is considered for the compensating signal extraction while the generation of the gating signals is done based on hysteresis controller as illustrated in Figures 8-3 and 8-4 respectively [152].

8.3.1 *Instantaneous reactive power theory*

The p-q theory was proposed by Akagi et al. in 1983 [153] . The p-q theory is based on conversion of a-b-c coordinate into α-β-0 coordinates and α-β-0 coordinates into a-b-c coordinates, popularly known as Clarke's transformation and inverse transformation respectively [154]. Basic block diagram of p-q theory is shown in Fig. 8. In this method the source voltage signals and load currents are converted into αβ0 coordinates as in (8.1) and (8.2).

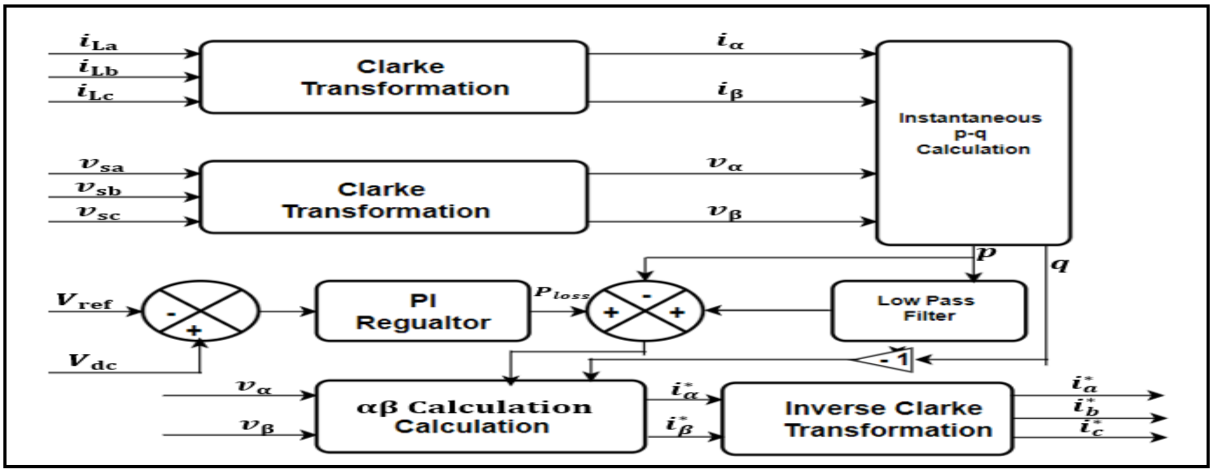


Figure 8-3: Control block for constant instantaneous P-Q Theory

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{8.1}$$

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \tag{8.2}$$

The instantaneous active and reactive powers are calculated using (8.3) while compensating currents in α-β-0 coordinates are determined using equation (8.4) after the decomposition of the calculated power into the average and oscillating components either low pass or high pass filters. Equation (8.5) is used for the extraction of the compensating currents.

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{8.3}$$

$$\begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \frac{1}{v_\alpha^2+v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} p^{\sim} \\ q^{\sim} \end{bmatrix} \tag{8.4}$$

$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} \tag{8.5}$$

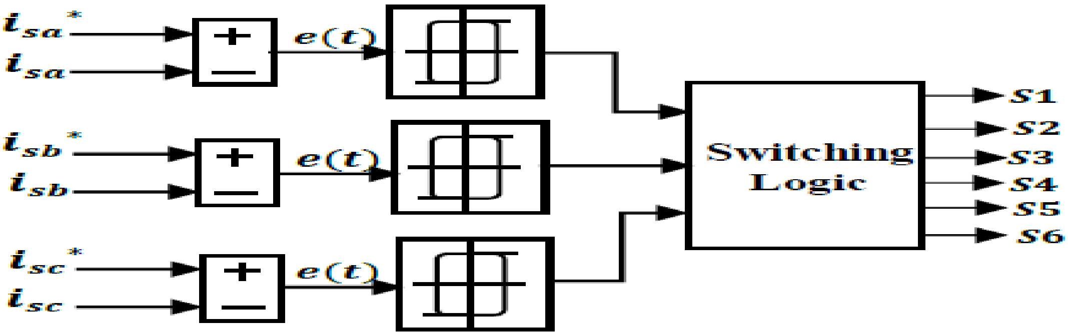


Figure 8-4: Hysteresis controller [152]

8.4 Parameters Determination of Shunt Active Filter

Several journals and conference papers have been published on shunt APF. Most of the surveyed papers are based on the control techniques, design configurations and topology. Very few considered the appropriate design procedure of the components as applicable in the distribution system [155]. Irrespective of the topologies, types of converter used and control methods, the basic and very important parameters that are required for proper design and operation of the Shunt APF are:

1) DC Reference Voltage
2) DC link Capacitor
3) Filter Inductance

8.4.1 Selection of the DC Reference Voltage

For effective control of the filter current, the dc reference voltage Vdc must be equal to or higher than the peak value of the **line voltage** depending on the modulation mode of the converter [156].

$$V_{dc} = \frac{2\sqrt{2}\, V_f}{m_a} \tag{8.6}$$

In equation (8.6), the **V**

In equation (8.6), the $\mathbf{V_f}$ and $\mathbf{m_a}$ represent the fundamental component of the AC side and modulation index of the converter respectively, while the value of $\mathbf{m_a}$ ranges between 0.1 – 1.0. The authors in [156] proposed that for a very switching frequency, the value of $\mathbf{V_f}$ would be equal to the source voltage, **Vs**.

$$V_{dc} = \frac{2\sqrt{2}\, V_S}{m_a} \tag{8.7}$$

8.4.2 Selection of the DC link Capacitor

The DC link capacitor is responsible for maintaining the reference voltage at steady state, storing of energy for reactive and harmonic power supply to the load and supply the active power during transient period [155]. Therefore, the choice of the link capacitor is very important. As described by the authors in [155], [156], [157], the followings are the methods for determining the value of the DC link capacitor.

$$C_{dc} = \frac{I_h}{\varepsilon \omega_h\, V_{dc}} \tag{8.8}$$

$$C_{dc} = \frac{\pi * I_f}{\sqrt{3}\, \omega\, V_{dc[\max]}} \tag{8.9}$$

$$C_{dc} = \frac{2 * E_m}{{V_{dc}}^2 - {V_{dc[min]}}^2} \tag{8.10}$$

Equation (8.8) considers the lowest harmonic current for the determination of the d.c capacitor value which could lead affect its effectiveness for the compensating signals extraction. In the same vein, equation (8.10) uses the expected energy supplied by the capacitor to determine its value and this would involve another estimation to arrive at an appropriate value for the capacitor while equation (8.9) used the full load rated current to determine the value of the d.c capacitor. The equation (8.9) is considered in this research since the focus is the compensation of the load current operating at its full load.

8.4.3 Selection of the Coupling Inductance

There are three major factors that determine the value of the interfacing inductor. The interfacing inductor must be able to transfer attenuated harmonics required, provides the necessary reactive power to obtain almost unity factor and ensure the filtering of the output current and the source voltage at the point of coupling point [157]. There are three commonly used approaches as stated by authors in [158] [159], [160], [161] as follows:

$$L_f = \frac{V_{dc}}{6f_s\, \Delta I_{\max ripple}} \tag{8.11}$$

$$L_f = \frac{V_s}{2\sqrt{6}\, f_s\, \Delta I_{\max ripple}} \tag{8.12}$$

$$L_f = 1.5V_s\, \frac{V_f}{\pi f Q_L}\left(1 - \frac{V_s}{V_f}\right) \tag{8.13}$$

Equations (8.11) and (8.12) involve the use of change in the maximum current ripples of the load while (8.13) depends mainly of the supply voltage. The performance of the filter is determined based on the values of the inductance at which the current harmonics of the load are minimum. Therefore, in this research, equation (8.13) is considered for the performance evaluation of shunt APF for load compensation.

8.5 MATLAB/Simulink Simulation

The performance of the active power filter is studied with instantaneous p-q theory and hysteresis controller with reference voltage of 800V for the source line voltage of 415V. The reference voltage was determined using (8.7) with modulation value of 0.9 while the values of the DC-link capacitor and coupling inductor were determined using (8.9) and (8.13) respectively based on the reasons stated in sections 8.42 and 8.43 respectively.

The LV distribution network used as test system is a 4-bus network with linear and nonlinear loads connected to the network at bus 3 and 4 respectively with point of common coupling at bus 2 while the source is applied at bus 1 as represented in Figure 8.5. The test system is modelled in MATLAB/Simulink as shown in figure 8.6.

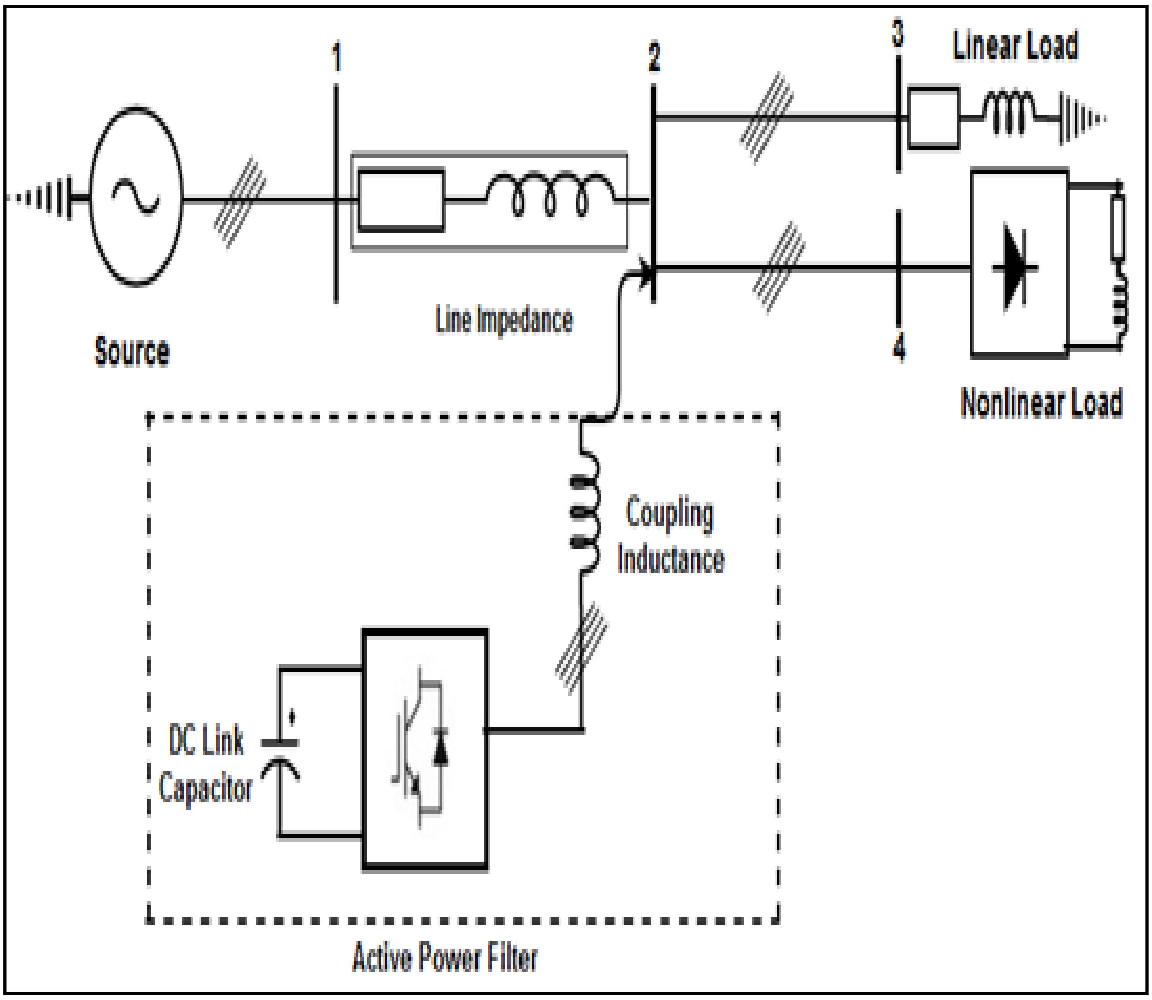


Figure 8-5: Single line diagram of a 4-bus Test System

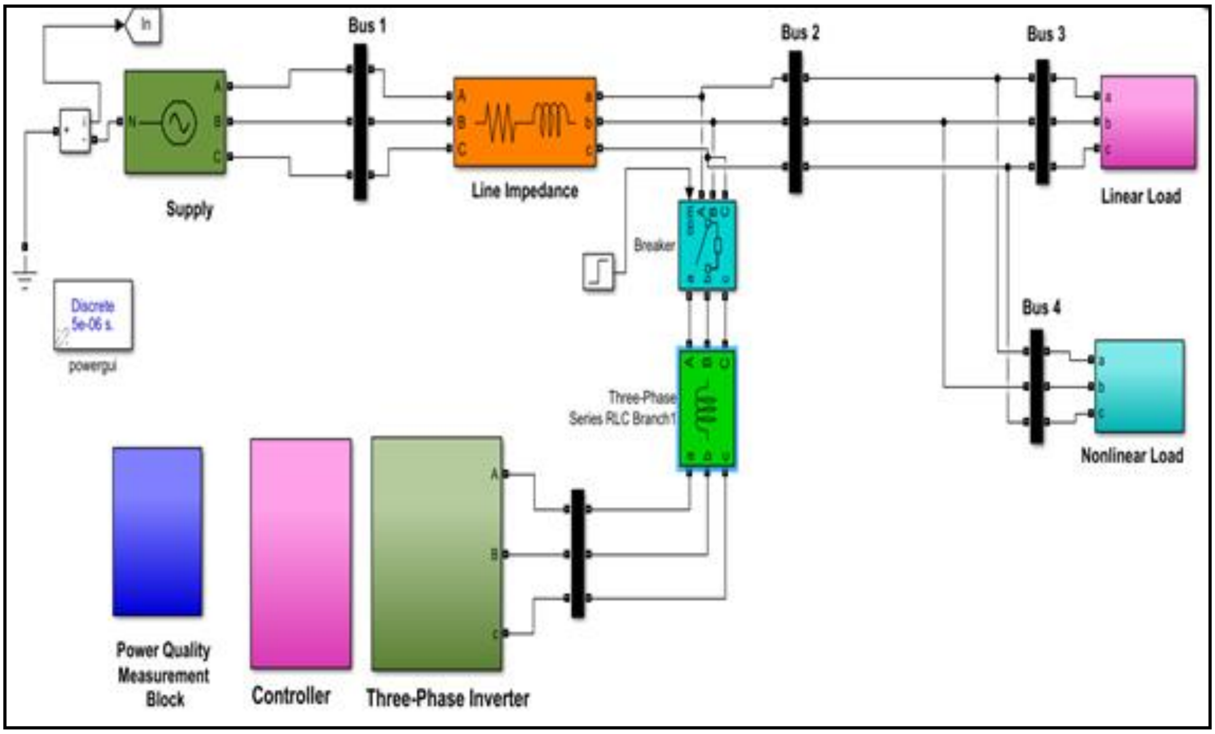


Figure 8-6: MATLAB/Simulink Model of the Test System

Table 8-1: Parameters used for the Simulation

Source and Load Parameters		
Line Voltage	400 V	
Supply Frequency	50 Hz	
Line resistance	0.25 Ω	
Line inductance	10 mH	
Load Parameters		
Phase	Linear	Nonlinear
Case I		
Three-phase	5.0 kW at 0.86 p.f lag	R = 20 Ω, L= 0.1 mH
Case II		
Red	2.5 kW at 0.86 p.f lag.	R =15 Ω, L= 0.1 mH
Yellow	1.0 kW at 0.89 p.f lag	R = 5 Ω, L= 0.1 mH
Blue	1.5 kW at 0.83 p.f lag	R= 10 Ω, L= 0.1 mH
Compensation Parameters		
DC link Capacitor	1200 μF	
Coupling Inductor	1 mH	
Voltage Reference	800 V	

The simulations were performed for 5s with the APF connected at 0.15s to evaluate the power quality parameters without and with the APF in the distribution system. Two cases were simulated using numerical data taken from Table 8-1. The cases under study can be summarized as follows:

I. Balanced three phase linear and nonlinear loads

II. Unbalanced linear and nonlinear loads

8.6 Discussion of results

Case I: A balanced Three-phase linear load of 5 kW at 0.86 p.f. linear and nonlinear loads of 20 Ω and 0.1 mH connected to bus 5 through rectifier. Figure 8.7 shows the current measured at bus 1 which represents the supply and the compensating current waveforms without and with the connection of the APF. The result shows the current THD reduced from 22 % to 6 % while the power factor improved from 0.89 to 0.97as shown in Figure 8-8. The reactive power with and without harmonics were also effectively compensated as illustrated in Figure 8-9 and Table 8.2.

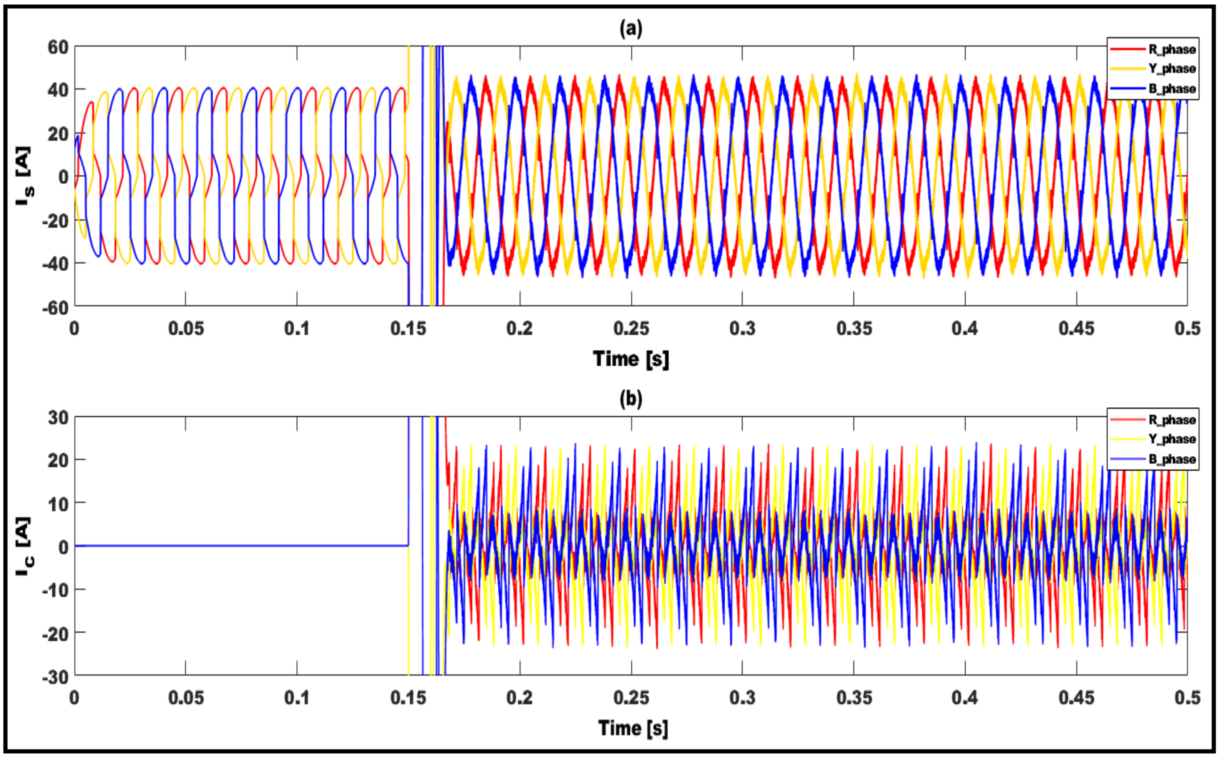


Figure 8-7: Supply current and Compensating current before and after compensation -Case I

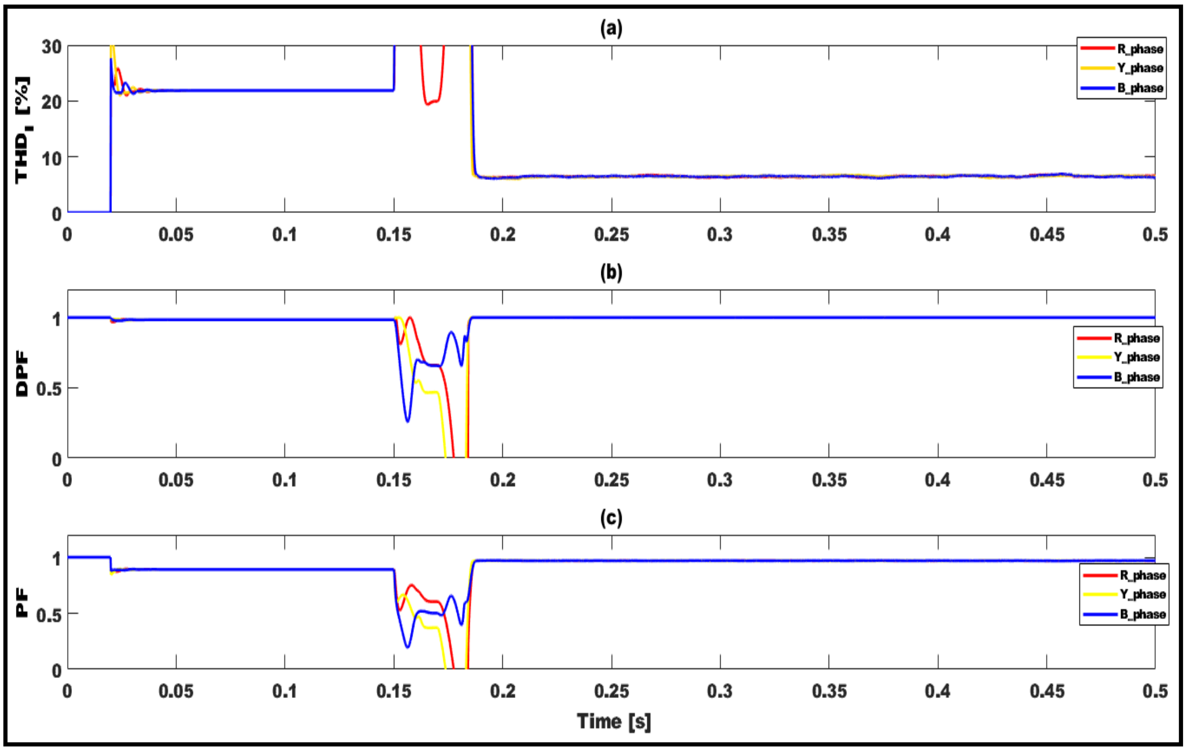


Figure 8-8: Current THD, Displacement Power Factor and True Power Factor before after compensation - Case I

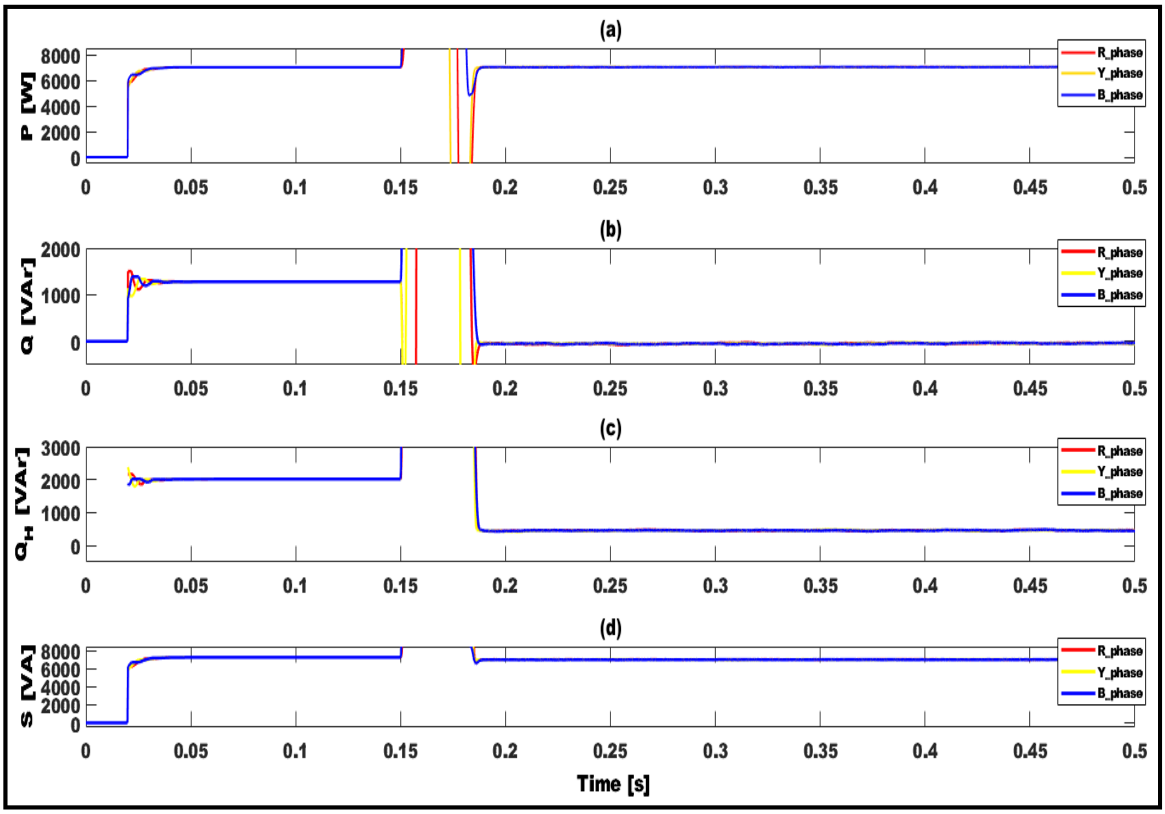


Figure 8-9: Active, Reactive & Apparent Power before and after Compensation – Case I

Table 8-2: Simulation Results for Case I

Parameters	Before Compensation			After Compensation		
	A	B	C	A	B	C
Active Power (W)	7018.2	7018.2	7018.2	7022.5	7029.7	7047.0
Reactive Power @ 50Hz (Var)	1277.6	277.6	1277.6	-34.4	-35.6	-37.3
Reactive Power + Harmonics (Var)	2015.7	2015.7	2015.7	467	458	445
Apparent Power (VA)	7301.8	7301.8	7301.8	7022.6	7029.9	7047.1
Displacement Power Factor	0.984	0.984	0.984	1.000	1.000	1.000
True Power Factor	0.891	0.891	0.891	0.968	0.969	0.969
THDi (%)	21.9	21.9	21.9	6.6	6.4	6.3
Supply rms current	30.5	30.5	30.5	29.4	29.4	29.5

Case II: An unbalanced Three-phase linear load of 2.5 kW at 0.86 p.f lag, 1.0 kW at 0.89 p.f lag. and 1.5 kW at 0.83 p.f connected to red, yellow and blue phases respectively. An unbalanced nonlinear loads are connected also to bus 4 through a rectifier with values stated in Table 8.1. The current during this case is unequal in the three-phases. Figure 8-9 shows the unbalanced and distorted current measured at bus 1 which represent the source and the compensating current waveforms without and with the connection of the APF. It shows there is an improvement in the current waveform after the compensation while the THD also reduced from 20% to 6% and the power factor improved from 0.86 to 0.96 as shown in Figures 8-10 and 8-11 while the numerical values are stated in Table 8.3. The measured parameters at the supply bus also show balanced condition, compensation of reactive power with and without harmonics and reduction in the apparent power which confirm the effectiveness of the APF for load compensation and improvement of distribution network.

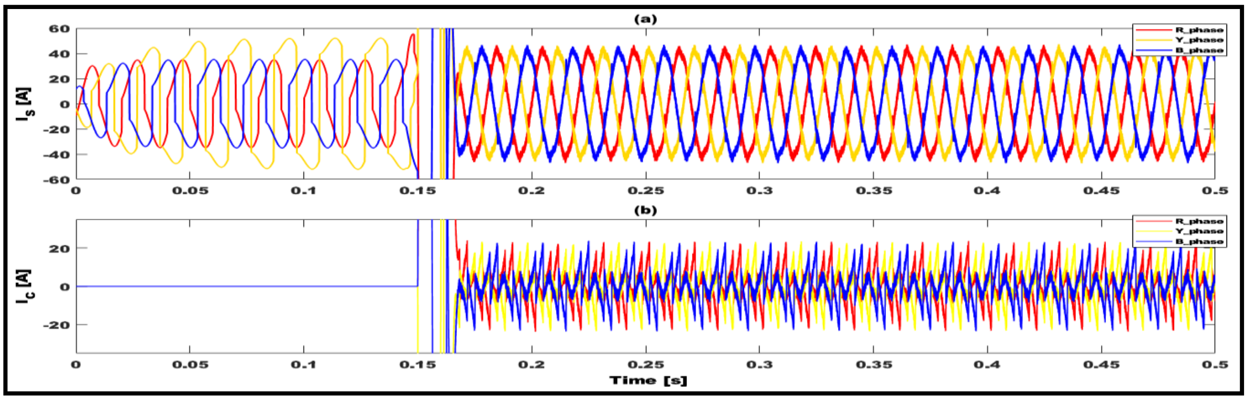


Figure 8-10: Supply current and Compensating current before & after compensation– Case II

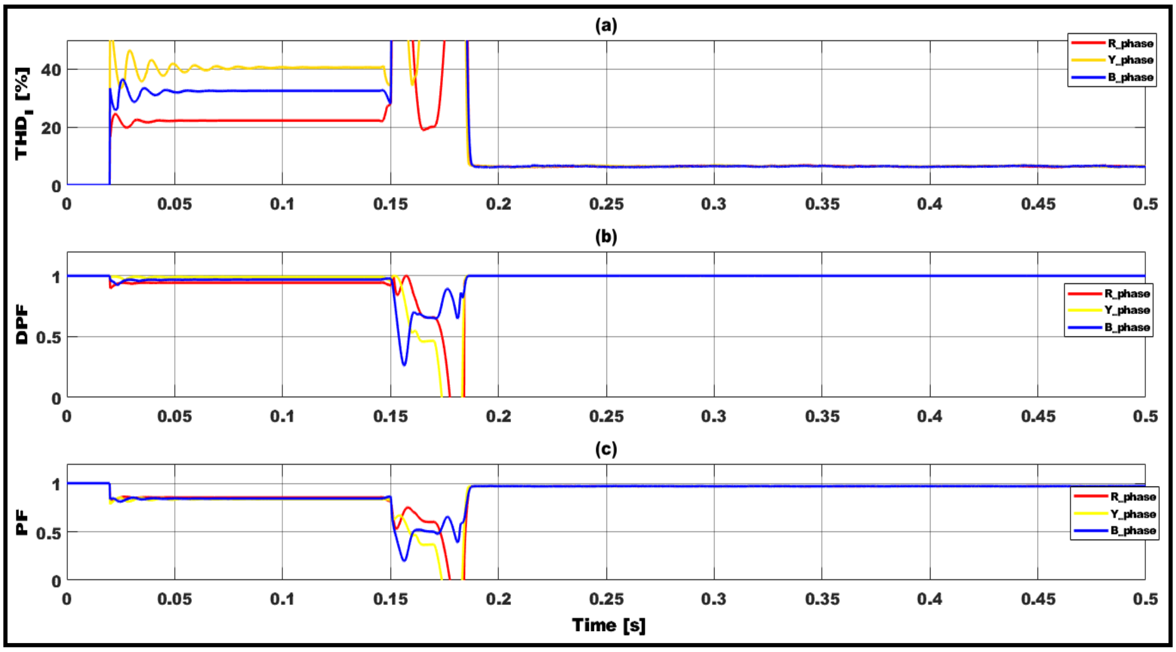


Figure 8-11: Current THD, Displacement Power Factor and True Power Factor before and after compensation - Case II

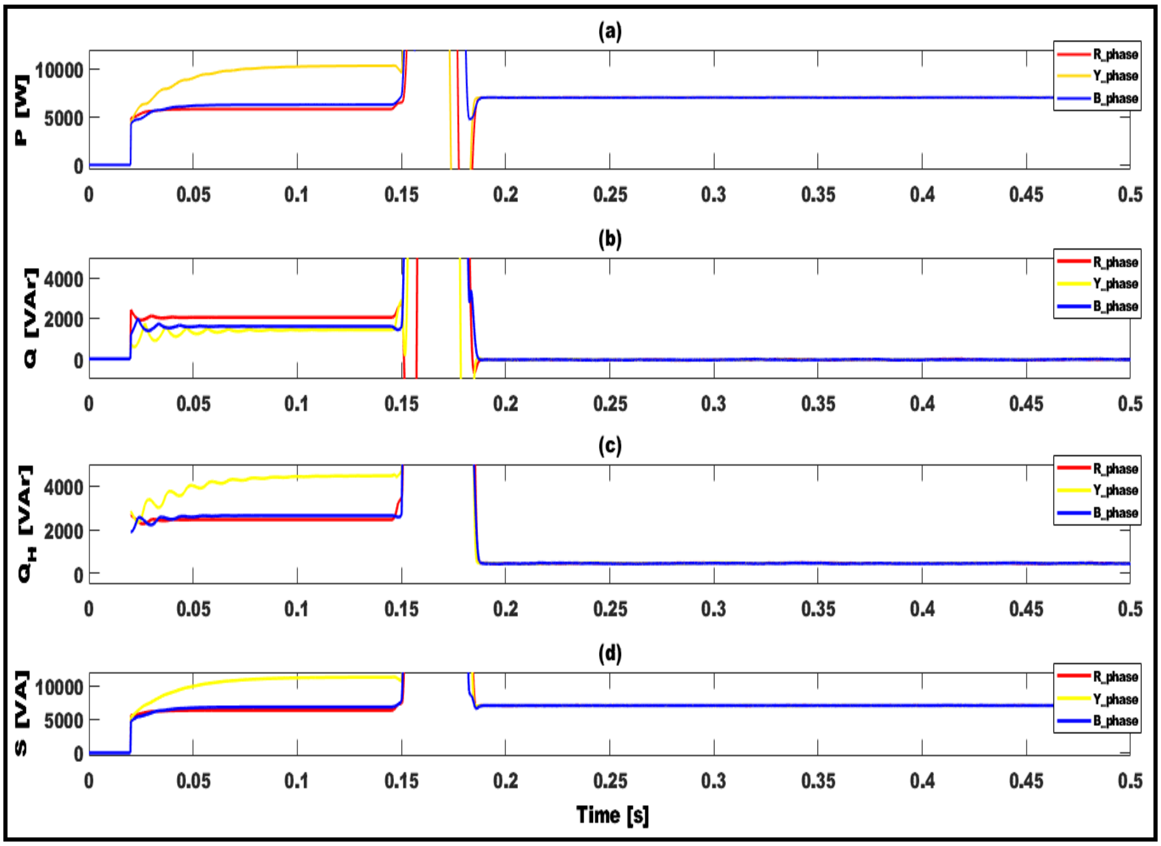


Figure 8-12: Active, Reactive & Apparent Power before & after Compensation –Case II

Table 8-3: Simulation Results for Case II

Parameters	Before Compensation *a*	 *B*	 *c*	After Compensation *a*	 *b*	 *C*
Active Power (W)	5821.3	10329	6279.8	7502	7532	7541
Reactive Power @ 50Hz (Var)	2047.9	1429.6	1607.8	-25.6	-38.2	-30.4
Raective Power + Harmonics (Var)	2465.6	4467.6	2650.9	842.4	868.6	889.6
Apparent Power (VA)	6321.9	11254.4	6816.4	7549.1	7581.9	7593.3
Displacement Power Factor	0.943	0.991	0.969	0.998	0.997	0.969
True Power Factor	0.853	0.835	0.842	0.985	0.979	0.986
THDi (%)	22.3	40.6	32.5	6.86	7.02	6.96
Supply rms current	26.39	46.97	28.44	29.4	29.4	29.5

8.7 Summary

In this chapter, the use of instantaneous p-q theory control strategy for reference current generation and the hysteresis band current controller for generating switching signals of shunt APF in three-phase four-wire distribution system have been investigated. The performance evaluation has shown the capability of APF for load balancing, reactive power compensation and harmonic suppression under balanced and unbalanced linear/nonlinear loads conditions for the improvement of power quality in a LV distribution network as indicated by reduction in the kVA demand of the network thereby improving the performance of the entire network.

9. Conclusions and Suggestions for Further Work

This chapter presents the conclusions and recommendations for future work.

9.1 Conclusion

In the scope of this research, an extensive literature review and experimental survey on power quality are presented. The research also presented load compensation methods using passive and active components for the performance improvement of distribution network. It was observed that load compensation can be used for load balancing, reactive power compensation and harmonic reduction in the distribution network. The conclusion of this research has been summarized as follow:

Power Quality Issues

This research has shown the common loads such as CFLs, Laptops, Desktop computers, LED lamps as the loads responsible for harmonic injection in distribution networks considering commercial consumers and it has also revealed the methods suitable for the monitoring and assessment of power quality of some loads and a typical distribution network using different power quality analyzers.

Passive Load Compensation

The research formulated and investigated the load compensation method using a hybrid compensator in a three-phase four wire network through a mathematical model derived from the combination of phase and sequence components of the load current considering load balancing, power factor correction and neutral current elimination. The methodology, which is complementary to previous methods, achieved the sizing of the compensating elements based on the load current phase and sequence components as compared to others based on the load admittance which might be difficult to measure. It also demonstrates the useful application of MATLAB/Simulink for the study of load compensation which has useful applications in both low and medium voltage networks. It also demonstrated the modelling of power meter capable of measuring power quality parameters such as rms voltage and current, voltage and current waveforms, separation of reactive power into fundamental and non-fundamental quantities, voltage and current THDs, Active and Apparent powers, unbalance factor of voltage and current suitable for any network model in MATLAB/Simulink environment.

Active Load Compensation

This research also investigated the application of shunt APF using the instantaneous p-q theory control strategy for reference current generation and the hysteresis band current controller for generating compensating currents for load compensation in three-phase four-wire distribution networks. The performance of this method under balanced/unbalanced linear and nonlinear loads has been presented with focus on load balancing, reactive power compensation and harmonic suppression. The results show that the load currents (as measured at PCC) are balanced, sinusoidal and in-phase with the source phase voltage. The observed current at PCC was seen to be balanced, the reactive power requirement was minimized while the current harmonics also was reduced after compensating the load which verifies the effectiveness of shunt APF in load compensation.

9.2 Recommendations

For necessary enhancement of the performance of distribution networks, the following recommendations are made:

1. There is a need for the distribution companies to make regulations through which each consumer is held responsible for the quality of their loads and made to undertake in-house compensation or otherwise be penalized especially in the area of unbalance and harmonic loading.
2. The consumers are equally encouraged to monitor and assess the power quality of their loads in terms of unbalance and harmonic pollution to determine the extent and suitable mitigation techniques.
3. Electricity companies must ensure even distribution of loads on their distribution transformers through installation of the proposed load compensator at distribution sub-stations to avoid neutral conductor break-down and prevent power losses due to reactive power burden and unbalance loads
4. Electricity consumers such as tertiary institutions, hospitals, and Industries should be encouraged to compensate their load to reduce cost of electricity consumption and improve the capacity of the distribution network.

9.3 Recommendations for Future Work

The followings are recommended for future study:

1. The load compensation techniques investigated in this research considered only the steady state respond of the load, the dynamic load response can be investigated.
2. The effectiveness of the active method used in the research can be extended to renewable energy sources both in low and medium distribution network.
3. Finally, the load compensation can be investigated through experimental set-up.

List of References

[1] "News24, South Africa's premier news source, provides breaking news on national, world, Africa, sport, entertainment, technology & more," 25 January 2008. [Online]. Available:http://www.news24.com/News24/South_Africa/News/0,,2-7-1442_2258449,00.html. [Accessed 5 October 2018].

[2] R. Keneilwe and N. Ramaano, "South African Energy Report," Department of Energy, South Africa, Nov. 2018. [Online]. Available: https://www.energy.gov.za/files/media/explained/2018-south-african-energy-sector-report.pdf. [Accessed 30 June 2019].

[3] G. V. David and C. H. Thomas, The Political Economy of Power Sector Reform : The Experiences of Five Major Developing Countries, Cambridge, United Kingdom: Cambridge University Press, 2009.

[4] Eskom, "Eskom_Integrated_Report," 31 March 2017. [Online]. Available: https://www.eskom.co.za/wp-content/uploads/2021/02/Eskom_integrated_report_2017.pdf. [Accessed 16 May 2020].

[5] H. Khobai, G. Mugano and P. Le Roux, "The Impact of Electricity Price Increases on various sectprs of the south Africa Economy," *International Journal of Energy Economics and Policy,* vol. 7, no. 71, pp. 108-116, 2017.

[6] M. Noble and P. Dale, "Shunt capacitor banks increase capacity of distribution networks," May 2011. [Online]. Available: https://www.ee.co.za/energize/energize-technical/energize-technical-transmission-distribution/page/3. [Accessed 3 July 2018].

[7] C. W. Gellings, "The concept of demand-side management for electric utilities," *Proceedings of the IEEE,* vol. 73, no. 10, pp. 1468-1470, 1985.

[8] R. Helen Catherine and A. Soundarrajan, "A Literature Review on Demand Side and Energy Efficient Management," *International Journal of Current Trends in Engineering & Research (IJCTER) ,* vol. 2, no. 10, pp. 131-137, 2016.

[9] R. Mike, "Industrial power and energy savings initiatives in South Africa," EE Publishers, Gauteng, South Africa, 2014.

[10] C. Palanichamy, Y. C. Wong and Cassandra, "Power System Performance Enhancement Through Compensation Techniques," *Indian Journal of Science and Technology,* vol. 8, no. 19, pp. 1-5, 2015.

[11] A. A. Tellez, G. Lopez, I. Isaac and J. Gonzalez, “Optimal reactive power compensation in electrical distribution systems with distributed resources. Review,” *Heliyon,* vol. 4, no. 8, pp. 1-30, 2018.

[12] A. Ojo, K. Awodele and A. Sebitosi, “Power Quality Monitoring and Assessment of a Typical Commercial Building,” in *IEEE Africon*, Accra, Ghana, 2019.

[13] R. Dugan, M. McGranaghan, S. Santoso and H. Beaty, Electrical Power Systems Quality, New York: McGraw-Hill, 2004.

[14] J. Matias, “Reactive Power Compensation,” 5th June 2013. [Online]. Available: https://new.abb.com/docs/librariesprovider78/chile-documentos/jornadas-tecnicas-2013---presentaciones/4-jos%C3%A9-matias---reactive-power-compensation.pdf?sfvrsn=2. [Accessed 15th May 2018].

[15] A. Ojo, K. Awodele and A. Sebitosi, “Load Compensation in a Three-Phase Four-Wire Distribution System Considering Unbalance, Neutral Current Elimination and Power Factor Improvement,” in *Southern African Universities Power Engineering Conference/Robotics and Mechatronics/Pattern Recognitio*, Bloemfontaein, South Africa, 2019.

[16] S. Gheorghe and V. Branescu, “Power Quality and Improvement of the Performance in Electricity Distribution System,” in *CIGRE/IEEE PES International Symposium Quality and Security of Electric Power Delivery Systems*, Montreal,Canada, 2003.

[17] D. Mittal, P.Mahela and R.Jain, “Classification of Power Quality Disturbances in Electric Power System: A Review,” *Journal of Electrical and Electronics Engineering (IOSR-JEEE),* vol. 3, no. 05, pp. 6-14, 2012.

[18] P. Patel, “Improved Control method of UPQC for unbalanced and non linear load conditions,” *Journal of Emerging Technologies and innovative Research,* vol. 2, no. 6, pp. 1840-1848, 2015.

[19] A. Baggini, Handbook of Power Quality, John Willey & Sons, Ltd, 2008.

[20] Ikramullah, A. Muhammad and R. Abdur, “Comparison of Reference Current Generation Techniquies for Shunt Active Power Filter,” in *5th International Conference on Electrical and Electonics Engineering*, Istanbul, Turkey, 2018.

[21] H. Rashmi and P. Desai, “A Review on Power-Quality Improvement of Distribution Networks by Active Filtering Method,” *International Journal of scientific Development and Research,* vol. 3, no. 2, pp. 6-13, 2018.

[22] L. Wang, “Research on Reactive Power Compensation Based on Distribution Network,” in *International Conference on Mechatronics, Electronic, Industrial and Control Engineering (MEIC 2015)*, Shenyang, China, 2015.

[23] H. Ng, M. Salama and A. Chikhani, “Classification of capacitor allocation techniques,” *IEEE Transactions on power delivery,* vol. 15, no. 1, pp. 387-392, 2000.

[24] C. Rachana and S. L. Rakesh, “Review on Reactive Power Compensation in Short Transmission Line,” *International Journal of Engineering and Computer Science,* vol. 05, no. 09, pp. 17938-17943, 2016.

[25] R. H. S. Soeprapto, A. F. A. Abd.Rahman, M. N. M. Nasir and Z. Bohari, “Analysing of a Shunt Compensator Installation,” *The International Journal Of Engineering And Science (IJES),* vol. 3, no. 12, pp. 61-67, 2014.

[26] K. K. Das and M. M. Biswas, “Voltage level improving by using static VAR compensator (SVC),” *Global Journal of Reserachs in Engineering,* vol. 11, no. 05, p. Online, 2011.

[27] J. Bollen, Understanding Power Quality Problems: Voltage Sags and Interruptions, New York: Wiley-IEEE Press, 2000.

[28] C. Ozgur and S. Biricik, “A Research and Solution Proposal for Reactive Power Problems in North Cyprus Industries,” *Journal of the chamber of Electrical Engineer,* vol. 2, no. 1, pp. 48-50, 2009.

[29] J. Zhou, Q. Sun, H. Zhang and Y. Zhao, “Load balancing and reactive power compensation based on the capacitor banks shunt compensation in low voltage distribution networks,” in *Chinese Control Conference*, Hefei, China, 2012.

[30] L. Origa de Oliveira, M. Barros Neto and J. de Souza, “Load compensation in four wire electrical power system,” in *International Conference on Power System Technology*, Perth, Australia, 2000.

[31] M. Mishra, A. Ghosh, A. Joshi and H. Suryawanshi, “A novel method of Load compensation under unbalanced and distorted voltages,” *IEEE Transactions on Power Delivery,* vol. 22, no. 01, pp. 288-294, 2007.

[32] T. E. Seiphetlho and A. P. J. Rens, “On the Assessment of Voltage Unbalance,” in *International Conference on Harmonics and Quality of Power*, Bergamo, Italy, 2010.

[33] J. Pati and J. Sahu, “Unbalanced Load compensation,” *International Journal of Advanced Research in Science and Technology,* vol. 1, no. 01, pp. 74-80, 2012.

[34] Z. Aung, “Shunt capacitor banks increase capacity of distribution networks,” *International Journal for Innovative Research in Multidisciplinary Field,* vol. 5, no. 1, pp. 1-8, May 2019.

[35] T. B. Mohammad and K. Amir, “Three-phase unbalance of distribution systems: Complementary analysis and experimental case study,” *International Journal of Electrical Power & Energy Systems,* vol. 33, no. 4, pp. 817-826, 2011.

[36] Z. Jiajie, W. Jiacheng, Z. Jianwen and Z. Jianqiao, “Overview of grounding schemes for solid-state transformers indistribution networks,” *IET Generation, Transmission & Distribution,* vol. 15, no. 22, pp. 3081-3099, 2021.

[37] M. J. Ghorbani and H. Mokhtari, “Impact of Harmonics on Power Quality and Losses in Power Distribution Systems,” *International Journal of Electrical and Computer Engineering (IJECE),* vol. 5, no. 1, p. 166~174, 2015.

[38] S. Arthur, P. D. Gerald, Y. Peter, F. Stephen, H. Aidan and Z. Daniel, “Harmonic cancellation within AC low voltage distribution for a realistic office environment,” *International Journal of Electrical Power & Energy Systems,* vol. 134, pp. ISSN 0142-0615, 2022.

[39] G. Prachi, “Effect of harmonics on active power flow and apparent power in the power system,” in *Second International Conference on Emerging Trends in Engineering (SICETE)*, Jaysingpur,Indian, 2017.

[40] D. Balakrishnan and R. S. Balog, “Capacitor-less VAR compensator based on matrix converter,” in *North American Power Symposium*, Arlington, TX, USA, 2010.

[41] Ö. C. Özerdem and S. Biricik, “Development of a solution for reactive power problems in North Cyprus industries,” *Journal of the Chamber od Electrical Engineers,* vol. 2, no. 01, pp. 48-50, 2009.

[42] Shazma, J. KBalvinder and M. Prachi, “A Review on power Quality Problems and its Improvemnet techniques,” in *International conference on innovations in power and Advanced computing Technologies*, Vellore, India, 2017.

[43] P. Rajashekar and R. Udyakumar, “Power Quality Issues in Electrical Distribution system and industries,” *Asian Journal of Engineering and Technology Innovation,* vol. 2016, no. 3, pp. 64-69, 2016.

[44] R. Dugan, M. McGranaghan, S. Santoso and H. Beaty, Electrical Power Systems Quality, New York: McGraw-Hill, 2004.

[45] M. G. Tejashree, R. Pooja Asabe and S. Chawda, “Power Quality Issues and It’s Mitigation Techniques,” *International Journal of Engineering Research and Applications,* vol. 4, no. 4, pp. 170-177, 2014.

[46] F. Ahmed, H. Shady, A. Abdel and E. Murat, Power Systems Harmonics - Analysis, Effects, and Mitigation Solutions for Power Quality Improvements, London, United Kingdom: Intechopen, 2018.

[47] P. Balaubramania and S. Prabha, “Power Qaulity Issues, Solutions and Standards: A technology review,” *Journal of Applied Science and Engineering,* vol. 1, no. 8, pp. 371-380, 2015.

[48] S. Jhampati, J. Chakraborty, S. Lahiri and T. Halder, “Assessment of Power Quality,” in *Proceedings of the 2015 Third International Conference on Computer, Communication, Control and Information Technology (C3IT)*, Hooghly, 2015.

[49] A. Zobaa and A. Abdel, Power Quality in Future Electrical Power Systems Engineering, United Kigdom: IET Digital Library, 2017.

[50] P. Alexis, “Power Quality and Voltage Sag Indices in Electrical Power Systems,” in *Electrical Generation and Distribution Systems and Power Quality Disturbances*, United Kingdom, Intechopen, 2011, pp. 140-160.

[51] IEEE Std 1668-2007, “Recommended Practice for Voltage Sag and Short Interruption Ride-Through Testing for End-Use Electrical Equipment Rated Less than 1000 V,” IEEE, New York, 2017.

[52] Eskom, “NRS 048-2: Electricity Supply - Quality of Supply Part 2: Voltage Characteristics, Compatability Levels, Limits and Assessment Methods,” 2003.

[53] O. J. Daniel and A. H. Kabiru, “Issues of Power Quality in Electrical Systems,” *International Journal of Energy and Power Engineering,* vol. 5, no. 4, pp. 148-154, 2016.

[54] M. Kurt, M. Balci and S. Abdel-Aleem, “Algorithm for estimating derating of induction motors supplied with under/over voltage using response surface methodology,” *Journal of Engineering,* vol. 12, no. 6, pp. 627-633, 2017.

[55] A. de Almeida, L. Moreira and J. Delgado, “Power Quality Problems and New Solutions,” in *International Conference on Renewable Energy and Power Quality*, Vigo, 2003.

[56] N. Jakob, K. R. Sarah and H. J. B. Math, “An Analysis of Frequency Variations and its Implications on Connected Equipment for a Nanogrid during Islanded Operation,” *Energies,* vol. 11, pp. 1-13, 2018.

[57] M. Tlhoriso, “Power Quality Enhancement in Electricity Networks Using Grid-connected Solar and Wind Based DGs, MSc Dissertation,” University of Cape Town, Cape Town, 2017.

[58] V. RoshanLal and S. Pallavi, “Frequency Fluctuation in Power System: Sources, Control and Minimizing Techniques,” *International Journal of Advanced Research in Electrical,Electronics and Instrumentation Engineering,* vol. 3, no. 8, pp. 11378-11382, 2014.

[59] IEEE 1159-2019, “IEEE Recommended Practice for Monitoring Electric Power Quality,” IEEE, New York, 2019.

[60] IEC 61000-4-7, “Electromagnetic compatibility (EMC) – Part 4-7: Testing and measurement techniques – General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto,” IEC, 2009.

[61] IEEE Standard 112-1991, “IEEE Standard Test Proceedure for Polyphase Induction Motors and Generators,” IEEE, USA, 1991.

[62] A. Saeed, S. Abdel Aleem, A. Ibrahim, M. Balci and E. El-Zahab, “Power conditioning using dynamic voltage restorers under different voltage sag types,” *Journal of Advanced Research,* vol. 7, no. 1, pp. 95-103, 2016.

[63] A. Santosh and A. Tejulal, “Effects of Harmonics on Electrical Equipment and their Compensation by using Shunt Active Power filter,” *International Refereed Journal of Engineering and Science (IRJES),* vol. 3, no. 11, pp. 126-131, 2014.

[64] P. Nirav, G. Kenil, M. Digpal and C. Praful, “A review on Power Quality Issues ansd Standards,” *International Research Journal of Engineering and Technology,* vol. 04, no. 02, pp. 247-250, 2017.

[65] R. P. Bingham, “Measurement instruments for power quality monitoring,” in *IEEE/PES Transmission and Distribution Conference and Exposition*, Chicago, 2008.

[66] S. Bhim, C. Ambrish and A.-H. Kamal, Power Quality Problems and Mitigation Techniques, United Kingdom: WILLEY, 2015.

[67] J. Das, Power System Analysis - Short-Circuit Load Flow and Harmonics, New York: Marcel Dekker, 2002.

[68] C. Sankaran, Power Quality, New York: CRC Press LLC, 2002.

[69] 242-2001 IEEE Std, “IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems,” IEEE, 2001.

[70] IEEE Std 1159-2009, “IEEE Recommended Practice for Monitoring Electric Power Quality,” IEEE, 2009.

[71] EN50160, “Voltage Charactericstics of Electricity supplied by public distribution systems,” EN50160, 1994.

[72] 61003-2-2001, IEC std., “Electromagnetic compatibiliy (EMC)-part 3-2 Limits- Limits for harmonic current emissions for equipment input current <= 16 A per phase,” IEC, 2001.

[73] NEMA MG 1-2009, “NEMA Standard Publication -Motors and Generators,” NEMA, Rosslyn, 2009.

[74] A. Umar, K. Sandeep and V. Satyendra, “A Solution for Power Quality issues in Power Systems,” *International Journal of Advanced Research in Electrical,Electronics and Instrumentation Engineering,* vol. 7, no. 1, pp. 73-79, 2018.

[75] C. Faks, “Capacitor Faks,” Captron, 2019. [Online]. Available: https://www.capacitorfaks.com/post/an-introduction-to-capacitor-based-pfc-circuits. [Accessed 13 September 2019].

[76] B. S. Patil and V. Pawar, “Power Quality Effects of Nonlinear Loads,” *International Research Journal of Engineering and Technology,* vol. 4, no. 6, pp. 3244-3247, 2017.

[77] C. L. Collocot, “Harmonic Emission of Non-Linear Loads In Distribution Systems & Their Measurements "B.Sc. Project",” Department of Electrical Engineering, University of Cape Town, Cape Town, 2015.

[78] T. R. Kuphaldt, “Lessons In Electrical Circuits Volume II - AC Circuits,” Ibiblio, 2007. [Online]. Available: https://www.ibiblio.org/kuphaldt/electricCircuits/AC/index.html. [Accessed 30 August 2019].

[79] StarLine, “StarLine,” [Online]. Available: https://cmbuck.com/wp-content/uploads/2014/12/Neutral-Ratings-for-power-busway-distribution.pdf. [Accessed 31 July 2019].

[80] S. G. Bankar, A. P. Bhurbhure, A. R. Bhedarkar and B. S. Rakhonde, “Impact of Non linear Load on Power Quality,” *International Journal on Recent and Innovation Trends in Computing and Communication,* vol. 5, no. 1, pp. 223-226, 2017.

[81] A. Olatoke, “Investigations of Power Quality Problems in Modern Buildings "PhD Thesis",” Brunel University School of Engineering and Design, London, 2011.

[82] J. Arrillaga and N. Watson, Power Ssytem Harmonics, Chichester: John Willey & Sons Ltd, 2003.

[83] J. Das, “Passive filters-potentialities and limitation,” *IEEE Transactions on Industry Applications,* vol. 5, no. 2, pp. 312-318, 2004.

[84] U. O. Emmanuel, N. N. Samuel and K. I. Gerald, “Electric Power Transmission Enhancement: A Case of Nigerian Electric Power Grid,” *American Journal of Electrical and Electronic Engineering,* vol. 4, no. 1, pp. 33-39, 2016.

[85] Ajeet, Kumar Rawat; Pandey, A.S; Ankit, Kumar Srivastava, “Reactive Power Compensation in Single Phase Distribution System using SVC, STATCOM & UPFC,” *International Research Journal of Engineering and Technology,* vol. 04, no. 09, pp. 360-367, 2017.

[86] B. Kumar, “Determination of optimal Account and loaction of series compensation and SVS for an AC Transmission System,” *International Journal of Computational Engineering Research (IJCER),* vol. 4, no. 5, pp. 50-57, 2014.

[87] M.Maheshkumar, “A Study of Reactive Power Compensation in Power System and Its Compensation Techniques,” *International Journal of Innovative in Engineering and Technology,* Vols. Special Issue NCRTEEFOSS-2016, no. Special Issue NCRTEEFOSS-2016, pp. 250-256, 2016.

[88] A. Sebitosi, “Load Compensation: Design of a Real Time Analysis and Control Device "M.Sc Dissertation",” University of Cape Town, Cape Town, 2001.

[89] L. S. Czarnecki, “Adaptive balancing Compensator,” *IEEE Transactions on Power Delivery,* vol. 10, no. 3, pp. 1663-1669, 1995.

[90] W. Watanabe, R. Stephen and M. Aredes, “New concepts of Instantaneous active and reactive powers in electrical system with generic loads,” *IEEE Transactions on power Delivery,* vol. 8, no. 2, pp. 697-703, 1993.

[91] H. Akagi, H. W. Edson and A. Mauricio, Instantaneous Theory and applications to power conditioning, Hoboken, United States: John Wiley and Sons Ltd, 2017.

[92] T. Miller, Reactive power Control in Electric System, New York: John willey & Sons, 1982.

[93] V. Sastry and M. Sarma, Power Quality: VAR Compensation in Power System, New York: CRC Press, 2008.

[94] L. Czarnecki, “Supply and loading quality improvement in sinusoidal power systems with unbalanced loads supplied with asymmetrical voltage,” *Journal of Electrical Engineering,* vol. 77, no. 3, pp. 169-177, 1994.

[95] Y. Baghzouz and M. Cox, “Optimal shunt compensation for unbalanced linear loads with nonsinusoidal supply voltages,” *Electrical Machines and Power Systems,* vol. 19, no. 2, pp. 171-183, 1991.

[96] K. Bhimsingh and C. Ambrish, “A Review of Active Filters for Power Quality Improvement,” *IEEE Transactions on Industrial electronics,* vol. 45, no. 5, 1999.

[97] S. Bhim, C. Ambrish and A.-H. Kamal, Power Quality Problems and Mitigation Techniques, United Kingdom: Willey, 2015.

[98] S. Arpit and V. Nirav, “Shunt Active Power Filter for Power Quality Improvement in Distribution Systems,” *International Journal of Engineering and Research,* vol. 1, no. 2, pp. 23-27, 2014.

[99] M. Albadi, A. Al Hinai, A. Al-Badi, M. Al Riyami, S. Al Hinai and R. Al Abri, “Unbalance in power systems: Case study,” in *IEEE International Conference on Industrial Technology (ICIT)*, Seville, Spain, 2015.

[100] A. K. Singh, G. Singh and R. Mitra, “Some Observations on Definitions of Voltage Unbalance,” in *39th North American Power Symposium*, Las Cruces, NM, USA, 2007.

[101] IEEE, “IEEE Standard Test Procedure for Polyphase Induction Motors and Generators[IEEE Standard 112],” IEEE, 1991.

[102] CIGRE, “A new simple and effective approximate formulation for the determination of three-phase unbalances by voltmeter method,” CIGRE, Belgique, 1986.

[103] A. Jouanne and B. Banerjee, “Assessment of Voltage Unblance,” *IEEE Transaction on Power Delivery,* vol. 16, no. 4, pp. 982-790, 2001.

[104] A. Hossein and P. Mitra, “Unbalanced current Tariff,” in *24th International conference & exhibition on Electrity distribution (CIRED)*, Glasgow, 2017.

[105] A. Adebayo, “Allocation of Transmission Losses to Determine Tariff, Ph.D Thesis,” University of Cape Town, Cape Town, 2018.

[106] J. Ogunyemi and N. .. Adelakun, “Investigation of Voltage Unbalance in a Distribution Network: A Case Study of Federal Polytechnic Ilaro,” *Journal of Energy Technology and Environment ,* vol. 3, no. 1, pp. 16-22, 2021.

[107] S. Reyes and R. Jesus, “Identification of unbalanced loads in electric power systems,” John willey and Sons, Ltd., Spain, 2013.

[108] T. E. Seiphetlho and A. P. J. Rens, “On the Assessment of Voltage Unbalance,” in *International Conference on Harmonics and Quality of Power*, Bergamo, Italy, 2010.

[109] M. Chindris, A. Cziker, A. Miron, H. Balan, A. Iacob and A. Sudria, “Propagation of unbalance in Electric Power systems,” in *9th International Conference of Electic Power Quality and Utilisation*, Barcelona, 2007.

[110] H. Mohsen, K. Houshang and M. Hossein, “Harmonic and Negative Sequence Current Control in an Islanded Multi-Bus MV Microgrid,” *IEEE Transactions On Smart Grid,* vol. 5, no. 1, 2014.

[111] L. Ching-Yin, “Effects of Unbalanced Voltage on the opeartion Performance of a three-phase induction motor,” *IEEE Transactions on Energy Conversion,* vol. 14, no. 2, pp. 202 - 208, 1999.

[112] W. Janakrani, P. Updesh, Y. Mala and K. K. Amit, “A Review on Power Quality Problems and Improvement Techniques,” *International Journal of Engineering Research & Technology (IJERT),* vol. 8, no. 10, pp. 197-200, 2020.

[113] P. Oluseyi, G. Jatto, O. Okoro and T. Akinbulire, “Assessment of the Influence of Voltage Unbalance on Three-Phase Operation of Power System,” *Nigerian Journal of Technology (NIJOTECH),* vol. 40, no. 5, p. 901 –912, 2021.

[114] E. O. Daniel, O. O. Henry, G. R. Coneth, F. N. Agha and W. B. Bertus, “Harmonic generation of variable speed drive under complex-voltage unbalance conditions,” *Journal of Engineering and Applied Science,* vol. 69, no. 96, pp. 1-16, 2022.

[115] Ngo, L. A. Tuan and N. Y. Do, “Effect of Voltage Unbalances on the Performance of a Three-phase Transformer,” *IOP Conference Series: Earth and Environmental Science,* vol. DOI, no. 10.1088/1755-1315/1111/1/012050, pp. 1-8, 2022.

[116] A. P. Nurul and R. Yuni, “Evaluation of Unbalanced Load Impacts on Distribution Transformer Performances,” *Frontier Energy System and Power Engineering,* vol. 2, no. 1, pp. 28-35, 2020.

[117] C. A. Reineri, J. C. Gomez and N. Campetelli, “Adjustable Speed Drives Supplied with Unbalanced Voltages: Study under Complex Voltage Unbalance Factor Parameter,” in *Transmission and Distribution Conference and Exposition IEEE/PES*, Latin America, 2008.

[118] S. Jeong and J. Choi, “Line Current Characteristics of Three-Phase Uncontrolled Rectifiers Under Line Voltage Unbalance Condition,” *IEEE Trans. on Power Electronics,,* vol. 17, no. 6, pp. 935-945, 2002.

[119] M. Krarti, “Utility Rate Structures and Grid Integration,” in *Optimal Design and Retrofit of Energy Efficient Buildings, Communities, and Urban Centers*, Butterworth-Heinemann, Elsevier, 2018, pp. 189-245.

[120] O. Osahenvemwen, M. E. Okhumeode and S. Emakpor, “The Effects of Unbalanced Load in Power Distribution Sub - Station Network,” *American Journal of Sciences and Engineering Research,* vol. 3, no. 5, pp. 1-12, 2020.

[121] P. Jinyuan, L. Jian, C. Xiaoqian and Z. Kanghua, “Three-phase unbalanced load control based on load–electricity transfer index,” *Energy Reports,* vol. 7, no. 1, pp. 312-318, 2021.

[122] B. Guanghai and K. Sikai, “Load Transfer Device for Solving a Three-Phase Unbalance Problem Under a Low-Voltage Distribution Network,” *Energies,* vol. 12, pp. 1-18, 2019.

[123] R. V. Madhusudhan and M. S. Lalit, “Load balancing of electrical power distribution system: An overview,” in *International Conference on Power, Instrumentation, Control and Computing (PICC)*, Thrissur, India, 2018.

[124] E. S. Taufik, A. Makbul and T. Mohammad, “Performance Analysis of Shunt Reactive Power Compensators,” in *Third Asia International Conference on Modelling & Simulation*, Bundang, Indonesia, 2009.

[125] S. George and V. Agarwal, “A novel DSP based algorithm for optimizing the harmonics and reactive power under non-sinusoidal supply voltage conditions,” *IEEE Trans. on Power Delivery,* vol. 20, no. 4, pp. 2526-2534, 2005.

[126] IEEE Working Group on Nonsinusoidal Situations, “A survey of north American electric utility concerns regarding nonsinusoidal waveforms,” *IEEE Trans. on Power Delivery,* vol. 11, no. 1, pp. 73-77, 1996.

[127] R. Patidar and S. Singh, “DSP based shunt active filter controller for customer-generted harmonics and reactive power compensation,” *Electric Power Components and Systems,* vol. 38, no. 1, pp. 937-959, 2010.

[128] K. M. Seraphin, “A comprehensive study of Power System Harmonics "M.Sc Dissertation",” University of Johannesburg, Johannesburg, 2013.

[129] M. P. Rajashekar and Y. R. Udyakumar, “Power Quality Issues in Electrical Distribution Systems and Industries,” in *National Conference on recent Advances in control Strategies for integration of distributed Generation sources*, Bangalore, 2016.

[130] IEEE Std 1459-2010, “IEEE Standard Definitions for the Measurement of Electric Power Quantities Under Sinusoidal, Nonsinusoidal, Balanced, or Unbalanced Conditions,” IEEE, New York, 2010.

[131] A. Baggini, Handbook of Power Quality, Southern Gate, London: John Willey & sons, Ltd, 2008.

[132] C. Sankaran, Power Quality, New York: CRC Press LLC, 2002.

[133] M. I. Ahmed, E. Hany and M. E. Ahmed, “Elimination of Zero Sequence Currents Effect on Differential Protection For Power Transformers Connected to Power Grid,” in *21st International Middle East Power Systems Conference (MEPCON)*, Cairo, Egypt, 2019.

[134] T. Ortmeyer, K. Chakravarthi and A. Mahmoud, “The Effects of power system harmonics on power system equipment and loads,” *IEEE Transactions on Power Apparatus and Systems,* vol. 104, no. 9, pp. 2555-2563, 1985.

[135] A. H.-E. Ahmed and M. H. Reda, “Study of the effect of harmonics on measurements of the energy meters,” in *International Middle-East Power System Conference, MEPCON*, El-Minia, Egypt, 2006.

[136] I. Diahovchenko, V. Volokhin, V. Kurochkina, M. Špes and M. Kosterec, “Effect of harmonic distortion on electric energy meters of different metrological principles,” Higher Education Press and Springer-Verlag, Germany, 2018.

[137] A. Benjamin and S. K. Jain, “A Review of Literature on Effects of Harmonics on Protective Relays,” in *International Conference on Innovative Smart Grid Technologies*, Singapore, 2018.

[138] T. Hillary, A. Abu-Siada and M. Masoum, “Impact of harmonics on the performance of over-current relays,” in *Australasian Universities Power Engineering Conference*, Brisbane,Australia, 2011.

[139] W. S. Bogale, “Evaluating the level of harmonic distortion in a typical distribution feeder "M.Sc Dissertation",” University of Nevada, Las Vegas, 2015.

[140] A. Santosh and A. Tejulal, "Effects of Harmonics on Electrical Equipment and their Compensation by using Shunt Active Filter," *International Referred journal of Engineering and Science,* vol. 3, no. 11, pp. 126-131, 2014.

[141] B. Singh, B. N. Singh, A. Chandra, K. Al-Haddad, A. Pandey and D. P. Kothari, "A review of three-phase improved power quality ac-dc converters," *IEEE Transactions on Industrial Electronics,* vol. 51, no. 3, pp. 641-660, 2004.

[142] H. A. Kazem, "Harmonic mitigation techniques applied to power distribution networks," *Advances in Power Electronics,* vol. 2013, pp. 1-10, 2013.

[143] M. McGranaghan, "Economic Evaluation of Power Quality," *IEEE Power Engineering Review,* vol. 22, no. 2, pp. 8-12, 2002.

[144] M. Gao and K. Awodele, "Investigation of Power Electronics Solutions to Power Quality Problems in Distribution Networks," in *IEEE Africon 2015*, Addis Ababa, 2015.

[145] R. Sriranjani and S. Jayalalitha, "Design of shunt active filter using iterative method to mitigate the harmonics and reactive power," *Journal of Engineering and Applied Sciences,* vol. 12, no. 24, pp. 7239-7249, 2017.

[146] H. Akagi, H. W. Edson and A. Mauricio, Instantaneous Theory and Applications to Power Conditionings, United States: John Willey and Sons Ltd, 2007.

[147] S. MathWorks, *Getting started Guide,* 3 Apple Hill Drive,Natick, MA 01760-2098, 2017.: The MathWorks, 2017.

[148] S. Sagar and R. Metri, "Power Quality Improvement Using Shunt Active Power Filter," in *International Conference on Data Management, Analytics and Innovation*, Pune, India, 2017.

[149] M. Montero, E. Cadaval and F. Gonzalez, "Control Strategies for Shunt Active Power Filters in Three-Phase Four -Wire Systems," *IEEE Transactions on Power electronics,* vol. 22, no. 1, 2007.

[150] A. Duzgun and E. Huseyin, "Design of Active Power Filters for Harmonics on Power System and Reducing Harmonic Currents," *International Journal of Electrical and Computer Engineering,* vol. 8, no. 7, pp. 1114-1120, 2014.

[151] G. Jegadeswari, "Performance Analysis of \power \quality Improvement uisng Shunt Active Power Filter," *International Journal of Recent Technology and Engineering,* vol. 7, no. 5, pp. 1-5, 2019.

[152] S. Arpit and V. Nirav, "Shunt Active Power Filter for Power Quality Improvement in Distribution Systems," *International Journal of Engineering Development and Research,* vol. 1, no. 2, pp. 23-27, 2014.

[153] H. Akagi, Y. Kanazawa and A. Nabae, "Generalized Theory of the Instantaneous Reactive power in Three-Phase circuits," in *International Power Electronics Conference*, Tokyo, Japan, 1993.

[154] H. Akagi, E. H. Watanabe and A. Mauricio, Instantaneous Theory and applications to power conditionings, Hoboken, United States: John Wiley and Sons Ltd, 2007.

[155] K. Shafiuzzaman, B. Malabika and F. Micheal, "Harmonic Power Compensation Capacity of Shunt active Power filters and its relationship with design parameters," *IET Power Electronics,* vol. 7, no. 2, pp. 418-430, 2014.

[156] F. Krim, "Parameters Estimation of Shunt Active Filter for Power Quality Improvement," in *5th International Power Engineering and Optimization Conference*, Selangor, Malaysia, 2011.

[157] R. Sriranjani and S. Jayalalitha, "Design of shunt active filter using iterative method to mitigate the harmonics and reactive power," *ARPN Journal of Engineering and Applied Sciences,* vol. 12, no. 24, pp. 7239-7249, 2017.

[158] S. Ponnaluri and A. Brickwedde, "Generalized System Design of Three-Phase Active Filters," in *IEEE PESC Conference*, Canada, 2001.

[159] S. Jain and P. Agarwal, "Design, Simulation and Experimental investigation on Shunt active power filter for harmonics and reactive power compensation," *Electric power Components and Systems,* vol. 31, no. 7, pp. 671-692, 2003.

[160] S. Jain and P. Agarwal, "Fuzzy Logic Controlled Shunt Active power Filter for Power quality improvement," *IEEE Proc. Electric Power Applications,* vol. 149, no. 5, pp. 123-129, 2002.

[161] G. Singh, A. Singh and R. Mitra, "Fuzzy Logic based robust active power filter for harmonics minimization under ransdom load variation," *Electric Power Systems Research,* vol. 77, no. 8, pp. 1101-1111, 2007.

[162] C. Lee, B. Chen and W. Lee, "Effects of unbalanced voltage on the operation performance of a three-phase induction motor," *IEEE Trans. Energy Conversion,* vol. 14, no. 2, pp. 202-208, 1999.

Appendices

Appendix A

Table A- 1: R.M.S Values of phase and Line voltages of a typical Distribution Feeder

	Time	V1_Avg [V]	V2_Avg [V]	V3_Avg [V]	V12_Avg [V]	V23_Avg [V]	V31_Avg [V]
1	29 Apr 2019 2:11:00 pm	226.3	226.6	227.1	391.7	393	392.9
2	29 Apr 2019 2:21:00 pm	226.5	226.9	227.4	391.9	393.7	393.4
3	29 Apr 2019 2:31:00 pm	226.4	226.7	227.2	391.6	393.5	392.9
4	29 Apr 2019 2:41:00 pm	226.2	226.6	227.1	391.4	393.5	392.8
5	29 Apr 2019 2:51:00 pm	226.1	226.6	226.9	391.2	393.3	392.6
6	29 Apr 2019 3:01:00 pm	226	226.8	226.8	391.4	393.3	392.3
7	29 Apr 2019 3:11:00 pm	226.3	227	226.9	391.8	393.6	392.6
8	29 Apr 2019 3:21:00 pm	226.1	226.7	226.7	391.4	393.2	392.2
9	29 Apr 2019 3:31:00 pm	226.4	227.1	227.2	391.8	393.8	393.2
10	29 Apr 2019 3:41:00 pm	226.1	226.5	226.6	391.1	392.8	392.3
11	29 Apr 2019 3:51:00 pm	225.7	226.3	226.3	390.6	392.4	391.8
12	29 Apr 2019 4:01:00 pm	227.7	228.4	228.4	394.1	396	395.4
13	29 Apr 2019 4:11:00 pm	228.1	228.6	228.9	394.6	396.8	396
14	29 Apr 2019 4:21:00 pm	227.9	228.4	228.5	394.3	396.4	395.3
15	29 Apr 2019 4:31:00 pm	228.5	228.9	229.2	395.2	397.2	396.6
16	29 Apr 2019 4:41:00 pm	228.6	229.2	229.4	395.8	397.5	396.8
17	29 Apr 2019 4:51:00 pm	227.2	227.7	228	393.2	395.1	394.4
18	29 Apr 2019 5:01:00 pm	227.1	227.4	227.8	393	394.6	394.1
19	29 Apr 2019 5:11:00 pm	226.4	226.9	226.9	391.9	393.3	392.8
20	29 Apr 2019 5:21:00 pm	226.8	227.2	227.5	392.6	394.1	393.5
21	29 Apr 2019 5:31:00 pm	226.6	226.9	227.2	392.1	393.7	393.1
22	29 Apr 2019 5:41:00 pm	228.2	228.5	228.7	394.8	396.5	395.8
23	29 Apr 2019 5:51:00 pm	228.2	228.2	228.9	395	396.1	395.9
24	29 Apr 2019 6:01:00 pm	227.8	227.9	228.5	394.4	395.5	395.2
25	29 Apr 2019 6:11:00 pm	226.6	226.6	227.4	392.2	393.5	393
26	29 Apr 2019 6:21:00 pm	226.5	226.2	227.3	391.8	393.1	392.9
27	29 Apr 2019 6:31:00 pm	228.2	228	229.2	394.8	396.3	396.1
28	29 Apr 2019 6:41:00 pm	228.5	228.4	229.3	395.5	396.7	396.4
29	29 Apr 2019 6:51:00 pm	226.4	226.6	227.6	392.1	393.8	393.1
30	29 Apr 2019 7:01:00 pm	227.3	227.4	228.8	393.6	395.3	394.8
31	29 Apr 2019 7:11:00 pm	228	227.8	229.3	394.6	396	395.9
32	29 Apr 2019 7:21:00 pm	229.1	228.7	230.1	396.4	397.5	397.5
33	29 Apr 2019 7:31:00 pm	229.3	229	230.2	396.7	397.8	397.9
34	29 Apr 2019 7:41:00 pm	229.7	229.7	230.5	397.7	398.8	398.3
35	29 Apr 2019 7:51:00 pm	228.7	228.7	229.4	396	396.9	396.5
36	29 Apr 2019 8:01:00 pm	229.2	229.1	229.9	396.8	397.6	397.4
37	29 Apr 2019 8:11:00 pm	229.9	229.7	230.6	398	398.9	398.5
38	29 Apr 2019 8:21:00 pm	229.3	229.2	230	397	397.8	397.5
39	29 Apr 2019 8:31:00 pm	228.4	228.3	229.2	395.4	396.5	396.2
40	29 Apr 2019 8:41:00 pm	229.8	229.3	230.5	397.5	398.4	398.5
41	29 Apr 2019 8:51:00 pm	229.4	228.9	230.2	397	397.6	397.9
42	29 Apr 2019 9:01:00 pm	230.3	229.9	231.3	398.7	399.4	399.7
43	29 Apr 2019 9:11:00 pm	227	226.8	227.9	393	393.8	394
44	29 Apr 2019 9:21:00 pm	227.7	227.3	228.5	394	394.9	394.9
45	29 Apr 2019 9:31:00 pm	229.6	229.3	230.4	397.3	398.4	398.2
46	29 Apr 2019 9:41:00 pm	229.6	229.4	230.7	397.4	398.6	398.7
47	29 Apr 2019 9:51:00 pm	228.8	228.6	229.6	396	396.9	396.9
48	29 Apr 2019 10:01:00 pm	228.9	228.8	229.6	396.3	397.3	396.8
49	29 Apr 2019 10:11:00 pm	229.1	229.2	229.8	396.8	397.9	397.2
50	29 Apr 2019 10:21:00 pm	229.8	229.8	230.6	397.9	399	398.5
51	29 Apr 2019 10:31:00 pm	229.4	229.5	230.2	397.3	398.4	397.8
52	29 Apr 2019 10:41:00 pm	228	228	228.7	394.8	395.8	395.3
53	29 Apr 2019 10:51:00 pm	228.3	228.6	229.1	395.4	396.8	396
54	29 Apr 2019 11:01:00 pm	230.3	230.6	230.7	398.9	400.1	399
55	29 Apr 2019 11:11:00 pm	230.8	231.1	231.1	399.5	400.9	399.7
56	29 Apr 2019 11:21:00 pm	229	229.3	229.3	396.6	397.8	396.6
57	29 Apr 2019 11:31:00 pm	228.3	228.7	228.7	395.4	396.7	395.5
58	29 Apr 2019 11:41:00 pm	228.8	229	229.1	396.3	397.1	396.3
59	29 Apr 2019 11:51:00 pm	229.2	229.4	229.8	396.8	398	397.5
60	30 Apr 2019 12:01:00 am	229	229.1	229.6	396.3	397.6	397.3
61	30 Apr 2019 12:11:00 am	228.9	228.8	229.1	396.2	396.9	396.6
62	30 Apr 2019 12:21:00 am	228.1	228.3	228.3	395	395.8	395
63	30 Apr 2019 12:31:00 am	228.3	228.6	228.9	395.1	396.8	395.9
64	30 Apr 2019 12:41:00 am	229.2	229.2	229.6	396.6	397.8	397.3
65	30 Apr 2019 12:51:00 am	228.9	229.1	229.4	396.3	397.6	396.8
66	30 Apr 2019 1:01:00 am	229	229.4	229.6	396.6	397.8	397.1
67	30 Apr 2019 1:11:00 am	229.1	229.2	229.2	396.8	397.2	396.8
68	30 Apr 2019 1:21:00 am	228.7	228.9	229	396.1	397	396.3
69	30 Apr 2019 1:31:00 am	228.9	229.4	229.4	396.5	397.8	396.8
70	30 Apr 2019 1:41:00 am	229	229.1	229.1	396.6	397.1	396.5
71	30 Apr 2019 1:51:00 am	228.8	229.2	229.2	396.3	397.5	396.5
72	30 Apr 2019 2:01:00 am	228.4	228.8	228.8	395.7	396.8	395.6
73	30 Apr 2019 2:11:00 am	228.7	228.9	228.8	396.1	396.8	396

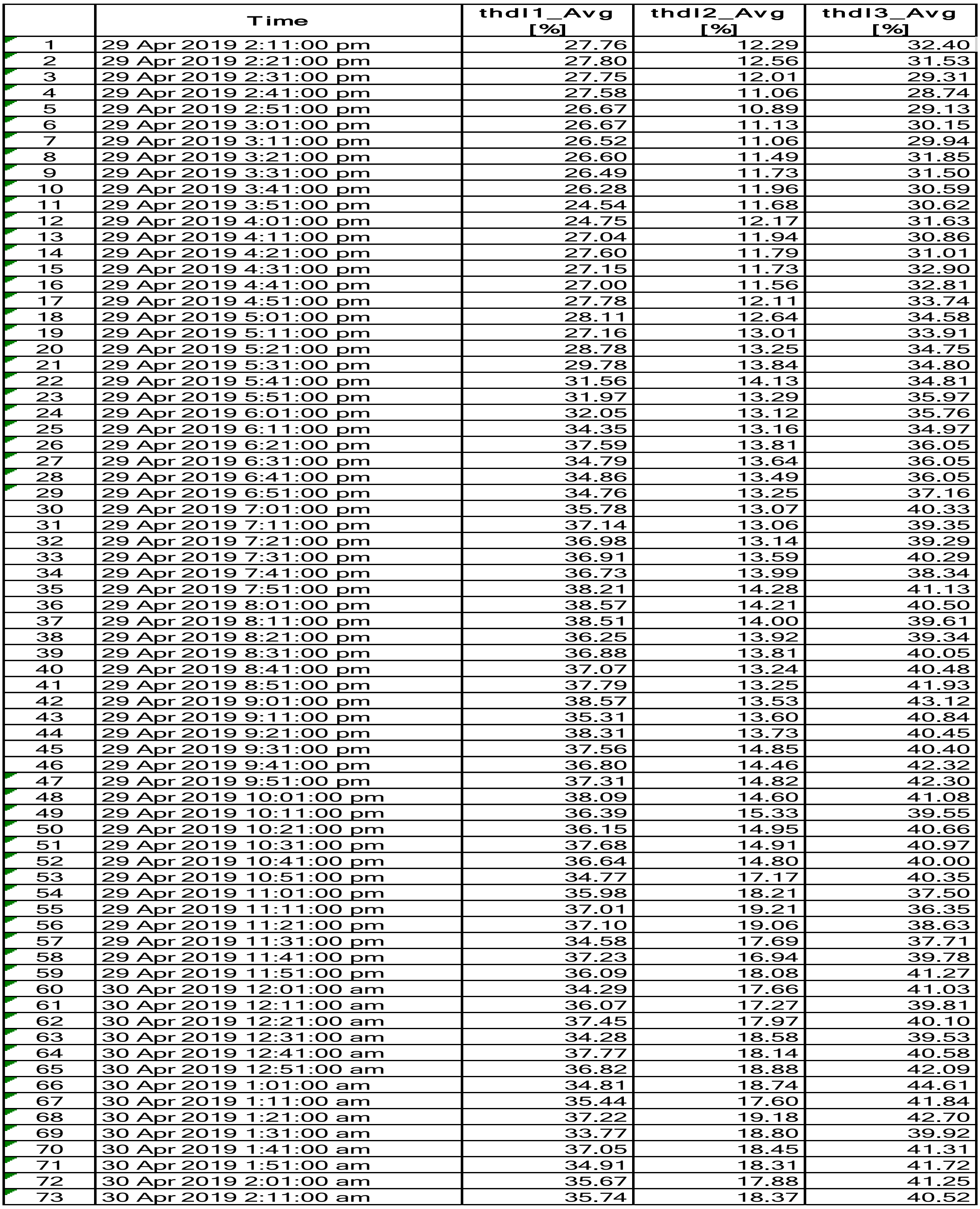
Table A- 2: R.M.S Values Phase and Neutral Currents of a typical Distribution Feeder

	Time	In_Avg [A]	I1_Avg [A]	I2_Avg [A]	I3_Avg [A]
1	29 Apr 2019 2:11:00 pm	65.11	163.90	175.70	170.50
2	29 Apr 2019 2:21:00 pm	63.91	161.00	171.50	172.20
3	29 Apr 2019 2:31:00 pm	65.03	158.90	174.20	181.10
4	29 Apr 2019 2:41:00 pm	63.70	159.90	177.90	181.50
5	29 Apr 2019 2:51:00 pm	63.65	162.60	170.90	177.00
6	29 Apr 2019 3:01:00 pm	64.64	164.00	167.20	175.30
7	29 Apr 2019 3:11:00 pm	63.42	164.20	170.60	177.50
8	29 Apr 2019 3:21:00 pm	64.80	163.50	165.80	166.90
9	29 Apr 2019 3:31:00 pm	66.98	166.80	163.90	166.80
10	29 Apr 2019 3:41:00 pm	64.92	164.50	166.60	172.50
11	29 Apr 2019 3:51:00 pm	65.78	169.50	165.90	169.10
12	29 Apr 2019 4:01:00 pm	65.59	169.30	159.60	166.20
13	29 Apr 2019 4:11:00 pm	64.65	154.80	151.70	165.00
14	29 Apr 2019 4:21:00 pm	63.79	151.80	148.90	161.80
15	29 Apr 2019 4:31:00 pm	64.65	149.10	148.10	152.80
16	29 Apr 2019 4:41:00 pm	62.25	149.80	150.90	150.80
17	29 Apr 2019 4:51:00 pm	62.17	142.50	148.30	148.90
18	29 Apr 2019 5:01:00 pm	59.06	142.30	147.50	146.20
19	29 Apr 2019 5:11:00 pm	60.95	144.90	148.70	148.20
20	29 Apr 2019 5:21:00 pm	59.99	135.10	147.90	144.90
21	29 Apr 2019 5:31:00 pm	59.69	132.60	141.40	145.30
22	29 Apr 2019 5:41:00 pm	60.23	123.30	136.30	144.50
23	29 Apr 2019 5:51:00 pm	56.38	125.30	143.40	140.30
24	29 Apr 2019 6:01:00 pm	55.49	124.20	144.10	140.50
25	29 Apr 2019 6:11:00 pm	53.38	115.20	145.30	142.60
26	29 Apr 2019 6:21:00 pm	52.90	106.20	138.30	138.40
27	29 Apr 2019 6:31:00 pm	52.38	115.10	138.80	137.70
28	29 Apr 2019 6:41:00 pm	51.83	113.00	139.80	137.10
29	29 Apr 2019 6:51:00 pm	51.38	112.30	139.90	132.80
30	29 Apr 2019 7:01:00 pm	51.81	105.70	140.50	121.00
31	29 Apr 2019 7:11:00 pm	51.72	102.00	141.70	123.30
32	29 Apr 2019 7:21:00 pm	51.25	102.70	140.90	123.40
33	29 Apr 2019 7:31:00 pm	50.59	102.80	138.50	120.50
34	29 Apr 2019 7:41:00 pm	52.12	102.60	131.90	124.30
35	29 Apr 2019 7:51:00 pm	51.22	100.30	130.90	118.30
36	29 Apr 2019 8:01:00 pm	50.46	97.39	131.60	119.00
37	29 Apr 2019 8:11:00 pm	50.15	98.69	135.50	121.70
38	29 Apr 2019 8:21:00 pm	51.25	104.80	135.60	121.90
39	29 Apr 2019 8:31:00 pm	50.98	103.00	135.00	119.80
40	29 Apr 2019 8:41:00 pm	51.59	100.50	139.50	117.70
41	29 Apr 2019 8:51:00 pm	51.28	97.57	139.70	114.10
42	29 Apr 2019 9:01:00 pm	51.47	95.87	138.10	111.50
43	29 Apr 2019 9:11:00 pm	52.10	105.40	138.40	116.70
44	29 Apr 2019 9:21:00 pm	51.36	97.65	136.80	117.40
45	29 Apr 2019 9:31:00 pm	50.87	99.02	126.70	116.80
46	29 Apr 2019 9:41:00 pm	51.00	101.30	126.20	111.90
47	29 Apr 2019 9:51:00 pm	52.92	100.70	123.70	112.80
48	29 Apr 2019 10:01:00 pm	52.95	98.66	123.60	115.90
49	29 Apr 2019 10:11:00 pm	52.24	102.40	118.80	119.30
50	29 Apr 2019 10:21:00 pm	51.60	101.20	121.70	115.70
51	29 Apr 2019 10:31:00 pm	50.56	96.73	121.40	114.70
52	29 Apr 2019 10:41:00 pm	51.46	100.00	122.10	116.20
53	29 Apr 2019 10:51:00 pm	51.17	104.20	106.70	115.30
54	29 Apr 2019 11:01:00 pm	50.23	100.20	99.04	121.40
55	29 Apr 2019 11:11:00 pm	48.91	95.63	91.17	123.20
56	29 Apr 2019 11:21:00 pm	49.34	96.85	90.73	118.00
57	29 Apr 2019 11:31:00 pm	49.69	102.00	96.40	119.80
58	29 Apr 2019 11:41:00 pm	50.39	94.64	101.30	115.80
59	29 Apr 2019 11:51:00 pm	49.18	96.99	94.51	112.10
60	30 Apr 2019 12:01:00 am	47.98	101.50	95.62	111.60
61	30 Apr 2019 12:11:00 am	48.36	96.37	97.72	114.30
62	30 Apr 2019 12:21:00 am	48.93	94.72	94.17	114.80
63	30 Apr 2019 12:31:00 am	49.91	104.60	93.01	117.20
64	30 Apr 2019 12:41:00 am	49.05	93.41	94.23	114.40
65	30 Apr 2019 12:51:00 am	49.39	95.56	91.90	111.70
66	30 Apr 2019 1:01:00 am	50.69	101.30	92.18	106.10
67	30 Apr 2019 1:11:00 am	49.26	97.88	96.46	110.50
68	30 Apr 2019 1:21:00 am	49.34	93.78	91.06	108.80
69	30 Apr 2019 1:31:00 am	49.21	102.80	92.95	115.00
70	30 Apr 2019 1:41:00 am	48.57	92.38	93.36	111.90
71	30 Apr 2019 1:51:00 am	47.84	98.37	92.81	110.10
72	30 Apr 2019 2:01:00 am	47.22	96.85	95.03	110.90
73	30 Apr 2019 2:11:00 am	47.24	95.97	92.95	112.70

Table A- 3: Active Power Demand of a typical Distribution Feeder (for one Day)

	Time	Pt+_Avg [W]	P1+_Avg [W]	P2+_Avg [W]	P3+_Avg [W]
1	29 Apr 2019 2:11:00 pm	111600	35460	39250	36690
2	29 Apr 2019 2:21:00 pm	110400	34860	38380	37200
3	29 Apr 2019 2:31:00 pm	112700	34410	39010	39330
4	29 Apr 2019 2:41:00 pm	114100	34600	39860	39490
5	29 Apr 2019 2:51:00 pm	112000	35270	38270	38420
6	29 Apr 2019 3:01:00 pm	110900	35580	37490	37920
7	29 Apr 2019 3:11:00 pm	112800	35660	38260	38450
8	29 Apr 2019 3:21:00 pm	108400	35460	37110	35910
9	29 Apr 2019 3:31:00 pm	108900	36210	36760	35990
10	29 Apr 2019 3:41:00 pm	110400	35740	37250	37230
11	29 Apr 2019 3:51:00 pm	110300	36890	37020	36450
12	29 Apr 2019 4:01:00 pm	109100	37150	35940	36060
13	29 Apr 2019 4:11:00 pm	104300	33780	34180	35950
14	29 Apr 2019 4:21:00 pm	101700	33080	33490	35170
15	29 Apr 2019 4:31:00 pm	99090	32600	33350	33130
16	29 Apr 2019 4:41:00 pm	99670	32810	34020	32740
17	29 Apr 2019 4:51:00 pm	96160	30900	33270	31990
18	29 Apr 2019 5:01:00 pm	95130	30810	33030	31290
19	29 Apr 2019 5:11:00 pm	96300	31410	33210	31670
20	29 Apr 2019 5:21:00 pm	93220	29170	33080	30960
21	29 Apr 2019 5:31:00 pm	90950	28380	31530	31040
22	29 Apr 2019 5:41:00 pm	88140	26430	30630	31070
23	29 Apr 2019 5:51:00 pm	89180	26850	32310	30010
24	29 Apr 2019 6:01:00 pm	89040	26570	32410	30040
25	29 Apr 2019 6:11:00 pm	87270	24300	32500	30450
26	29 Apr 2019 6:21:00 pm	82360	22070	30860	29430
27	29 Apr 2019 6:31:00 pm	85160	24420	31190	29530
28	29 Apr 2019 6:41:00 pm	84900	24030	31460	29400
29	29 Apr 2019 6:51:00 pm	83100	23660	31320	28120
30	29 Apr 2019 7:01:00 pm	79260	22220	31560	25470
31	29 Apr 2019 7:11:00 pm	79630	21430	31830	26140
32	29 Apr 2019 7:21:00 pm	79860	21670	31810	26270
33	29 Apr 2019 7:31:00 pm	78610	21740	31290	25570
34	29 Apr 2019 7:41:00 pm	78200	21720	29900	26580
35	29 Apr 2019 7:51:00 pm	75440	20990	29570	24870
36	29 Apr 2019 8:01:00 pm	75300	20390	29780	25130
37	29 Apr 2019 8:11:00 pm	77240	20660	30670	25890
38	29 Apr 2019 8:21:00 pm	78820	22200	30610	25910
39	29 Apr 2019 8:31:00 pm	77380	21700	30380	25300
40	29 Apr 2019 8:41:00 pm	77730	21230	31550	24940
41	29 Apr 2019 8:51:00 pm	76010	20500	31520	23980
42	29 Apr 2019 9:01:00 pm	74930	20180	31320	23430
43	29 Apr 2019 9:11:00 pm	77610	22210	30970	24420
44	29 Apr 2019 9:21:00 pm	75620	20310	30650	24650
45	29 Apr 2019 9:31:00 pm	74180	20860	28580	24740
46	29 Apr 2019 9:41:00 pm	73490	21440	28490	23550
47	29 Apr 2019 9:51:00 pm	72540	21170	27780	23580
48	29 Apr 2019 10:01:00 pm	72780	20660	27790	24310
49	29 Apr 2019 10:11:00 pm	73690	21630	26800	25250
50	29 Apr 2019 10:21:00 pm	73470	21480	27480	24490
51	29 Apr 2019 10:31:00 pm	71890	20290	27390	24200
52	29 Apr 2019 10:41:00 pm	72850	21000	27370	24470
53	29 Apr 2019 10:51:00 pm	70140	22030	23880	24230
54	29 Apr 2019 11:01:00 pm	69620	21320	22290	26000
55	29 Apr 2019 11:11:00 pm	67390	20230	20560	26580
56	29 Apr 2019 11:21:00 pm	65750	20340	20330	25070
57	29 Apr 2019 11:31:00 pm	68590	21620	21510	25440
58	29 Apr 2019 11:41:00 pm	67080	19840	22770	24460
59	29 Apr 2019 11:51:00 pm	65240	20470	21210	23560
60	30 Apr 2019 12:01:00 am	66490	21610	21400	23450
61	30 Apr 2019 12:11:00 am	66300	20290	21890	24110
62	30 Apr 2019 12:21:00 am	64940	19790	21040	24110
63	30 Apr 2019 12:31:00 am	67700	22190	20780	24710
64	30 Apr 2019 12:41:00 am	64680	19490	21100	24070
65	30 Apr 2019 12:51:00 am	63990	20090	20590	23310
66	30 Apr 2019 1:01:00 am	64170	21550	20670	21950
67	30 Apr 2019 1:11:00 am	65420	20700	21550	23160
68	30 Apr 2019 1:21:00 am	62730	19630	20380	22700
69	30 Apr 2019 1:31:00 am	67040	21940	20830	24270
70	30 Apr 2019 1:41:00 am	63700	19360	20900	23440
71	30 Apr 2019 1:51:00 am	64630	20790	20810	23020
72	30 Apr 2019 2:01:00 am	64860	20390	21260	23200
73	30 Apr 2019 2:11:00 am	64700	20210	20790	23680

Table A- 4: Total Current Harmonic Distortion of a typical Distribution Feeder (One Day)



	Time	thdI1_Avg [%]	thdI2_Avg [%]	thdI3_Avg [%]
1	29 Apr 2019 2:11:00 pm	27.76	12.29	32.40
2	29 Apr 2019 2:21:00 pm	27.80	12.56	31.53
3	29 Apr 2019 2:31:00 pm	27.75	12.01	29.31
4	29 Apr 2019 2:41:00 pm	27.58	11.06	28.74
5	29 Apr 2019 2:51:00 pm	26.67	10.89	29.13
6	29 Apr 2019 3:01:00 pm	26.67	11.13	30.15
7	29 Apr 2019 3:11:00 pm	26.52	11.06	29.94
8	29 Apr 2019 3:21:00 pm	26.60	11.49	31.85
9	29 Apr 2019 3:31:00 pm	26.49	11.73	31.50
10	29 Apr 2019 3:41:00 pm	26.28	11.96	30.59
11	29 Apr 2019 3:51:00 pm	24.54	11.68	30.62
12	29 Apr 2019 4:01:00 pm	24.75	12.17	31.63
13	29 Apr 2019 4:11:00 pm	27.04	11.94	30.86
14	29 Apr 2019 4:21:00 pm	27.60	11.79	31.01
15	29 Apr 2019 4:31:00 pm	27.15	11.73	32.90
16	29 Apr 2019 4:41:00 pm	27.00	11.56	32.81
17	29 Apr 2019 4:51:00 pm	27.78	12.11	33.74
18	29 Apr 2019 5:01:00 pm	28.11	12.64	34.58
19	29 Apr 2019 5:11:00 pm	27.16	13.01	33.91
20	29 Apr 2019 5:21:00 pm	28.78	13.25	34.75
21	29 Apr 2019 5:31:00 pm	29.78	13.84	34.80
22	29 Apr 2019 5:41:00 pm	31.56	14.13	34.81
23	29 Apr 2019 5:51:00 pm	31.97	13.29	35.97
24	29 Apr 2019 6:01:00 pm	32.05	13.12	35.76
25	29 Apr 2019 6:11:00 pm	34.35	13.16	34.97
26	29 Apr 2019 6:21:00 pm	37.59	13.81	36.05
27	29 Apr 2019 6:31:00 pm	34.79	13.64	36.05
28	29 Apr 2019 6:41:00 pm	34.86	13.49	36.05
29	29 Apr 2019 6:51:00 pm	34.76	13.25	37.16
30	29 Apr 2019 7:01:00 pm	35.78	13.07	40.33
31	29 Apr 2019 7:11:00 pm	37.14	13.06	39.35
32	29 Apr 2019 7:21:00 pm	36.98	13.14	39.29
33	29 Apr 2019 7:31:00 pm	36.91	13.59	40.29
34	29 Apr 2019 7:41:00 pm	36.73	13.99	38.34
35	29 Apr 2019 7:51:00 pm	38.21	14.28	41.13
36	29 Apr 2019 8:01:00 pm	38.57	14.21	40.50
37	29 Apr 2019 8:11:00 pm	38.51	14.00	39.61
38	29 Apr 2019 8:21:00 pm	36.25	13.92	39.34
39	29 Apr 2019 8:31:00 pm	36.88	13.81	40.05
40	29 Apr 2019 8:41:00 pm	37.07	13.24	40.48
41	29 Apr 2019 8:51:00 pm	37.79	13.25	41.93
42	29 Apr 2019 9:01:00 pm	38.57	13.53	43.12
43	29 Apr 2019 9:11:00 pm	35.31	13.60	40.84
44	29 Apr 2019 9:21:00 pm	38.31	13.73	40.45
45	29 Apr 2019 9:31:00 pm	37.56	14.85	40.40
46	29 Apr 2019 9:41:00 pm	36.80	14.46	42.32
47	29 Apr 2019 9:51:00 pm	37.31	14.82	42.30
48	29 Apr 2019 10:01:00 pm	38.09	14.60	41.08
49	29 Apr 2019 10:11:00 pm	36.39	15.33	39.55
50	29 Apr 2019 10:21:00 pm	36.15	14.95	40.66
51	29 Apr 2019 10:31:00 pm	37.68	14.91	40.97
52	29 Apr 2019 10:41:00 pm	36.64	14.80	40.00
53	29 Apr 2019 10:51:00 pm	34.77	17.17	40.35
54	29 Apr 2019 11:01:00 pm	35.98	18.21	37.50
55	29 Apr 2019 11:11:00 pm	37.01	19.21	36.35
56	29 Apr 2019 11:21:00 pm	37.10	19.06	38.63
57	29 Apr 2019 11:31:00 pm	34.58	17.69	37.71
58	29 Apr 2019 11:41:00 pm	37.23	16.94	39.78
59	29 Apr 2019 11:51:00 pm	36.09	18.08	41.27
60	30 Apr 2019 12:01:00 am	34.29	17.66	41.03
61	30 Apr 2019 12:11:00 am	36.07	17.27	39.81
62	30 Apr 2019 12:21:00 am	37.45	17.97	40.10
63	30 Apr 2019 12:31:00 am	34.28	18.58	39.53
64	30 Apr 2019 12:41:00 am	37.77	18.14	40.58
65	30 Apr 2019 12:51:00 am	36.82	18.88	42.09
66	30 Apr 2019 1:01:00 am	34.81	18.74	44.61
67	30 Apr 2019 1:11:00 am	35.44	17.60	41.84
68	30 Apr 2019 1:21:00 am	37.22	19.18	42.70
69	30 Apr 2019 1:31:00 am	33.77	18.80	39.92
70	30 Apr 2019 1:41:00 am	37.05	18.45	41.31
71	30 Apr 2019 1:51:00 am	34.91	18.31	41.72
72	30 Apr 2019 2:01:00 am	35.67	17.88	41.25
73	30 Apr 2019 2:11:00 am	35.74	18.37	40.52

Table A- 5: Voltage Total Harmonic Distortion of a typical Distribution Feeder (One day)

	Time	thdV1_Avg [%]	thdV2_Avg [%]	thdV3_Avg [%]
1	29 Apr 2019 2:11:00 pm	2.95	2.26	3.21
2	29 Apr 2019 2:21:00 pm	2.90	2.30	3.16
3	29 Apr 2019 2:31:00 pm	2.88	2.25	3.11
4	29 Apr 2019 2:41:00 pm	2.88	2.18	3.10
5	29 Apr 2019 2:51:00 pm	2.85	2.10	3.08
6	29 Apr 2019 3:01:00 pm	2.89	2.09	3.12
7	29 Apr 2019 3:11:00 pm	2.94	2.11	3.15
8	29 Apr 2019 3:21:00 pm	2.95	2.12	3.14
9	29 Apr 2019 3:31:00 pm	2.89	2.09	3.04
10	29 Apr 2019 3:41:00 pm	2.86	2.12	3.08
11	29 Apr 2019 3:51:00 pm	2.77	2.10	3.03
12	29 Apr 2019 4:01:00 pm	2.76	2.09	2.94
13	29 Apr 2019 4:11:00 pm	2.75	2.05	2.86
14	29 Apr 2019 4:21:00 pm	2.74	2.03	2.82
15	29 Apr 2019 4:31:00 pm	2.70	2.05	2.82
16	29 Apr 2019 4:41:00 pm	2.67	2.03	2.77
17	29 Apr 2019 4:51:00 pm	2.60	2.03	2.74
18	29 Apr 2019 5:01:00 pm	2.57	2.04	2.72
19	29 Apr 2019 5:11:00 pm	2.55	2.05	2.71
20	29 Apr 2019 5:21:00 pm	2.53	2.04	2.67
21	29 Apr 2019 5:31:00 pm	2.59	2.05	2.72
22	29 Apr 2019 5:41:00 pm	2.63	2.00	2.71
23	29 Apr 2019 5:51:00 pm	2.61	1.97	2.70
24	29 Apr 2019 6:01:00 pm	2.53	1.93	2.64
25	29 Apr 2019 6:11:00 pm	2.49	1.92	2.66
26	29 Apr 2019 6:21:00 pm	2.46	1.92	2.69
27	29 Apr 2019 6:31:00 pm	2.46	1.90	2.68
28	29 Apr 2019 6:41:00 pm	2.44	1.90	2.67
29	29 Apr 2019 6:51:00 pm	2.47	1.91	2.71
30	29 Apr 2019 7:01:00 pm	2.54	1.96	2.77
31	29 Apr 2019 7:11:00 pm	2.57	1.99	2.78
32	29 Apr 2019 7:21:00 pm	2.53	2.00	2.77
33	29 Apr 2019 7:31:00 pm	2.51	2.00	2.78
34	29 Apr 2019 7:41:00 pm	2.55	1.99	2.74
35	29 Apr 2019 7:51:00 pm	2.57	2.00	2.73
36	29 Apr 2019 8:01:00 pm	2.57	2.03	2.74
37	29 Apr 2019 8:11:00 pm	2.61	2.07	2.71
38	29 Apr 2019 8:21:00 pm	2.66	2.08	2.77
39	29 Apr 2019 8:31:00 pm	2.73	2.18	2.90
40	29 Apr 2019 8:41:00 pm	2.77	2.18	2.89
41	29 Apr 2019 8:51:00 pm	2.79	2.20	2.92
42	29 Apr 2019 9:01:00 pm	2.76	2.18	2.91
43	29 Apr 2019 9:11:00 pm	2.72	2.11	2.88
44	29 Apr 2019 9:21:00 pm	2.73	2.12	2.88
45	29 Apr 2019 9:31:00 pm	2.75	2.16	2.90
46	29 Apr 2019 9:41:00 pm	2.73	2.12	2.89
47	29 Apr 2019 9:51:00 pm	2.73	2.12	2.89
48	29 Apr 2019 10:01:00 pm	2.76	2.14	2.86
49	29 Apr 2019 10:11:00 pm	2.82	2.19	2.90
50	29 Apr 2019 10:21:00 pm	2.80	2.15	2.89
51	29 Apr 2019 10:31:00 pm	2.77	2.13	2.84
52	29 Apr 2019 10:41:00 pm	2.76	2.17	2.88
53	29 Apr 2019 10:51:00 pm	2.76	2.16	2.86
54	29 Apr 2019 11:01:00 pm	2.80	2.18	2.85
55	29 Apr 2019 11:11:00 pm	2.79	2.17	2.80
56	29 Apr 2019 11:21:00 pm	2.79	2.12	2.83
57	29 Apr 2019 11:31:00 pm	2.79	2.11	2.84
58	29 Apr 2019 11:41:00 pm	2.81	2.07	2.84
59	29 Apr 2019 11:51:00 pm	2.78	2.11	2.86
60	30 Apr 2019 12:01:00 am	2.72	2.10	2.89
61	30 Apr 2019 12:11:00 am	2.74	2.07	2.85
62	30 Apr 2019 12:21:00 am	2.74	2.07	2.86
63	30 Apr 2019 12:31:00 am	2.76	2.08	2.85
64	30 Apr 2019 12:41:00 am	2.74	2.07	2.80
65	30 Apr 2019 12:51:00 am	2.74	2.07	2.80
66	30 Apr 2019 1:01:00 am	2.80	2.11	2.85
67	30 Apr 2019 1:11:00 am	2.85	2.15	2.91
68	30 Apr 2019 1:21:00 am	2.82	2.15	2.91
69	30 Apr 2019 1:31:00 am	2.82	2.15	2.85
70	30 Apr 2019 1:41:00 am	2.83	2.14	2.87
71	30 Apr 2019 1:51:00 am	2.83	2.17	2.91
72	30 Apr 2019 2:01:00 am	2.82	2.14	2.90
73	30 Apr 2019 2:11:00 am	2.79	2.11	2.86

Appendix B

Calculation of the Source Current after compensation

$$\boldsymbol{I_S^0} = \frac{1}{3}\left[I_{ar} + I_{br} + I_{cr}\right] - j\frac{1}{3}\left[I_{ai} + I_{bi} + I_{ci}\right] + 0 + \frac{1}{3}\left[\frac{\sqrt{3}}{2}\left(I_c^Y - I_b^Y\right) + j\,\frac{1}{2}\left(I_b^Y + I_c^Y - 2 * I_a^Y\right)\right]$$

(Zero Sequence of the Source Current after compensation)

$$\boldsymbol{I_S^+} = \frac{1}{3}\left[I_{ar} - \frac{1}{2}\left(I_{br} + I_{cr}\right) + \frac{\sqrt{3}}{2}\left(I_{ci} - I_{bi}\right)\right] + j\,\frac{1}{3}\left[I_{ai} - \frac{1}{2}\left(I_{bi} + I_{ci}\right) - \frac{\sqrt{3}}{2}\left(I_{br} - I_{cr}\right)\right] + -j\frac{1}{\sqrt{3}}\left[I_{ab}^D + I_{bc}^D + I_{ca}^D\right] + -j\,\frac{1}{3}\left(I_a^Y + I_b^Y + I_c^Y\right)$$

(Positive Sequence of the Source Current after compensation)

$$\boldsymbol{I_S^-} = \frac{1}{3}\left[I_{ar} - \frac{1}{2}\left(I_{br} + I_{cr}\right) + \frac{\sqrt{3}}{2}\left(I_{bi} - I_{ci}\right)\right] + j\,\frac{1}{3}\left[I_{ai} - \frac{1}{2}\left(I_{bi} + I_{ci}\right) - \frac{\sqrt{3}}{2}\left(I_{br} - I_{cr}\right)\right] + \frac{1}{2}\left[\left(I_{ab}^D - I_{bc}^D\right) + j\frac{1}{\sqrt{3}}\left(2 * I_{bc}^D - I_{ab}^D - I_{ca}^D\right)\right] + \frac{1}{3}\left[\frac{\sqrt{3}}{2}\left(I_b^Y - I_c^Y\right) + j\,\frac{1}{2}\left(I_b^Y + I_c^Y - 2 * I_a^Y\right)\right]$$

(Negative Sequence of the Source Current after compensation)

Considering these six conditions represented in the equations below in the source currents yields

$I_{ab}^D + I_{bc}^D + I_{ca}^D = 0$	*Condition 1*
$Imag\ I_s^+ = 0$,	$Condition\ 2$
$Imag I_s^- = 0$	$Condition\ 3$
$Real\ I_s^- = 0$,	$Condition\ 4$
$Imag I_s^0 = 0$	$Condition\ 5$
$Real\ I_s^0 = 0$,	$Condition\ 6$

$$\begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \\ X_6 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 1 & 1 & 1 \\ -2 & 1 & 1 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 & 0 & 0 \\ -1 & -1 & -1 & -\sqrt{3} & -\sqrt{3} & -\sqrt{3} \\ -2 & 1 & 1 & -\sqrt{3} & 2\sqrt{3} & -\sqrt{3} \\ 0 & 1 & -1 & \sqrt{3} & 0 & -\sqrt{3} \end{bmatrix} \begin{bmatrix} I_a^Y \\ I_b^Y \\ I_c^Y \\ I_{ab}^D \\ I_{bc}^D \\ I_{ca}^D \end{bmatrix}$$

Where X1 – X6 represents the conditions stated above