POWER QUALITY ENHANCEMENT IN SECONDARY ELECTRIC POWER DISTRUBUTION NETWORKS USING DYNAMIC VOLTAGE RESTORER

UNIVERSITY OF KWAZULU-NATAL™
INYUVESI YAKWAZULU-NATALI

By

Patrick Taiwo Ogunboyo
216076235

A thesis submitted in fulfilment of the requirements for the award of the
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School of Engineering
College of Agriculture, Engineering and Science

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CERTIFICATION

I, Patrick Taiwo Ogunboyo, hereby certify that the research work presented in this thesis entitled ‘‘Power Quality Enhancement in Secondary Electric Distribution Networks using Dynamic Voltage Restorer’’ is an authentic record of my own work carried out under the guidance of Dr Remy Tiako and Professor Innocent E. Davidson. The work contained in this thesis has not been previously submitted in part or whole for an award of any degree at this or any other University/higher education institution. To the best of my knowledge, this thesis contains no material previously published or written by another person except where due references have been made.

Signed: ……………………………………………
Patrick Taiwo Ogunboyo
Date: May 2018

As the candidate’s Supervisor I agree / do not agree to the submission of this thesis.

…………………………………………… ………………………………..
Dr Remy Tiako Date

…………………………………………… ………………………………..
Professor Innocent E Davidson Date

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DECLARATION 2 – PUBLICATIONS

Publications emanating from the PhD research study are as follows:

Articles in Peer Reviewed DHET Accredited Journals:

[1] P. T Ogunboyo, R. Tiako and I. E Davidson, "Application of Dynamic Voltage Restorer for Power Quality Improvement in Low Voltage Electrical Power Distribution Network: An Overview," *International Journal of Engineering Research in Africa*, vol. 28, pp. 142-156, Jan. 2017.

[2] P. T Ogunboyo, R. Tiako and I. E Davidson, "Voltage Unbalance Mitigation and Voltage Profile Enhancement in Secondary Distribution System Using Dynamic Voltage Restorer," *International Journal of Engineering Research in Africa*, vol. 34, pp. 88-101, Jan. 2018.

[3] P. T Ogunboyo, R. Tiako and I. E Davidson., **“**Investigation of Voltage Unbalance Profile in Low Voltage Electrical Distribution Network with Normal Mode Operation Using MATLAB,**’’** *International Journal of Engineering Research in Africa,* vol. 35, pp. 60-76, March 2018.

[4] P. T Ogunboyo, R. Tiako and I. E. Davidson, “Effectiveness of Dynamic Voltage Restorer for Unbalanced Voltage Mitigation and Voltage Profile Improvement in Secondary Distribution System,’’ A manuscript accepted for publication by *Canadian Journal of Electrical and Computer Engineering*, Manuscript ID-CJECE-OA-2017-Oct-144. 17th July 2018. [in press]

[5] P. T Ogunboyo, R. Tiako and I. E. Davidson, “Effectiveness of Dynamic Voltage Restorer in Mitigating Unbalance Voltage and Enhancing Low Voltage Profile in Secondary Distribution System,’’ Revised Manuscript ID: ISTE-D-17-00323R2 submitted to the *Iranian Journal of Science and Technology, Transactions of Electrical Engineering,* January, 2018.

Peer Reviewed Conferences Papers

[6] P. T Ogunboyo, R. Tiako and I. E. Davidson, “An Investigation of Voltage Quality in Low voltage Electric Power Distribution Network under Normal Operation Mode,” *EAI International Conference for Research, Innovation and Development for Africa ACRID, 2017,* Victoria Falls, Zimbabwe, *ACRID,* June 20–21, pp. 1-12, 2017. DOI 10.4108/eai.20-6-2017.2275689

[7] P. T Ogunboyo, R. Taiko and I. E. Davidson, “Voltage Profile Enhancement in Low Voltage 11/0.4 kV Electric Power Distribution Network Using Dynamic Voltage Restorer under Three Phase Balance Load”, Proceedings of the *13th IEEE Africon Conference,* Cape Town, South Africa, 18-20 September 2017, pp. 1034-1039.

[8] P. T Ogunboyo, R. Tiako and I. E. Davidson, "An Improvement of Voltage Unbalance in a Low Voltage 11/0.4 kV Electric Power distribution Network under 3-phase Unbalance Load Condition using Dynamic Voltage Restorer." Proceedings of the *IEEE PES-IAS PowerAfrica Conference*, Accra, Ghana, June 27-30, pp. 126 – 131, 2017.

[9] P. T Ogunboyo, R. Tiako and I. E. Davidson, "Investigation of Voltage Unbalance in Low Voltage Electric Power Distribution Network under Steady State Mode,'' Proceedings of the *3rd IEEE International Conference on Electro-Technology for National Development (NIGERCON) Conference,* Owerri, Nigeria, 7-10 November 2017, pp. 932-939, 2017.

[10] P. T. Ogunboyo, R. Tiako and I. E. Davidson, "Effectiveness of Dynamic Voltage Restorer in Enhancing Voltage Profile in Low Voltage Electric Power Distribution Networks under Normal Mode Operation". Proceedings of the *3rd IEEE International Conference on Electro-Technology for National Development (NIGERCON) Conference*, Owerri, Nigeria, 7-10 November 2017, pp. 839-847.

Other Publications - Abstracts and Workshop Presentations

[11] P. T Ogunboyo, R. Tiako and I. E. Davidson, "Evaluation of Power Quality in Smart Electrical Power Distribution Networks,'' College of Agriculture, Engineering and Science, *Postgraduate Research and Innovation* Day 2016, University of KwaZulu-Natal, 29 November 2016, Shepstone Lecture Theatre Complex, Howard College Campus, pp. 188, 2016.

[12] P. T Ogunboyo, R. Tiako and I. E. Davidson, "Effectiveness of Dynamic Voltage Restorer in Enhancing Voltage Quality in Secondary Distribution System,'' College of Agriculture, Engineering and Science, *Postgraduate Research and Innovation* Day 2017, University of KwaZulu-Natal, 26 October 2017, T-Block, Westville Campus, pp. 60, 2017.

[13] P. T Ogunboyo, R. Taiko and I. E. Davidson, "Enhancing Voltage Profile of Low Voltage 11/0.4 kV Electric Power Distribution Network using Dynamic Voltage Restorer,'' *4th Eskom Power Plant Engineering Institute* (EPPEI) *Student Workshop at* Ian McRae Auditorium, General Section 4, Johannesburg, South Africa, 29 &30 May 2017, pp. 56-57, 2017.

Signed: ………Ogunboyo P.T………………………………………

DEDICATION

This research work is wholly dedicated to the Almighty God, the Ancient of days for His faithfulness throughout the period of this academic pursuit/study, may His name be praised forever.

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ABSTRACT

This research study investigates and proposes an effective and efficient method for improving voltage profile and mitigating unbalance voltage, voltage variation disturbances in rural and urban secondary distribution networks. It also proffers solutions for improving the performance of future distribution networks in order to increase the optimum functioning, security and quality of electricity supply to end users, thus making the power grid smarter. This study involves the compensation of power quality disturbance in balanced and unbalanced, short and long distribution networks. The mitigation of result of this voltage variation, poor voltage profile and voltage unbalance with an effective power electronics based custom power controller known as Dynamic Voltage Restorer (DVR) conceived. DVR is usually connected between the source voltage and customer load. An innovative new design-model of the DVR has been proposed and developed using a dq0 controller and proportional integral (PI) controller method. Model simulation was carried out using MATLAB/Simulink in Sim Power System tool box. An analysis of the results obtained when the new DVR is not connected to and tested on LV networks shows that the voltage profile, percentage voltage deviation and percentage voltage unbalance for 0.5 km for balanced and unbalanced distribution networks are within standards and acceptable limits, hence, the voltages are admissible for customers' use. It was further established that the voltage profile, percentage voltage unbalance, voltage drop and percentage voltage deviation for distribution networks of 0.8 km to 5 km range from the beginning to the end of the feeder are less than the statutory voltage limits of -5%, 2 %, 5 % and ± 5 % respectively, hence, voltages are inadmissible for customers' use. Others results obtained when DVR was connected recognized that for distribution feeder lengths of 0.5 km to 5 km range for balanced and unbalanced, short and long distribution networks the voltage profile, voltage variation, voltage drop and percentage voltage unbalance are within statutory voltage limits of 0.95 p.u and 1.05 p.u, -5 %, and less than 2 % respectively. Based on this investigation, and in order to achieve efficient, reliable and cost-effective techniques for improving voltage profiles, decreasing voltage variations and reducing voltage unbalances, the new DVR model is recommended for enhancing optimal performances of secondary distribution networks.

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LIST OF ABBREVIATIONS

DN	Distribution network
DNs	Distribution networks
VU	Voltage unbalance
VV	Voltage variation
PVU	Percentage voltage unbalance
ES	Energy storing
VDr	Voltage drop
VD	Voltage deviation
SEPDNs	Secondary electric power distribution system
PQ	Power quality
FACTS	Flexible alternate current transmission system
UPFC	Unified power flow controller
TCSC	Thyristor controlled switch capacitor
I	Symbol for current
kV	Kilovolt or 1000 volt
kVA	Kilovolt ampere or 1000 volt ampere
L	Symbol for Inductance
DC	Alternating current
LV	Low voltage
W	Watt
V	Volt
MW	Megawatt (10^6 Watt)
MVA	Megavolt Ampere or 10^6 volt ampere
R	Resistance
A	Ampere
UPQC	Unified power quality compensation
CPDs	Custom power devices
DSTATCOM	Distribution static compensator
DVR	Dynamic voltage restorer
APF	Active power filter
TSC	Thermistor switched capacitor
SVR	Static VAR compensator
UPS	Uninterruptible power supply
BESS	Battery energy storage systems
SMES	Super conducting magnetic energy system
SSTS	Solid state transfer switches
DSC	Distribution series capacitors
VSC	Voltage source converter

PWM	Pulse width modulator
ANSI	America national standard institute
NEC	National electricity commission
IEEE	Institute of electrical and electronics engineers
NEMA	National electrical manufacturers association
EPS	Electric power system
HT	High tension
LT	Low tension
TDN	Township distribution network
ACSR	Aluminium conductor steel reinforced
ITC	Intra township connection
NAERC	North American electric reliability council
EN	European norm
IEC	Electro-technical commission
PV	Photovoltaic
PI	Proportional integral
DQ0	Direct current quadrature
PLL	Phase locked loop
STATCOM	Static synchronous compensator
TCSR	Thyristor-controlled series reactor
Abc	Three phase load voltage
VP	Voltage Profile
EPDN	Electric Power Distribution Network
DVr	Voltage Drop
DS	Distribution System
SDS	Secondary distribution System

CHAPTER ONE

INTRODUCTION

1.1 Background

All purpose demand for electric power coupled with essential requirements of comparatively high security of power supply with low cost for rural and urban communities are the main drivers of present day electric power grid paradigm shift toward the direction of power quality. Power quality (PQ) problems of power systems have been receiving extensive attention in our present society. Goutsias [1] defined power quality as the suitability of consuming electrical energy to users of electrical devices and machines. In the same vein, Leborgne, Bollen, Dermott, Arrillaga and Bollen respectively [2-6] defined power quality as the distinct deviations between the specified normal operating condition of supply voltage, frequency, current and voltage curve wave-form which is able to make electrical device fail to work normally or disallowing them of being useful. Suitable power quality enables power systems to function in their designed way without meaningful reduction in effective operation of the system or life span. Without acceptable power quality, electrical device may end up being damaged or harmed or it may lead to complete stoppage in the operation of the electrical device. There are a large number of non-linear loads and impact loads, which results in problem of grid harmonics, phase unbalance, voltage variation and flicker. On the other hand, power customers demand for higher and higher power quality level [7]. The emergence of PQ problems not only depends on the power electricity enterprise, but also depends on the equipment manufacturers and power consumers. In particular some PQ indicators (such as harmonics, voltage variations and flicker) are often caused by customers. The ultimate solution relies on the power electricity enterprise, equipment manufacturers and customer [7].

It is required of distribution companies to ascertain that the users of electricity are provided with acceptable PQ. In secondary distribution systems, voltage unbalance and voltage variation are among the power quality issues which are of the utmost concerns [7]. In the distribution system, during the peak period’s decrease in voltage can be noticed while during the off-peak periods increase in voltage can be experienced [8]. The electricity distribution companies are saddled with the duty of ensuring that the electric potential in their distribution systems are within statutory limits in order to prevent customers’ electrical devices from failure to operate normally. Voltage unbalance is to a greater extent widely found in specific person end user loads as a result of phase load unbalance, mostly where large single-phase loads are utilized [8]. Notwithstanding, voltages are evenly stable and properly balanced on the transmission side, but as a result of inadequate transposition of the phases, larger or asymmetric distribution of single phase load, phase to phase load, unbalanced three phase loads and unevenly impedances of a three phase distribution system the voltages at the terminal can become unbalanced [8]. According to Jouanne [9], the purpose of energy companies' purpose is to share the end users loads evenly within the three-phases of electric power distribution system (DS). Amplification in unbalanced voltage leads to lower rating capability and overheating of all induction motor categories and loads [10]. Similarly, unbalanced voltage can result in system disturbances like failure of protective relays to function normally and mal-operation of equipment needed to perform voltage control and production of non-characteristics harmonics from power electronics loads [9].

The generation of flexible AC transmission system (FACTS) devices were employed in the early 1970s, FACTS controllers are employed in electric grid for the purpose of enhancing of power quality of such devices which include: VAR compensator (SVC), unified power flow controller (UPFC), thyristor-controlled switch capacitor (TCSC), static synchronous compensator (STATCOM), and thyristor-controlled series reactor (TCSR) and so on. These FACTS tools are designed purposely for the transmission grid. Nonetheless, in the present periods more concentration is on the electric power distribution networks (DNs) for the enhancement of acceptable power quality, these tools improve upon and generally recognized as custom power devices (CPDs) which are employed in electric power distribution system. The foremost CPDs which are employed in electric power DNs are active power filter (APF), thermistor switched capacitor (TSC), static var compensator (SVR), uninterruptible power supply (UPS), solid state transfer switches (SSTS), distribution series capacitors (DSC), unified power quality conditioner (UPQC), dynamic voltage restorer (DVR) and distribution static synchronous compensator (DSTATCOM)

In this research investigation, (CPD) generally recognized as DVR is used with proportional and integral (PI) controller and pulse width modulation (PWM), generator for the PQ enhancement in secondary electric distribution systems. Balanced and unbalanced secondary distribution system network are considered. Similarly, different distribution feeder lengths are considered with balanced and unbalanced loads to study the optimum effectiveness of DVR in improving the PQ in secondary electric power DNs.

1.2 Scope of the Research

It is examined from the literature that there is an urgent need to investigate the efficiency of compensating devices for voltage variation and voltage unbalance for balanced and unbalanced secondary electric power distribution network with maximum loading for short and long feeder lengths in secondary electric power DNs. This is to access the permissible standard voltage variation and specified acceptable voltage unbalance from the start of distribution feeder to the extreme of distribution feeder. Knowing that electric power DNs is positioned at the final end of power grid and is linked to the customers completely, it behoves therefore, that the dependability of the entire electric power supply largely relies on the performance of secondary electric power distribution system. In as much as the end users desire for quality and security of electric power supply is increasing every day. Therefore, the dependability and security of the secondary electric power DNs have to be intensified. Having the knowledge that electric power DN total failure or mal-functioning of customer equipment accounts for about ninety percent of the average end user interruptions, it is highly imperative to increase the quality of power and the security of supply of secondary electric power distribution networks. Hence the aim of this study is to investigate the existing secondary electric power distribution network with maximum acceptable loading condition with short and long, balanced and unbalanced feeder length at steady state condition. The network of an existing short and long, balanced and unbalanced secondary electric power distribution for possible voltage unbalance, voltage variation, voltage fluctuation, and low voltage profile will be designed and modelled using MATLAB/Simulink software in Sim Power System tool box. And also highlighting to find an effective solution using custom power electronic device known as DVR to provide efficacious, cost effective and easy to maintain technique to the power quality problems was conducted in this study.

1.3 Motivation for the Research

In the early 1960s, the major problem of end users was the consistent supply of electricity, which means security of power supply. Today’s consumers require security/guarantee of supply and quality of power. For illustration, a consumer may encounter unexpected voltage unbalance affecting its responsive loads. Depending on the responsiveness of the consumers’ loads, this voltage unbalance may cause malfunction or complete failure of the system or loads to operate normally. Examples of very sensitive loads can be found in industries, hospitals, houses, banks, institutions, airports and different companies. These require dependable, accurate, trusted and acceptable power supply. In previous investigations, methods have been proposed for the assessment of voltage unbalance and variations as seen in single and three phase equipment. This study points out that application of custom power device (CPD) will be high quality over present techniques to improve the voltage profile (VP) and mitigate voltage unbalance in secondary electric power DNs. The use of CPD referred to as a DVR which provides a fast response, easy maintenance, simple, effective, efficient and cost effective compensation to the secondary electric power DNs to mitigate voltage variation and voltage unbalance problems using MATLAB/Simulink software in Sim Power System tool box will be an effective and efficient approach to reducing PQ disturbances in secondary electric power DNs.

1.4 Key Research Questions

There are two principal questions this study attempts to answer:

- Can the custom power device known as DVR be employed for voltage unbalance correction, voltage profile enhancement, voltage variation reduction and for voltage regulation for short and long feeder length in secondary electric power distribution network?
- What is the effect of using the DVR for voltage unbalance correction, voltage profile enhancement and voltage variation reduction length in secondary electric power distribution network using MATLAB/Simulink software?

1.5 Aim and Objectives of the Research

1.5.1 Aim of the Research

The primary aim of this research is to investigate and proffer effective and efficient technique for improving the VP and mitigating voltage unbalance, voltage variation, voltage/fluctuation problems in secondary electric power DNs. This offers effectual solutions in enhancing the effectiveness of future electric power DNs so as to increase the optimum performance of energy supply to customers, thus making the power grid smarter.

1.5.2 Objectives of the Research

The objectives of this research are to:

a) design and model secondary distribution network using MATLAB/Simulink software;
b) investigate the problems of voltage unbalance and voltage variation in balanced and unbalanced star-connected load in secondary electric power DNs;
c) enhance voltage variation and mitigate low voltage profile in balanced star connected load using DVR in secondary electric power DNs;
d) mitigate voltage unbalance and enhance poor voltage profile in unbalanced star-connected load using DVR in secondary electric power DNs; and
e) make recommendations for voltage variation enhancement and voltage unbalance correction in balanced and unbalanced star connected load in secondary electric power DNs, thus making the DN grid smarter.

1.6 Limitation of the Research

The research is limited to secondary distribution systems and does not include generation, transmission systems. The study investigates the power quality problems such as: voltage unbalance and voltage variation/fluctuation in secondary electric power distribution network of 11/0.4 kV, with permissible maximum load and for short and long, balanced and unbalanced feeder length. Finally the research offers an efficacious and cost effective solution to solve the power quality problems investigated using custom power device known as dynamic voltage restorer.

1.7 Research Methodology and Design

This study entails a thorough investigation of PQ such as: voltage unbalance, voltage variation and low VP in relation to secondary electric power distribution network under balanced and unbalanced system with short and long feeders. The main focus of the study is to provide efficient and cost-effective technique for voltage unbalance mitigation, voltage variation and low voltage profile enhancement method. The study followed the following steps:

- Thorough study of secondary distribution network to be investigated;
- Design and model of a network for the investigated study;
- Simulation of the modelled network;
- Analysis of results.

The second focus is to find an effective custom power device in order to mitigate the power quality disturbances observed during investigation. The following steps were followed:

- Thorough study of custom power device known as DVR;
- Design and model of the DVR circuit to the investigated network;
- Simulation of the modelled network; and
- Analysis of results.

1.8 Significance of the Research

Voltage unbalance, voltage variation and low voltage profile are amongst the extremely unpleasant PQ problems in secondary electric power DNs. Solar, Photovoltaic (PV), and wind energy are emerging as the most competitive and environmentally friendly renewable energy options for generating electricity but these are intermittent sources. With the growing quantity of renewable energy supplied into Transmission and Distribution (T&D) grids, and the fast absorption of PVs installations in residential areas, PQ problems are anticipated to be extremely high in time to come. This study develops innovative way of solving the electric power quality problems such as: voltage variation/fluctuation, poor voltage profile and voltage unbalance in DNs. It is expected that the output of the study will improve or contribute in solving the problems of PQ and make electric power distribution systems smarter. This should consequently improve the security and quality of electricity supply to consumers.

1.9 Research Contribution to Knowledge

The research study provides some solutions to the PQ problems in secondary electric power DNs capable of improving reliability and security of power supply by quality and thermal requirements that will satisfy prevailing and future load conditions of end users. It employs advance solid-state power electronic device called DVR in secondary distribution system for balanced and unbalanced load, short and long feeders to improve the standard of voltage supply to the entire consumers to a statutory range of ± 5 % of the specified standard voltage value. It will ensure that voltage profile, for both balanced and unbalanced distribution system is maintained at constant magnitude. It also guarantees that the voltage drop and voltage unbalance experience on the network is kept at statutory limit of -5 % and less than 2 % respectively under any circumstances at steady state conditions. In summary, the proposed DVR technique offer:

(i) Reduction of voltage drops along the feeder length to standard permissible value of – 5 % specified nominal voltage value;

(ii) Enhancement of voltage profile to statutory voltage limits of ±5% of nominal voltage value and frequency to ± 1% from the start of the distribution feeder length to the terminal end of the network length;

(iii) Reduction of phase voltage imbalances in the network to acceptable standard of less than 2 %;

(iv) Improvement of voltage variation/fluctuation to acceptable allowable value within 0.95 p.u to 1.05 p.u of the specified nominal system voltage value

(v) Correction of phase shift and frequency shift to acceptable standards by the use of phase locked loop; and

(vi) Optimum performance of electric power distribution network and reduction of harmonic to the minimum acceptable value.

1.10 Organization of the Thesis

Chapter 1: **Introduction**

Chapter one presents the introduction to the research, motivation for the research, aim and objectives of the research, significance of the study, scope and limitation of the study, research methodology and research contribution to knowledge.

Chapter 2: Literature review

Chapter two introduces the concept of power quality in electric power system. The chapter also explains distribution system, voltage variations, voltage unbalance, voltage drops, custom power devices, conventional techniques for distribution network improvement and finally, review of recent related studies on power quality issues on electric power distribution systems.

Chapter 3: Investigation of voltage unbalance and voltage variation

Chapter three presents voltage unbalance and voltage variation investigation for secondary electric power DNs 11/0.4 kV, 500 kVA, urban and rural network under normal operating mode. The secondary electric power network was designed and modelled in MATLAB/Simulink software in Sim Power System tool box. Simulation and analysis of results were carried out for balanced and unbalanced distribution network with short and long feeder length.

Chapter 4: Dynamic voltage restorer

Chapter four discusses the operation and application of DVR in secondary electric power DNs. Different basic DVR topologies are presented with control techniques for real energy access in the event of voltage unbalance and voltage variations. Lastly, DVR protection is discussed.

Chapter 5: Application of DVR to the network

Chapter five presents the connection of DVR to the investigated network in chapter three.

- Design and model of DVR to the investigated network
- Network simulation
- Analysis of results
- Discussion of results

Chapter 6: Conclusions and Recommendations

Chapter six discusses conclusions and recommendations drawn from the study and recommend possible future research topics.

CHAPTER TWO

LITERATURE REVIEW

The subject of PQ is examined in this chapter, including voltage variations, voltage unbalance, custom power devices, conventional techniques of distribution network improvement and the review of recent related studies on power quality issues on electric power distribution systems.

2.1. Introduction

PQ describes the steady supply of voltage that remains within the recommended specified nominal value, constant AC frequency near the rated standard value and smooth voltage curve wave-forms in electric power systems. Electric Power DNs are considered the utmost route between large-scale production company and the end users. The DNs section is open to all people to see, access and evaluate. Therefore, it is highly important to investigate PQ in DNs. Consequently, electric power DNs are at all times vulnerable to traditional influence of voltage unbalance, voltage variation, fluctuation, dip, sag, swell and harmonics, which damage the sine wave shape and reduce PQ as well as the security of supply of DNs. These are the abnormal conditions which are forced on the DNs by the end users causing unpleasant situation to other users of energy and the system value items. Therefore, the distribution industry is devoted to making available to the end users a dependable, acceptable power of standard quality. PQ problems are examined to be of unpleasant harm for the power generation and distribution system [11-14]. PQ and associated subjects are of utmost concern in distribution system.

The widespread use of power electronic devices, electronic goods, adjustable speed drives, energy sufficient lighting, programmable logic controllers, result in total change of type of system loads. These loads are directly the main causes and the most affected of PQ problems. As a result of load non-linearity, it leads to system disruptions in waveform of the voltage profile. With the advent of new technology development, the organization of the entire world economy has developed gradually towards globalization and the benefit limit of considerable number of events are likely to reduce. In the event of system disruptions, enormous financial losses may occur, with the effect of reduction in rate of production and less competitiveness. Notwithstanding, a lot of energy which has been asserted by power companies, quite a few end users need an amount of PQ above the level made available by present day distribution systems. This means that actions must be taken to accomplish acceptable and correct state of PQ. How important it is to effectively use energy, reflecting on its significance in the modern time and the resources committed in power generation, power transmission and electric power distribution. Firstly, in the DN very large number of end users of electricity consume energy in the same way. Secondly, it is proven that the highest quantity of power losses happens in the distribution system level. Thirdly, the electricity distribution market has been advanced technologically and the electricity distribution industries have been unbundled. Depending on the stated information about DN, the distribution companies that provide dependable, reliable and high quality acceptable energy for the consumers will record significant achievements.

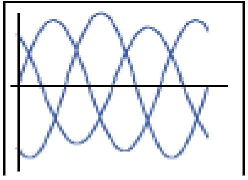
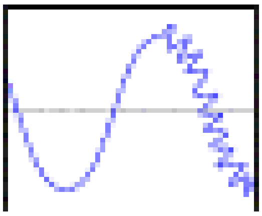
2.2. PQ in Electric Power DN

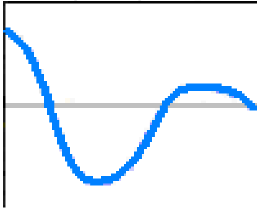
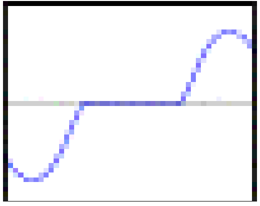
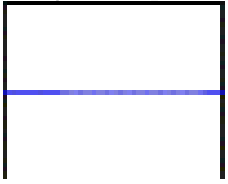
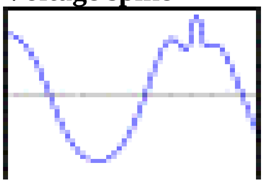
Roger [15] stated that PQ disturbances are enigmas that manifest in deviations of frequency, voltage and current. The consequence of this is failure or end user electrical devices mal-operation. IEEE Standard 100-1992 [12] defined PQ as broad principle of supplying power and providing suitable earthing system in a way that makes the electrical device operate in acceptable way. IEC 61000-2-1 (199990-05) [11] defined PQ as a measurable quantity showing the attributes of energy supply as provided to the consumer in steady state mode in term of voltage defining feature and continuity of energy supply. With reference to these cited definitions, it can be concluded that PQ is the deviation of voltage, frequency and current from normal operating conditions due to system disturbances. A long-term PQ occurrence results in electrical devices and customer components overheating, which in turn results in increased production of heat, the performance of network is greatly reduced and tools joined to it. Mostly, this leads to extra-repair works and eventually extra expenses for the distribution companies and the end users of electricity [9].

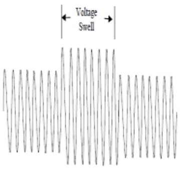
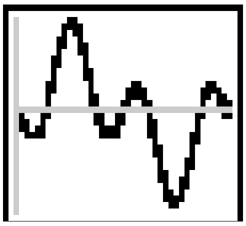
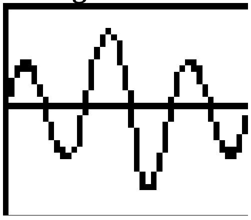
2.3. The Power Quality Issues

PQ problems comprises a comprehensive range of various phenomena, as depicted in Table 2.1. The occurrence has specific kind of causes, consequences and various ways of solving the problems in order to enhance the PQ in electric power DNs.

Table 2.1: **Power Quality Related Problems** [9], [16]

Power Quality Problems	Description	Causes	Consequences
Voltage Unbalance 	This is a situation in which the amplitude of distribution lines are not the same or the phase angle difference between them are not equal.	Large single phase loads; induction furnaces, traction loads, motors, improper arrangement of distribution single phase lines on 3-phase system.	The distribution system will not operate reliably, periodic cessation of controllers, overheating of elements, and considerable number of relays will not perform effectively.
Noise 	Incorporating top level signals on the shape of the wave of distribution system frequency.	A radio wave produced due to electromagnetic interference. Electromagnetic interference of a particular type of	Interruptions on responsive electronics items, usually not destructive. This may result in loss of information and mistakes in processing information

		microwaves, television diffusion.	
Voltage Sag (Dip) 	A reduction in voltage standard value within ten and ninety percent of acceptable voltage value for a period of one minute.	Failure of T&DNs. Failure in end user electrical devices.	Information technology devices fail to function normally, such as computers, control devices; this may result in complete stoppage. Breaking of mechanical devices. Separation and electrical machines loss of performance.
Very short interruption 	Complete break in operation of energy supply for some period within some seconds.	Primarily as a result of regulated opening and closing of safeguarding tools to disconnect a section that is malfunctioning in a distribution system. The principal causes of the failure include electric discharge around insulator, insulation failure, and so on.	Breaking of safeguarding devices, missing of data and improper performance of information processing devices. Complete stop of responsive electrical devices, for example ASDs, PLCs, when they are not ready to solve a particular problem.
Long interruption 	Overall disruption of electricity supply for maximum period of two seconds	Electrical devices poor performance in DNs, lightning and vehicles causing havoc to distribution lines or electric poles, bad coordination or poor operation of safeguarding devices.	Total Stoppage of all electrical devices and tools
Voltage spike 	Extremely fast voltage variation for a period of a few milliseconds.	Switching on of capacitors for pf mitigation on the distribution lines, or as a result of sudden breaking away of relatively large amount of loads.	Complete destruction of electronic elements. Failure of information processing errors or mistake in information loss,

Voltage swell  	A short time amplification of voltage and frequency, not within acceptable statutory range with period usually quite a few seconds.	Start/stop of heavy loads, badly dimensioned power sources, badly regulated transformers (mainly during off-peak hours).	Information missing, loss, adverse effect/ injury to responsive electrical devices, in the event of extremely high voltage
Harmonic distortion 	The shape of the wave of current and voltage takes up non sine wave form.	Switching of solid state power electronic devices, switching of information processing electrical devices and switching on of extreme effective light	Stochastic of resonance, probability of three-phase neutral system being overloaded, electrical devices and electrical wires can be overheated.
Voltage Variation 	Produce rhythmic motion within a set of voltage values within a period of time.	Electrical devices regular failure, periodic failure of motor controllers, and intermittent failure of elevators.	The results are widely found in low voltages. The main effect is unacceptable operation of electrical devices, equipment failure to very well and periodic shutdown of electronic devices.

2.4. Power Quality Standards

Worldwide, there are many standards on PQs. Different countries and regions of the world normally have their national or regional standards which regulate electricity from generation to distribution. However, the international standards have greater acceptability in many countries. Three most popular standards in PQ applications are briefly discussed.

2.4.1. IEC Standards

The International Electro-technical Commission (IEC) is a global body for maintaining quality with the objective of promoting international compliance on all questions relating to levels of quality and excellence in the area of electrical engineering. IEC prepares global acceptable norms among others which are popularly accepted worldwide. Examples on PQ are: IEC 61000-4-7, IEC 61000-3-2 IEC 61000-4-15 and the new IEC 61000-4-30 which provides general requirement for testing and measurement.

2.4.2. IEEE Standards

The Institution of Electrical and Electronic Engineer (IEEE) Standards is also an international standard commonly applied in PQ. IEEE 1159 Standard classifies various PQ problems. IEEE Std C57.110-1998 gives acceptable performance for setting up transformer competence when providing non-sine wave load currents.

2.4.3. EN 50160 Standards

The European Norm (EN) 50160 [17] standard is for low and medium voltage, usually experienced in the DNs. It specifies the potential parameter at the point of widely found joining. For instance, the standard on “voltage defining feature of energy provided by the state distribution organization” is given by EN 50160:2000.

2.5. Causes of Problems in Electric Power Distribution Networks.

According to Uhunmwangho [18] power system problems are unpleasant, but they do occur, especially as they cause power supply and quality failures. The causes of failures include ageing of power system infrastructures, increase in demand for energy which strains the system which leads ultimately to failure. Other causes include lightning, overgrown vegetation which causes short circuits in overhead lines, and severe weather conditions. Heavy storms do fall on overhead lines and also cause clashing of phase conductors in overhead lines.

In countries where there are reliability standards, violations of such standards contribute to the frequency of failures. The North American Electric Reliability Council (NAERC) in Bryar [19] reported that there is substantial increase in the violations of reliability voluntary rules. He [19] further stated that old fashioned and inadequate monitoring and protection system contribute to blackouts. Adeyemo et al [20] established that vandalization of electric power distribution system facilities is a one of causes of power outage. Rather unusual, power outage events involving animals, especially reptiles have been observed, and poor maintenance of substations allowing human and animal traffic into them causes short circuits. Uhunmwangho [18] found out in their study that transformer failures are a major problem in the DNs; these failures are due to overloading, inadequate maintenance as a result of irregular examination of components and reconditioning, and insulator breakdowns. The employment of substandard and outdated safeguarding equipment in Electric Power system (EPS) distribution substations also causes transformer failures.

An appraisal of these works shows that the causes of problems in electric power distribution network are varied and include: power quality problems; ageing of infrastructures; increase in demand and consequent overbearing strains on aged system; lightning strikes, causing overvoltage faults; overgrown vegetation which causes short circuits in overhead lines; and severe weather conditions, causing physical damage to lines; and violations of standards of system installations and operations.

2.6 Electric Power Distribution Systems

According to Gupta [21], electric power distribution network links the high voltage transmission system to the customer loads. In Rao and Uppal [22], a distribution network is defined as the medium through which power is being distributed to the load point. With reference to these cited definitions, it can be inferred that the distribution network is the component of a power grid that connects the consumers load points and services to the electric supply system.

2.6.1. Basic Distribution Systems

There are two most important configurations of distribution systems, namely: radial distribution system; and ring distribution system.

a) **Radial distribution system**: radial system is a system in which the electrical distributor is linked to the supply system on one end. This is depicted in Figure 2.1. In that situation, the terminal of the distributor closer to the distribution substation would be with great weight of load and the end users at the distant end of the distributor would be prone to large voltage variation (VV) as the load varies. The end user relies only on a single distribution feeder so that a failure or fault on any distribution feeder or distributor cuts off the power supply to the end users who are on the side of the fault away from the substation. There is a complete shut down until the fault is rectified.

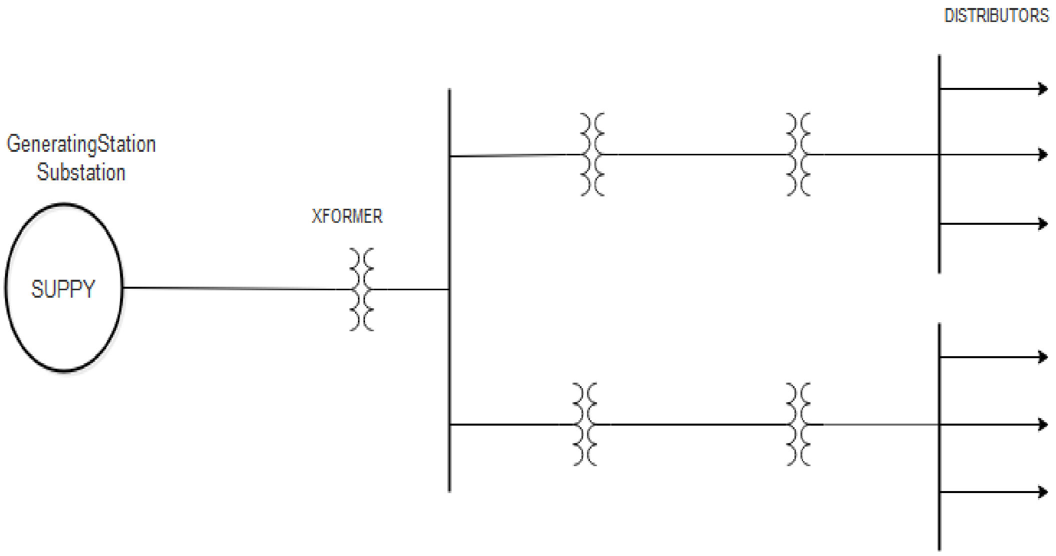


Figure 2.1 Radial distribution system

b) **Ring Main Distribution System:** The demerit of radial DN can be conquered by bringing in a ring main DN. Many distribution feeders are employed to feed the distributors of the ring system. In the event that a feeder is under repair as a result of failure or the network due for routine services or maintenance to improve the general condition of the network, the device that convey electricity is supplied with electrical power through other distribution feeders linked firmly to it. With this arrangement the feeder is always supplying needed electrical energy to the consumers feeding on the feeder, even in the event any feeder is under major repair or completely damaged. Furthermore, section isolators are made available on the feeder to ensure efficient separation of sections in the occurrence of fault on the EPS. This helps to open and close the faulty section during fault. Figure 2.2 shows the ring main distribution network.

Consequently, feeding the end users linked to the good and physical condition section of the ring system, the system can be kept in working order without difficulty even during cessation or maintenance periods. The following factors will determine the number of distribution feeders needed to be linked to ring main DNs:

- Greatest possible request of the network: if the consumer demand is much, the more the numbers of distribution feeders that supply the ring system;
- The ring main distributor overall Length: in case the distributor length is much, distribution feeder must be linked to the ring, to mitigate voltage drop in the distribution line; and
- Voltage regulation requirement: The number of distribution feeders linked to the ring system likewise, relies on the acceptable statutory voltage drop on the distribution line.

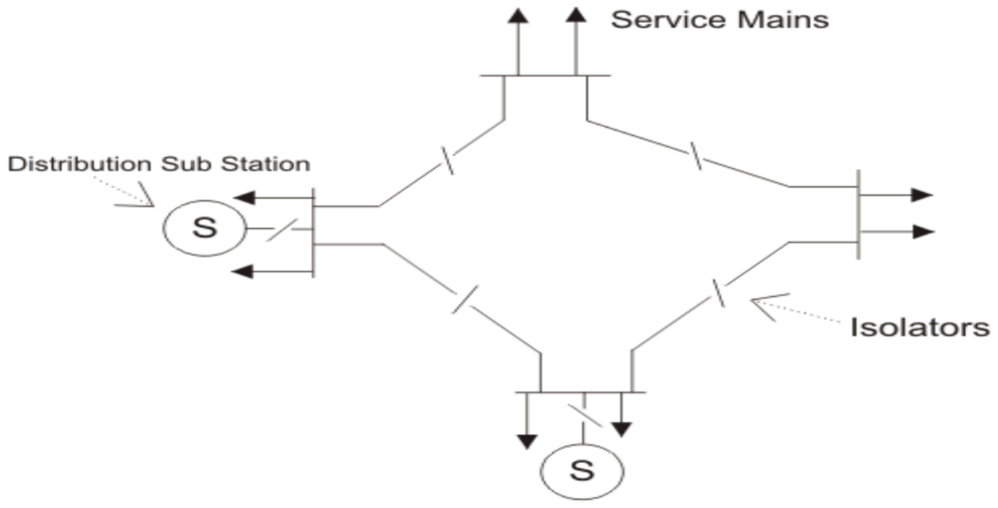


Figure 2.2 Ring main distribution network

2.7 Performance Evaluation of Distribution Systems

Grigsby [23] defined the performance evaluation of a network as an evaluation of how efficient a network provides assistance for its purpose under normal and abnormal states. He further stated that abnormal condition can either be caused by DN element or introduced by events that produce unexpectedly high load shedding. Liu et al. [24] in their study recognized the importance of DN as effective assessment on the evaluation of how often the unusual condition and the examination of the effect on the consumers would be. Stevenson [25] further indicated that the overall efficiency of a power system (PS) relies primarily on the optimal operation of the distribution networks. From these studies, performance evaluation of DNs is summarily conceptualized as a study involving the assessment of: network functionality under normal and abnormal load condition, and frequency of abnormal conditions and its impact on electricity users.

2.8 Types of Distribution Network

Ewesume [26] in his study categorized distribution network into two types, they are:

i. **Intra-Township Connection (ITC)** – This is usually the planting of high tension poles along major the roads whereby 150 mm^2 ACSR aluminium conductors are usually strung on the poles. The span between two poles is about 70-90 m. The distribution transformers may be installed by the roadside if and only if there is a major town located on the highway.

ii. **Township Distribution Network (TDN) -** This is the planting of high tension or low tension poles within a community where aluminium conductors of 50/100 mm^2 (ACSR) are strung on the HT/LT poles. Transformer substances are located within the electrical network. The span between two poles is either 45 m or 50 m depending on the discretion of the electrical engineer.

2.9 Parameters of Distribution Network and Mode

Uppal et al. [22] defined electric power distribution network and mode parameters as: impedance of the line; the bus voltages; phase currents; the frequency; power flow; and losses. The values of these parameters must be constantly controlled so they do not exceed safe limits (permissible maximum). Based on the values of these quantities in a given time, the working mode of an EPS can be classified into the following: normal mode-one in which regime parameter does not fall outside safe limits; and fault mode-one in which the regime parameters fall outside safe limits.

Table 2.2 represents the classification of nominal voltages in electrical distribution networks.

Table 2.2: Nominal Voltages; Types and Phases Gupta [21]

Nominal Voltage	Type	Phase
33 kV	High Voltage	3-phase A.C, 50Hz
11-22 kV	High Voltage	3-phase A.C, 50Hz
0.4-0.415 kV	Lower Voltage	3-phase A.C, 50Hz
220-240 V	Lower Voltage	1-phase A.C, 50Hz

2.10 System Reliability

Billinton and Allan [27] indicated that the utmost purpose of DNs is to fulfil or meet system load condition with sufficient valid confidence of uninterrupted and unchanging high quality of service. The capability of a DN to make available sufficient in quality energy is termed reliability or security of power supply.

2.11. Voltage Unbalance

Voltage unbalance in three-phase distribution system is the difference in the phase voltages, or situation where the angle between the three-phases is not 120^0 degrees. The same for current unbalance in DN with big levels of current unbalance which usually result in voltage unbalance [11-14]. The reasons for voltage and current unbalance in secondary DNs include: very big or uneven distribution single phase load, this happen when secondary single phase systems are linked to the phase nearest to the neutral. The same enigma can happen at the primary distribution levels in the event single phase distribution transformers are joined to the connecting electrical wires that are not difficult to connect to. Similarly, voltage unbalance will occur when electrical devices that needs single phase, but are connected to line to line voltage. Also, when three phase system consisted of single and three phase electrical devices, in this situation, the loads on the system must be balanced to satisfy the distribution company's acceptable standards. Similarly, uneven DNs impedances of three phase system can lead to voltage unbalance. This happens when the distribution system does not have enough transposition of the phases so as to ensure system impedance is effectively balanced [28]. The ANSI, NEMA, IEEE and Australia advocates that for optimum operation of DNs, the system must be designed to operate within percentage voltage unbalance of less than 2 % [29]. The percentage voltage unbalance is given by equation (2.1).

$$V_{(percent)} = \frac{\text{Maximum deviation from average voltage}}{\text{Average voltage}} * 100 \qquad 2.1$$

The main difference between the IEEE and NEMA percentage voltage unbalance calculation is the use of phase voltages by IEEE while NEMA uses line voltages.

The primary effects of voltage unbalance in DNs are: it leads to losses in the system, it results in increase in current imbalance in the system, it reduces the effective performance of electronic equipment and it increases thermal stress of the distribution system which may later result in an increase in the harmonics of the system.

2.12. Voltage Variation (VV)

Voltage variations are the root mean square differences at power frequencies for more than 1 minute. ANSI C84.1 stipulates the acceptable state of voltage limits anticipated on the DNs. VV is taken to be long period greater than the acceptable standard of ANSI tolerances which is more than 1 minute. Voltage variation can either be when voltage supply to the customers are more or less than the specified statutory system voltage limits of ± 5 % of the specified nominal system voltage value. This may not necessarily be as a result of system failure or defect in the system, but are happening mostly as a result of distribution feeder long lines, overload on one or more phases, and as a result of switching operations in the distribution system.

2.12.1. Over-Voltage

An overvoltage occurs when the sinusoidal AC system voltage is more than the standard statutory voltage limits of + 5% of the nominal voltage value and the power frequency is more than + 1% of the approved operating frequency for a period more than 1 minute. Over voltages are typically as a result of sudden switching on a capacitor bank, improper tap settings on the distribution transformers and when distribution network is extremely not intense for acceptable voltage regulation.

2.12.2. Under-Voltage

An under voltage happens when the AC sinusoidal voltage is less than the approved statutory voltage limits of – 5% of the standard nominal system voltage limits and when the power frequency is less than – 1% of the standard frequency for a period more than 1 minute. Under voltages are usually caused as result of a distribution transformer feeding too long distribution lines. Likewise, under-voltage can be as a result of too much customer load on a distribution line at the same time and lastly it may be as a result of switching activities which are opposite the ones causing overvoltage in the system.

2.13. Voltage Drop

The high-ranking restriction on DN design is the voltage level of the customer intake point. It is specifically for the greatest number of end users of electricity in secondary distribution system being fed at various points and this can show the healthy and feeble components of the DN.

Voltage drop is said to be the deviation of the nominal voltage of the supply side and the load voltage received by the customers [23].

V_S is the source voltage

V_R is the load voltage, then

$$V_S = V_R + Line\ drop\ (Vd) \qquad 2.2$$

% voltage drop is given as equation (2.3)

$$\%Vd = \sqrt{3}\,\frac{IR\cos\varphi + IX\sin\varphi}{V} * L * 100 \qquad 2.3$$

where,

V is the line rated voltage

In terms of kVAs,

$$\%Vd = \sqrt{3}\,\frac{kVIR\cos\varphi + IX\sin\varphi}{10(kV)^2} * L * 100 \qquad 2.4$$

To estimate the correct voltage equation (2.5) is used

$$V_R = V_S + IR\cos\varphi + IX\sin\varphi - \sqrt{V^2{}_S - (IX\sin\varphi - IR\cos\varphi)^2} \qquad 2.5$$

In overall, distribution system require standard acceptable voltage to operate optimally, since the request for security of power supply and dependable energy is increasing globally, most particularly in the semi urban and rural areas of the less developed nations of the world. To supply electrical energy and service of acceptable standard that correspond to the international standard to all the end users of electricity in DN at minimum affordable price, there is need to mitigate the voltage drop on the secondary DNs to statutory voltage limits of ± 5% and frequency limits of ± 1% of the nominal values.

2.14. The DNs Criteria for Voltage Drop

There are many factors which voltage drop in DNs depends on. Some of these factors are: the distribution feeder line, kind and natural state of electrical wires employed, the dimension of the electrical wire used and many more. The used electrical wire must be of appropriate dimension and of suitable type. If not, it will result in more than the acceptable voltage drop in DNs. The NEC standard voltage drop in secondary distribution system, including the branch circuits, heating, and feeders must not exceed – 5 % of the nominal voltage value.

2.15. The Effects of Voltage Drop in DNs

Low operation effectiveness of electrical devices, derating of apparatus and components, unusual and rapid breaking of safeguarding devices and unacceptable burn outs are the indications of inadequate voltage at the end user’s side. In distribution system, unusually high voltage can be observed at the source of the feeder, this is as a result of light load on the system during the off-peak period, at the middle of the night and the weekends. Similarly, under voltage can happen at the end side of the customer’s distribution line of long length or when the distribution line is loaded above eighty percentage of the transformer capacity. In the event that customer end side voltage of the employing electrical devices is different from the voltage value on the electrical device of the nameplate, the effectiveness and the working period of the electrical device is infected or harmed. The result may be smaller or noticeable depending on the defining features of the electrical devices and the quantity of the differences of the voltage drop on the device nameplate. Vaguely, effectiveness must be of acceptable statutory utilization voltage minimum and maximum allowable in ANSI. But this may change for precise device of voltage responsive electrical devices.

2.16. Causes of Voltage Drop in DNs

Voltage drop in DNs may happen as a result of following factors:

- Electrical load kind and natural state;
- Electrical Installations design and the electrical devices;
- Arrangement of components and elements in the Installations; and
- Inadequate and lack of repair work in the system.

2.17. Advantages of PQ Enhancement in DNs

- Reduction of distribution line and electrical device currents, losses and consequent reduction in power charges;
- The expenses of net worth investment are removed as a result of freedom of blocked measure of electric output;
- Enhancement of power factor and removal of poor power factor unpleasant consequences;
- Decrease in customer greatest requests and demand payments is minimized;
- Greater initial reduction in assets and good effects for power saving tools;
- Enhancement of voltage profile followed by efficient performance of equipment;
- Removal of harmonic alteration and effect decrease in electrical losses;
- Safeguarding the failure of electrical devices and prevention of malfunction of equipment which puts an end to failure and less outputs;
- Removal of unscheduled temporary loss of power and decrease in loss of income and expected outputs;
- Decrease in malfunctioning of electrical devices as a result of decreased thermal and electrical strains; and

- Security of power supply, reliability and long life of equipment are enhanced as a result of reduction in functioning temperatures and reduction of losses.

2.18. Voltage Unbalance and Voltage Variation Enhancement Conventional Techniques

Well established techniques of VU reduction and VP enhancement employed by electricity distribution companies and industries are examined in this section, in addition to the merits and drawbacks. To decrease and enhance this PQ disturbances, six well-established improvement techniques are considered, the summary of their advantages and disadvantages are also tabulated.

2.18.1. Load Transfer

The electric energy distribution networks are generally unbalanced; this is as a result of unbalanced loads and various numbers of phases per circuit. Load transfer on DNs is typically performed with main attention on improving voltage profile, balancing loads and reducing electrical losses, removing the excessive electrical loads from the network. Load transfer is carried out in electrical distribution networks when there is an overload and under voltage problems and to reduce losses in the system. Load transfer provides a rapid lengthy time and provides a detailed cost-effective solution to excessive electrical load and under voltage in the electrical distribution network, it also reduces losses significantly. In improving load transfer, the following problems may occur; load transfer may result in shifting of a switch employed in the breaking process, numerous restrictions and hazards connected with the safety of load transfer system, which increases substation losses and amplifies phase voltage losses. Similarly, it increases load unbalance in the network, hence amplified voltage unbalance in the system.

2.18.2. Load Unbalance Correction

In electric power distribution network, uneven flow of electric charge results in a zero-sequence electric charge, which sends back to the primary source through the earthing system and the system neutral conductor. Electric charge increase may result in quite a few problems as soon as it gets to an inevitable state, this includes: increasing in negative sequence potential may result in overheating of electric motor; amplify voltage drop on distribution line with heavy phase load; increase in problems associated with high level ground current; and increase in losses. Rebalancing of phase loads needs the movement of loads from the phase that is heavily loaded to the phase that is less loaded. Minimum losses are recorded when the phases are having equal electric charge. This load balancing must be carried out with minimum acceptable loss and with voltage unbalance enhancement. The greatest disadvantage of this method is the use of trial and error method in determining the best improvement method to use.

2.18.3. Capacitor Installation or Feeder Reactive Compensation

IEEE standard for the use of series and parallel capacitors for employment of series and shunt capacitors for evenly shared loads, the installed position of the capacitor must be 2/3 in length from the transformer used [30]. With the use of correct and appropriate capacitor regulator, joined to the distribution phase that is less than the acceptable per-unit voltage value of 0.95 p.u; the magnitude of the voltage can be enhanced and produce nearer to the voltage magnitude of other phases on the distribution line. This will effectively enhance unbalance voltage in the system. Furthermore, application of capacitors in electrical DNs will help to enhance network stability, correction of power factors and compensation of voltage profile, and so, strengthening the system capacity and reducing losses. Electric power distribution networks need painstaking system to achieve the reactive power conditions by appropriately positioning the parallel capacitors. The advantages that can be obtained from parallel capacitor placement in the electric DNs are as follows: increased line voltages; reduces lagging component of current; reduced losses; increases voltage level at the load; decrease in capital spending on the network electrical devices; enhances voltage profiles; decreases the kVA demand where power is purchased. The degree of these advantages varies on the type, dimensions, location and the quantity of capacitors employed in the network coupled with the operational level of device used. The utmost drawback of this technique is its high expensiveness to install and maintain.

2.18.4. Line Conductor Replacement and Network Reconfiguration

In electric power distribution networks, it is an expected standard to use an even electrical cable for the whole distribution feeder length. This may not be essential in DNs from the detailed examination of electric charge carrying a measure of electrical output. Because of this, in the transition from the distribution substation to the customer side of the distribution network, the size of the electrical cable employed should be decreased. In designing electric DNs, grading of electrical cables must be given required attention in order to have minimum losses on the network, reduce cost and minimise reactive power demand while enhancing voltage profile of the DNs. Electrical cables excessive loads occurs when the electric charge in an electrical wire exceeds the electrical cables standard allowable limit. In three-phase distribution lines, this may occur only on one or two phases, the determining factor for load imbalances between phases is the size of the electrical wire used. This may result in improper overheating or damaging of the cables during summer. This situation needs an improved action, such as line conductor grading and network reconfiguration. The resulting voltage increase from the distribution line upgrading, coupled with overall improvement of the distribution network is very encouraging. The outcome will be decreased voltage drop which eventually causes decrease in voltage drop along the DN feeder and hence, no significant deviation in magnitude and phase among the distribution line phases of the customer terminal. The major disadvantage of this technique is that it is not cost effective to carry out.

2.18.5. Installation or Relocation of Voltage Regulators

This technique of enhancing voltage profile in electric power DNs is to utilize the needed number of voltage regulators with appropriate tap settings at correct positions. Placement of the device in electric DN will assist in decreasing the power losses in the entire system. Similarly, it will enhance the system's ability to adjust to load changes and improves power factor correction. Voltage regulators method is the only viable solution in some cases since other technique of improving PQ problems is quite expensive. Nevertheless, this technique is not well favoured as a result of large electrical losses within the device itself. The device requires greater repair work which is significantly more expensive. Voltage regulators also need more maintenance and can be considerably expensive. Notwithstanding, the application of the device has quite a few merits. For example, it typically provides a higher benefit compared to other techniques employed for voltage enhancement in distribution systems. It also permits the problem of low voltage profile to be rectified.

2.18.6. Distributed Transformers

In electric power distribution networks, the placement of distributed energy producers different from the main power producing stations nearer to the end user buildings mostly where demand for power is very high is a practice. Distributed power producers are little modular backup supply such as: converter of radiation to electricity, fuel cells, photovoltaic cells, moving air energy producers. These distributed generators have many advantages from the point of external factor limits and site of position delays.

The vital justification for the prevalence of distributed generators can be recapped as:

- it is very easy to locate sites for little generators;
- reduce line losses; improvement in power quality problems and voltage profile;
- improve system security and reliability;
- increase overall efficiency and reduction in fuel cost;
- costs are reduced with the distributed generator units installed closer to customers; and
- the investment risk is not as high since the distributed generator plants require shorter time of installation.

Since the electrical distributed networks are not made to give reinforcement for the placement of distributed power producers at different sites, placement of distributed generators improves the general performance of the electrical distribution networks. In contrast, it causes new problems to the electrical distribution networks which may include: change in protection schemes, the cost of installation, grid connections to the distribution generators and the most severe one is increasing PQ disturbances in the electric power distribution networks (EPDNs) as a result of: voltage unbalance, voltage variation, harmonics, flickers and fluctuations.

Table 2.3: Summary of Advantages and Disadvantages of Conventional Methods

Method	**Advantage**	**Disadvantage**
Load Transfer	Losses reduction. Improve voltage profile.	It affects load balance correction. It affects adding shunt capacitor. Relative cost of executing. It causes increase in distribution substation losses and amplifies phase voltage losses. High risks associated with network protection. Very difficult to locate the position of the switch and the breaker.
Load Unbalance Correction	Losses reduction. Voltage improvement. Low cost.	Voltage drop on the phases with heavy load is increased. Due to unbalance that may occur in the system, losses may be amplified. The use of trial and error technique makes the system prone to incessant failure. Amplification of disturbances associated in increasing in stray voltage telecommunication signal interference and increase in ground voltage.
Capacitor Installation	Reduce voltage unbalance by increase line voltage. Reduce losses.	Relative cost of installing. It leads to overvoltage when installed at the customer side of the distribution system at the time on relative low load. It reduces voltage gain when located nearer to the source.
Line Conductor Replacement and Network Reconfiguration	Reduce losses. Improve voltage profile.	Very expensive to implement
Installation or Relocation of Voltage Regulator	Very cheap compared to other methods. Greater gain in voltage than other methods.	Increase losses. Maintenance relatively expensive.
Distributed Transformers	Improves voltage amplitude when load is connected. Enhances voltage regulation and Reduces lagging component of current.	Very expensive. Increase power quality problems such as harmonics, flickers, fluctuations and others.

2.19. Solution of PQ Problems

For the improvement of PQ in electric DN, there are two distinct methods. The first method, the technique of solving PQ disturbances can be achieved from the customer end. This is known as load conditioning. This method makes sure that the electrical devices are less responsive to disturbances, enabling the system to function effectively even under meaningful voltage alteration. The second method is to position line controlling systems to reduce the system disruptions. In this method, the mitigating tool is connected to medium and secondary DN in series or in parallel. The series and parallel active filters function as controllable voltage and current sources respectively. The two connecting systems are carried out using voltage source pulse-width modulator (PWM) generator, with a direct current source having a reactive component such as a capacitor. Nevertheless, with the reorganization of energy sector and with the general changing tendency in the direction of dispersed and distributed generation, the line conditioning systems solution method will perform a significant part in enhancing the basic supply quality. The economic, efficient and effective measures for power quality enhancement in electric power distribution networks are thus presented.

2.19.1. Thyristor Based Static Switches

The static switch is an active tool for switching a modern component in the circuit when the voltage enforcement is necessary. It has an active and purposeful response time of about one complete process. To improve voltage unbalance, voltage variation, swells, sags and voltage spikes, it can be employed to control many devices such as power storage system, interchanging distribution line, circuit breaker, relay, filter, and capacitor. The device can be employed in the application of interchanging grid line.

2.19.2. Energy Storage Systems (ESS)

ESS can be utilized to secure responsive production equipment from complete failure, which happens as a result of voltage unbalance or voltage variations. These are usually direct current storage devices such as storage capacitors, uninterrupted power supply (UPS) and superconducting magnet energy storage (SMES). The output of the energy storage is supplied to the model system through an inverter circuit on a gradual basis by a dynamic, fast response advance power electronic switch such as thyristors, diodes, ideal switches, switching-function based VSC, and average-model based VSC. During the disturbances in an electric power distribution network like voltage unbalance, voltage variation, sags, swells; sufficient energy is supplied to the network to mitigate for power lost from the energy storage systems. Although, there are several techniques compensating voltage unbalance and variation, but the employ of a CPD is considered to be the greatest effective technique. The FACTS devices are designed purposely for the transmission systems, the same way CPD is employed in electric power distribution networks to deal with a different type of PQ disturbances. As FACTS enhances energy movement capabilities and ensure ability to adjust to any load changes. CPD ensures the end user of energy receives the minimum permissible quality and security of power supply [31-32].

The foremost custom power devices which are used in electric power distribution networks are active power filter (APF), thermistor switched capacitor (TSC), static var compensator (SVR), uninterruptible power supply (UPS), battery energy storage systems (BESS), super conducting magnetic energy system (SMES), solid state transfer switches (SSTS), distribution series capacitors (DSC), unified power quality conditioner (UPQC), dynamic voltage restorer (DVR) and distribution static synchronous compensator (DSTATCOM).

2.20. Custom Power Devices (CPD)

CPDs are power electronic controllers, which are extensively employed in electrical DNs for PQ enhancement. CPDs are effective devices based on semiconductor, switches principle to safeguard responsive loads in case of disruption from distribution networks [33]. The principal CPDs employed in electric DN for PQ enhancement are grouped into three kinds: DVR; DSTATCOM; and UPQC devices. These are existing methods engaged in improving quality of power and security of power supply and also mitigate all types of disturbances in distribution networks [32]. These CPDs are working on the basic principle of the voltage source converter.

Various power providers have installed (CPD) for compensating power quality problems. For the past years, power quality devices such as DVR and DSTATCOM which are solid state electronic devices have been the heart of many close examinations, methodical investigations, research works and laboratory studies.

CPDs assume that the advanced solid state controller employed for PQ improvement on electric power DNs are rated from 1 kV to 38 kV. The curiosity in the deployment of PQ tools becomes intense due to the concern of PQ position to satisfy each day rising responsive end user demand and expected standards [34]. If PQ level is not attained, it can result in expensive downtimes and end user discontent. With respect to unforeseen emergency intention on distribution industry’s yearly report [32], periods of no production as a result power disruption causes significant financial losses. To address these PQ problems, advanced solid state electronic based tools have been designed recently. The effectiveness of these CPD has been clearly proved in medium electric power distribution system, and most are available as commercial product [34-35].

2.20.1. Purpose of Custom Power Devices

Power quality disturbances are one of serious worry in this present period. Electric power distribution system is located at the terminal of electric grid system and is directly connected to the end user, so the dependability of electric energy supply primarily relies on electric power

DN. With the inclusion of complicated tools, whose effectiveness is very much responsive to the standard of energy supply, the PQ problem reveals itself in form of substandard voltage, current and frequency that results in malfunctioning of end user electrical devices. The electric power DN malfunctioning is made of about ninety percent of total end user disturbances. As end users request for acceptable standard of electricity supply is rising each day, therefore the dependability and acceptable standard of the electric power DN has to be amplified. The principal enigmas dealt with in this research study are voltage unbalance and variation. Electric DNs should perfectly supply end users without obstructions of free of energy at perfect sine wave voltages at acceptable standard amplitude level and statutory frequency limit. Nonetheless, in practice, electric grid systems, most specifically the electric power DNs have many non-linear loads, which importantly have adverse effect on the standard of electric energy supplies. Due to the non-linear loads, the sinusoids of the wave shape of network produce are reduced. Finally, this ends up producing large number of PQ disturbances Even though: PQ problems exist on every electric power network, the responsiveness of the present time advanced power electronic tools makes them more inclined to the acceptable standard of energy supply. To a small extent, quite a few sensitive devices, a short-lived disturbance can cause equipment failure, malfunctioning of electronic components, interrupted communications and system crashes.

To deal with the problem of PQ successfully, CPDs are employed. DVR is very efficacious, cost effective CPDs employed in electric DNs. It has merit which includes easy maintenance, less expensive, relatively little size and has a dynamically quick reaction to disruption.

2.20.2. The Advantage of CPDs

The CPDs such as DSTATCOM, DVR, and UPQC are employed to amplify acceptable standard of the electric power DNs by providing voltage reinforcement at extreme important buses in the network and to control movement of energy in essential distribution networks. The advantages of CPDs are:

(i) reduction in problem of sags experienced in the event of starting of industrial loads;

(ii) increase in the signal balance region is enhanced, this is achieved by giving support to the controllers to reduce oscillations in frequency;

(iii) the conundrum of over voltage and variation in voltages can be conquered by the CPDs controller [32-34];

(iv) improvement in movement of power in most essential distribution lines can be minimized, also the controlling limits can be decreased by very fast responding controller;

(v) voltage disturbances in secondary distribution system can be aimed at more accurately using CPDs;

(vi) electricity consumers in most cases have just a point of access to the secondary distribution system, because of this, CPDs could be located by the electricity distribution companies or the end users of electricity;

(vii) the use of distribution transformer in secondary distribution system significantly decreases the short circuit fault, hence, safeguarding of CPDs is made simple;

(viii) increasing in energy carrying capability of the distribution lines to estimate the values of the thermal limits; and

(ix) reduction in the operating system limits by the use of CPDs fast controllers.

2.20.3. Dynamic Voltage Restorer (DVR)

DVR is a CPD employed to enhance voltage disruptions of electric power DNs. A diagram showing the layout of DVR is presented in Figure 2.3. DVR is a series linked device utilized to mitigate voltage disturbances in the DNs [36]. The DVR is made of a voltage source inverter, a series voltage injection transformer, AC filter, controlling unit, and a storage unit [37-42]. The fundamental principle of functioning of a DVR is to provide sufficient and suitable voltage in series with the distribution network with the help of boosting transformer each time there is voltage variation and voltage unbalance in DN. Besides, mitigation of VV and VU, DVR can also carry out mitigation of sags and swells, harmonic mitigation and correction of power factor.

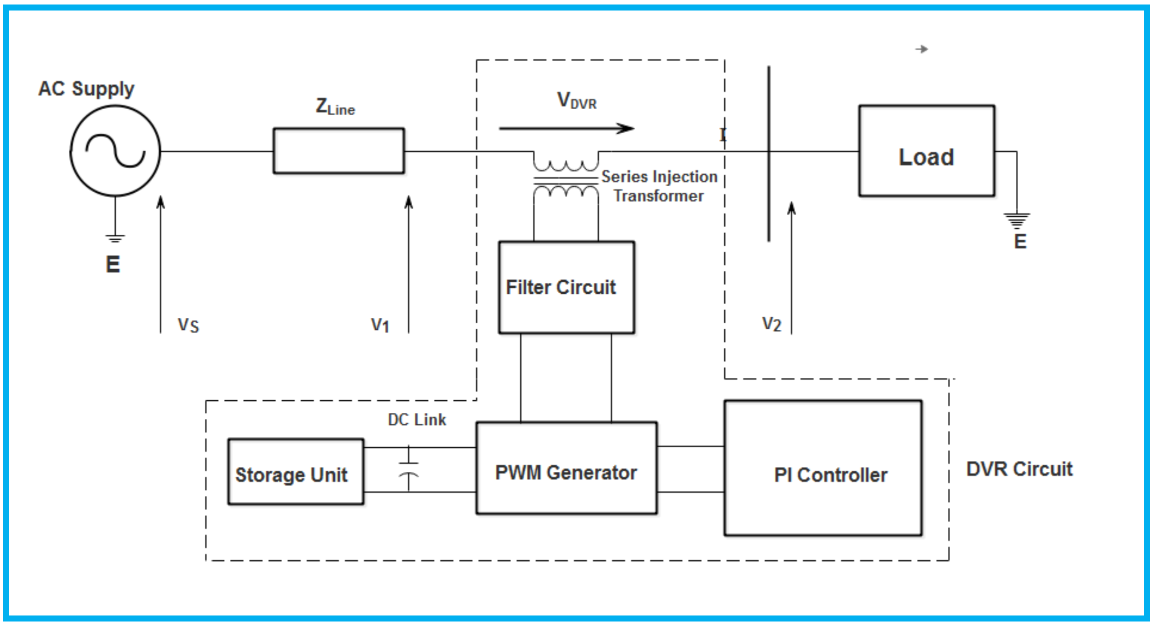


Figure 2.3 Schematic diagram of Dynamic Voltage restorer

2.20.4. Distribution Static Compensator (DSTATCOM)

DTATCOM is a parallel linked device which helps to solve the PQ disturbances. DSTATCOM is a solid-state device which is placed in parallel to the electric distribution network to militate the power quality disturbances like voltage unbalance, flicker, and voltage fluctuations associated with low voltage electric power DN. DSTATCOM performs voltage regulation and more acceptable compensation of distribution associated disturbances in society. DSTATCOM is a three-phase equipment which generates/absorbs the non-active power which end result can be changed in appropriate condition to manage the precise variable quantity of the distribution network. Figure 2.4 indicates schematic diagram and basic elements of DSTATCOM. A DSTATCOM is a CPD that is solid state power electronic based device. It comprises a DC energy storing medium, a two-level voltage source inverter, a filter and an isolating transformer linked in parallel to electric network [7], [32], [43-50].

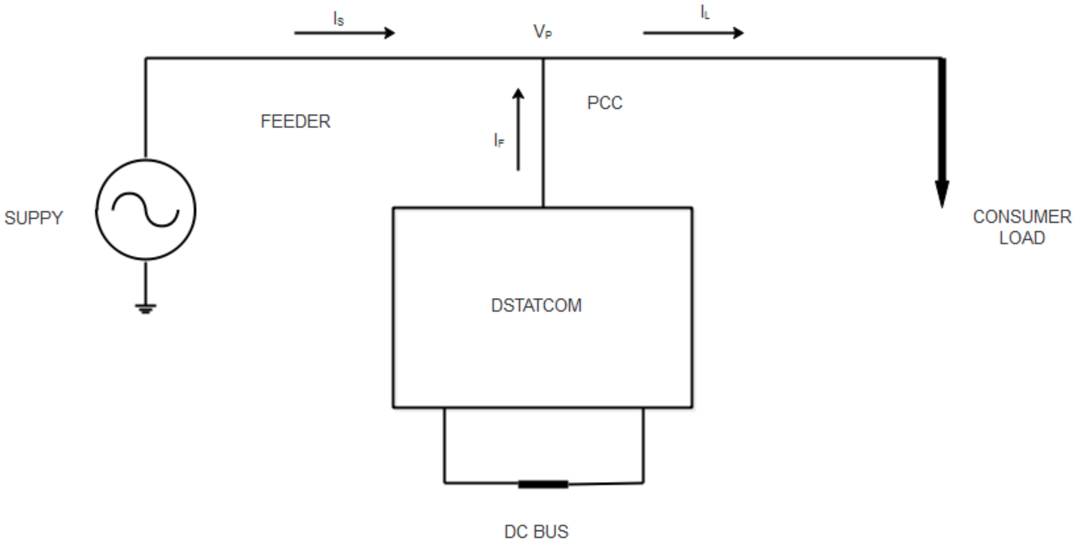


Figure 2.4 Schematic Diagram of DSTATCOM

2.20.5. Unified Power Quality Compensation (UPQC).

UPQC involves the formation of mitigating device by the bringing together of parallel and series filters. The storage component is distributed between two series voltage source inverter bridges functioning as active series and active shunt compensators. It is examined as a tool that can be employed in different ways, supply current in parallel and voltage in series at the same time in an inflected form for control purpose. It can stabilize and control end and remove negative sequence currents. The critical disadvantage of the UPQC is it’ complexity and high cost. It is very complicated in its controls due to comparative numbers of solid state devices that is connected. Figure 2.5 shows the schematic diagram of UPQC [51-56].

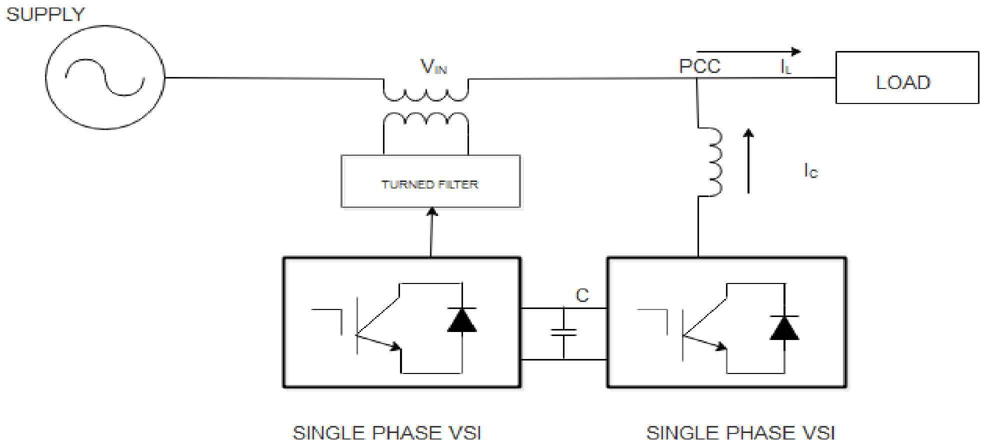


Figure 2.5 Schematic Diagram of UPQC

2.21.Recent Studies on Power Quality Issues

The present day electric power DS are of great concern. PQ disturbances have harmful economic consequences for utilities, end users and electrical equipment producers. The effect of poor PQ is increasingly felt by the end users, which includes commercial users, industrial users and the residential users. Some of the principal PQ disturbances are voltage unbalance, voltage variation, harmonics, interruption swells, spikes, oscillatory transient, momentary interruptions, sag [57-58].

In electric power distribution networks, a set of devices is described by the general name of CPDs referring's to advance solid state electronic based controlling devices employed for PQ enhancement on electric power DNs. The rating is within 1 to 38 kV [59-60]. The curiosity in the practice of PQ devices comes into existence from the desire to achieve increasing acceptable PQ to satisfy each day's intense responsiveness to customers need and expectation [61]. One of those CPDs is known as a DVR, which is simple, produces desired results, cost-effective, fast dynamic response, easy to maintain and efficacious. Advanced present day CPD employed in electric power DS compares favourably with others which are difficult to maintain of high cost and large sized [62]

Various research papers and projects dealt with issue of enhancing acceptable power quality in electric power DN by the employ of custom power devices. Research studies carried out so far showcase development and improvements. Farhad [63] presented assessment and compensation of voltage profile in secondary distribution network having PVs cell and electric vehicles. In the study, responsiveness investigation and random assessment for PVs positioned by the house owners against their connection point, their normal ability and penetrating capability of the network operate in two various forms were carried out, with the recommendation that the dynamic and steady behaviour of voltage variation and unbalance should be investigated.

Amed et al. [64] proposed power conditioning with DVR under various voltage sags kinds. The study carried out modelling of a DVR using PI controller for voltage correction using MATLAB software. This was done under various forms of short circuit faults. The result of the simulation demonstrated that DVR is capable of correcting voltage sags and also can minimize the system unbalance voltage and alter shape, in spite of any kind of fault. Farhad et al. [65] presented an enhancement of unbalance voltage in secondary private house networks with rooftop PVs using CPDs. The study carried out two various enhancement techniques based on the use of shunt and series CPDs to investigate the improvement of voltage unbalanced enigma in networks with rooftop PVs. This was based on the load flow analysis on MATLAB and their efficacious was investigated from the connection and assessment point of perspective. A Monte Carlo based random assessment was performed to study their efficiency for various unpredictability: of load and PV assessment and position in the system. The simulation result was done on PSCAD/EMTDC to attest the effectiveness of the suggested structure and control algorithm.

Tiwari et al. [66] presented DVR against voltage sag by injecting missing voltage into the electric distribution network. The compensation capability of the DVR was influenced by the greatest voltage sag to be mitigated and the power factor. This study is to absorb the quantity of direct current storage energy which relies on voltage sag.

Katole et al. [67] proposed the DVR with ESS and PI controller techniques to mitigate voltage dip in a balanced system. Most of the end user equipment failures are as a result of voltage dip which is one of the principal problems of PQ. The objective of the study was to suggest an effective method of improving voltage dip.

Rosli and Rahim [68] developed and designed of DVR system for voltage sag correction using dq0 change method. The use of dq0 frame transformation as controller in dq0 coordinates has higher standard effectiveness compared to the conventional methods. The result of simulation in MATLAB/Simulink shows that DVR effectively mitigates voltage sag in secondary distribution system at various conditions of disturbances.

Teke et al. [69] presented the design and assessment of a fuzzy logic controller DVR and extended it to accomplish quick fault location. The latest controller for DVR is suggested by joining fuzzy logic with a pulse width modulation generator. The suggested technique for voltage swell and sag detection has the capability for detecting various types of power disruptions more than the well-established techniques of detection. The robustness of the suggested detection methods are demonstrated by comparison with the well-established techniques.

Dominik and Juraj [70] developed a model of a DVR which was implemented in a laboratory environment. The designed series-connected injection transformer has the ability to make available a compensating voltage to the lines; and the load potential is reliable and satisfactory. Rosil and Rahim [71] addressed PQ enhancement in secondary distribution network using DVR. The study discussed the mitigation of PQ disturbance in secondary distribution network (DN) due to voltage swells. A recent setup of DVR was suggested with an enhanced dq0 controller method. The simulation was accomplished using MATLAB/Simulink. The simulation result carried out validates the efficacy of the suggested setup.

Bukar et al. [72] discussed the use of DVR to solve the PQ disturbances in a secondary DN. The designed model used sequence analyser and PI controller to mitigate various types of balanced and unbalanced fault conditions such as sags, swells, and harmonics without having any difficulties in injecting the required missing component to correct the supply voltage. The implementations were proposed for primary voltage levels in order to safeguard responsive loads from PQ disturbances with MATLAB/Simulink software.

Singh et al. [73] described the use of a DVR for voltage sag occurring at the distribution level under fault conditions. From the result, it was seen that the enigma of voltage dip can be compensated by introducing a well-designed DVR for the system. Bhutto et al. [74] presented the mitigation of unbalanced voltage dip in CIGRE secondary test system. This was achieved by using STATCOM device in test line performed in DigSILENT software. The result shows that the minimum acceptable limit for voltage unbalance is not attained with STATCOM.

Chodavadiya et al. [75] described the mitigation methods of rectifying supply voltage sags, swell and disturbance consequences in a distribution network using DSTATCOM, DVR and SSTS. The use of DVR and DSTATCOM for voltage sags, swells and interruptions demonstrated that the DVR and DSTATCOM give high quality voltage, enhancement of practical ability, but this depends mainly on the capability of storage device and the defining features of the connecting transformer. Parmar et al. [76] introduced an enhancement of the voltage profile using DSTATCOM under voltage fluctuation conditions. The study explained DSTATCOM mode of operation and techniques for balanced and unbalanced voltage variation restoration DN. The result of simulation shows the effectiveness of DSTATCOM for voltage sags and voltage swells.

Mahyavanshi et al. [77] presented the use of DSTATCOM controlled by power balance theory (PBT) to compensate reactive power and mitigate voltage sag. The use of PSIM based simulation investigation of this operational philosophy is presented for DSTATCOM. The result validates the performance of the operational procedure employed for mitigation of non-active power and correction of sag. Rasool and Jyoti [78] investigated a control system based on dq0 controller scheme to mitigate sags and swells voltages during single line to ground (SLG) and three-phase faults using DVR. Simulation outcome performed in MATLAB/Simulink proves the effectiveness of the suggested technique.

Rosli and Rahim [79] designed a control system based on dq0 controller and proportional integral controller which was coded to digital processor (DSP) to mitigate voltage puzzles assisting 3-phase load up to 5 kVA. The suggested technique is demonstrated with simulation and is carried out in a prototype. Suresh and Govindaraj [80] presented an investigation of DSTATCOM control for PQ enhancement in a delta connected DS with a modern method of control. The study deals with the modelling and assessment of power electronics-based equipment intended at enhancing the ability to maintain balance, dependability and reliability of power flow in secondary electric power distribution network. A latest control plan was suggested to produce the PWM signal based on the estimation of voltage, without reactive power measurement. Simulations were performed in MATLAB/PLECS. The result shows the effectiveness of the control plan in the system response to the instabilities as a result of system faults demonstrated.

Rodda and Jyothi [81] proposed VSI with (PWM) for flicker mitigation purpose. The proposed DSTATCOM modelled was used for simulation and proved for PF mitigation and voltage regulation along with neutral current mitigation, harmonic removal and load balancing with loads and non-linear loads. Suresh et al. [82] investigated the system faults with the use of MATLAB/PLECS using a recent control system to produce the PWM signal based on the measurement of voltage without non-active power measurements are needed. The reliability of the operational scheme is proved clearly in the simulation result.

Syed and Jyoti [83] implemented the control of voltage decrease in size and increase in voltage size in the event of single line ground and three phase faults using a space vector PWM operation method is based on voltage source information and the value at given instant of supply and load voltage in medium or low voltage consumers. By using DVR technology, the simulation waveforms show that power quality is enhanced.

Farhad et al. [84] investigated how rooftop PVs installations in secondary DNs can result in an increase in unbalance voltage. In the study, an assessment was performed to examine how PV connections, their stochastic location and energy production ability can lead to amplification in voltage unbalance. Various effective, efficient, practical techniques are explained for decrease in voltage unbalance. The satisfactory position for DSTATCOM and its effective control technique to decrease voltage unbalance was demonstrated. Result validated using PSCAD/EMTDC and Monte Carlo simulation.

Hazarika et al. [85] proposed the use of DVR in DN voltage sag correction. The study deals with modelling, assessment of DVR in MATLAB/Simulink using PI controller and PWM controller for control purpose. The work was carried out in medium voltage distribution network. The simulation results were demonstrated to explain the effectiveness of DVR under different fault states such as 3-phase to ground, line to line fault. The result obviously shows the effectiveness of DVR system in voltage sag correction.

Ferdi et al. [86] presented adjustable PI control of DVR using fuzzy logic. PI controller is widely found in the operation of DVR. Moreover, the demerit of this well-established method is the use of fixed gains. The PI controller may not provide an optimal and appropriate solution for the system, in case the system parameters vary. The simulation results show that the suggested control scheme greatly enhances the effectiveness of DVR when in comparison with the convectional controller. Tiwari et al. [87] introduced the general concern and the effect of different influence on the effectiveness of DVR systems. It was observed that voltage dip has significant impact on the effectiveness of responsive loads in electric power networks. The effect of harmonics, frequency, transformer, power factor, voltage, losses and power on healthy functioning of DVR system is investigated.

An analysis of these reports shows that extensive research has been conducted on PQ issues on electric power DNs with compensating devices which are very much varied and diversified. In spite of these, it is observed that there is an urgent need to investigate the efficiency of compensating devices for voltage variation, poor voltage profile and voltage unbalance for short and long, balanced and unbalanced secondary distribution networks with different distribution feeder lengths in secondary electric power DNs. This is to access the permissible standard voltage variation and acceptable voltage unbalance from the start of distribution feeder line to the extreme end of distribution feeder. In other words, the security of power supply and performance require a reassessment in the present and prospective conditions. Knowing fully that electric power DNs is positioned at the final end of power grid and is linked to the customers completely. Therefore, the dependability of entire electric power supply largely relies on the optimum performance of secondary electric power distribution system. In as much as the end users desire for quality and security of electric power supply is increasing every day, the dependability and security of the low voltage electric power DNs have to be intensified. Having knowledge that electric power DN failure or mal operation of end user equipment account for about ninety percent of the average end user interruptions. So it is highly imperative to increase the quality of power and the security of power supply in secondary electric power distribution networks. This position requires verification through investigative study as established in this study.

2.22 Summary

In this chapter, a general review on electric power distribution networks is extensively reviewed. Different custom power devices and areas of applications were explained in detail. Similarly, six conventional techniques were investigated for reduction in unbalance voltage and voltage profile improvement on secondary voltage electric power distribution networks. These conventional methods used by the Industries and electricity distribution companies for power system networks as listed cannot provide effective solution for the electric power distribution system because of the highlighted disadvantages. Hence an effective, efficient and robust method for solving electric power distribution systems with power quality problems is of utmost necessity. To ascertain that acceptable PQ is supplied to the end users, it is of great importance to improve the voltage profile and decrease voltage unbalance by selecting appropriate mitigating techniques such as the use of CPDs known as DVR which are cost effective, dynamic, fast in response, reliable, most effective, efficient and robust in size and operation, easy to maintain/less maintenance in reducing voltage unbalance, decreasing voltage drop and improving voltage profile in secondary electric power distribution networks.

CHAPTER THREE

INVESTIGATION OF VOLTAGE UNBALANCE AND VOLTAGE VARIATION

3.1 Introduction

Voltage unbalance and voltage variation PQ disturbances was investigated and analysed for low voltage electric power DN 11/0.4 kV, 500 kVA, urban and rural system is presented in this chapter. The network was designed and modelled in MATLAB/Simulink software in Sim Power System tool box. Simulation and analysis of results were carried out for balanced and unbalanced distribution network with short and long feeder length. The assessment is performed to study and to predict the system PQ problems such as voltage profile, voltage variation and voltage imbalance

3.2. Voltage Profile and Voltage Unbalance in Distribution System

The power generally available by distribution companies are normally 220-240 Volts for nearly all the countries in the entire world or 110 Volts (in Canada and United States of America). Therefore, a suitable electric power DNs must keep the voltage variation at the end user's side at standard allowable limits. The regulated standard limit of voltage variation is ± 5 % of actual voltage value at the end user's side. Thus, if the stated voltage is 220 V, then the maximum voltage expected at the end user side must not be more than 231 V whereas the minimum voltage expected at the customer end must not be smaller than 209 V. International approved standards recommendation is that the actual voltage at the supply side should be within an acceptable difference of ± 5 % of the actual supply from the source. This is based on the IEEE approved standard for voltage monitoring electric PQ [88]. Voltage unbalance in power DN is a situation in which supplied voltages are not equal, or when three phase voltages are not the same in amplitude or when the angle between the phases are not equal to 120^0 or both three-phase voltages differ in phase with normal phase difference of 120 degree between each phase and/or differ in amplitude. Singh et al. [89], C. Tsai-Hsiang et al. [90] and Kini et al. [91] were in agreement to the various ways to define: calculate and interpret voltage unbalance in distribution systems.

Voltage unbalance also referred to as voltage imbalance is the ratio of the deviation from the mean of the three phase system voltages or currents to the mean of the three phase system voltages or currents, calculated in percentage [IEC 61000-2-1, (199990-05), 1990; IEEE Std 100-1992; IEC 61000-4-30, 2001; IEC 61000-4-15, 1997]. Voltage variations are the room mean square differences at power frequencies for more than 1 minute. American National Standard Institute (ANSI C84.1) and the European standard Institute (ESI) specify that the acceptable voltage limits anticipated in an electric DN to be ± 5% of nominal voltage value. This implies that the standard permissible/allowable voltage profile range is within ± 5 % of actual voltage value.

The ANSI C84.1 approved standard stated that power supply network under no load condition should be made to work and function to the highest voltage unbalance limit of ± 3% [29]. Voltage variation can be experienced as over voltages or under voltages. Over voltages and under voltages may not necessarily be as a result of system failure or defect in the system, but are happening mostly as a result of long distribution feeder lines, overload on one or more phases, and as a result of switching operations in the distribution system.

Mathematically, percentage voltage unbalance can be illustrated, using formula given as:

$$V_{(percent)} = \frac{Max\ difference\ \ from\ ave\ phase\ voltage}{Ave\ phase\ voltage} * 100 \qquad 3.1$$

3.3. Percentage Voltage Unbalance (PVU)

The percentage voltage unbalance (PVU) is the ratio of the sum of absolute value of the difference between the mean of all three phase voltages and the phase voltage of each phase divided by the mean of the phase voltages. Equation 3.2 shows the mathematical expression for PVU which is largely employed and used to evaluate voltage unbalance in the DNs [92-93].

$$\%P_{VUM} = \frac{abs\ value\ of\ \max\ deviation\ of\ \ phase\ values\ \ from\ the\ mean\ phase\ voltage}{mean\ \ phase\ voltage} \qquad 3.2$$

In primary and secondary DNs the PVU must be less than 2 % and less than 1 % in high voltage network before compensation can be carried out. Similarly, the PVU must not be more than 4 % at any point in time on the network [17], [92]. In practice, proper mitigation of VU is only performed when the PVU is equal or more than 2 % in the system. In considerable number of time to complete factual information for proper comparison with the acceptable high quality standard must be gotten, hence it is necessary to prove the range of PVU variation at various distribution feeder buses so that it will not be more than 2 % [24]. IEEE [88] indicated that the accepted standard for voltage unbalance is restricted to 2% in secondary and primary DNs. In United Kingdom, acceptable engineering practice P29 does not set only the voltage unbalance limits for the entire DNs to 2 %, it limits the PVU at load point to 1.3 % [93]. ANSI high quality acceptable norms for ‘electrical devices and distribution systems with (60 Hz) advocates that power supply must be made to work and function with the highest PVU of 3 % under no-load state when the measurement is being taken on the electricity distribution company terminals [94].

IEEE [95] shows that electrical devices which are single-phase devices power electronic based like household devices such as radio, microwave, entertainment, laptops, PC systems, television, monitor, alarm systems may be exposed to voltage disturbances in the event the PVU exceeds 2 %.

The voltage unbalance has unfavourable and negative result on the three-phase power electronic based electrical devices in the DNs (for example air cooling device with central speed variable) [96-97]. Similarly, voltage unbalance has undesirable and harmful effect on the induction motors employed in houses, offices, and small commercial centers for the purpose of pumping water, elevators and so on [98].

3.4. Requirements of a Secondary Electric Power Distribution Systems

Significant worthy of energy is needed to keep energy supply within different end users demand. These demands for acceptable secondary DNs include: correct and appropriate voltage, accessible and obtainable power on request and dependability of power.

(i) **Correct and Appropriate Voltage:** the utmost demand of end users in the SDS is that voltage variations at the end user's side should be within acceptable limits. The variations in voltage are usually as a result of load variation or long distribution feeder length on the system. Low voltage result in high loss of income, ineffective lighting and likely motor malfunctioning and complete failure. Higher voltage results in devices that produce light completely worn out, power stoppage which may lead to electrical device failure. Thus, a high quality and standard DNs must keep voltage variations at the end user's end within acceptable standard range. The regulated limit of voltage variations is ± 5 % of actual voltage value at the end user's side. Therefore, if the stated voltage is 230 V, then the maximum voltage expected at the end user side must not be more than 242 V whereas the minimum voltage expected at the customer end must not be smaller than 219 V.

(ii) **Accessible and Obtainable Power on Request:** Energy must be accessible and obtainable by the end users in any quantity that they may be required from period to period. For illustration, electric motors may start or fail to start; lighting system may make or break, without giving warning ahead of time to the power distribution industry. Because, energy cannot be stored for future use, the DNs must be having the capability for providing customers' load demand always. This obliges the distribution company staffs to repeatedly investigate the load arrangements in order to forecast ahead the main load changes which come after generally recognized work plans.

(iii) Dependability of Power: Present day distribution companies always depends on electric energy for its day to day function. Commercial centers, business centers, private houses, and office buildings are provided with lighting systems, heating systems, cooling systems and ventilation by the electricity supply. These services demand for dependable and trusted energy. Regrettably, electricity distribution system, like all other systems is artificial in nature. It is prone to failure; hence it cannot be completely dependable. Nevertheless, the dependability and security of power supply of the distribution systems can be made stronger and healthier to a significant degree by: employing compensation devices; using dependable regulated process control system; making available extra reserve skills; and employing a system that is interconnected in operation.

3.5. Low Voltage Electric Power Distribution System Arrangement

A sample of secondary DN radial system residential urban/rural is examined for voltage unbalance and voltage variation studies. A secondary DN simplified single line layout of 11/0.4 kV system is described in Figure 3.1. In the designed model, the distribution transformer is delta/star connected.

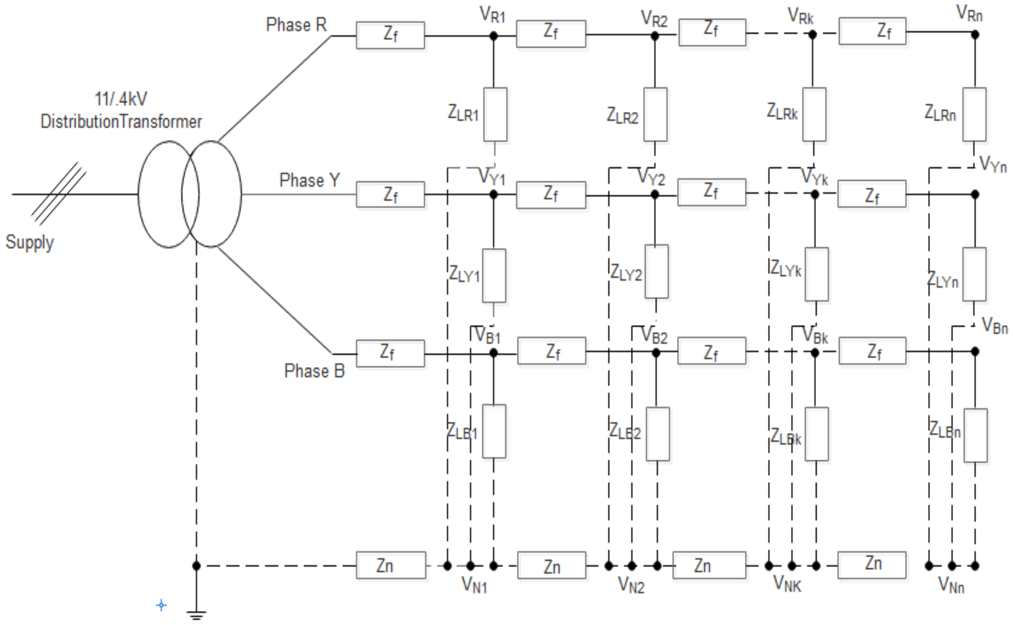


Figure 3.1: A single line layout of secondary distribution system

3.6 Determination of Electric Power DS Parameters and Load

To determine the voltage profile and current profile at each load point on the electric power distribution network, a simulation was carried out on the modelled electric power DN using MATLAB/Simulink Sim Power System tool box. This was done in order to estimate the voltage drop on each phase at balanced load and at unbalanced load on the network, hence the voltage profile, percentage voltage deviation and voltage drop on the network was evaluated in powerlib. The results were shown in Tables 3.2, 3.3, 3.4 and 3.5 respectively.

3.6.1. Network Parameters

The line parameters resistance R, inductance H, and the capacitance C, were determined by computation. The line resistance was determined using the following procedure:

The length of each segment of the line, L is determined by using equation 3.3.

$$L = 50d \tag{3.3}$$

where d is the number of spans and 50 m is the average length of each span.

The resistance, R of the line is determined by using equation 3.4.

$$R = \frac{\ell L}{A} \tag{3.4}$$

where ℓ is the resistivity of all aluminium conductors (ACC) and is given as 2.85 μΩ-cm, L is the length of each segment of the line, and A is the cross sectional area of the all aluminium conductors used.

The cross sectional area, A of the all aluminium conductors is determined by using equation 3.5.

$$A = \frac{\pi D^2}{4} \tag{3.5}$$

where π is $\frac{22}{7} = 3.142$ and D is the diameter of the all aluminium conductors.

For 100 mm^2 size all aluminium conductors, it has 7/4.39 mm strands of conductors. Equations 3.3 to 3.5 were evaluated for the network

The inductance of the line is a function of the configuration of the line conductors and the radius of each line conductor.

Since the line conductors are three and are in a vertical formation, the distances between the pairs of conductor are D_{ry}=11 inches, D_{yb}=11 inches, and D_{br}=22 inches for overhead LV electric power distribution network.

The values of geometric mean distance (GMD) and geometric mean radius (GMR) are calculated using equations 3.6 and 3.7 respectively.

$$GMD = \sqrt[3]{D_{ab} \times D_{bc} \times D_{ac}} \tag{3.6}$$

$$GMR = re^{-0.25} \tag{3.7}$$

where r is the radius of the all-aluminium conductors D_{ab} is the distance between conductors on Phase A and Phase B, D_{bc} is the distance between conductors on Phase B and Phase C and, $D_{ac}$is the distance between conductors on Phase A and Phase C.

The inductance, L, per phase per meter (H) is determined using equation 3.8.

$$L = 2\times10^{-7}\ln\left(\frac{GmD}{GmR}\right)H/m \qquad 3.8$$

The inductance per phase was therefore a product of the inductance per meter and the length of the line in meters.

where f, 50 Hz is the frequency of the power supply.

The capacitance per phase can be calculated using equation 3.9.

$$C = \frac{2\pi\varepsilon}{\ln\left(\frac{GMD}{r}\right)}F/m \qquad 3.9$$

Where ε_0 is 8.85×10^{-12}

3.6.2. Determination of (U_{DEV}, %) of the Network by Calculation

In an attempt to determine the voltage deviation of the 11/0.4 kV EPDN, a three phase V-I measurement instrument in the Simulink model was employed for voltage measurements between phase and neutral on the network. Readings obtained are presented in Tables 3. 3 and 3.4 respectively.

The voltage deviation, U_{dev}, % is determined using equation 3.10.

$$U_{dev},\% = \frac{U_{ph} - U_{nom}}{U_{nom}}*100,\% \qquad 3.10$$

where U_{ph} is the measured phase voltage and U_{nom} is the normal voltage.

3.6.3 Determination of (P_{VUM}, %) of the Network by Computation

The percentage voltage imbalance on unbalanced distribution network under investigation was carried out using NEMA, IEEE and Australia standards methods. The NEMA, IEEE and Australia standards set the minimum limit of percentage voltage unbalance for which reliable, long time effective operation of most electrical tool, devices and components on distribution system demands must be less than two percent (< 2%). Any value greater than two percent means the network has too much imbalance.

Voltage unbalance is when the phase angle between the supplied phase voltages are not equal, or when three phase voltages are not equal in magnitude or the phase shift between voltages of any two phases is not 120^0 or both.

Equation (3.11) is an improved equation from what NEMA, IEEE and Australia equations used in calculating the percentage voltage unbalance using line voltage and voltage phase respectively.

The percentage voltage unbalance mitigation (% P_{VUM}) is calculated using equations (3.11 and 3.12) for the studied unbalanced in distribution network.

$$\%P_{VUM} = \frac{abs\ value\ of\ \max\ deviation\ of\ phase\ values\ from\ the\ mean\ phase\ voltage}{mean\ phase\ voltage} \quad (3.11)$$

Mathematically, percentage voltage unbalance (% P_{VUM}) is given by (12).

$$\%P_{VUM} = \frac{\sum \frac{1}{2} \left| \left(V_{abc} - aveV_{abc} \right) \right|}{aveV_{abc}} * 100\% \quad (3.12)$$

Where, *Vabc* is the phase voltage on each phase and *aveVabc* is the average voltage of all the three phases.

3.7 System Model of 11/0.4 kV, Secondary Electric Power Distribution System

This research work focuses on investigating the unbalanced voltage and voltage variation in low voltage electric power distribution system using model simulated in MATLAB/Simulink in Sim Power System tool box. The software simulation parameters for the studied distribution system are given in Table 3.1. Figures 3.2a illustrates a typical power system model for the secondary distribution system, and Figure 3.2b describes the proposed MATLAB/Simulink test system model.

The length of the secondary electric power distribution feeder lines under study ranges from 0.5 km, 0.8 km, 1 km, 1.5 km, 2 km, 2.5 km, 3 km, 3.5 km, 4 km, 4.5 km to 5 km respectively. The voltage levels and conductor type of the secondary access network consist of 400 V_{L-L}, 220 V_{L-N} via 11/0.4 kV, distribution transformer, based on all aluminium conductors (AAC) standard. In the proposed Simulink model two cases were carefully investigated.

CASE 1: a balanced three-phase load star connected at 80 % transformer rating is considered. The total load injected in the three-phase is 360 kW at 0.9 pf. The load on Phase A, B and C is 120 kW for each phase respectively.

CASE 2: an unbalanced three-phase load star connected at 80 % transformer rating is considered. The total load injected in the three-phase is 360 kW at 0.9 pf. The load on Phase A is 150 kW, Phase B is 110 kW, and Phase C is 80 kW respectively.

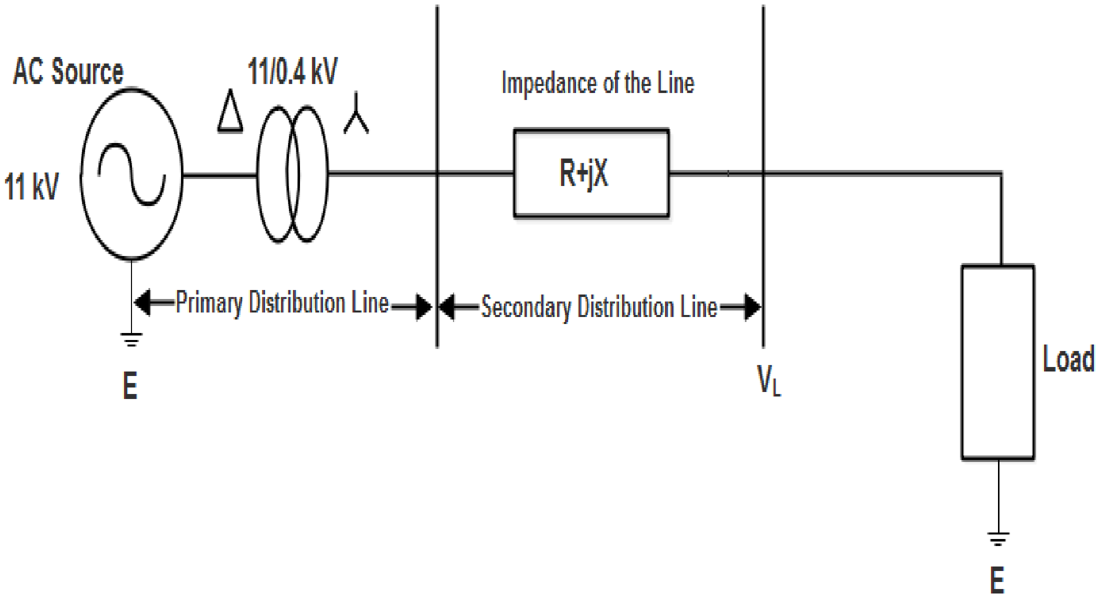


Figure 3.2a: Typical model of 11/ 0.4 kV secondary distribution test system

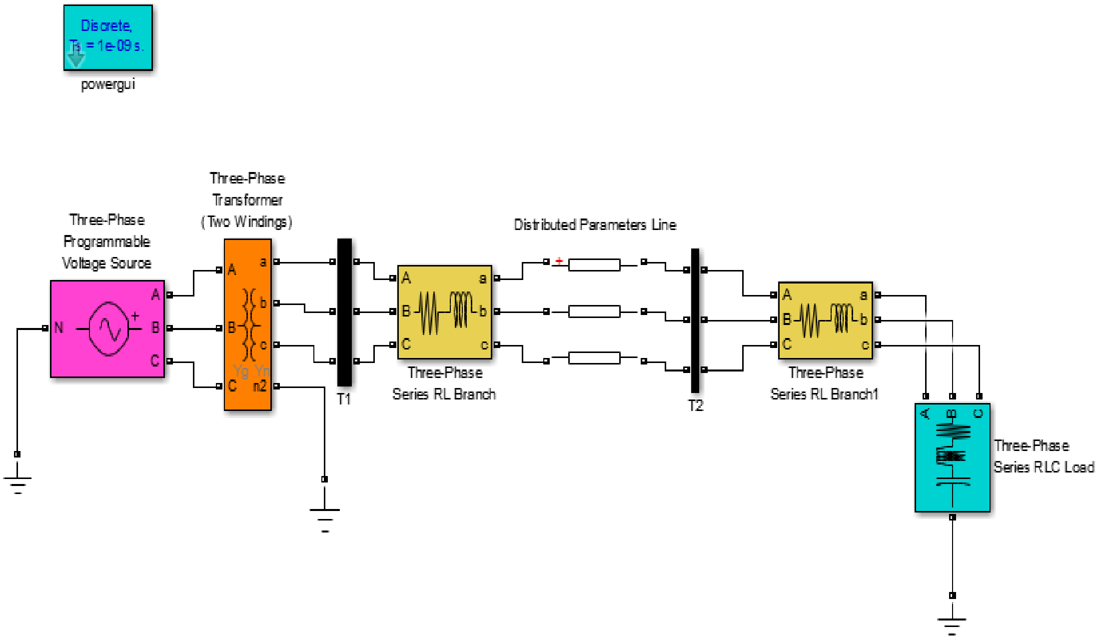


Figure 3.2b: Simulation model of 11/0.4 kV, secondary distribution test system.

A sample radial secondary (400 V) residential urban/rural electrical secondary DN is examined for the voltage variation and unbalance voltage investigations. The network provides energy to a combination of private houses, shops, business centers, and offices. The secondary distribution feeder has three phases and four wire system with equal length. The electric poles are positioned at a length of 50 meters from one another. At each pole, houses are supplied from each phase. The software simulation parameters of electric power distribution system are depicted in Table 3.1.

Table 3.1: Secondary Distribution Parameters

S/N	Material	Parameter
1	Distribution Transformer	11/0.4 kV, 500 kVA, Δ/Y grounded
2	MV Feeder	Three-phase 11 kV radial, overhead line
3	LV Feeder	3–phase 4-wire, 400 V, overhead all-aluminium conductors 100 mm^2
4.	Case one: balanced DN	Phase A, B and C load is 120 kW each at 0.9 pf, 80 % transformer rating.
5	Case two: unbalanced DN	Phase A 150 kW, Phase B 110 kW, Phase C 80 kW at 0.9 pf, 80 % transformer rating.

3.8 Results of the Voltage Variation and Voltage Unbalance Investigation

3.8.1 Simulation Results of Case One: Balanced Distribution network

The simulation results of the voltage profile variation investigation of 0.4 kV star connected networks are presented in Figures 3.3 to 3.13. Figure 3.14 depicts the curve of load voltage profile for the balanced distribution system and Table 3.2 shows the summary of the load voltage profile measurements of the electric power distribution network under considerations

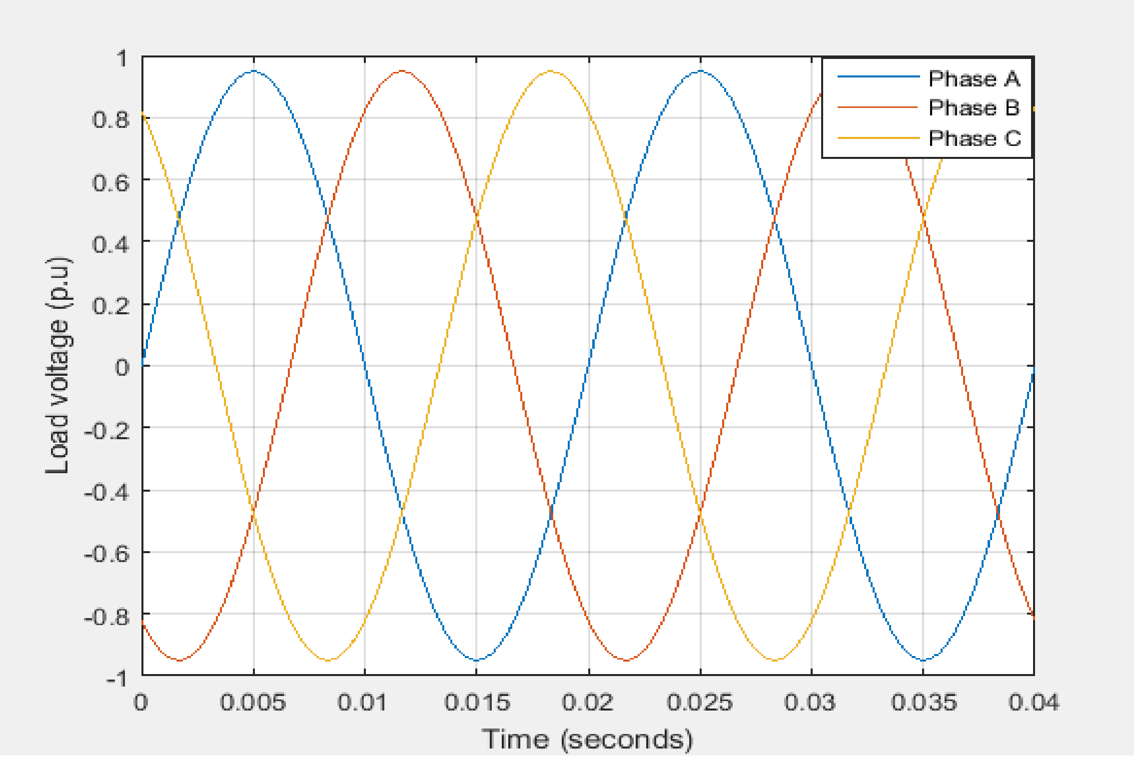


Figure 3.3: Per-unit load voltage profile of 0.5 km for balanced DN

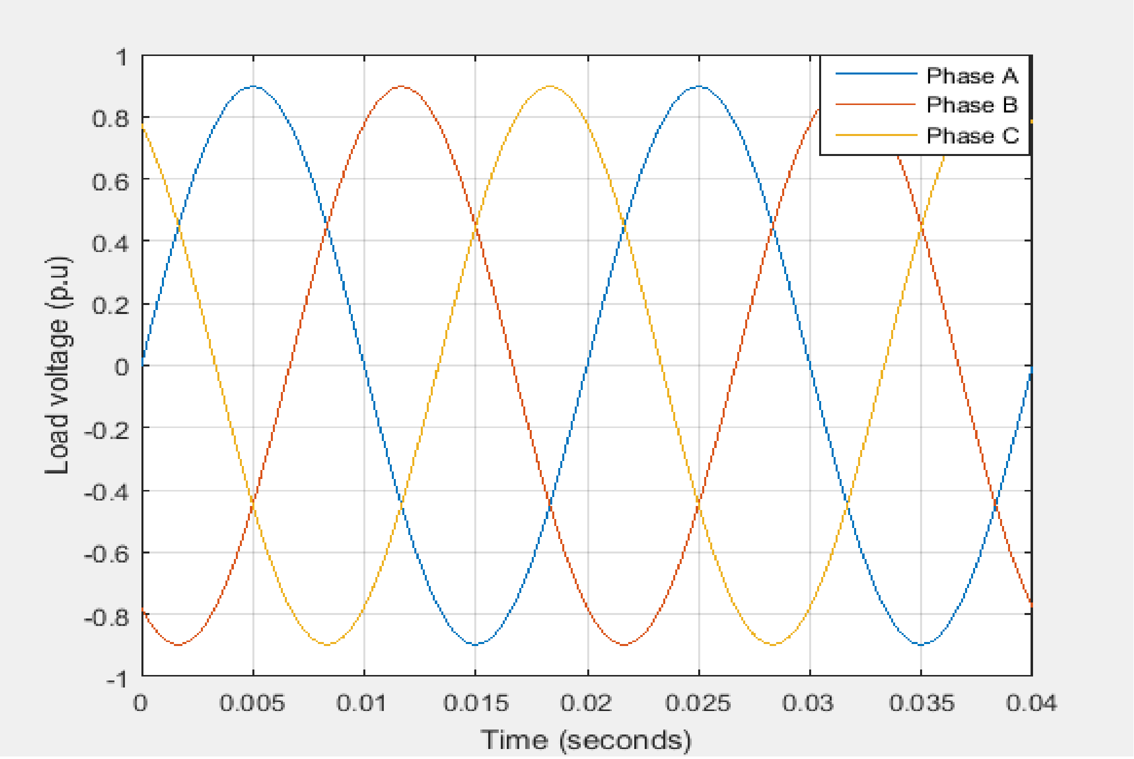


Figure 3.4: Per-unit load voltage profile of 0.8 km for balance DN

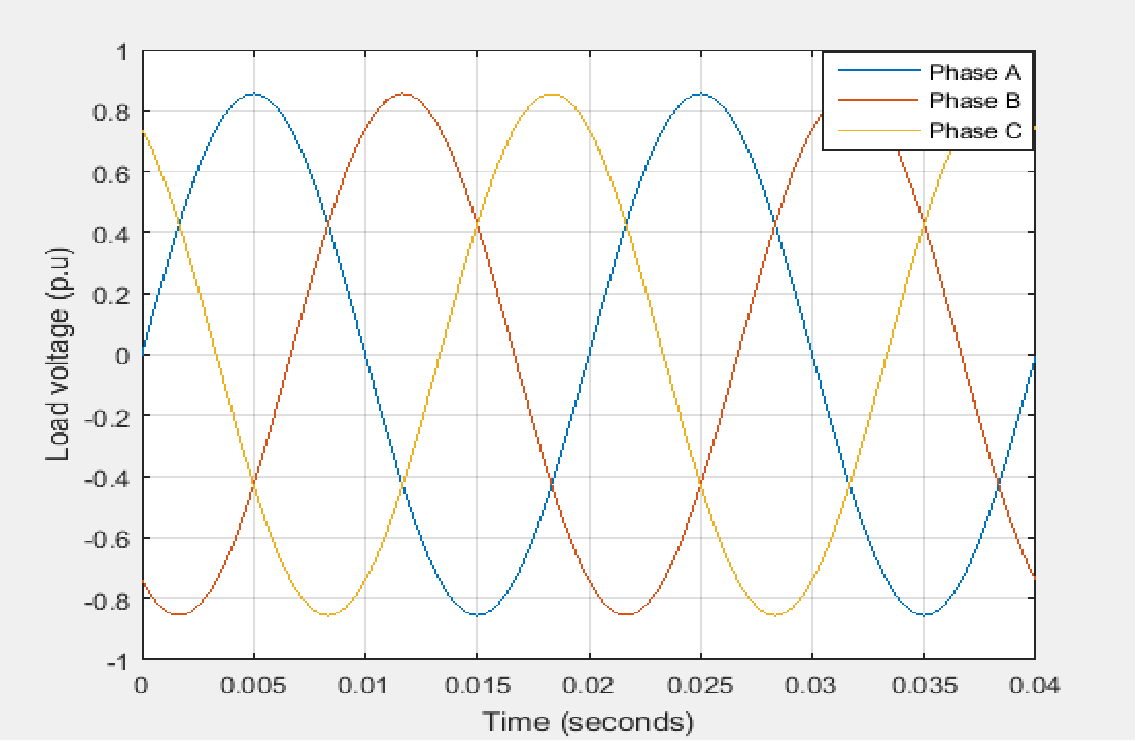


Figure 3.5: Per-unit load voltage profile of 1 km for balanced DN

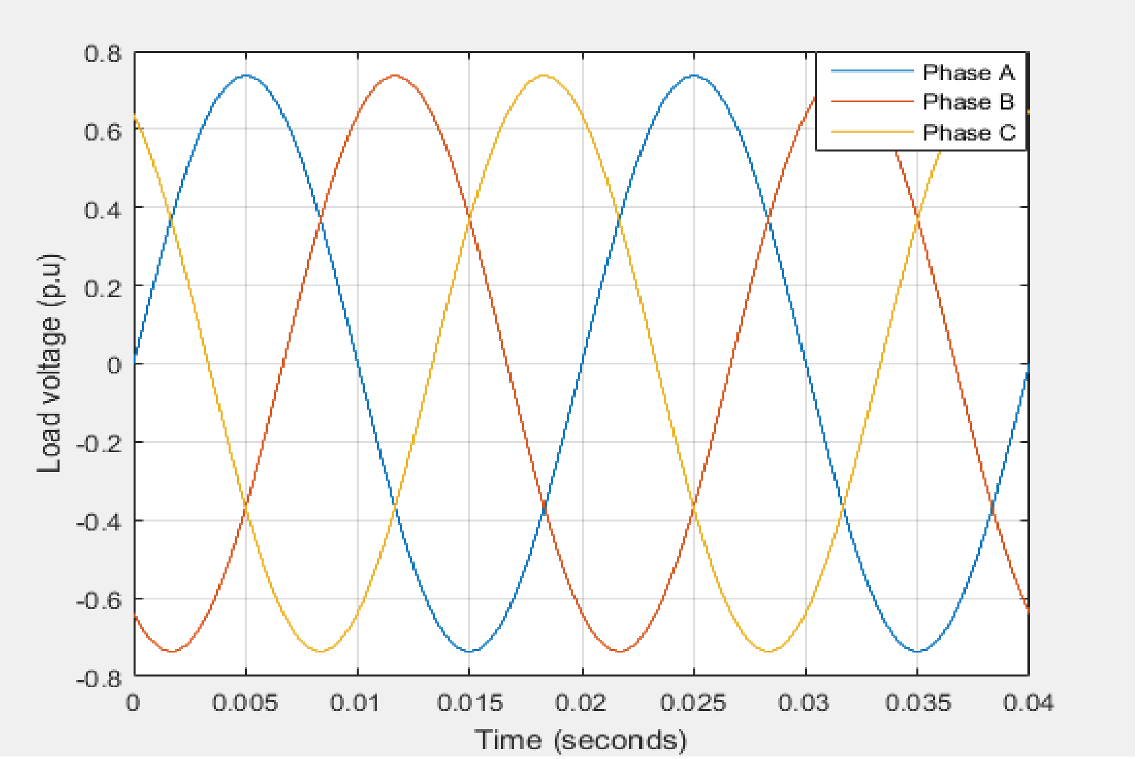


Figure 3.6: Per-unit load voltage profile of 1.5 km for balanced DN

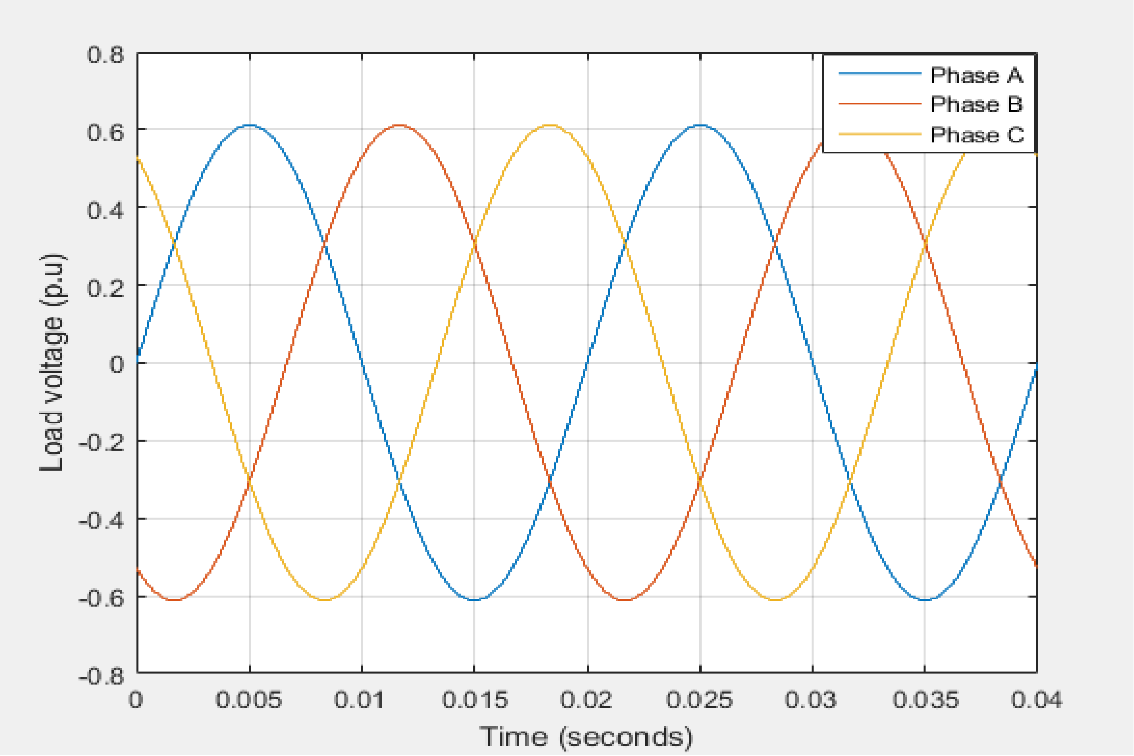


Figure 3.7: Per-unit load voltage profile of 2 km for balanced DN

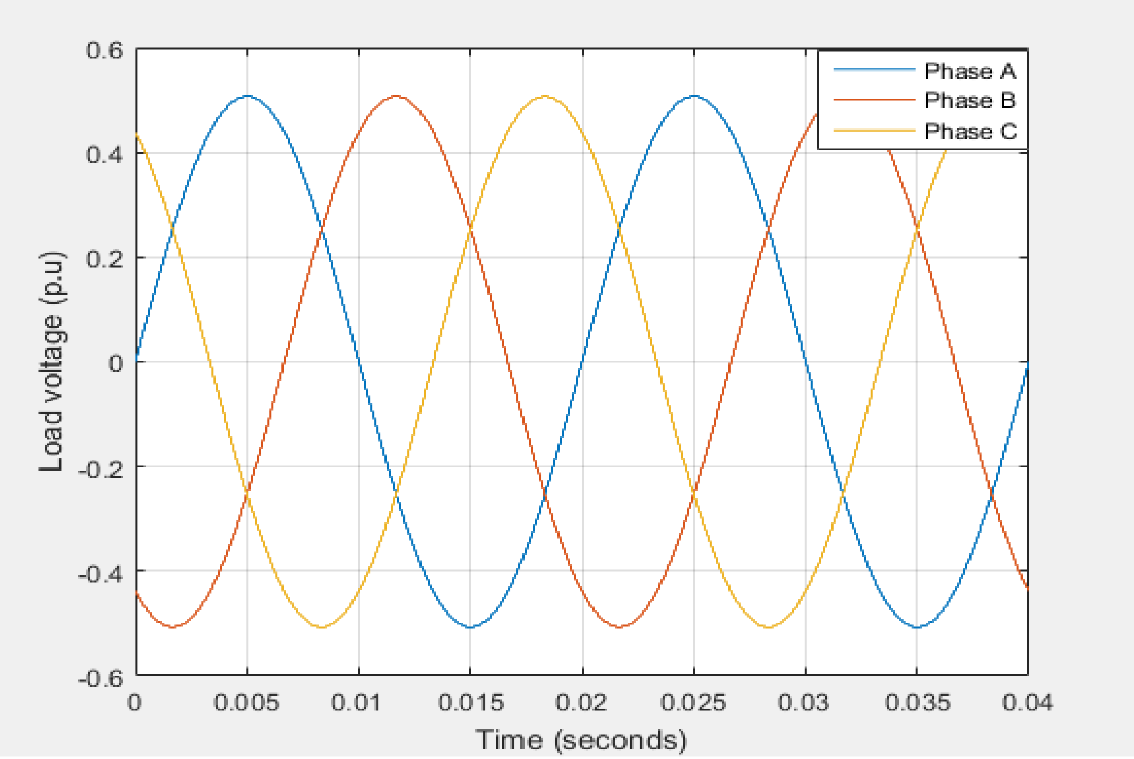


Figure 3.8: Per-unit load voltage profile of 2.5 km for balanced DN

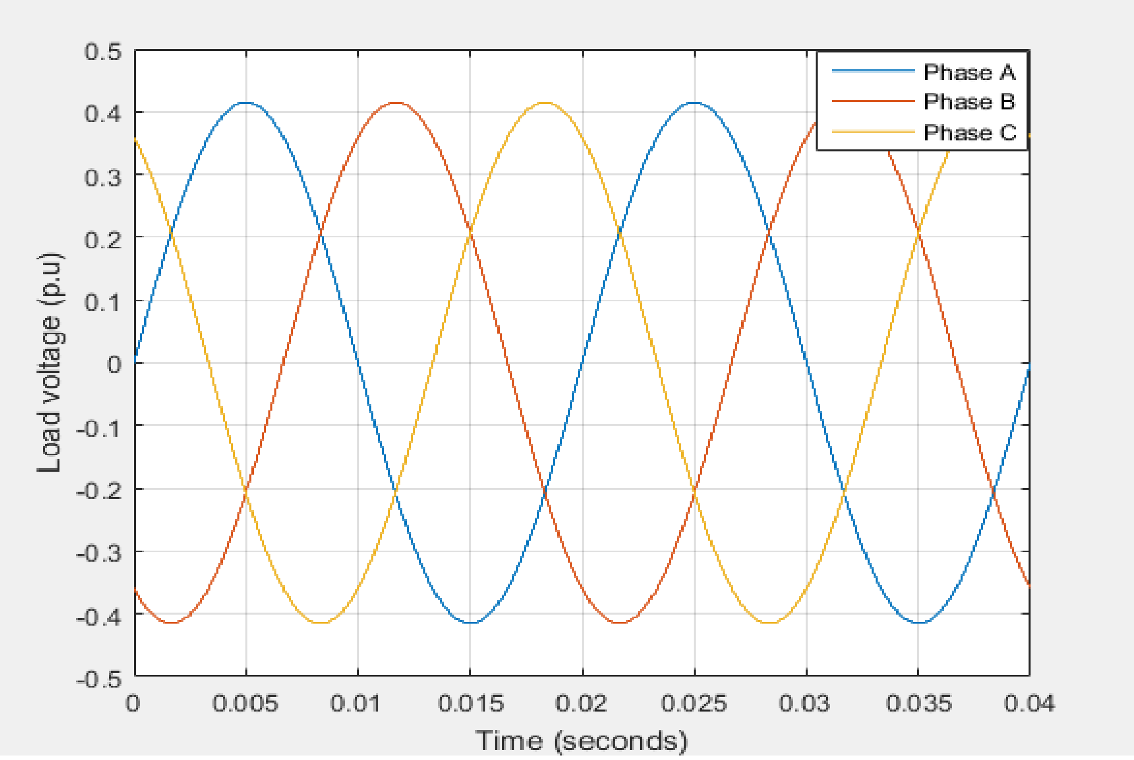


Figure 3.9: Per-unit load voltage profile of 3 km for balanced DN

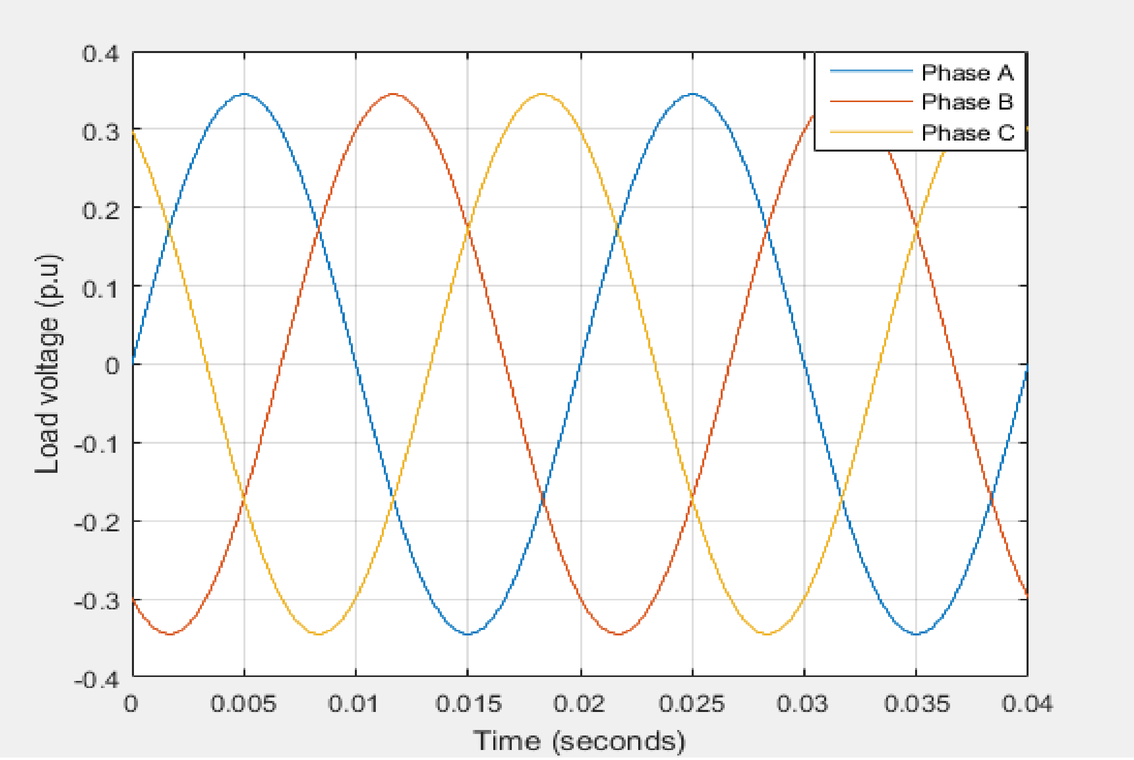


Figure 3.10: Per-unit load voltage profile of 3.5 km for balanced DN

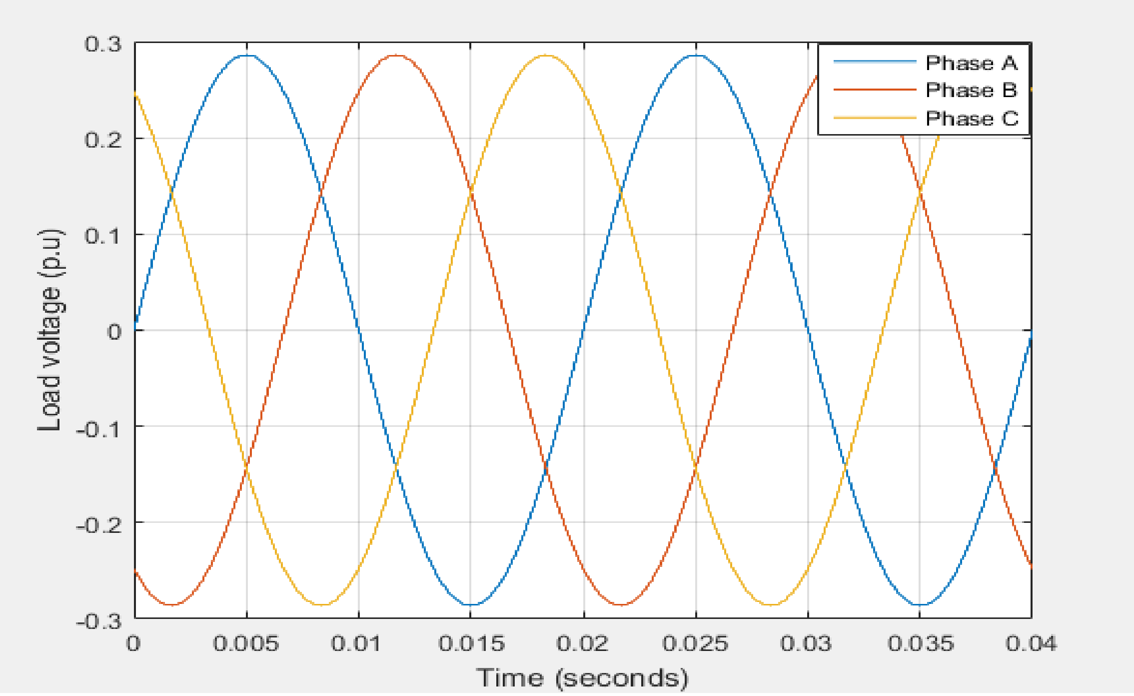


Figure 3.11: Per-unit load voltage profile of 4 km for balanced DN

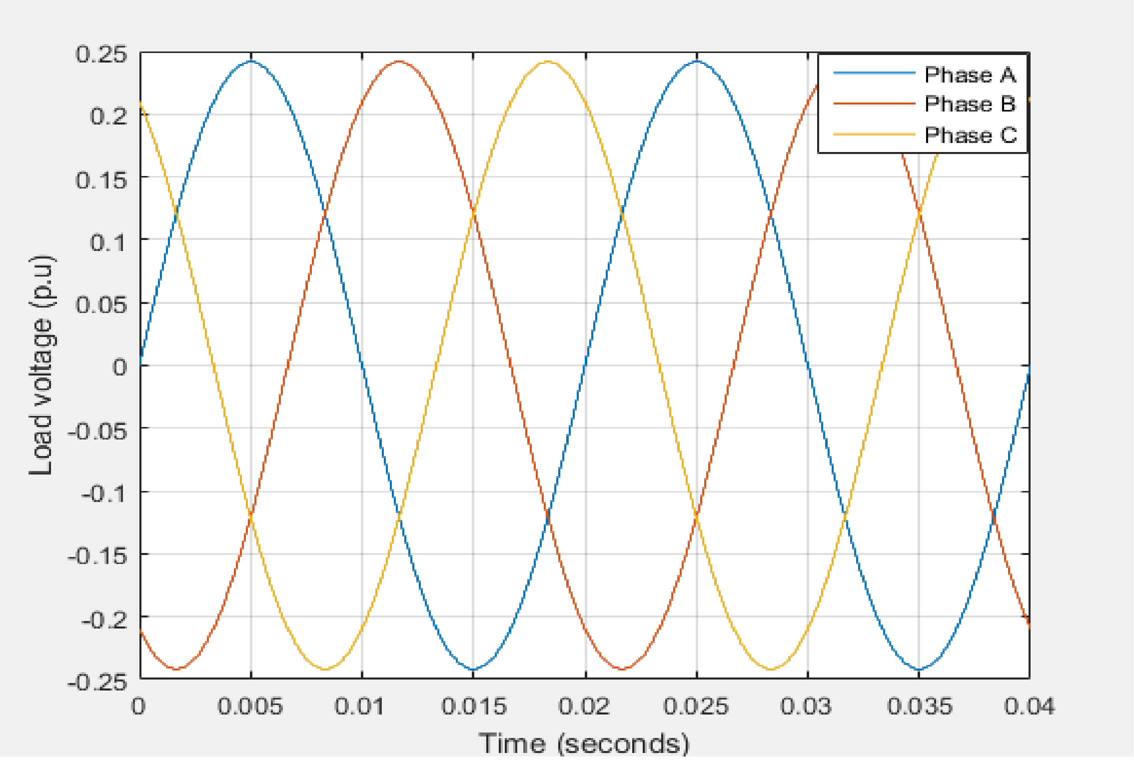


Figure 3.12: Per-unit load voltage profile of 4.5 km for balanced DN

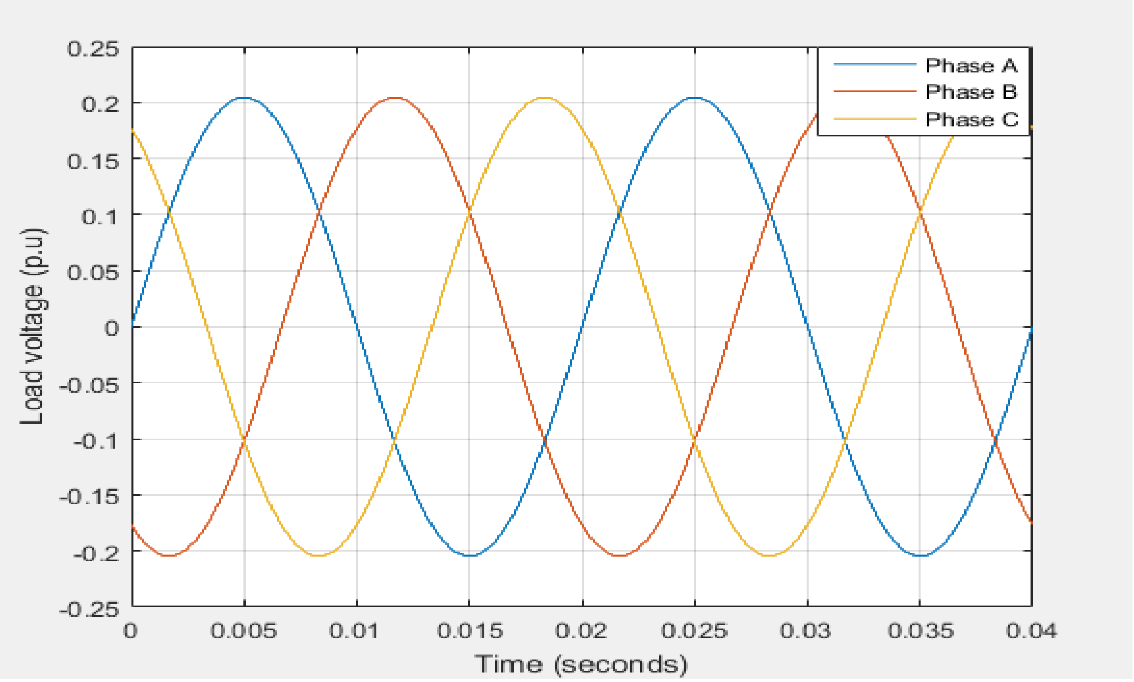


Figure 3.13: Per-unit load voltage profile of 5 km for balanced DN

Table 3.2: Per-Unit Measurement of VP for Balanced DN

Network Length, (km)	Voltage Profile (p.u)
0.5	0.95
0.8	0.90
1.0	0.85
1.5	0.73
2.0	0.61
2.5	0.50
3.0	0.41
3.5	0.34
4.0	0.28
4.5	0.23
5.0	0.20

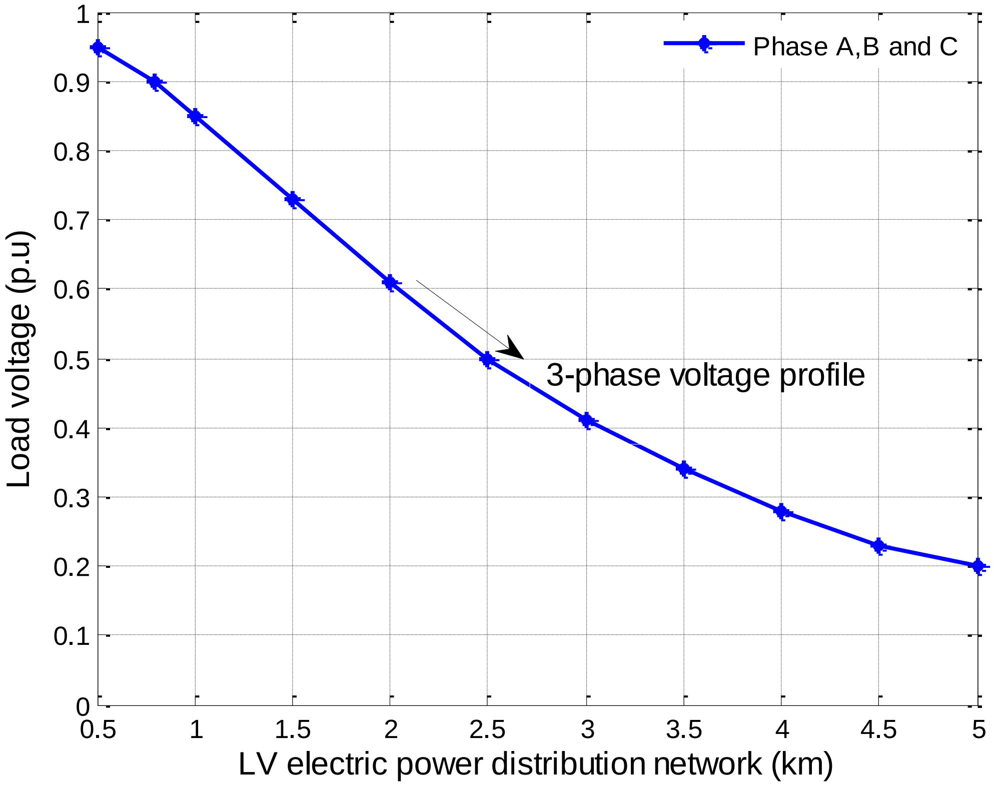


Figure 3.14: Curve of load voltage profile for balanced DN

3.8.2 Simulation Results of Case Two: Unbalanced Distribution Network

The simulation results of voltage unbalance investigation for unbalanced distribution network are presented in Figures 3.15 to 3.25. Tables 3.3 shows the summary of the voltage profile measurements for unbalanced network. Figures 3.26a and 3.26b show the curves and the histogram of voltage profiles for unbalanced 3-phase loads neutral connected for 11/0.4 kV and LV electric power DN.

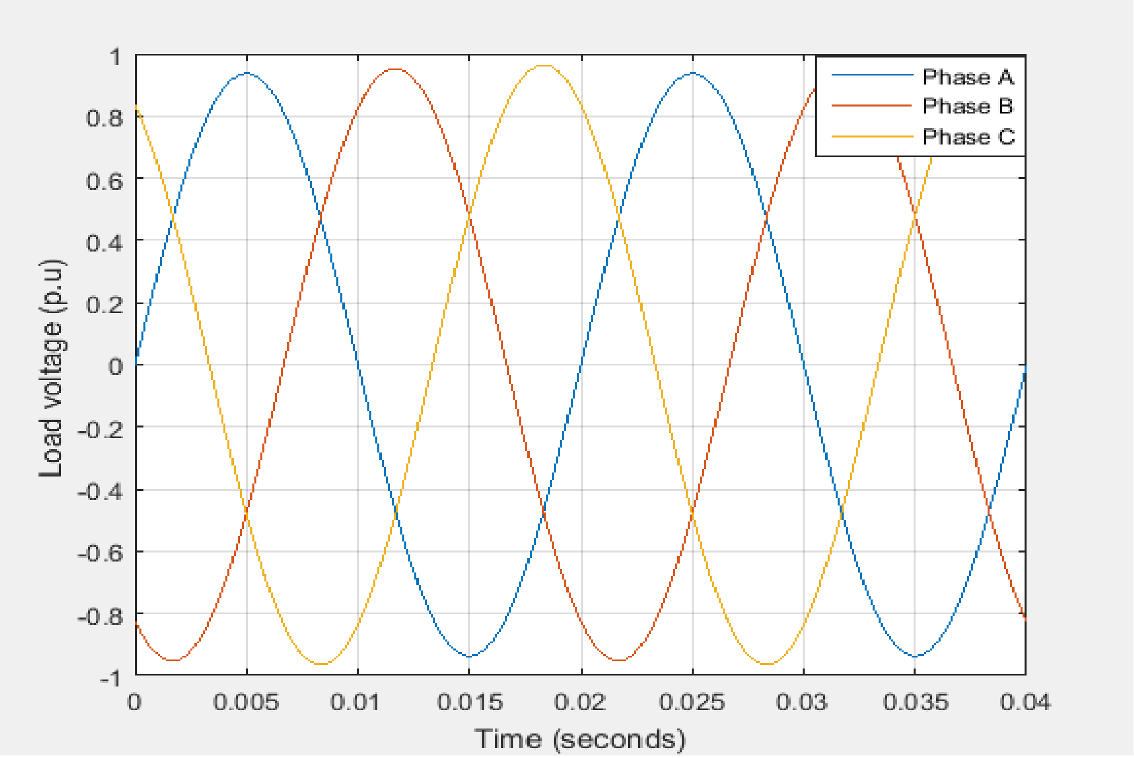


Figure 3.15: Per-unit load voltage profile of 0.5 km for unbalanced DN

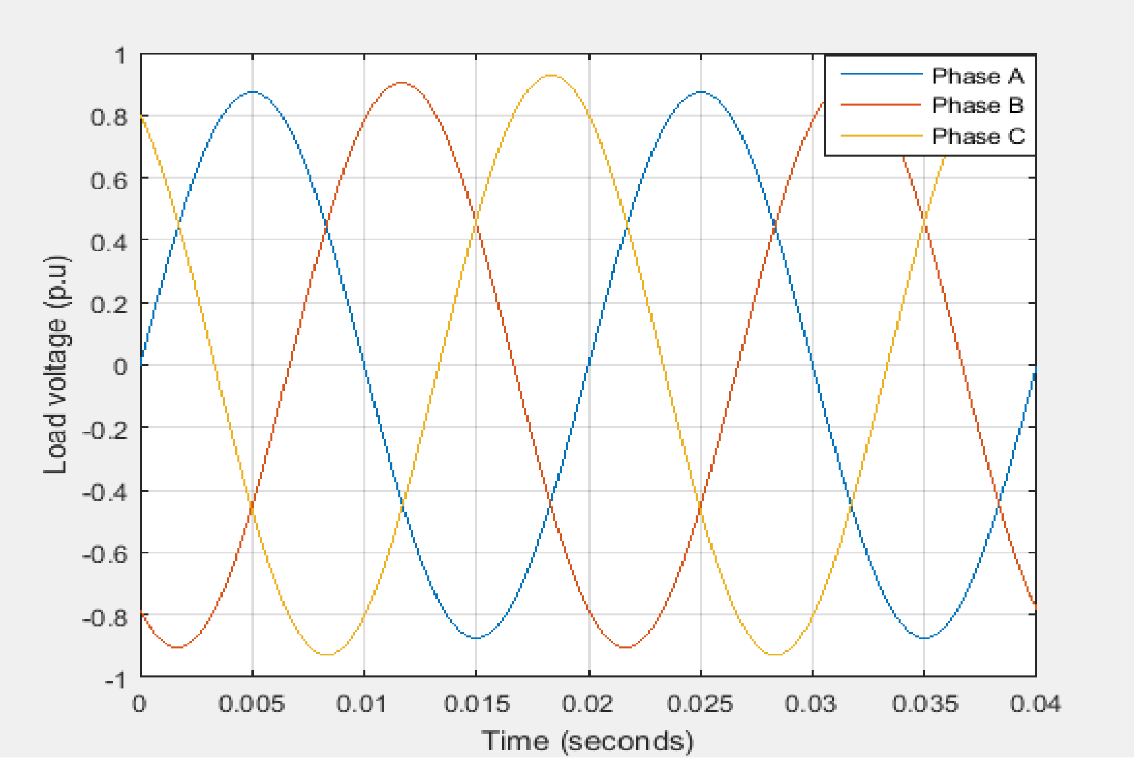


Figure 3.16: Per-unit load voltage profile of 0.8 km for unbalanced DN

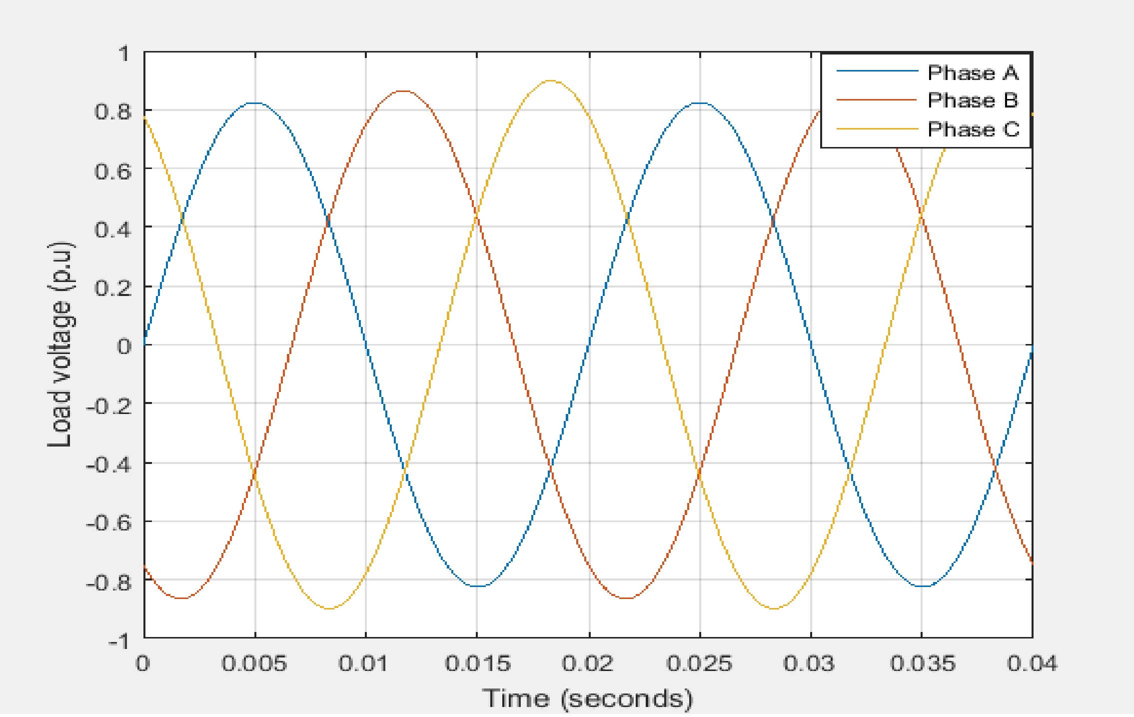


Figure 3.17: Per-unit load voltage profile of 1 km for unbalanced DN

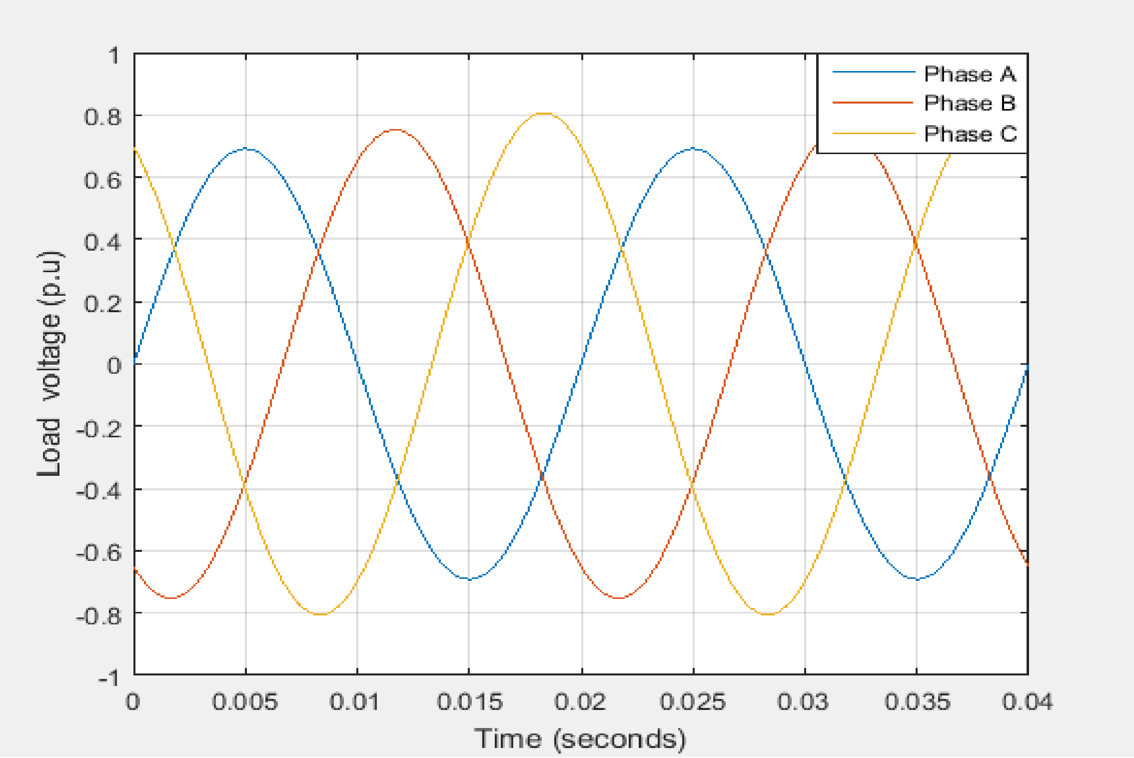


Figure 3.18: Per-unit load voltage profile of 1.5 km for unbalanced DN

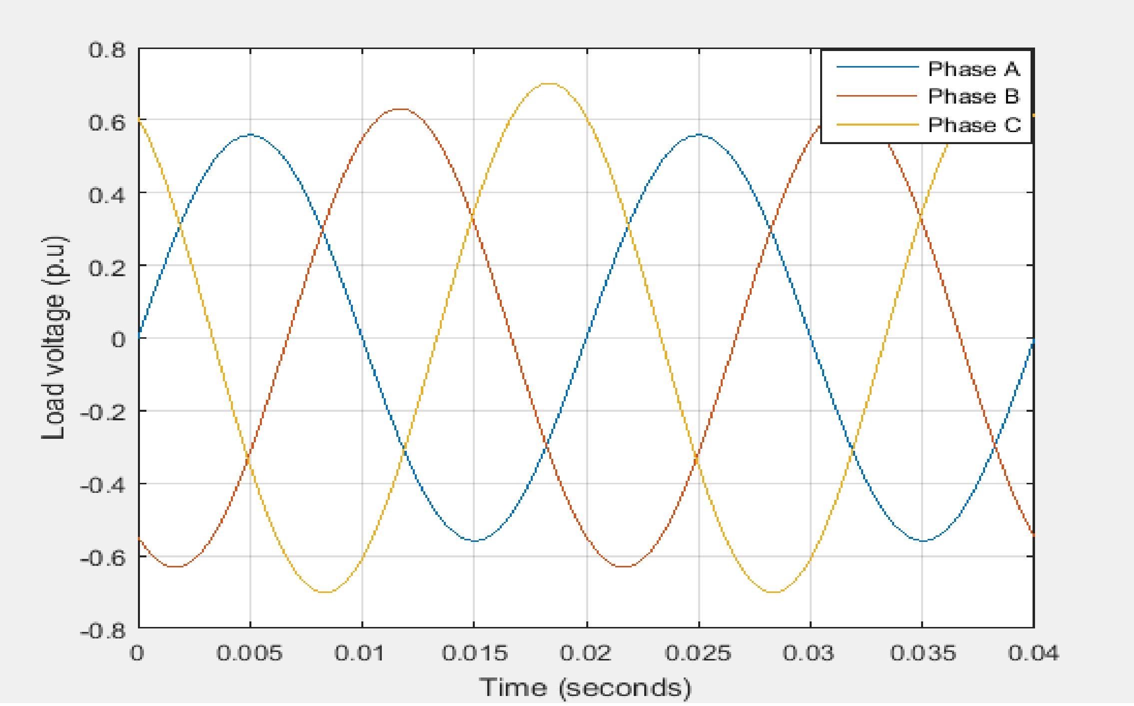


Figure 3.19: Per-unit load voltage profile of 2 km for unbalanced DN

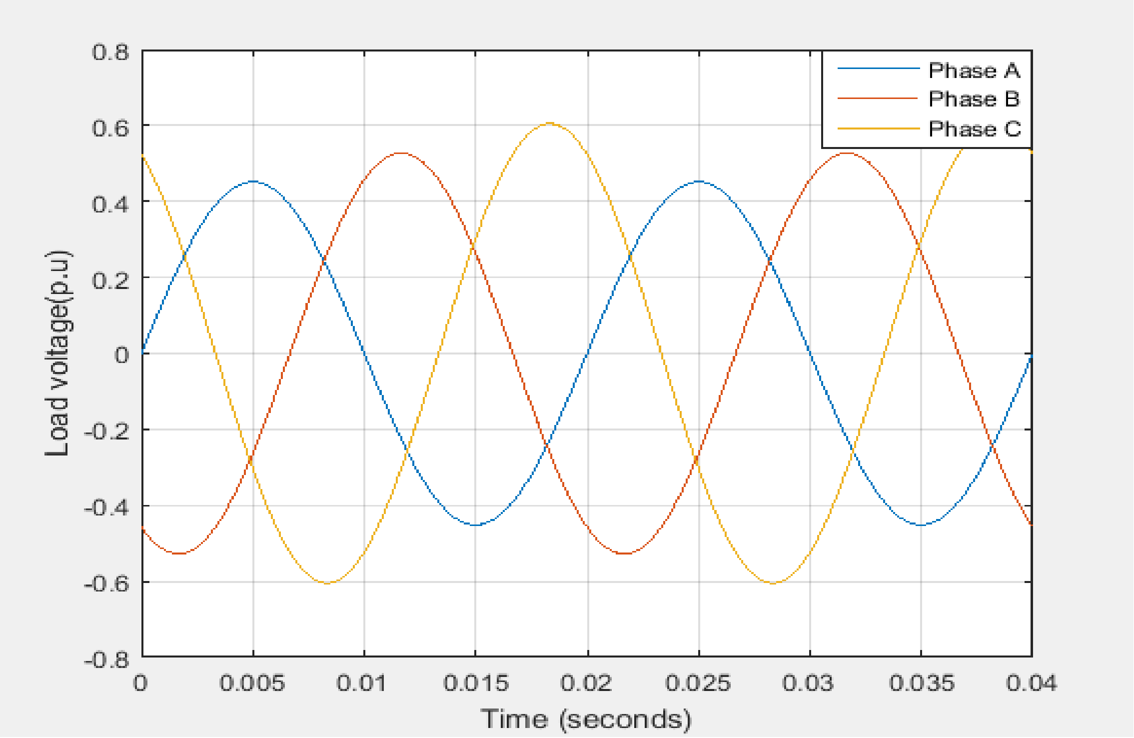


Figure 3.20: Per-unit load voltage profile of 2.5 km for unbalanced DN

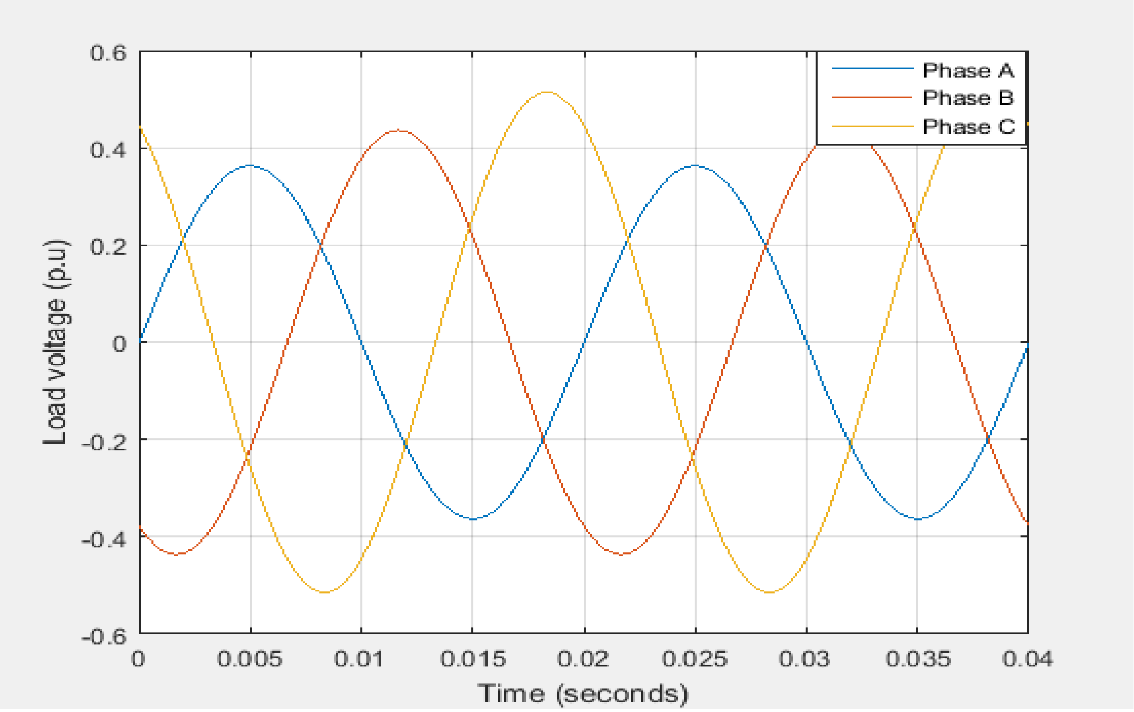


Figure 3.21: Per-unit load voltage profile of 3 km for unbalanced DN

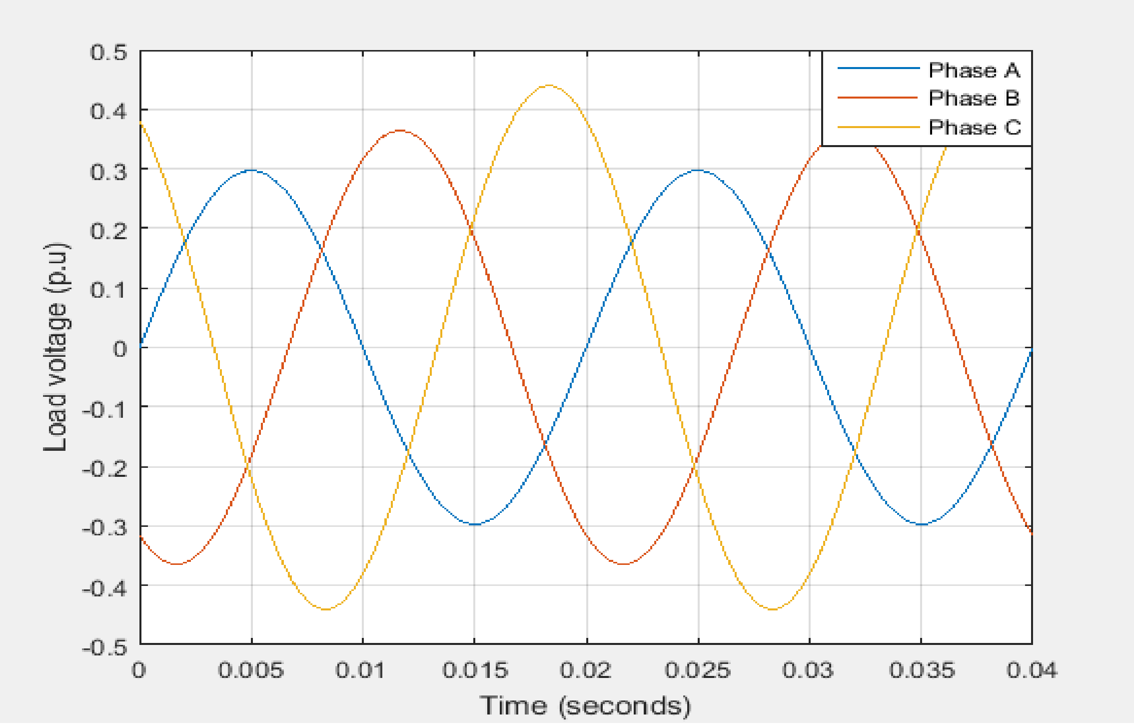


Figure 3.22: Per-unit load voltage profile of 3.5 km for unbalanced DN

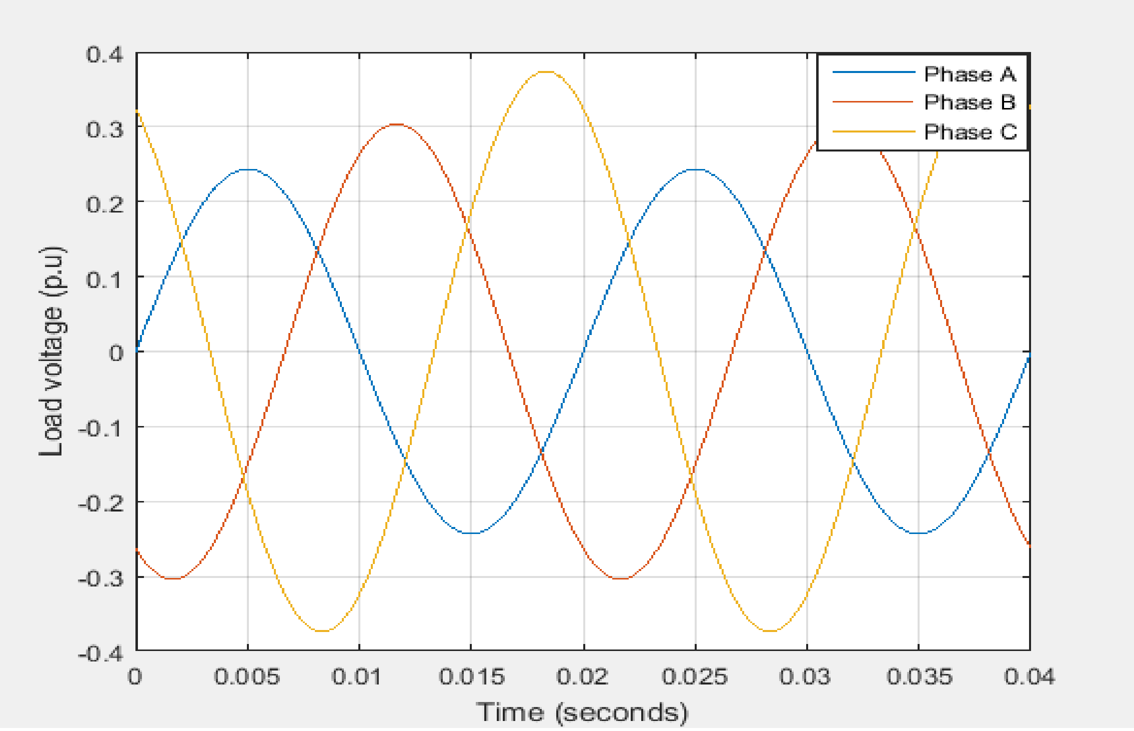


Figure 3.23: Per-unit load voltage profile of 4 km for unbalanced DN

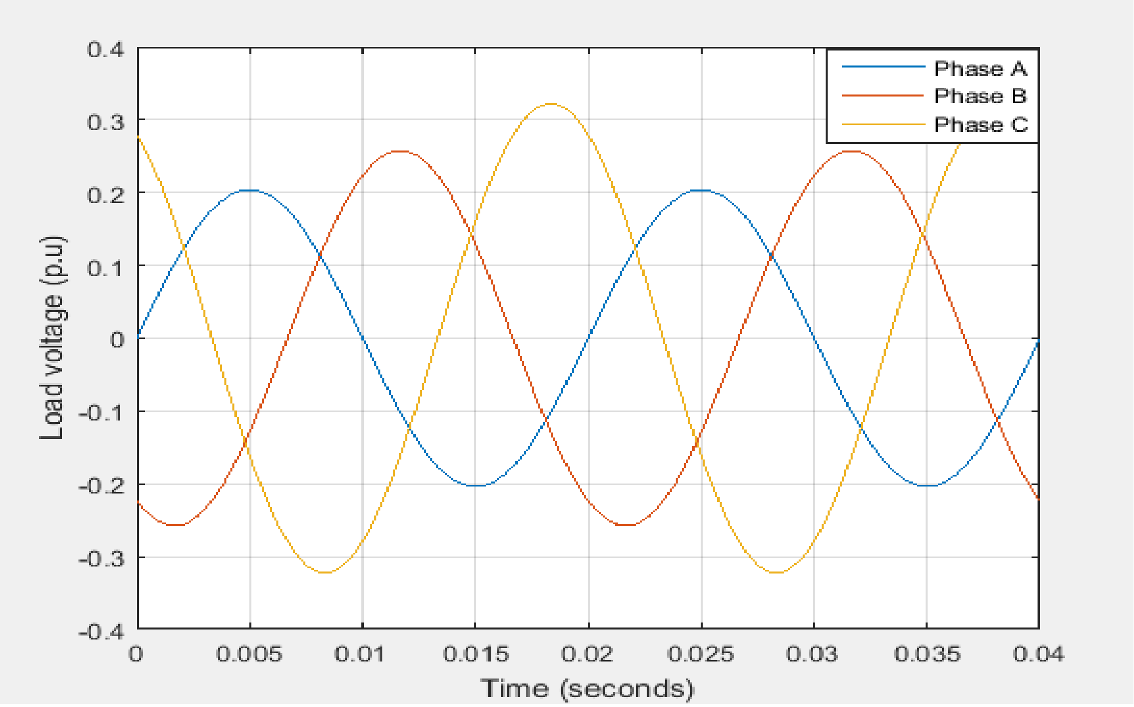


Figure 3.24: Per-unit load voltage profile of 4.5 km for unbalanced DN

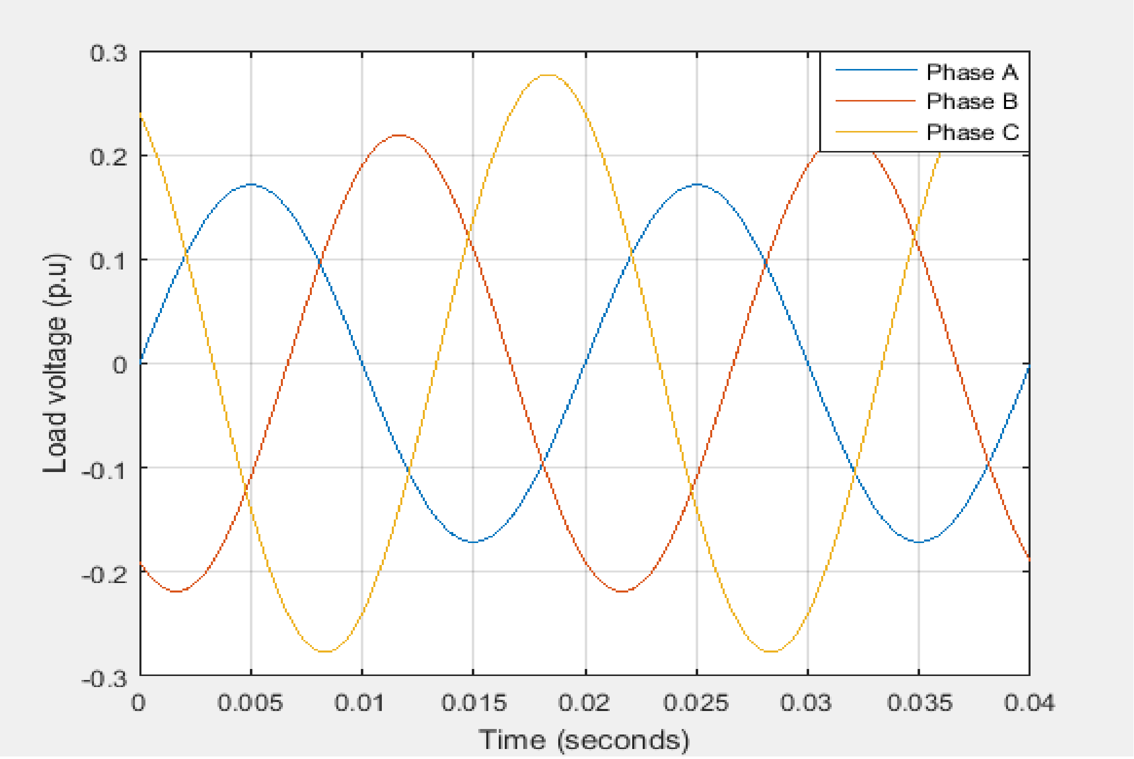


Figure 3.25: Per-unit load voltage profile of 5 km for unbalanced DN

Table 3.3: Per-Unit Measurement of VP for Unbalanced DN

L, (km)	VP, Phase A (p.u)	VP, Phase B (p.u)	VP, Phase C (p.u)
0.5	0.94	0.95	0.97
0.8	0.87	0.90	0.93
1.0	0.82	0.87	0.90
1.5	0.68	0.75	0.80
2.0	0.56	0.63	0.70
2.5	0.45	0.52	0.60
3.0	0.36	0.43	0.51
3.5	0.29	0.36	0.44
4.0	0.24	0.30	0.37
4.5	0.21	0.25	0.32
5.0	0.17	0.22	0.28

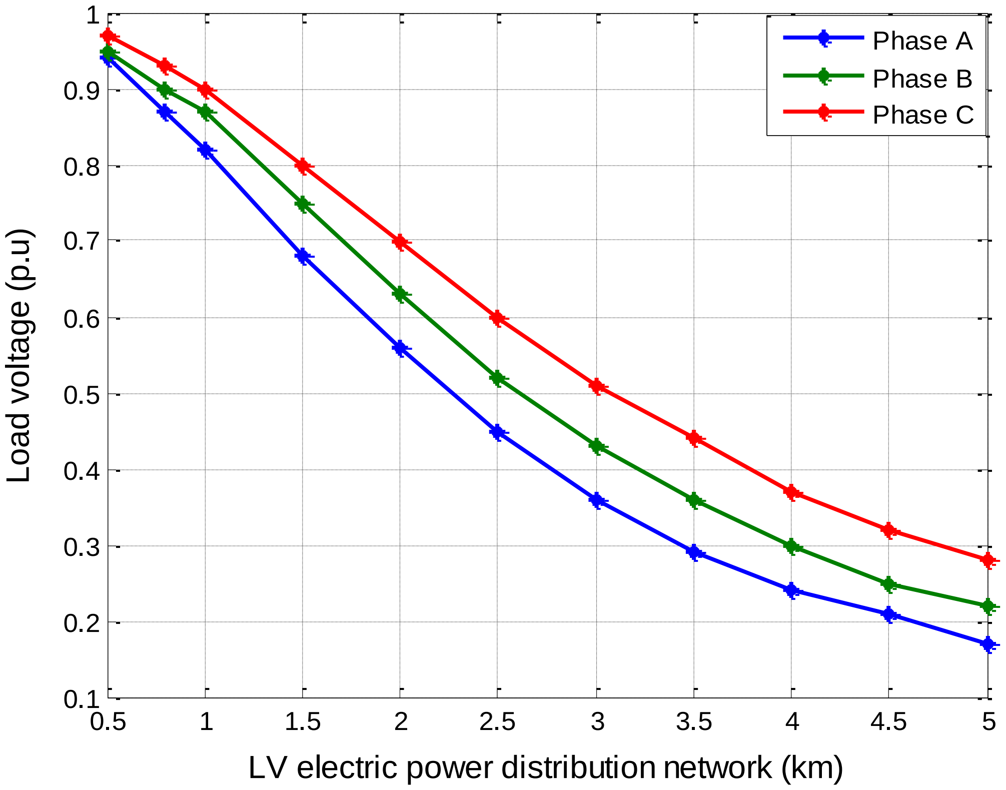


Figure 3.26a: Curve of voltage profile for unbalanced DN

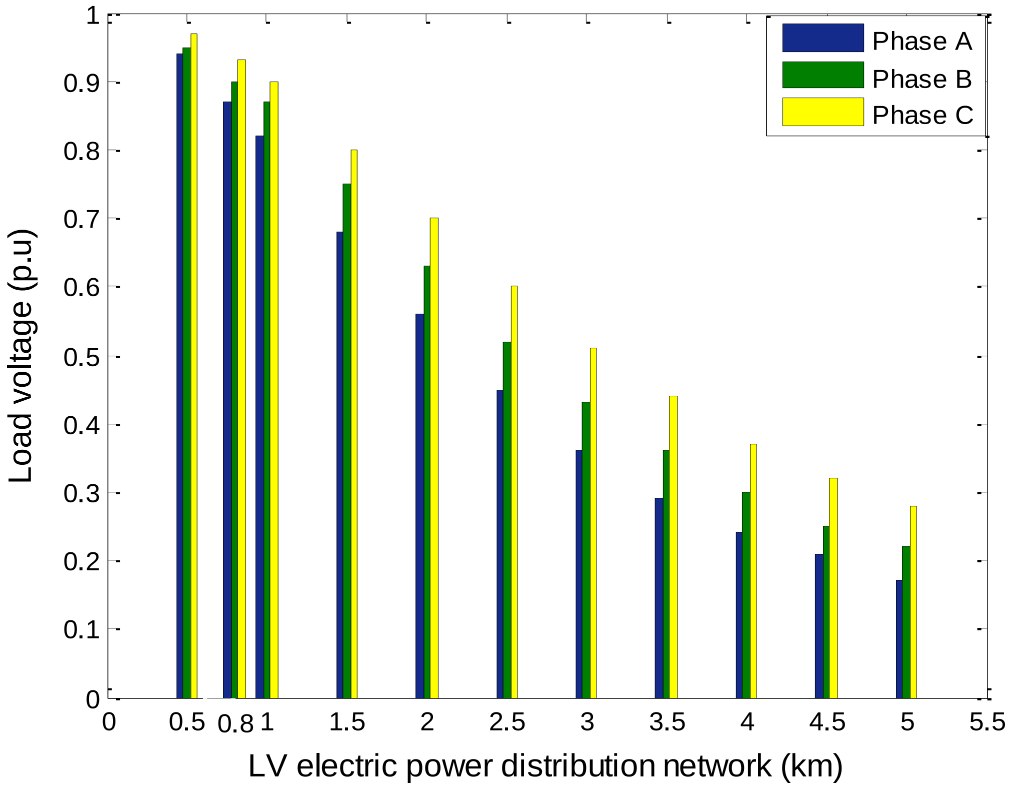


Figure 3.26b: Histogram of voltage profile for unbalanced DN

3.9 Voltage Deviation for 11/0.4 kV Secondary Electric Power DN

The purpose of measuring voltages at the load points is to determine the profile of voltages across the distribution feeder network, voltage drop, voltage deviation, percentage voltage deviation and as well as assess the loading condition.

3.9.1. Voltage Deviation for Balanced Distribution Network

Computation results of voltage deviation (ΔU_{dev}), voltage drop (ΔU), and percentage voltage deviation (U_{dev}, %) of the three-phase voltages of 11/0.4 kV, LV EPDN are presented in Table 3.4. Figure 3.27 shows the pie chart of percentage voltage deviation of network and Figure 3.28 shows the bar chart of voltage drop along the feeder length of balanced distribution network.

Table 3.4: Computation Of Percentage VD And Voltage Drop For Balanced DN

S/N	L, (km)	ΔUdev, (p.u)	ΔUdev,%	ΔU, (V)	ΔUstd. min and max %
1	0.5	0.05	5	11	±5%
2	0.8	0.1	10	22	±5%
3	1.0	0.2	20	44	±5%
4	1.5	0.27	27	59	±5%
5	2.0	0.37	37	81	±5%
6	2.5	0.5	50	110	±5%
7	3.0	0.59	59	130	±5%
8	3.5	0.66	66	145	±5%
9	4.0	0.72	72	158	±5%
10	4.5	0.77	77	169	±5%
11	5.0	0.8	80	176	±5%

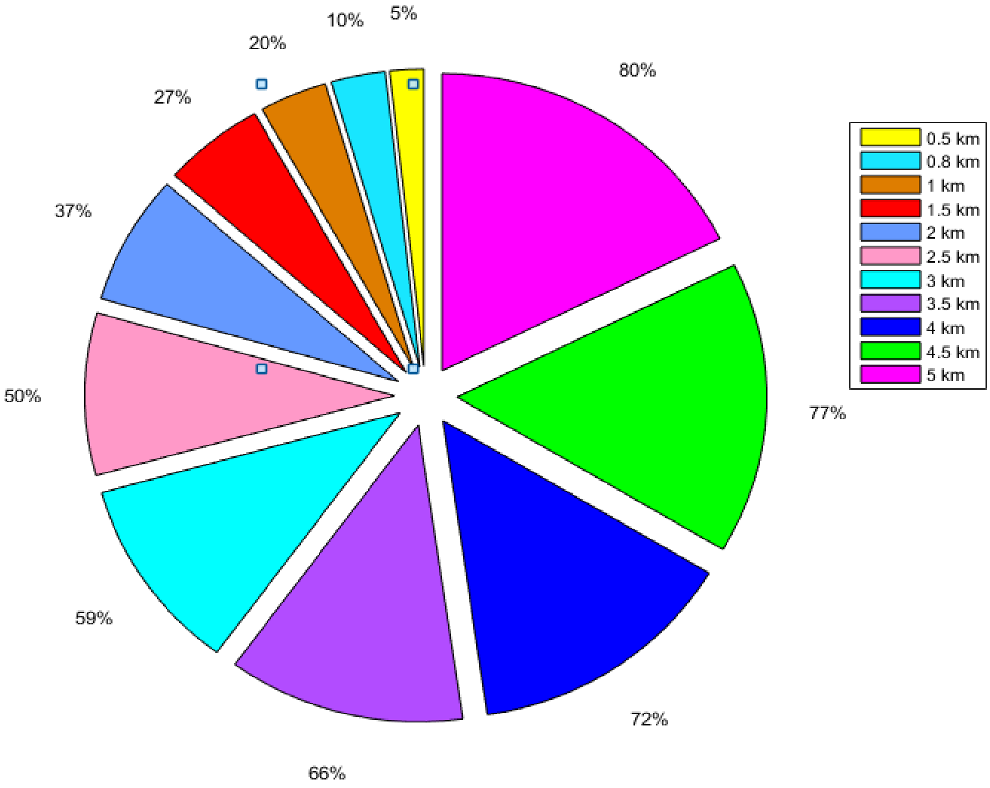


Figure 3.27: Pie chart of percentage voltage deviation of balanced DN

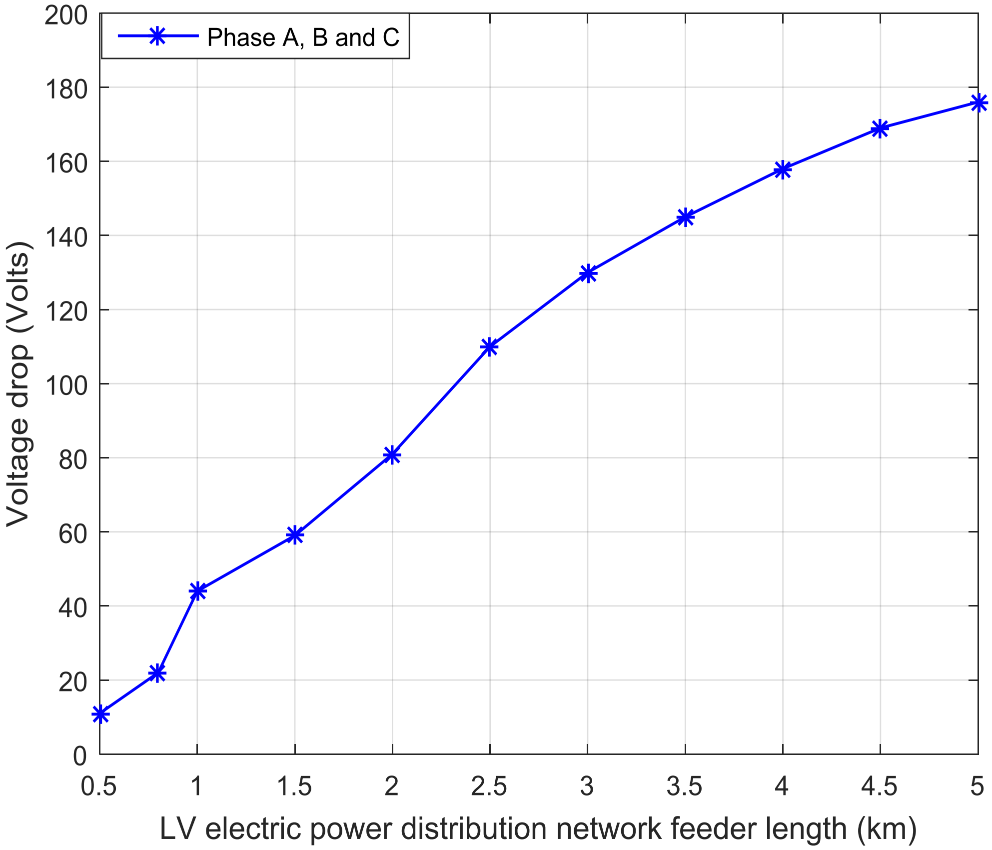


Figure 3.28: Curve of voltage drop on balanced DN

3.9.2 Voltage Deviation for Unbalanced Distribution Network

Computation results of voltage deviation (ΔUdev), the voltage drop (ΔU), and percentage voltage deviation (ΔUdev, %) of the three-phase voltages of 11/0.4 kV, LV EPDN are presented in Table 3.5. Figures 3.29 to 3.31 show the pie charts of percentage voltage deviation of unbalanced three-phase load for each phase. Figure 3.32a and 3.32b show the curve and the bar-chart of the voltage drop along the distribution feeder length of unbalanced three-phase load star connected respectively.

Table 3.5: Computation Of VD And Voltage Drop Of Unbalanced DN

L, (km)	**Δudev V, Ph, A**	**ΔUdev V, Ph, B**	**ΔUdev V, Ph, C**	**ΔU , V, A**	**ΔU , V, B**	**ΔU, V, C**	**ΔUdev ,%, Ph, A**	**ΔUdev ,%, Ph B**	**ΔUdev %, Ph C**	**ΔEstd. Min & Max., %**
0.5	0.06	0.05	0.03	13	11	6.6	6	5	3	±5
0.8	0.13	0.10	0.07	29	22	15	13	10	7	±5
1.0	0.18	0.13	0.10	40	29	22	18	13	10	±5
1.5	0.32	0.25	0.20	70	55	44	32	25	20	±5
2.0	0.44	0.37	0.30	97	81	66	44	37	30	±5
2.5	0.55	0.48	0.40	121	106	88	55	48	40	±5
3	0.64	0.57	0.49	141	125	108	64	57	49	±5
3.5	0.71	0.64	0.56	156	141	123	71	64	56	±5
4.0	0.76	0.70	0.63	167	154	139	76	70	63	±5
4.5	0.79	0.75	0.68	174	165	150	79	75	68	±5
5.0	0.83	0.78	0.72	183	172	158	83	78	72	±5

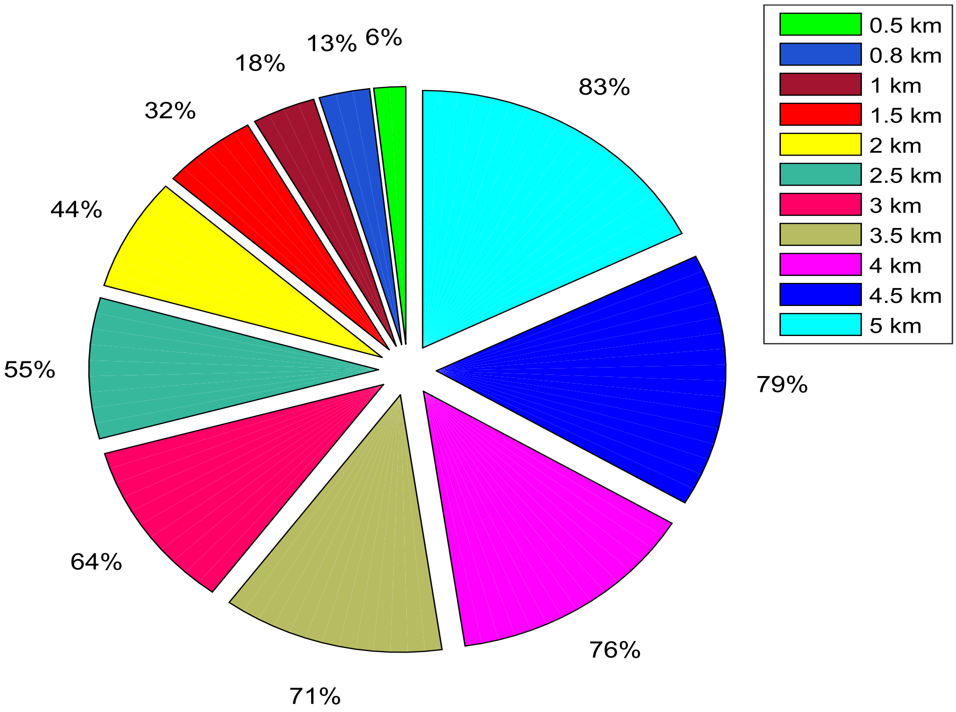


Figure 3.29: Pie chart of PVD of unbalanced phase A

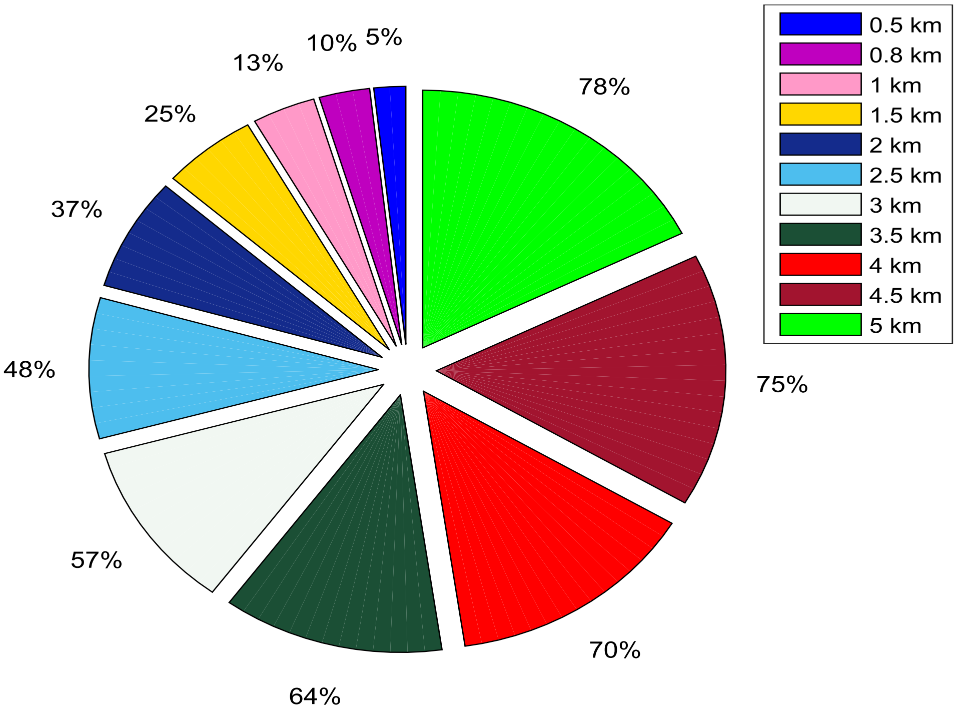


Figure 3.30: Pie chart of PVD of unbalanced phase B.

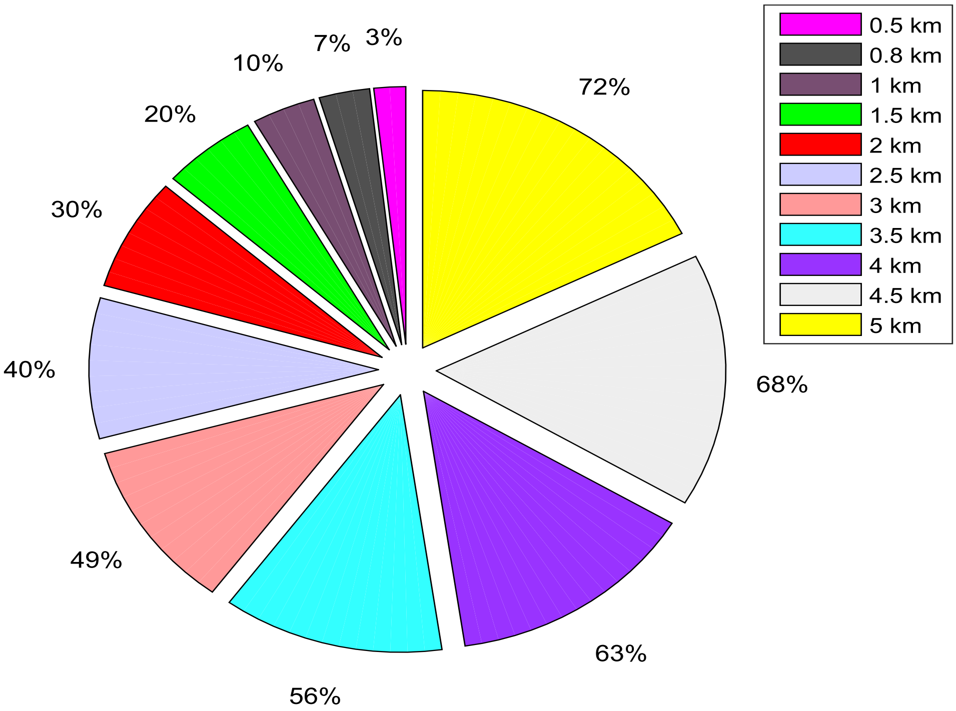


Figure 3.31: Pie chart of PVD of unbalanced phase C

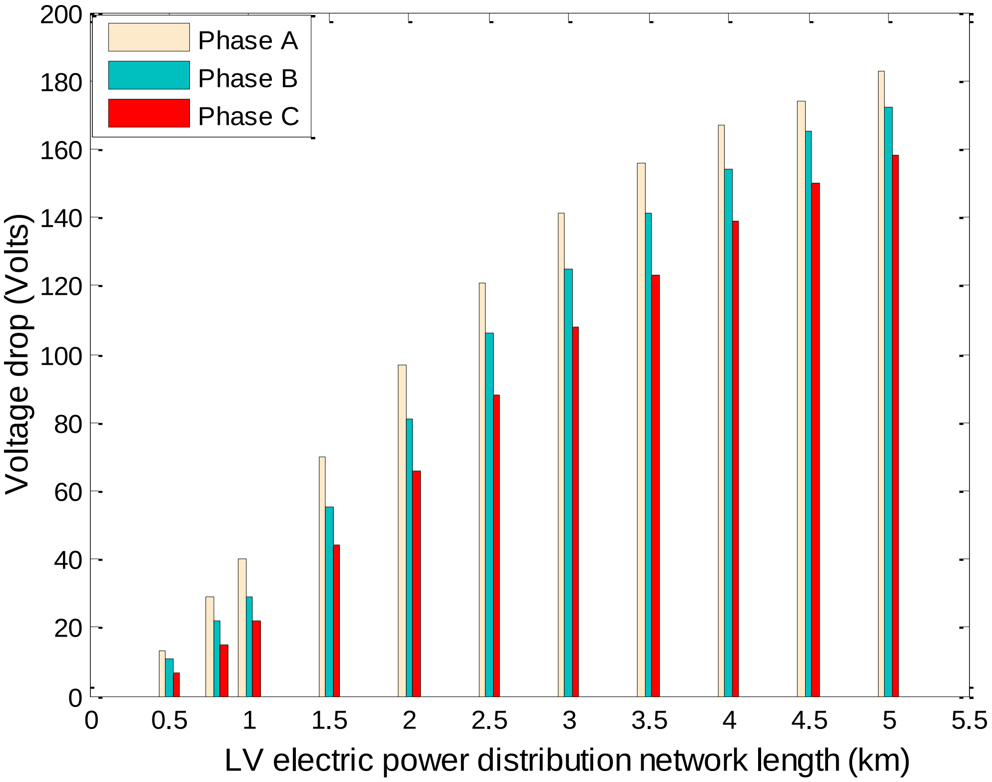


Figure 3.32a: Bar chart of voltage drop on unbalanced DN

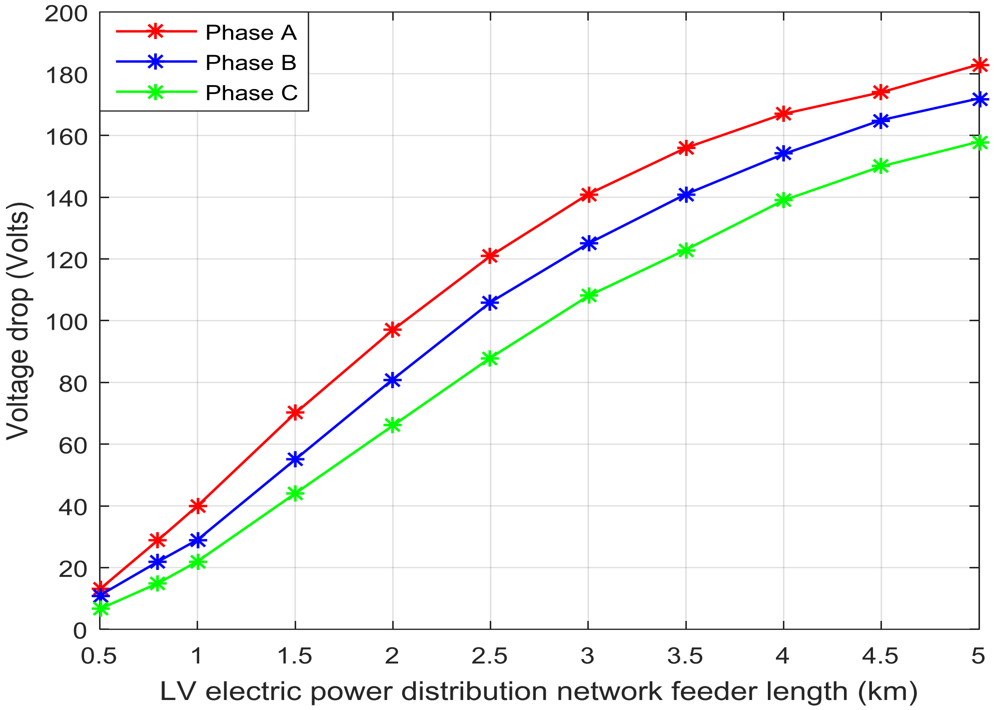


Figure 3.32b: Curves of voltage drop on unbalanced DN

3.10. Percentage Voltage Unbalance of Uncompensated Unbalanced DN

Computation results of percentage voltage unbalance (P_{VUM}, %), of uncompensated unbalanced three-phase voltages of 11/0.4 kV, secondary EPDN is presented in Table 3.6. Figure 3.33 shows the curve of percentage voltage unbalance of unbalanced three-phase load. The calculation is achieved by using equation (3.12) which is a more accurate and exact method for calculating voltage imbalance in distribution system. The mean of all three phase voltages is estimated, followed by finding the sum of absolute value of the difference between the mean of all three phase voltage and the phase voltage of each phase. The total imbalance is halved to obtain an adjusted imbalance. The adjusted imbalance is divided by mean value of all three phase voltage and multiplied by 100 to have percentage imbalance. Table 3.6 shows the percentage voltage unbalance for uncompensated unbalanced three phase distribution network.

Table 3.6: Computation of PVU for Uncompensated Unbalanced DN

L, (km)	VP, Phase A (p.u)	VP, Phase B (p.u)	VP, Phase C (p.u)	Ave (A, B % C (p.u)	P_{VUM}, %
0.5	0.94	0.95	0.97	0.95	1.7
0.8	0.87	0.90	0.93	0.9	3.3
1.0	0.82	0.87	0.90	0.86	5.0
1.5	0.68	0.75	0.80	0.74	8.5
2.0	0.56	0.63	0.70	0.63	11.1
2.5	0.45	0.52	0.60	0.52	14.6
3.0	0.36	0.43	0.51	0.43	17.7
3.5	0.29	0.36	0.44	0.36	21.0
4.0	0.24	0.30	0.37	0.30	22.0
4.5	0.21	0.25	0.32	0.26	23.1
5.0	0.17	0.22	0.28	0.22	25.4

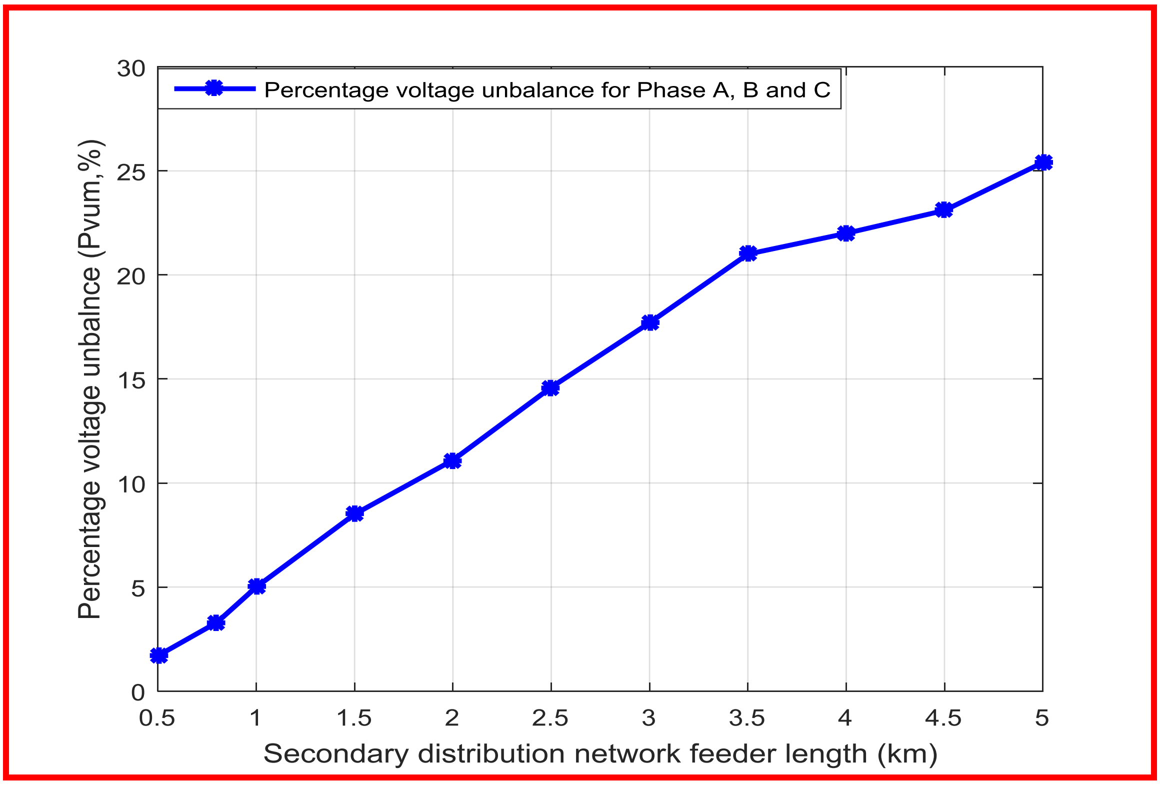


Figure 3.33: The curve of PVU for uncompensated unbalanced DN

3.11. Analysis of Load Voltage Variation Investigation of LV EPDN

3.11.1. Results Obtained from the Voltage Variation in Balanced DN

From the simulation results of load voltage profile investigation presented in Figures 3.3 to 3.13, the curve of per-unit load voltage profile shown in Figure 3.14, and the summary of the load voltage profile measurements taken from MATLAB/Simulink shown in Table 3.2, the following could be observed: Analysis of the results show that at DN feeder length of 0.5 km, the voltage drop falls within standard allowable voltage range of ±5% of the specified nominal system voltage value with per unit voltage value of 0.95 p.u at the feeder end. In remaining distribution network feeder lengths of 0.8 km, 1 km, 1.5 km, 2 km, 2.5 km, 3 km, 3.5 km, 4 km, 4.5 km and 5 km the voltage drops are not within the standard minimum permissible limit of -5 % of nominal voltage value. From the curve of load voltage profile for the 3-phase balanced load, it is obvious that the voltage profile decreases sharply with increases in distribution network feeder lengths. At 2.5 km feeder length, the load voltage profile measured is 0.50 p.u meaning that voltage reaching the consumers end is half the nominal voltage value. At 5 km feeder length, the load voltage profile measured is 0.20 p.u, which is the worst scenario. The voltage drop in the distribution network feeder lengths 0.8 km to 5 km is significant since it does not fall within -5 % and +5 % allowable voltage drop range. Hence the voltage supply is not admissible for customers feeding from the secondary distribution network under this study due to the low voltage supplying from 0.8 km, 1 km, 1.5 km, 2 km, 2.5 km, 3 km, 3.5 km, 4 km, 4.5 km and 5 km feeder lengths. It is observed that there is an urgent need to boost the voltage along the distribution feeder lengths, in order, to improve the voltage supplying to consumers at load end, this will in turn enhance the reliability supply of secondary electric power DN.

3.11.2. Results Obtained from the Voltage Unbalance in Unbalanced DN

The simulation results of the voltage unbalanced investigation of secondary electric power 11/0.4 kV distribution network are presented in Figures 3.15 to 3.25 while Table 3 3 shows the summary of the load voltage profile measurements. Figure 3.26 shows the curves of load voltage profiles for 3-phase unbalanced load. Analysis of the results shows that the VP for distribution feeder length 0.5 km is 0.94 p.u 0.95 p.u and 0.97 p.u for phases A, B and C respectively. This implies that the voltage profile of phase B and C are within the voltage permissible range of ±5 % of nominal voltage value, whereas in phase A, voltage profile value of 0.94 p.u is 0.01 p.u less than the standard minimum voltage permissible limit of 0.95 p.u. Therefore, the voltage profile for phase A is unacceptable for customer use. In the remaining distribution network feeder lengths of 0.8 km, 1 km, 1.5 km, 2 km, 2.5 km, 3 km, 3.5 km, 4 km, 4.5 km and 5 km the voltage drop is far less than the standard allowable voltage range of 0.95 p.u and 1.05 p.u of nominal voltage value, and so are not acceptable for end users electrical equipment, devices and apparatuses. The voltage profile at the beginning of the distribution feeder lengths decreased from 0.94 p.u to 0.17 p.u for phase A, 0.95 p.u to 0.22 p.u for phase B and 0.97 p.u to 0.28 p.u for phase C at the end of the electric power DN feeder lengths.

3.11.3. Analysis of Voltage Deviation for Balanced DN

Table 3.4 shows the percentage voltage deviation (ΔU_{dev}, %) and voltage drop (ΔU, Volts) computations on balanced three-phase load for distribution feeder lengths 0.5 km, 0.8 km, 1 km, 1.5 km, 2 km, 2.5 km, 3 km, 3.5 km, 4 km, 4.5 km, and 5 km respectively. Analysis shows that in 0 5 km distribution feeder lengths the percentage voltage deviation is 5 % which falls within the standard allowable permissible range of ± 5 % of the nominal voltage value. The percentage voltage deviation of feeder lengths from 0.8 km to 5 km as shown in Figure 3.29 varies from 10 % to 80 % respectively. These show that the percentage voltage deviations of distribution feeder lengths from 0.8 km to 5 km are not within the standard permissible range, implying a poor voltage reaching end users. It therefore mean that all values of Udev, % are less than the standard minimum -5 % of nominal voltage value. Similarly, the computed voltage drop on the distribution feeder lengths as shown in Figure 3.29 reveals that 11 Volts voltage drop was computed for feeder length of 0.5 km. This is within the set limit for minimum voltage drop expected on secondary distribution network which is -5% of the nominal voltage value. Moreso, the voltage drop computed from the feeder lengths is: 0.8 km, 22 Volts; 1 km, 44 Volts; 1.5 km, 59 Volts; 2 km, 81 Volts; 2.5 km, 110 Volts; 3 km, 130 Volts; 3.5 km, 145 Volts; 4 km, 158 Volts; 4.5 km, 169 Volts; and 5 km, 176 Volts are not within the minimum acceptable voltage drop on secondary distribution network. From the analysis of voltage deviations, and voltage drop on 11/0.4 kV LV EPDN, the present voltage quality for 0.8 km to 5 km distribution feeder length is inadmissible for optimal operation of customer equipment, household devices, apparatuses, electronics and computer accessories, hence, voltage boosting measures need to be upgraded to achieve the standard permissible voltage range.

3.11.4. Analysis of Voltage Deviation for Unbalanced DN

Table 3.5 shows the percentage voltage deviation (ΔU_{dev}, %) and voltage drop (ΔU, V) computations on unbalanced distribution network feeder lengths. Analysis of ΔU_{dev}, % of feeder length 0.5 km for phase A, B and C are 6 %, 5 % and 3 %, respectively. It is observed that the ΔU_{dev}, % values for phase B and C are within the standard allowable range of ± 5 % of nominal voltage value, whereas, the ΔU_{dev}, % on phase A which has the highest load value is 1 % less than the minimum standard allowable value as recommended. The ΔU_{dev}, % of the remaining distribution feeder lengths starting from 0.8 km has 13 %, 10 %, and 7 % for phase A, B and C respectively, and the last distribution feeder length investigated under this study (5 km) has ΔU_{dev}, % of 83 %, 78 %, and 72 % on phase A, B and C respectively. From the above values of ΔU_{dev}, % for distribution feeder lengths for 0.8 km to 5 km. It is obvious that the computed values are less than the standard minimum allowable value of -5 % or 0.95 p.u of the nominal voltage value required for acceptable voltage supply to end users in secondary electric power distribution systems. In addition, the computed voltage drop for distribution feeder length 0.5 km is 13 V, 11 V and 6.6 V on phase A, B and C respectively. It is shown that the ΔU, V on phase B and C is within acceptable standards of - 5 % of nominal voltage value while the computed value of ΔU, V on phase A is 2 Volts more than the standard acceptable voltage drop on electric power distribution system. The voltage drop on distribution feeder lengths 0.8 km, 1 km, 1.5 km, 2 km,2.5 km, 3 km, 3.5 km, 4 km, 4.5 km, and 5 km are: 29 V, 22 V, 15 V; 40 V, 29 V, 22 V; 70 V, 55 V, 44 V; 97 V, 81 V, 66 V; 121 V, 106 V, 88 V; 141 V, 125 V, 108 V; 156 V, 141 V, 123 V; 167, 154 V, 139; 174 V, 165 V, 150; and 183 V, 172 V, 158 V. The computed ΔU, V values for distribution feeder lengths 0.8 km to 5 km shown are greater than the allowable standard value of voltage drop on 11/0.4 kV electric power DN. Hence there is an urgent need to enhance voltage of the network under consideration for optimal performance to the customers, so as to enhance the voltage profile and security of supply to the end users. Thereby reducing load shedding during winter and peak load. It will also decrease incidents of decrease malfunctioning of customers single and 3-phase sensitive loads. By extension, this will raise the general living of standard of the customers deriving from the 11/0.4 kV EPDN.

3.11.5 Analysis of PVU of Uncompensated Unbalanced DN

Table 3.6 shows the percentage voltage unbalance (P_{UVM}, %) computation on unbalanced distribution network feeder lengths. Figure 3.34 shows the curve of percentage voltage unbalance for uncompensated unbalanced three phase load. Analysis of (P_{UVM}, %) of distribution feeder length 0.5 km shows that the percentage phase voltage imbalance calculated is 1.7 %, which is less than 2 %. It implies that the distribution system can operate reliably and effectively for long period of time with electrical devices, components, tools and equipment without any problem. Moreover, the percentage voltage unbalance for distribution feeder length of 0.8 km, 1 km, 1.5 km, 2 km, 2.5 km, 3 km, 4 km, 4.5 km are: 3.3%, 5%, 8.5%, 11%, 15%, 18%, 21%, 23% and 25% respectively. Therefore, from the values of percentage voltage unbalance for the distribution feeder lengths are all above the acceptable standard of less than 2% for optimum operation of distribution system. Hence, the measured voltages at the customers end are not acceptable for optimum operation of secondary distribution system. Hence, there is an urgent need to mitigate phase voltage imbalances of the network under consideration for optimal performance to the customers, so as to ensure dependable, trusted, effective and long-time functioning of electrical equipment, components and electronic devices in secondary distribution network.

3.12 Summary

In this chapter, investigation of voltage variation and voltage unbalance in secondary electric distribution network for short and long feeders' network and for balanced and unbalanced LV distribution network using MATLAB/Simulink was presented. Through the studies, it is shown that the VP for 0.5 km EPDN feeder length for both balanced and unbalanced LV distribution network are admissible for customers from the beginning to the end of the feeder length as designed with engineering standards and judgements. In addition, the PVU, correct VP and minimum VDr of 0.5 km EPDN is of specified permissible system voltage limit, hence the DN functions at most desirable operation. Nevertheless, it is shown that the VP for EPDN lengths of 800 m to 5000 m for short and long, balanced and unbalanced EPDN from the start to the end user terminal of the EPDN feeder are less than the specified permissible voltage limit of – 5 % of the specified nominal system voltage value. Hence, voltages are not admissible for the end users of electricity. Consequently, the PVU, VP and DVr on 800 m to 5000 m EPDNs are all less than specified permissible system voltage limits and so, the DN functions far below the expected specified nominal standard. Furthermore, it is also established that a permissible voltage range can be attained, if the electricity distribution companies must follow the minimum standard for distribution network feeder length and must provide effective voltage boosting device on the feeder bus of 11/0.4 kV transformer to boost the supply voltage to standard + 5 % nominal voltage value. This will eliminate the problem of critical voltage drops in the network feeder lengths. Finally, it was found that low voltage profile, voltage variation and voltage unbalance in secondary electric power DS will amplify or reduce depending on the network feeder length and the load on the phases.

CHAPTER FOUR

THE DYNAMIC VOLTAGE RESTORER (DVR)

This chapter discusses the operation modelling and application of DVR in secondary electric power DNs; including the fundamental components of DVR. Hence, different DVR topologies are presented with control techniques to have real energy access in the event of voltage unbalance and voltage variations disturbances. Lastly, DVR protection scheme is discussed.

4.1 Introduction

Amongst power quality disturbances in secondary electric power distribution network are harmonics, swell, voltage sags and so on. Unbalanced voltage and voltage variation is an extremely unpleasant disruption in secondary networks. To overcome these disturbances, a broad concept of CPDs is presented not long ago. DVR is very unique among the CPDs tools. A DVR is a recent efficacious, effective and efficient present day CPD employed in electric distribution systems.

DVR is a newly proposed series linked strikingly new advance solid-state power electronic device that supplies required voltage to distribution system, so as to control voltage at load side to desire standard acceptable voltage range of ± 5 % of the nominal voltage value. DVR is usually linked to distribution networks between the essential load feeder and supply via a boosting transformer at a place of power transfer link. In addition to voltage unbalance mitigation and voltage variation compensation, dynamic voltage restorer can also perform voltage harmonic reduction, reduction of fluctuations, mitigation of overvoltage and under voltages and reduction in fault current.

4.2 The Fundamental Elements of a DVR

The DVR is a series linked advanced solid state tool. It has an extremely good excellent natural ability. If placed between source and a trouble feeder, DVR mitigates voltage quality disturbances very fast. Figure 4.1 depicts some of the basic components of a DVR, which are:

4.2.1 Voltage Boosting Transformer (VBT)

The VBT is employed in secondary distribution network for the primary purpose of voltage injection and the effective protection of DVR in case of fault(s). VBT links DVR to the secondary system through the high voltage coils and joins the supplied mitigating voltages produced by the voltage source inverter (VSI) to the arriving source voltage.

4.2.2 AC Line Filter

Essentially, filter is employed to convert the inverter pulse width modulation (PWM) wave shape to sine wave. Similarly, filter is utilized to remove or reduce the unwanted switching harmonics produced by VSI from the supplied wave shape so as to maintain an acceptable harmonic state.

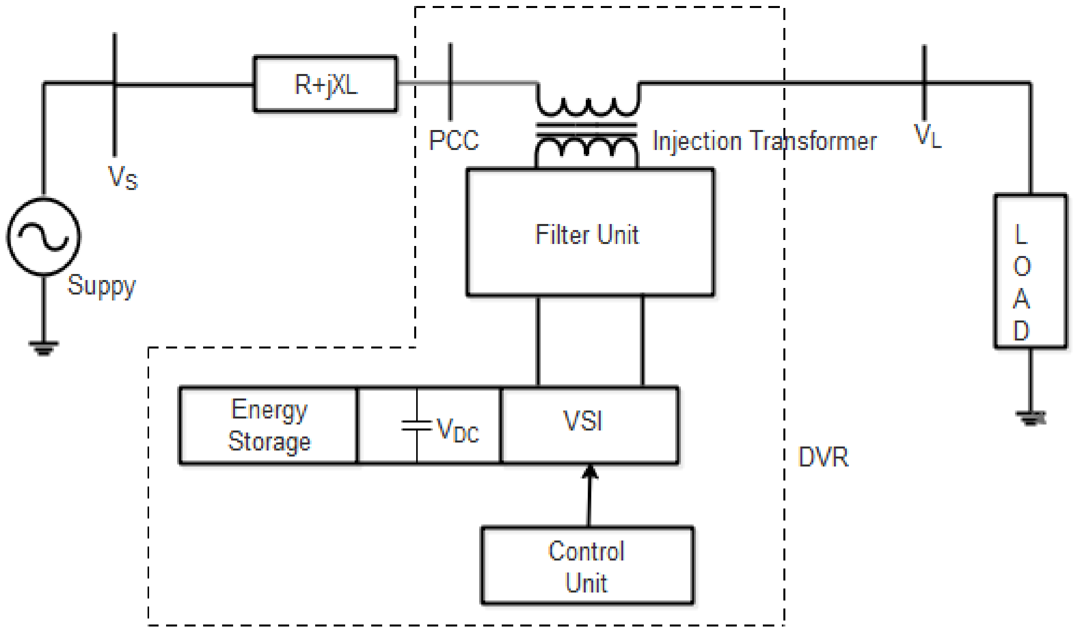


Figure 4.1: Basic components of a single-phase representation of DVR [98]

4.2.3 Three phase PWM Inverter

The inverter system is utilized to transform DC voltage injected by the DC link/storage device to sinusoidal voltages injected into the network.

4.2.4 DC Charging Unit

This charges the power battery during and after voltage mitigation period. Similarly, it keeps DC link voltage at the actual DC link voltage and provides a discharge circuit and grounding equipment for maintenance purposes.

4.2.5 A Pass Switch

In order to safeguard the DVR system from fault currents caused by fault in the distribution system, a protective device known as by-pass switch is incorporated to the DVR system.

4.2.6 Voltage Source Converters

A voltage source converter comprises six pulse voltage source converters (VSC) with their sinusoidal results linked to the secondary coils of the boosting transformer. It is a modern advanced power electronic system comprising of a switching devices and storage device which can produce a sine wave voltage at any needed phase angle, amplitude and frequency. VSC can be a three phase delta connected or three phase star connected. VSC can be employed in DVR application to progressively produce the needed voltage to keep the supply voltage to standard acceptable value. The four primary kinds of switching devices are: insulated gate bipolar transistors (IGBTs), metal oxide semiconductor field effect transistors (MOSFETs), integrated gate commutated thyristors (IGCTs) and gate turn-off thyristors (GTOs).

4.2.7 Energy Storage

The primary purpose of energy storage tools is to provide the needed power to the VSC by means of a DC link for the production of needed potentials. There are various categories of energy storage devices which include: flywheel energy storage, hydraulic accumulator, batteries, super capacitors and electrochemical systems.

4.2.8 Control Unit

A controller is employed for effective functioning of DVR systems. DVR senses the load voltage and move via a dq0 controller. The amplitude of the terminal voltage is examined with the set voltage. PWM control method is utilized for inverter switching so as to generate a 3-phase 50 Hz sine wave voltages at the customer side [66, 98] The control of mitigating tool is carried out in three steps, detection of voltage disturbances that happens in the system, examining the detected voltage disturbance with the set value and production of gate pulses to the voltage source inverter via pulse width modulation generator to produce the DVR needed voltages to mitigate voltage disturbances experienced in the distribution system. Proportional and integral (PI) control mechanism is employed with two levels IGBT PWM inverter to keep the voltage at the load terminal at one pre-unit (1 p.u). The dq0 and PI controllers are utilized in the control circuit in DVR test model described in chapter six of this thesis. The proportional and integral control mechanism providing the signal is the significant change between the load or actual voltage and the reference voltage known as error signal. The primary benefit of PI control mechanism is that its integral part allows the steady state error to be zeroed for a unit step input [67].

4.3 DVR Location in Electric Power Distribution System

The DVR can be located both in primary and secondary sides of the distribution network. This research work focuses on the suggested design of DVR in secondary distribution networks. In primary and secondary networks, the principal desired effect of DVR is to supply the needed electric potential during disturbances experienced in the network [98-99]. The utmost distinction between primary distribution link to DVR and secondary link to DVR is the free movement of zero sequence currents and the production of zero sequence electric potentials. In three phase star connected distribution network the DVR should reliably ensure low impedance for zero sequence currents and the zero sequence must either move freely in the voltage source inverter or in a three phase coil of the boosting transformer [100]. DVR typical location in secondary distribution network is described in Figure 4.2. DVR location in secondary distribution network is presented in Figure 4.3 while Figure 4.4 shows a single line diagram showing the position of DVR in secondary radial distribution systems.

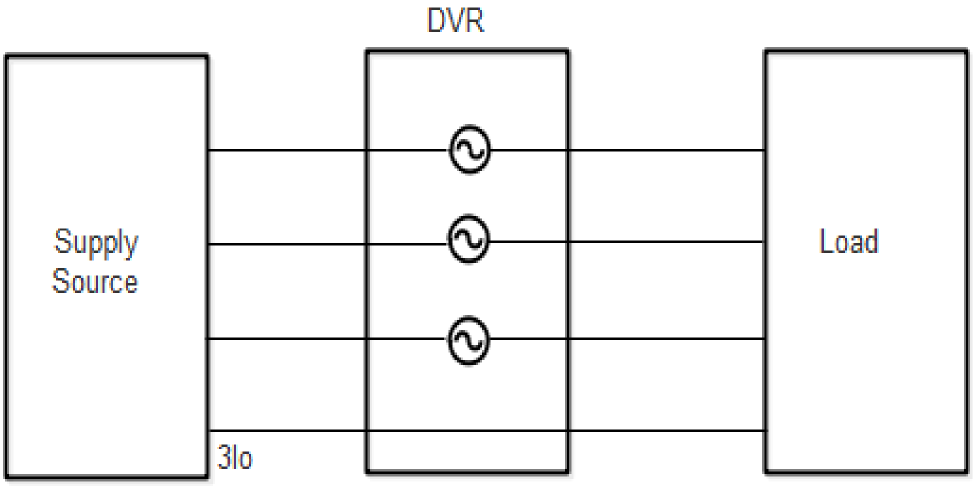


Figure 4.2: DVR typical location in secondary distribution system [97]

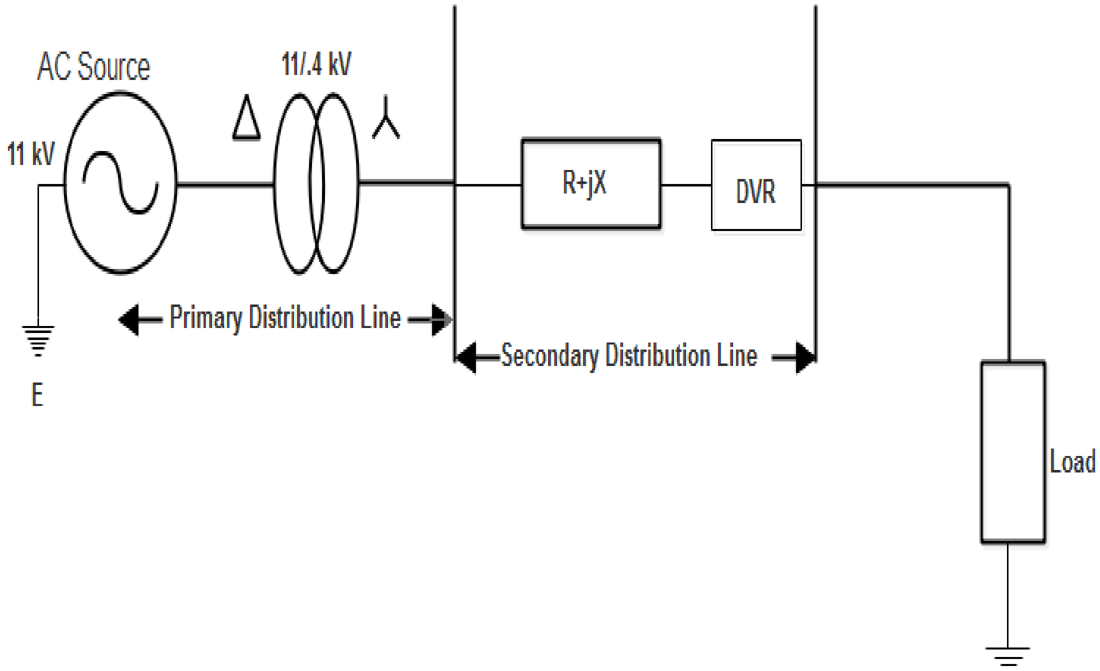


Figure 4.3: DVR proposed location in secondary distribution system

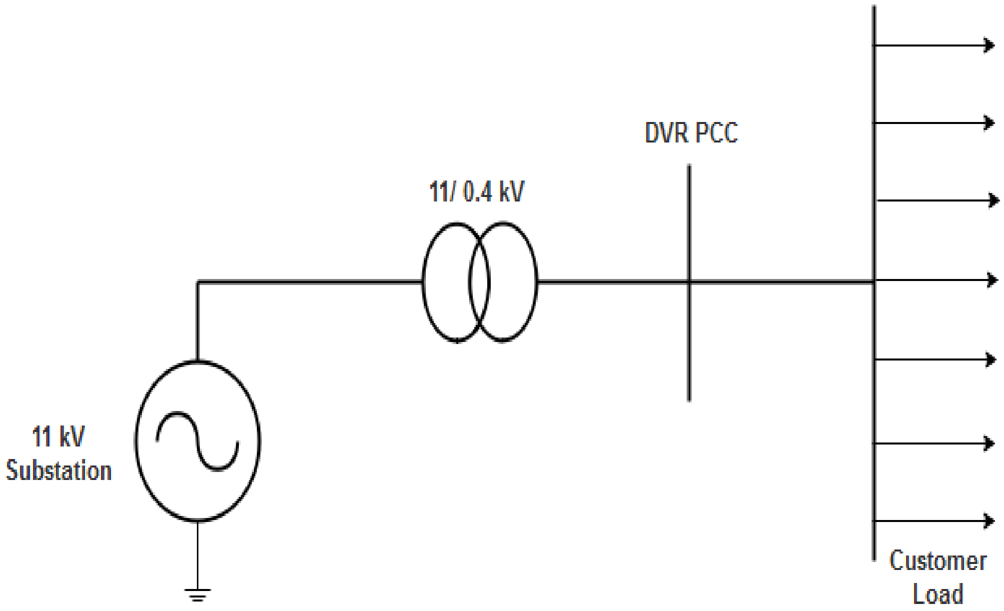


Figure 4.4: A single line diagram showing the position of DVR in LV radial DS

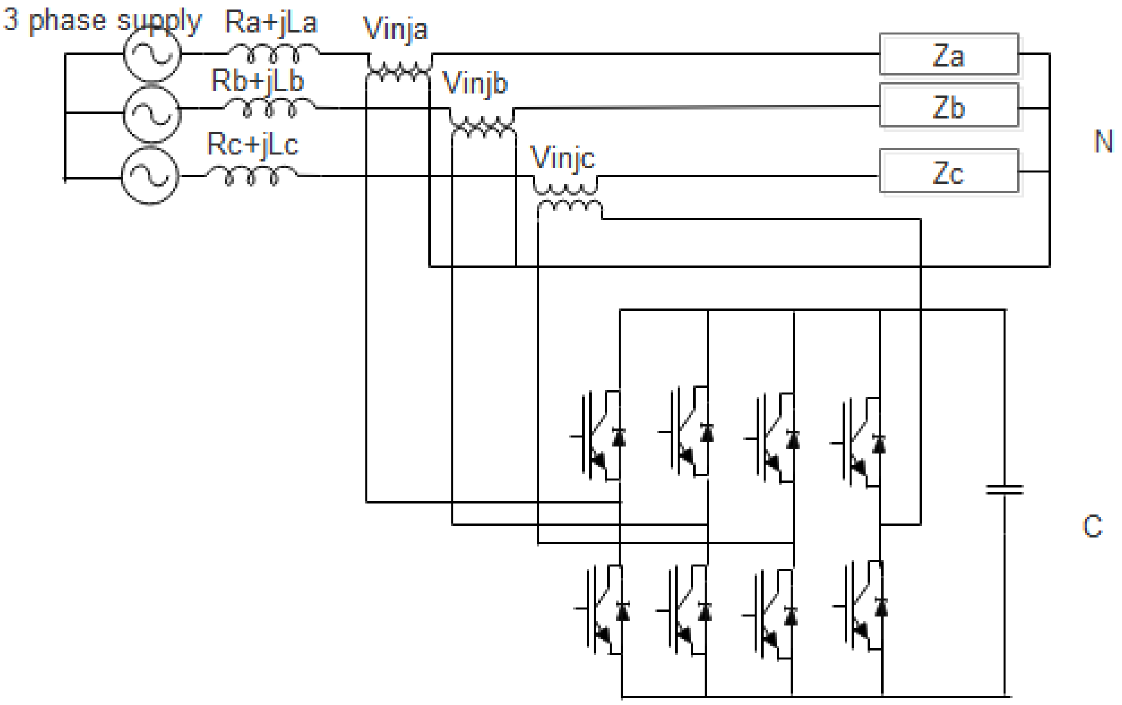


Figure 4.5: DVR 3-phase star connected [98]

Figure 4.5 presents relevance of DVR in secondary distribution system which forms the nucleus of this thesis. Ghosh et al. [101] and Tandjaoui et al. [102] listed benefits of application of DVR in secondary distribution system as follows:

- The use of distribution transformer in secondary distribution system significantly decreases the short circuit faults, hence, safeguarding the dynamic voltage restorer is made simple;
- Voltage disturbances in secondary distribution system can be aimed more accurately using dynamic voltage restorer;
- Electricity consumers in most cases have just a point of access to the secondary distribution system. Because of this; dynamic voltage restorer could be located by the electricity distribution companies or the end users of electricity.

4.4. Mathematical Expressions Associated With DVR

In secondary distribution system, at some point, the supply voltage V_{Supply} decreases from standard acceptable value of ± 5 % of the nominal voltage value. The dynamic voltage restorer will provide a sequential electric potential (V_{DVR}) via the boosting transformer in a way that standard acceptable customer electric potential (V_L) can be kept to at all times.

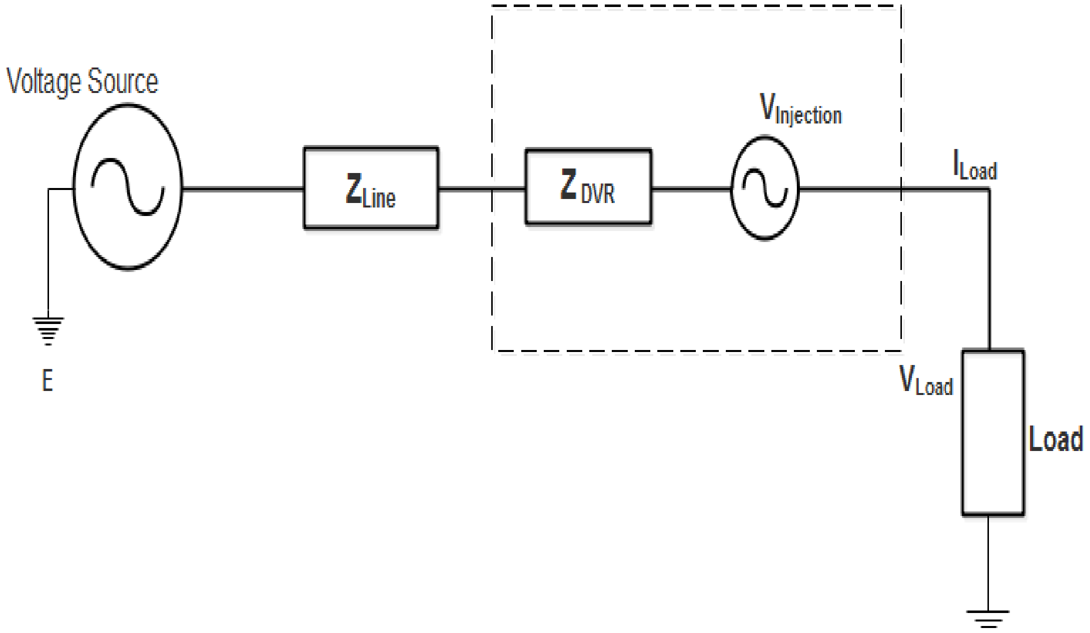


Figure 4.6: DVR equivalent circuit diagram

From DVR equivalent circuit shown in Figure 4.6 mathematically, the injected voltage can be expressed as:

$$V_{DVR} = V_{Load} + R_{Line} I_{Load} - V_{Supply} \tag{4.1}$$

Assume, I_{Load} is taken as I_L, V_{Load} is taken as V_L, V_{Supply} is taken as V_P and R_{Line} is taken as R_D

Therefore, equation (4.1) becomes

$$V_{DVR} = V_L + R_D I_L \ - V_P \tag{4.2}$$

Where,

V_L is the standard acceptable terminal electric potential

R_D is the line resistance and reactance

I_L is the load current

V_P is the supply electric potential at the period of disturbance

The load current I_L is written as (4.3)

$$I_L = \frac{P_L + jQ_L}{V_L} \tag{4.3}$$

The active power of the *DVR* is shown in equation (4.4)

$$P_{DVR} = I_L\left(V_L \cos\theta_L - V_P \cos\theta_P\right) \tag{4.4}$$

Where V_L as a reference mathematical expression is given as (4.5).

$$V_{DVR} = V_L\angle 0 + R_D I_L \angle(\beta - \theta) + V_P \angle\delta\ . \tag{4.5}$$

Where β is the angle of $R_{D,}$ θ is the load power angle, α is the angle of D_{DVR}**,** and **δ** is the angle of V_P

$$\theta = \tan^{-1}\frac{Q_L}{P_L}\ . \tag{4.6}$$

The DVR apparent power is given as in (4.7) respectively:

$$S_{DVR} = I_{LOAD} V_{DVR} \tag{4.7}$$

The DVR complex power supply is given as (4.8).

$$S_{DVR} = V_{DVR} I_L^{\ *}\ . \tag{4.8}$$

4.5 Operational Mode of DVR in Electric Power Distribution Networks

A DVR is employed for electric potential mitigation in secondary electric power distribution network as presented in Figure 4.1. The operational mode of a DVR can be grouped into as listed in [98, 103].

- Safeguarding form
- Emergency form and

- Injection form

4.5.1 Protection Mode Operation of DVR

In safeguarding form, the bypass switch can be expended as a safeguarding tool to keep safe the dynamic voltage restorer from the high current in the consumer side as a result of short circuit on the load or very big inrush currents [104]. The DVR can be safeguarded by employing bypass switches, which permit the excess current to flow through another path as shown in Figure 4.7.

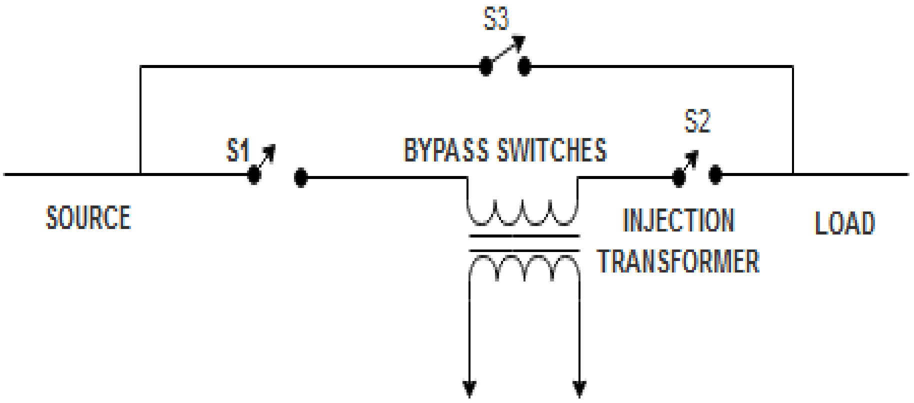


Figure 4.7: Operational mode of DVR [98]

4.5.2 DVR Emergency Mode Operation

In emergency operational form the dynamic voltage restorer voltage is equal to zero (V_{DVR}=0). During this period, the boosting transformer’s secondary coil is shorted via the inverter. No switching of semiconductors takes place in this form of operation for the reason that each inverter leg are fired in such manner as to put in place a short circuit route for the transformer connection. Hence, the very low conduction losses of the semiconductors in this current loop add to the losses. The DVR will regularly be in this mode. In the operation of DVR during standby operation, the two lower IGBT’s turned on while the two upper IGBT’s in each phase of the inverter remain turned off [104].

4.5.3 Injection Mode Operation of DVR

The dynamic voltage restorer goes to injection mode when the voltage of the DVR is greater than zero as soon as the disturbances are detected. The categories of electric potential unbalances, state of the load and DVR working capacity will influence the assurance of compensation of voltage disturbances experienced. The 3-phase sine wave electric potential is supplied in series with the needed wave shape, phase angle and, amplitude for mitigation [98, 104].

The DVR representation for single phase is shown in Figure 4.8. This is used to explain an excellent voltage source constitute of the reactive component X_{DVR} in the boosting transformer and AC filter, and the estimate of the R_{DVR} indicates the losses in the DVR. The resistance and reactance size of the DVR is associated with the power and the electric potential of the DVR.

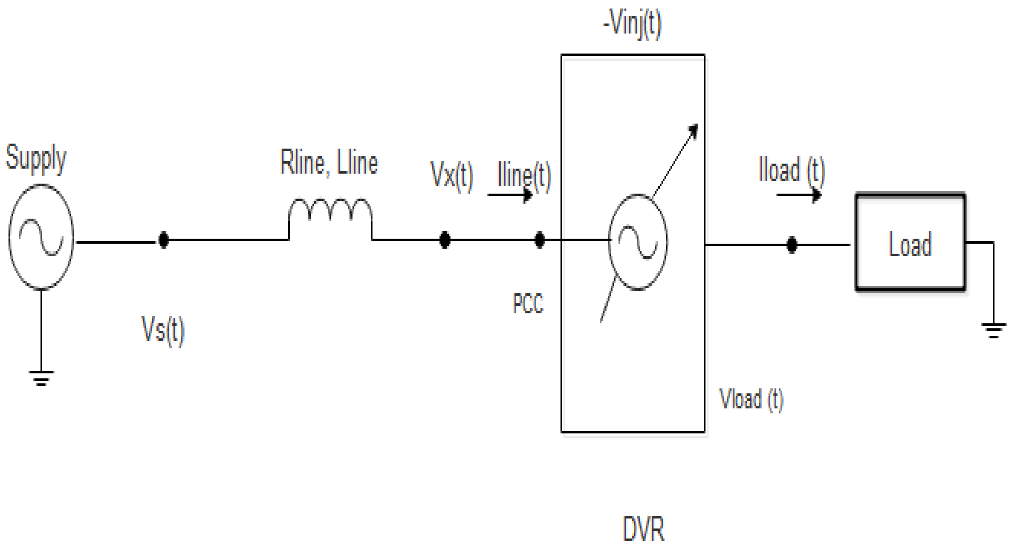


Figure 4.8: DVR single line model victual depiction

4.6 Method of Compensation in DVR

Figure 4.9 explains the procedures of amendment, which is employed in DVR, DVR compensation techniques are grouped into two: the real power compensation, and real and non-active power compensation.

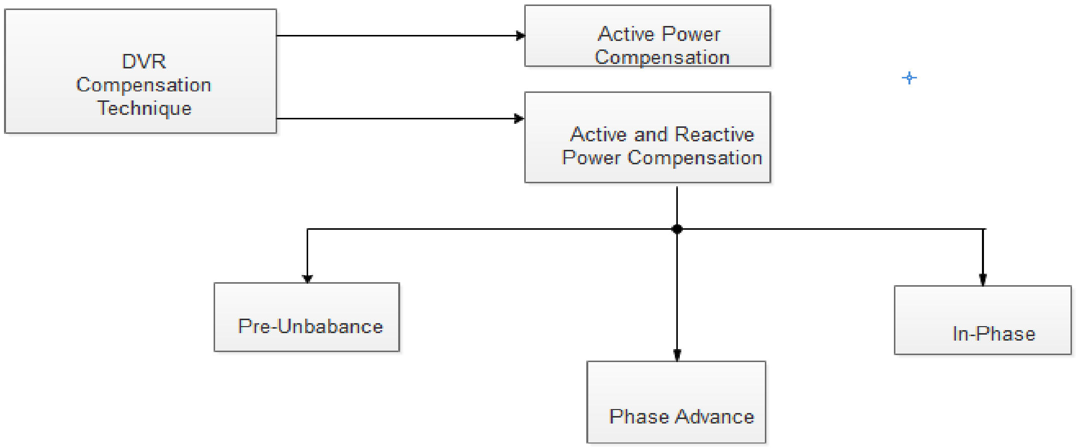


Figure 4.9: The compensation techniques of a DVR [98, 101]

The techniques for supplying require voltage can be detailed into in phase compensation, pre-unbalance compensation, and phase advance compensation [105-108]. In this thesis in-phase compensation technique was be utilized since is simple, flexible, clean and gives a desired result in the injection of voltage at the same phase with the supply electric potential [103,106]. When the supply voltage is unbalance or voltage falls below standard acceptable range due to disturbances in the distribution system, the supplying of electric potential created by the VSI will supply the needed voltage which depends on the unbalance or electric potential drop amplitude. This technique is illustrated in Figure 4.9.

4.7 Secondary Distribution Systems DVR Topologies

The DVR fundamental purpose is to ensure that the supply electric potential to customer terminal is up to standard acceptable value. Various investigative studies have suggested DVRs topologies. This includes topologies:

- Energy storage with and without;
- Grid connection; and
- Converter

4.7.1. Energy Storage with and without Topologies

Nielsen [109] proposed two different kinds of DVR topologies method consisting of with no energy storage and with energy storage. Ideally, in the event of any kind of disturbances in a distribution system, a DVR supplies a suitable electric potential to regain the voltage at the customer side. In this condition DVR requires to exchange real and non-active power with the environment network. Figure 4.10 describes two different kinds of topologies system for DVRs, namely with energy storage and without energy storage.

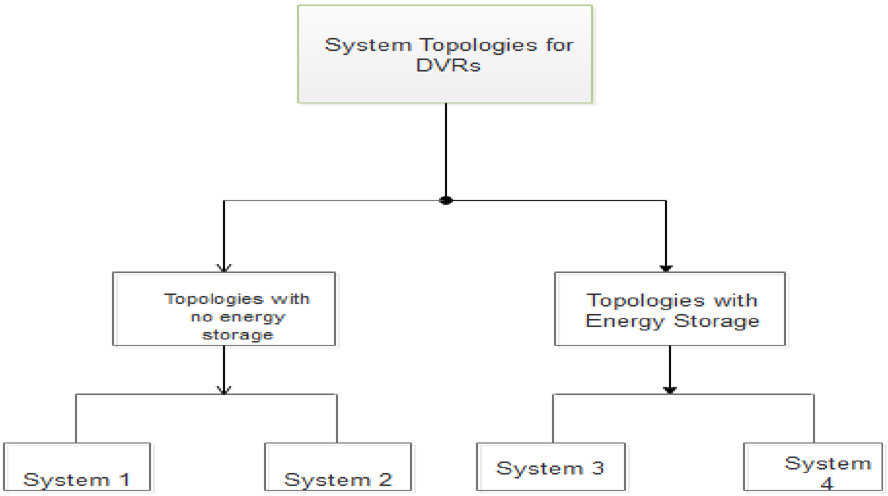


Figure 4.10: DVRs System Topologies

4.7.1.1 Energy Storage Topologies with DVR

In the event of disturbances in electric power distribution system, the DVR utilized the real power supplied by the stored energy for compensation process. Various kinds of energy storage devices that can be employed in secondary distribution network to supply the real power needed for mitigation of voltage disturbances exist they include: flywheel energy storage, hydraulic accumulator, batteries, super capacitors and electrochemical storage system. During voltage disruptions such as voltage imbalance, over voltage and under voltage the use of storage devices will enhance the effective performance of DVR notwithstanding the fact that energy storage is quite expensive. As presented in Figure 4.11a, the energy storage with topologies in which they are liable to change voltage DC- Link is employed. The capacitor DC- Link is utilized to keep safe the energy. The liable to change voltage DC-link can be operated with an easy topology. The accumulated energy needed to operate the DVR is directed related to the square of the electric potential value of the DC- link [109]. Figure 4.11b describes a topology that makes use of voltage constant DC–Link. Flywheel energy storage, super capacitors, and batteries and others methods of storing energy can be utilized as a direct method of storing energy using an inverter in the event of voltage disruptions in electric power distribution system.

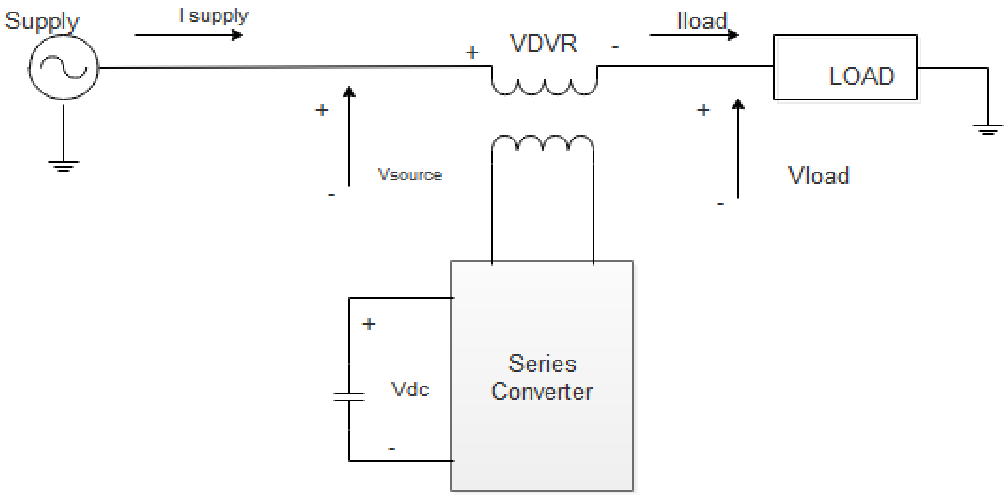


Figure 4.11(a): Variable voltage DC-link and energy storing techniques with DVR

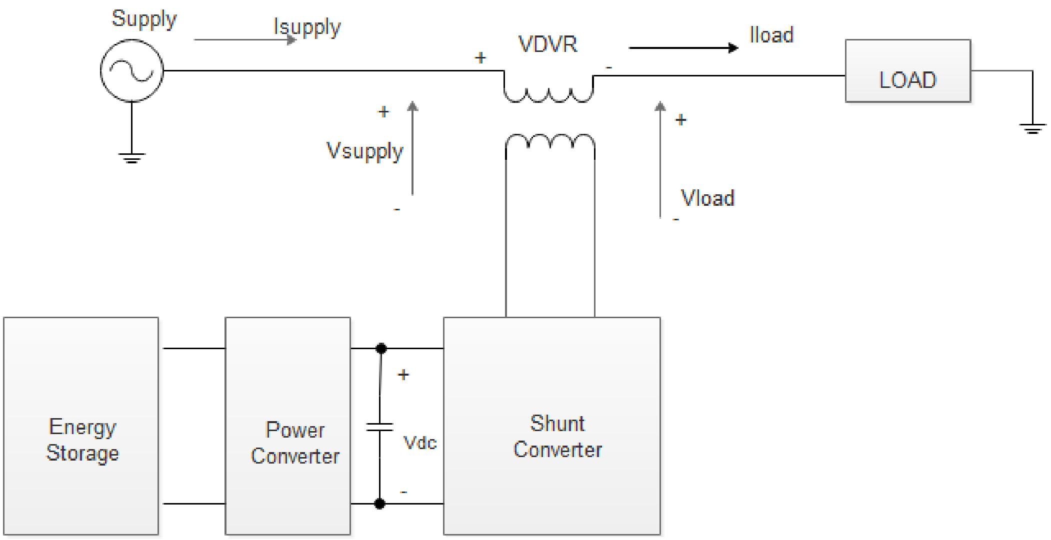


Figure 4.11(b): Constant voltage dc-link and method of storing energy with DVR

4.7.1.2 No Energy Storing System Topologies with DVR

The DVR with no energy storing system topologies is grouped into setup system 1 and 2. In System one as presented in Figure 4.12a shows that the main source of energy is from the grid supply via non-active parallel converter linked to the main source. Energy is therefore, being transported from the distribution network linked side via a non-active parallel converter linked to the main supply. Consequently, in system 2, energy is being transported from the distribution network linked side via a non-active parallel converter which is linked to the end users as described in Figure 4.12b. No energy storing system topologies with DVR utilizes an important aspect of the supply main electric potential continuously to keep in existence in the event of system disruptions. The main supply is employed to supply and improve power needed to keep the exact energy to standard acceptable electric potential.

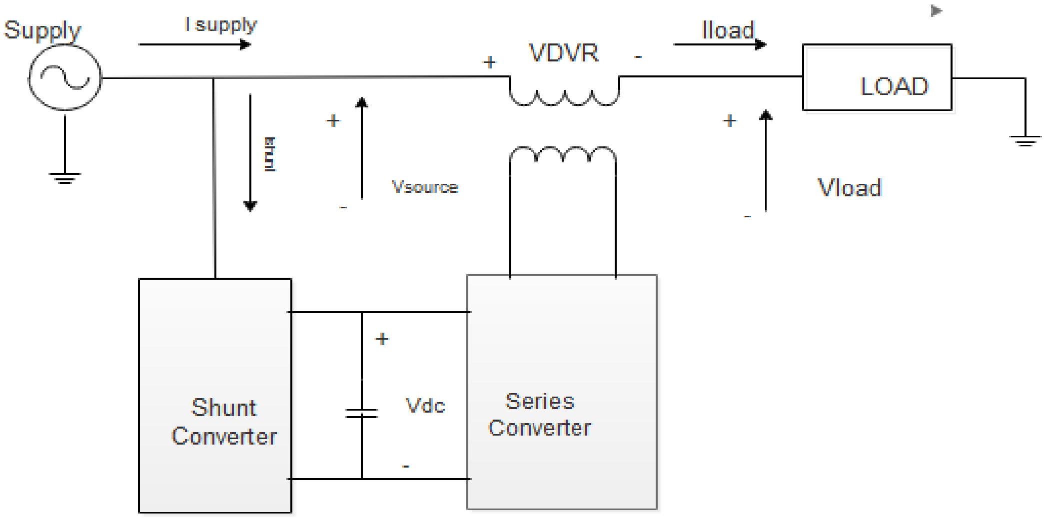


Figure 4.12(a): Main supply linked parallel converter and with no energy storing system DVR

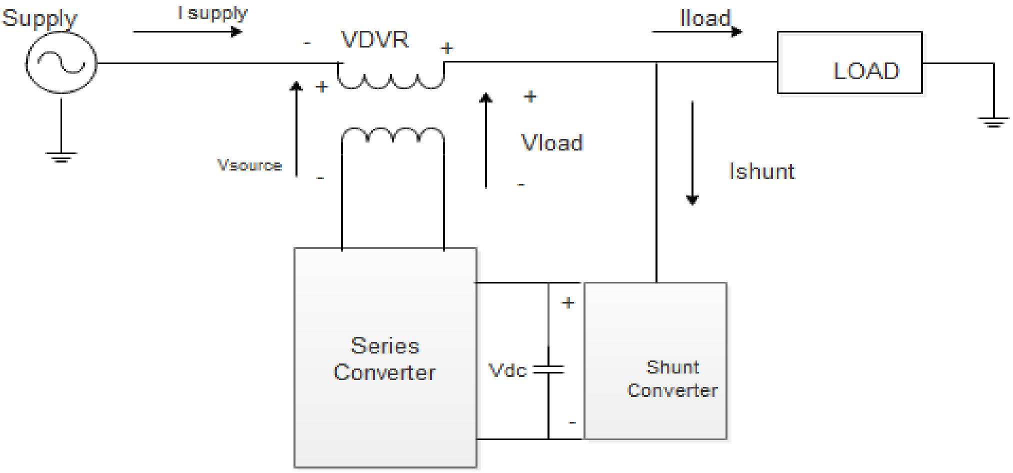


Figure 4.12(b): Load side linked parallel converter and energy storing system with DVR

4.7.2 Grid Connected Topologies with DVR

The DVR will supply sufficient electric potential in sequential order to the source voltage. This needs either galvanic separation to the voltage source converter or allowing the voltage source converter to float at the voltage of the source voltages. Two different ways can be employed, transformer connected converter or transformer-less connected converter sometimes called direct connected converter.

4.7.2.1 The Converter Linked Transformer

Transformer with 50 Hz or 60 Hz frequency is utilized to move the voltage inverter converter electric potential to series supplied electric potential. This is the method that is greatly applied. It is shown in Figure 4.13a. The following are the benefits of using a galvanic isolation with a low voltage transformer on electric power distribution network:

- The DVRs basic insulation level (BIL) is sufficiently taken care off by the use of transformer;
- The use of six active switches to inject the voltages into the network is relatively simple converter topology;
- A DC-Link is enough, which means a simple DC-link, voltage control DC-link and charging circuit;
- The ratio of the transformer can be selected at random, in reference to the electrical device which is modelled to an acceptable voltage value of the transformer used in industrial converter. To ensure the transformer work effectively, the voltage is either up or down; and
- The device for changing electrical energy can be employed as a very useful AC filter. The LCL filter setup used the capacitor that is placed between the two inductors in which the first is placed near the converter while the second is placed near the load.

Disadvantages of using injection transformers are:

- Low frequency injection transformer is very expensive, voluminous and heavy; and
- The losses of the injection transformer increases, have indirect proportional characteristic and can be a hindering influence on the outcome of the DVR system to perform effectively.

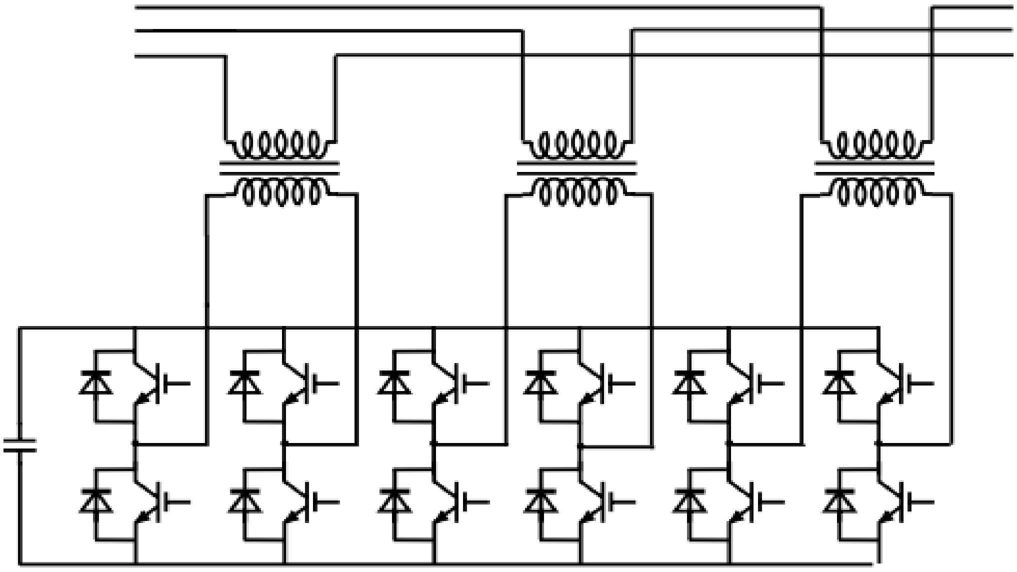


Figure 4.13(a): A DVR with Transformer to Couple to the Network

4.7.2.2 A Transformer-Less Connected Converter

A transformer-less series injection converter was proposed for VAr compensator [110]. Precise direct linked converter DVRs was presented as a concept and the method is employed [104, 109]. Practically, transformer-less link is the most favoured for series tools, since it exchanges non-active power with the network, since the movement of energy need three separate DC-links charging. Figure 4.13b describes a transformer-less DVR linked converter. The benefits of a transformer-less joined DVR converter include:

- Large size transformer can be prevented. The use of a small DVR with small volume and small weight can advance better solution; and
- Since the ability to perform is not reduced by the energy transforming device, indirect proportional operations and the reason for electric potential drop by the transformer are taken away.

The drawback of the directly connected DVR converter includes:

- Numerous numbers of elements are anticipated to be employed, since the said topologies are hard to be implemented;
- The converter topologies are very much difficult and a very high separation to earth has to be made available, and
- Safeguarding of solid state advance power electronics is much complex and basic insulation level (BIL) should be effectively made available.

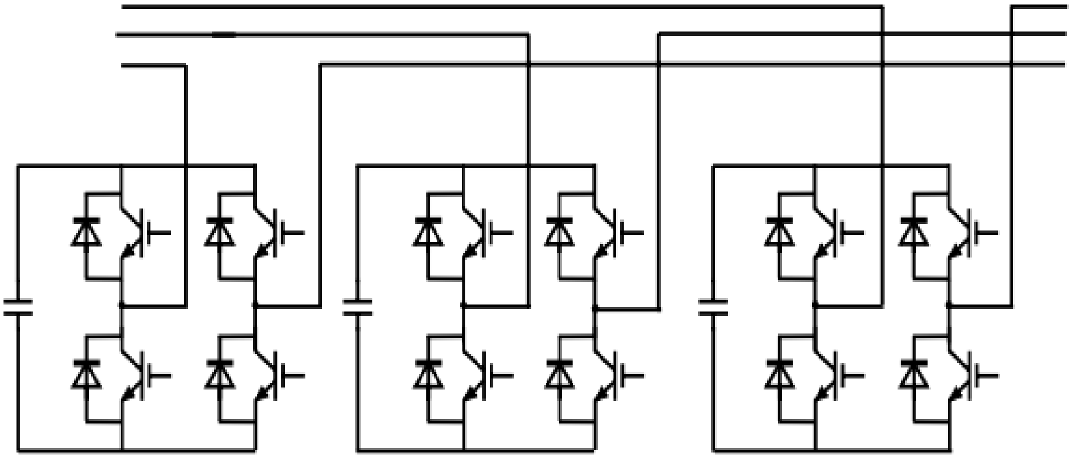


Figure 4.13(b): A DVR Directly Connected to the Network

4.7.3 Converter Topologies

The major block structure for DVR is the voltage converter; the effective performance of DVR selecting a suitable topology for specific area is of great importance. A DVR is linked in series and the resistance and reactance placed in the system result in unnecessary drop in voltage and losses in the system. A direct area of concern is in explaining suitable converter effective solutions for a DVR. DVR converter topologies are listed below.

A Topologies with Half Bridge

- An open star/delta transformer link with half bridge converter -Topology I.
- An open star/star transformer link with half bridge converter -Topology II.

B Topology with Full Bridge

- An open star/open star transformer link with full bridge converter-Topology III.

C Topology with Multilevel

- An open star/delta transformer link with half bridge three level converter - Topology IV.

For better comparison and correctness of separate DVR topologies, the following distinguishing features have been added:

- Utilization of DC-link voltage;
- To have a less difficulty with the system, better system reliability and simple cost, a good number of passive and active devices should be added to the converter circuit;
- The techniques to move the real power to DC-link and the voltage control of the DC-link;
- To reduce the AC filter employ in the system, an extreme effectual operating frequency must be used since it influences the size of the AC filter; and
- To calculate the resistive voltage drop and the losses on the network, the number of tools in current path must be properly estimated.

The stated variable features are extremely vital converter features for DVR specific area of uses and are studied for converter topologies.

4.8 Protection of the DVR

Safeguarding of DVR system is of paramount importance, as detailed by Newman and Holmes [112] and Moran et al. [113] in their studies. A DVR should be strong and healthy to withstand any failure or short-circuit in the system at the customer end and against any loss of link in the system. All safeguarding schemes of DVR must be carried out in the software. The differential safeguarding scheme of the boosting transformer or short-circuit current on the user side load side are two examples of possible safeguarding schemes [66]. Other means of safeguarding DVR against failure in the system and short circuit are: the use of booting transformer, variators, bypass switches, voltage source converters and thyristors.

In the event of loss of system connection or that the main supply voltage is extremely low, the DVR must be designed in such a way that it breaks away from the system network and stops the injection of needed voltage to the distribution system. This is to ensure that the DVR is not over depended upon by the entire system which can in turn result in severe damage to the DVR system. Various means of achieving this is proposed by Middlekauff and Collins [114]. Figures 4.14, 4.15 and 4.16 describe some three protection scheme employ in DVR operation.

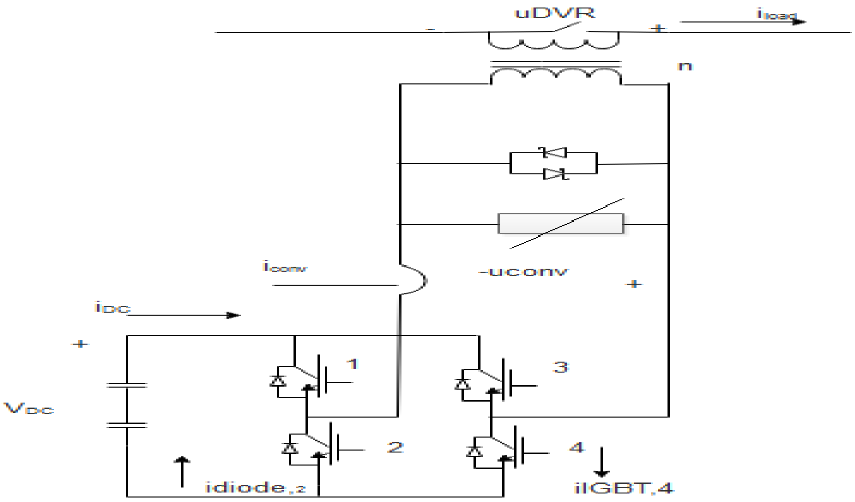


Figure 4.14: DVR with Protection Equipment Described for one Phase.

The passive control scheme is for the moment the most likely protection scheme for series connected power electronics. The VSC can be rated for relative low currents. For active control the VSC has to be rated to conduct short circuit currents and still to be able to inject voltages into the network. The protection of series connected devices is much more complex than the protection of shunt devices and a down-stream short circuit can be critical and needs extra protection equipment. During zero voltage injection the VSC conducts the load current and applying a zero state, the load current can flow in the diodes and the power switches. The full bridge converter has two zero state conditions for each phase with either the upper IGBT switches (1,3) turned on or the lower IGBT switches (2,4) turned on. The power switches can be of the most known types IGBTs, GTOs or IGCTs and for the DVR used in this project the IGBTs are used. The IGBT has current limiting capabilities and during a short circuit of an IGBT the current is limited to approximately 5-10 times the rated current and the full voltage drop across the switch. During this process the power dissipation in the switch is very high and usually the switch must be turned off before 10µs to be within its Safe Operating Area (SOA). The short circuit level before and after the DVR has a major influence on the protection equipment used. Knowing the DVR and supply parameters the short circuit current level can be estimated.

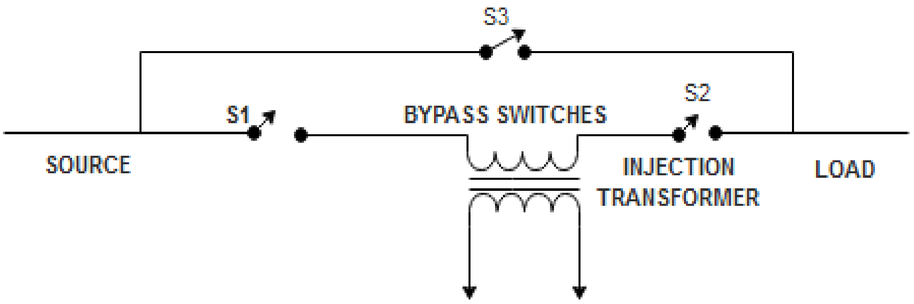


Figure 4.15: Mechanical bypass switch

The mechanical bypass switch can be expended as a safeguarding tool to keep safe the dynamic voltage restorer from the high current in the consumer side as a result of short circuit on the load or very big inrush currents. The DVR can be safeguarded by employing bypass switches, which permit the excess current to flow through another path as shown in Figure 4.15.

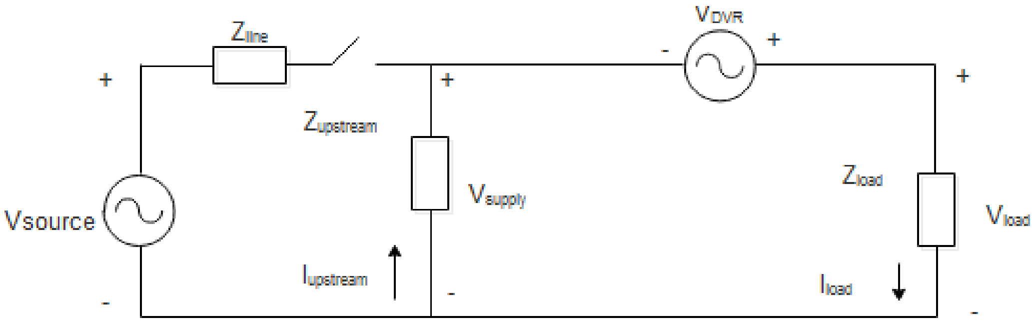


Figure 4.16: DVR with Upstream Load and Breaker

If the feeding supply voltage is low, the DVR has to stop injecting a voltage. A simplified diagram of this case is shown in Figure 4.16 during line breaking the DVR will try to compensate the load voltage to pre-voltage level and the load current will be forced through the downstream load. A voltage and current reversal can be expected at the downstream load unless the DVR detects the primary supply breaking and goes into a bypass state. A number of measures have been proposed in [114], and one method is to stop injecting at very low supply voltage, which in some cases would lead to a bypass even though the supply line is still intact. The voltage across the downstream load is equal to the voltage. This is given by equation 4.9

Mathematically, $V \sup ply = -V_{DVR} \frac{Z_{load}}{Z_{load} + Z_{upstream}}$ 4.9

4.9 Summary

The basic components and position of DVR in the secondary electric power distribution networks has been explained. Moreover, DVR mode of operation and mathematical expressions used have been highlighted including the topologies with and without energy storage. Thereafter, techniques for DVR compensations and converter topologies in distribution system have been discussed. Finally, the DVR protection schemes have been presented.

CHAPTER FIVE

APPLICATION OF DVR FOR VU MITIGATION, VV COMPENSATION AND LOW VP ENHANCEMENT IN SECONDARY DS

Designing and modelling of DVR to the investigated network, result of network simulation, analysis of results, and discussion of results is presented in this chapter

5.1 Introduction

A (DVR) is one of the families of advanced solid state custom power device employed in secondary distribution system to enhance voltage unbalance and voltage variation by supplying the appropriate voltage as well as needed energy to the network. The power factor, level of voltage unbalanced, level of voltage variation, distribution transformer loading and maximum loads are the determining factors for DVR mitigation capability in low voltage electric power distribution system. A DVR is linked in series within the secondary distribution system as depicted in Figure 5.1. The DVR supply, a relatively small quantity of voltage in series in a way that the voltage amplitude of reference voltage is the same with the expected value of V_{DVR}. The DVR is expected to provide both active and non-active power to the system through the power storage system.

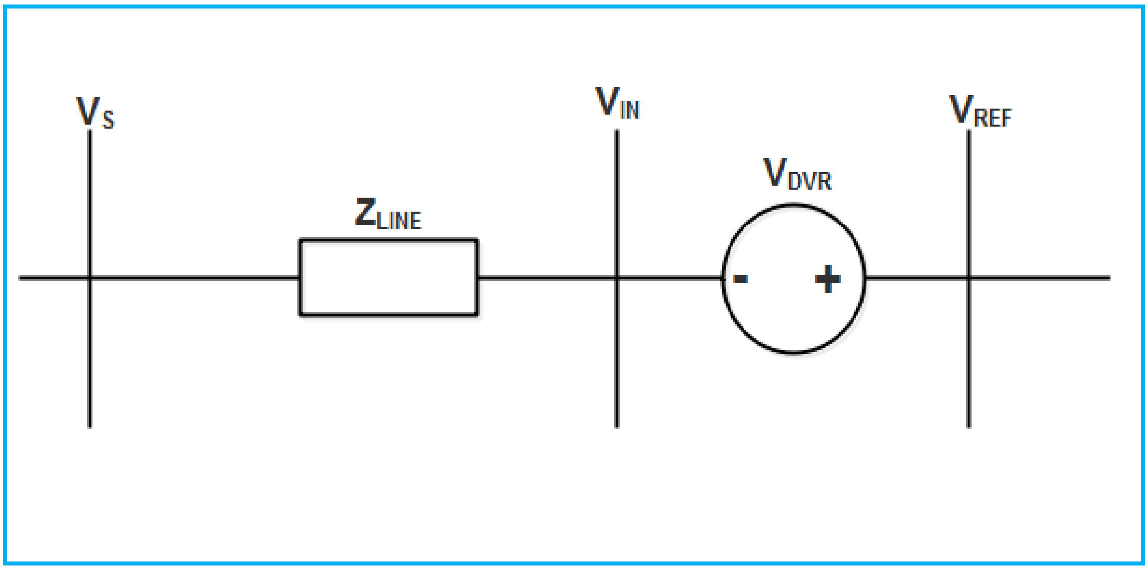


Figure 5.1: DVR layout diagram of the studied secondary DN

Mathematically, from Figure 5.1, the quantity of needed potential to be provided by the DVR to the system phases is given as in equation (5.1).

$$
\begin{aligned}
V_{DVR,A} &= V_{REF,A} - V_{IN,A} \\
V_{DVR,B} &= V_{REF,B} - V_{IN,B} \\
V_{DVR,C} &= V_{REF,C} - V_{IN,C}
\end{aligned}
\tag{5.1}
$$

For all the three phases, the expected potential at the produced energy end of DVR are based on equal expected amplitude and are separated from one another by phase angle of 120 ^{0}. These source potentials are adjusted depending on the phase angle of one the phase of the voltage supply on the network.

The DVR system is to convey the voltage that is needed for the mitigation for the DC storage system via the IGBT inverter circuit, then through the filtering circuit to the injection transformer. The mitigation ability of a choosing DVR relies on the greatest value of supply of voltage ability and the real power that the DVR can inject into the electric power distribution system. In the event of voltage disturbance or disruption, real power should be supplied from the DC storage systems which is joined to the input of inverter system. That will make up a big capacitor storage system. It supplies power to the customer load during disturbance states for the effective and continuous supply of energy needed by the DVR power circuit. The rating and size of the capacitor is vital, this will help the inverter circuit to generate the needed voltage to the system during disturbances. The direct current electrical storage element rating of a 3-phase network can be calculated. The high ranking merit of these electrical storage elements is the ability to inject high electric charge pulses continuously for hundreds of thousands of one complete oscillation. The choosing of storage component size is talked about on the idea of the root mean square value of the capacitor power size, current rating and voltage rating.

5.2 The Dynamic Voltage Restorer

The DVR is an advanced power electronics tool linked in series to the distribution network. It has an extremely good capability compared to the other custom power devices employed for the same purpose in distribution system. When placed between the load and the supply, for power quality problems mitigation. The DVR delivers controlled voltage whose vector is in phase with the source voltage, in order to achieve the load voltage to the accepted magnitude and shape of wave even when the supply voltage is imbalanced and altered in shape. Figure 5.2a points out the typical schematic diagram of DVR, while Figure 5.2b shows the proposed schematic diagram of DVR systems. The primary parts of DVR are: power circuit and control circuit.

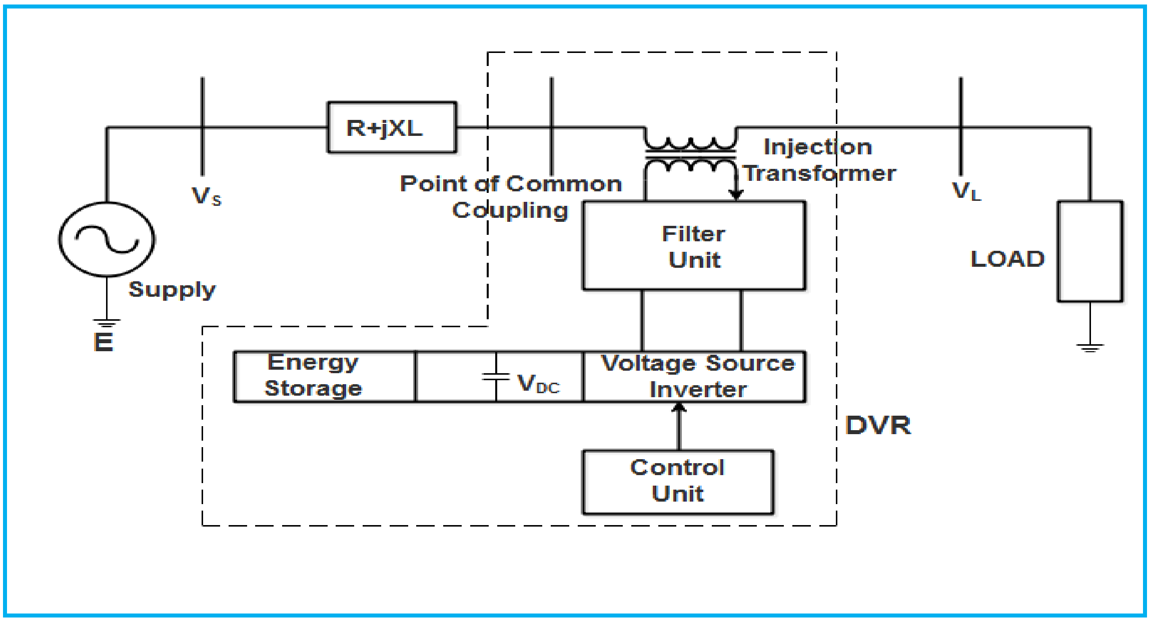


Figure 5.2a: Typical schematic diagram of DVR

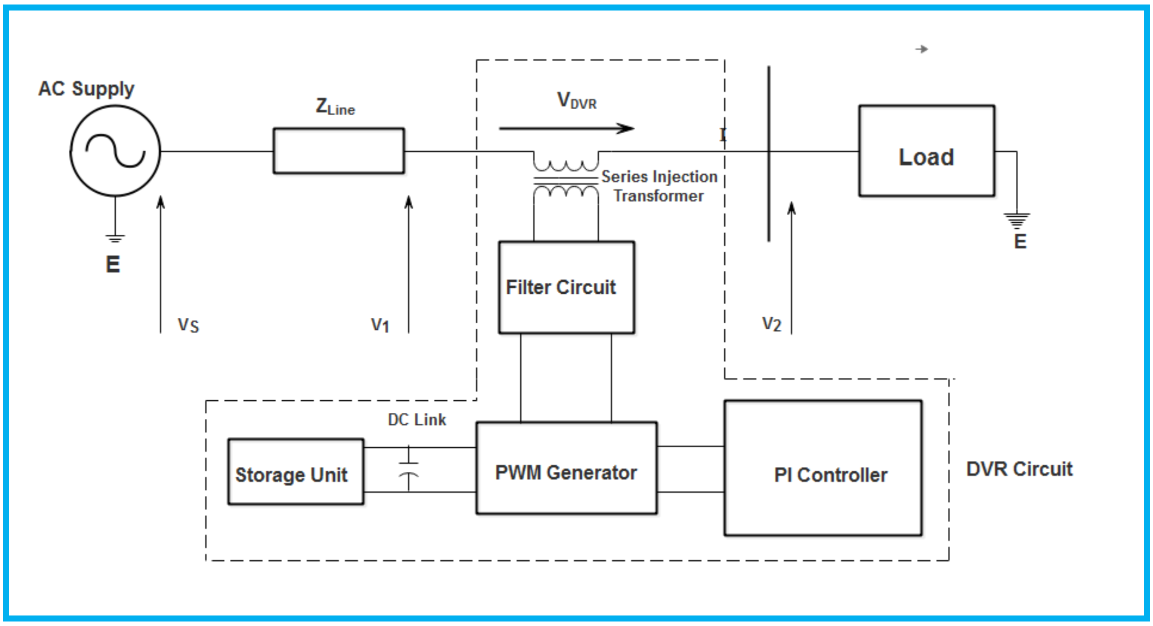


Figure 5.2b: Proposed Layout diagram of DVR

5.2.1 Series Voltage Boosting Transformer

The voltage boosting transformer is employed in secondary distribution systems most importantly for voltage injection operation to the secondary distribution system load side and for sudden separation of the DVR system in case of faults. The DVR links the secondary system through its windings and converts the supplied mitigated produced voltages by the source inverter to the approaching source voltage. The principal purpose of transformer is to step up the supplied voltage from the output of the filter to the desired nominal voltage level required by the customer load and for prompt isolation of the DVR from the power network. For DVR to properly compensate for the missing voltage, the secondary side of the voltage injection transformer must be equal to the main source voltage [98, 115-117].

5.2.2 AC Filter

Essentially, filters are utilized to transform the inverted pulse width modulation produced waveform into sine waves. Similarly, filter is employed to eliminate the switching harmonics present in the converted sinusoidal AC compensating voltage waveform, so as to keep a standard permissible harmonic distortion level.

5.2.3 Charging Unit

This charges the energy source after voltage sag and the variations compensation event and provides a discharge circuit and grounding equipment for maintenance purposes.

5.2.4 A Pass Switch

A pass switch is employed primarily in secondary distribution systems to safeguard the inverter from excess currents produced as a result of faults in the secondary distribution system.

5.2.5 Voltage Source Inverter (VSI)

The inverter is employed to change direct current voltage provided by the DC link device to sinusoidal voltages injected into the network. VSI comprises six pulses VSI with their sinusoidal produced energy linked to the secondary coils of the device. Used for changing electrical energy and the insulated gate bipolar transistors (IGBT) based VSCs produce the supplied voltages to mitigate for the voltage unbalances and variations. The value of the VSI employed is comparatively small in potential and high in electric charge of the presence of the step up boosting transformer.

5.2.6 Energy Storage

This provides the required energy to the VSC through a direct current link for the production of supply voltages during disturbances in the network. Electrolytic storage element bank can be employed for the energy source for DVR applications.

5.2.7 Control Unit

A controller is employed for correct control of DVR systems. DVR detects the presence of voltage unbalances/variations and compensates the voltage problem. The PWM control method is employed for inverter switching in order to generate a 3-phase, 50 Hz sine wave voltages on the load side. The control of compensating device is carried out in three steps, discovery of voltage variation occasion in the network, compared with the reference value and the production of gate pulses to the VSI to produce the DVR output voltages which will mitigate poor voltage profile and voltage variation.

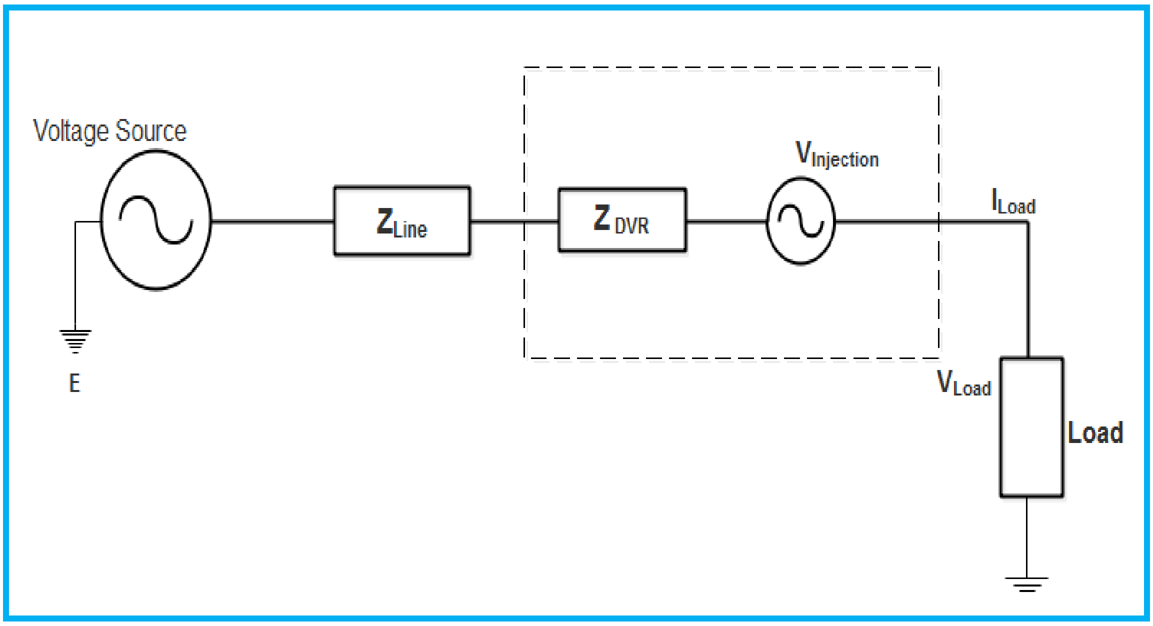


Figure 5.3: DVR equivalent circuit diagram

Mathematically, from Figure 5.3, the *DVR* can be represented by the equation (5.2).

$$U_{DVR} = U_{Load} + Z_d I_{Load} - U_d \tag{5.2}$$

Where, U_{DVR} is the injected voltage to the network, U_{Load} is the nominal load voltage, Z_d is the load impedance, I_{LOAD} is the load current and U_d is the system voltage during disturbances.

The load current I_{Load} is given by equation (5.3).

$$I_{Load} = \frac{[P_{Load} + jQ_{Load}]}{U} \tag{5.3}$$

The active power of the *DVR* is given as equation (5.4).

$$P_{DVR} = I_{LOAD}(U_{LOAD} \cos\theta_{LOAD} - U_S \cos\theta_S) \tag{5.4}$$

The DVR apparent power is given as in (5.5) and (5.6) respectively:

$$S_{DVR} = I_{LOAD} U_{DVR} \tag{5.5}$$

$$S_{DVR} = I_{LOAD} \sqrt{\{U_{LOAD} + U_S{}^2 - 2U_{LOAD} U_S \cos(\theta_{LOAD} - \theta_S)\}} \tag{5.6}$$

The DVR complex power injection is put forward as shown in equation (5.7).

$$S_{DVR} = U_{DVR} I^*{}_{LOAD} \tag{5.7}$$

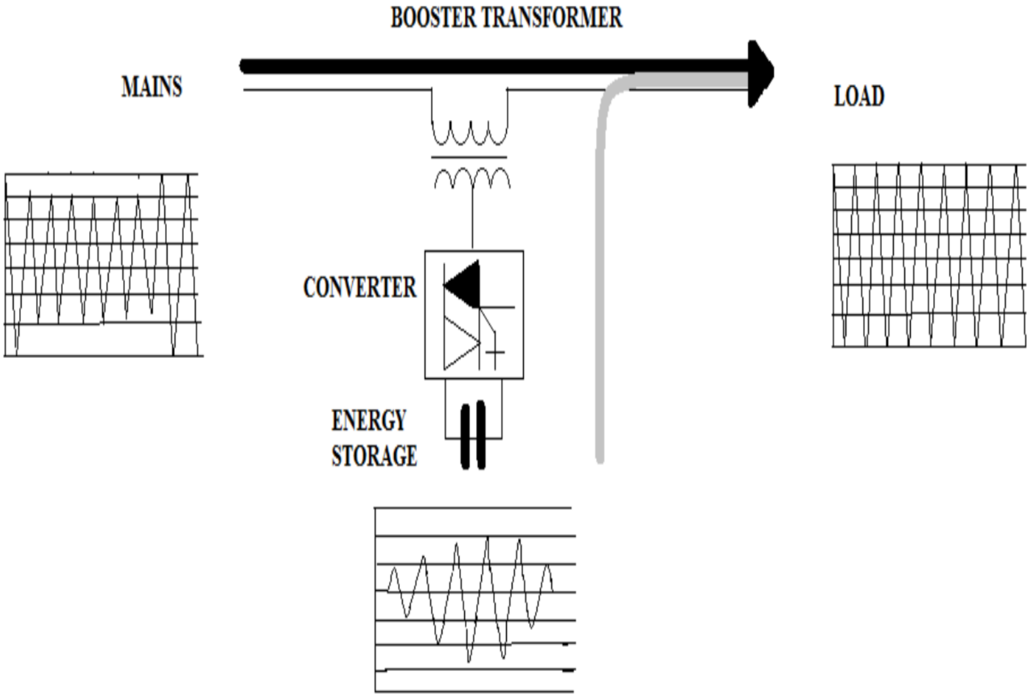


Figure 5.4: Principle/Standard of Operation of DVR System

5.3 The Power Circuit of DVR

The Simulink model of the DVR power circuit is depicted in Figure 5.5. It is comprised of the following parts namely: series inverter, energy storage, line filter and injection transformer. A two winding transformer is employed for each phase of the DN. The winding of the boosting transformer linked to the inverter is designated as the secondary while the winding linked o the supply side is designated as the primary.

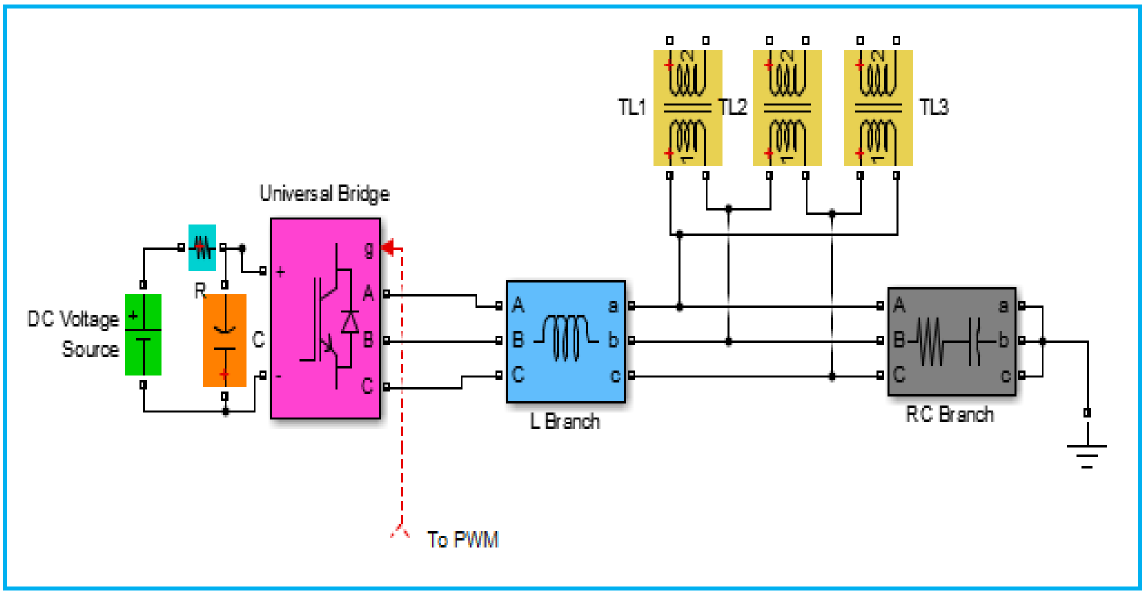


Figure 5.5: proposed Simulink model of DVR power circuit section

5.3.1 The Series Voltage Injection Transformer

A series voltage injection transformer has a high rank factor that requires careful selection in the process of designing the structure of DVR. The primary purpose of using a DVR in this research is to serve as a point of common link between the distribution system and the DVR system. Similarly, injection transformer is employed to safeguard the DVR system from excess flow of current from the supply side. Similarly, it provides an effective match between the power network and the DVR system. In addition, it ensures galvanic isolation of the DVR system from the entire power system network in the event of three-phase fault or other related faults. The step-up series voltage injection transformer is employed for this work due to the following benefits: it eliminates negative sequence, injects positive sequence and no effect on zero sequence.

For the purpose of this research study, a 5 kVA, 100/400 Volts and 50 Hz frequency step up series voltage boosting transformer is utilized to increase the supplied voltage from AC line filter output to the statutory level. The secondary side is linked to power system network while the primary side is linked to the power control circuit of the DVR system. It must be noted that for complete compensation to take place with DVR, the primary supply voltage of the distribution system must be the same voltage value with the secondary side of the series voltage boosting transformer. Since the mitigation ability of DVR system completely relies on the series voltage injection transformer rating, DVR fully supplies voltages of right of purpose amplitude and phase in series to the distribution system for compensation.

5.3.2 AC Line Filter

The AC line filter is incorporated in the design of DVR system to enhance elimination of undesired harmonics produced by the pulse width modulation generator series source voltage inverter. The passive filter of low pass band which contains elements such as resistors (R), inductors (L) and capacitors (C) is positioned on the output of the series source inverter circuit to completely remove the harmonics present in the converted compensating sinusoidal AC voltage. The design of the filter is carefully done, to get the desire bandwidth of the filter. The damping factor value is painstakingly chosen. The three element’s value is set to have the bandwidth and resonant frequency. The RCL is employed as a low pass filter as shown in the circuit diagram in Figure 5.6. Similarly, equations (5.8) and (5.9) show the frequency and the damping factor expressions for the filter utilized.

$$\omega_c = \frac{1}{\sqrt{LC}} \tag{5.8}$$

$$\varsigma = \frac{1}{2R_L}\sqrt{\frac{L}{C}} \tag{5.9}$$

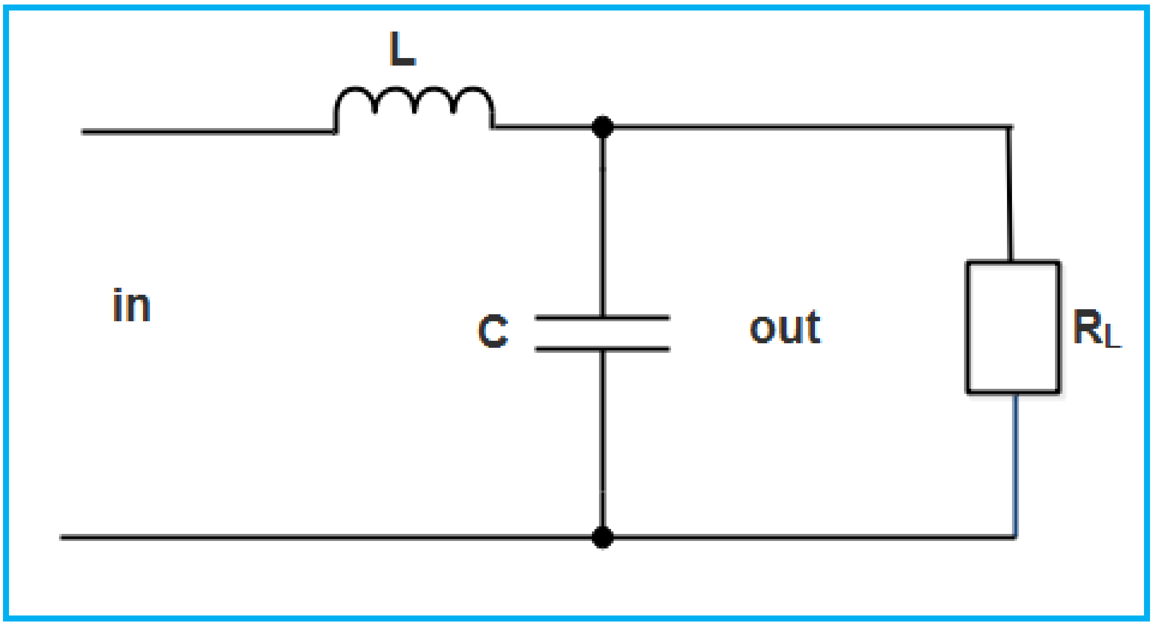


Figure 5.6: Filter circuit diagram

The resistor is employed to decrease the peak resonant frequency, it also increases the decay of oscillations in the system, which is called damping, and it has a meaningful result on the circuit system. The value of the three elements employed in this research is resistor 0.01 Ω, inductor 7 mH, and 10 µF respectively. The result shows that the entire switching harmonic produced by VSI was completely removed and the system does not oscillate.

5.3.3 Series Voltage Source Inverter (SVSI)

A SVSI is employed in this research work to change DC voltage generated from the energy storage device to sinusoidal voltage source which is to be supplied to the distribution line through the series step up voltage injection transformer when voltage disturbances occur in the distribution network. Figure 5.7 shows the circuit diagram of three phase voltage source inverter employed in this research. Since the series voltage used does not manufacture power, the power is produced by the energy storage element; hence, the output voltage, the total power and the frequency rely on efficient design of the inverter system. The designed voltage output waveform of the inverter system is sine wine which is regulated by the square wave width pulse gated via a pulse width modulated generator controller, in order to regulate the SVSI output voltage as shown in Figure 5.11. The output voltage and output frequency are regulated to be the same with the distribution line voltage and frequency which are 220 Volts and 50 Hz respectively. The output sinusoidal voltage from the voltage source inverter is connected to RLC line inverter to reduce the switching harmonics generated by the inverter in order to minimum acceptable value before connection is made to the primary side of the step up transformer used in this research.

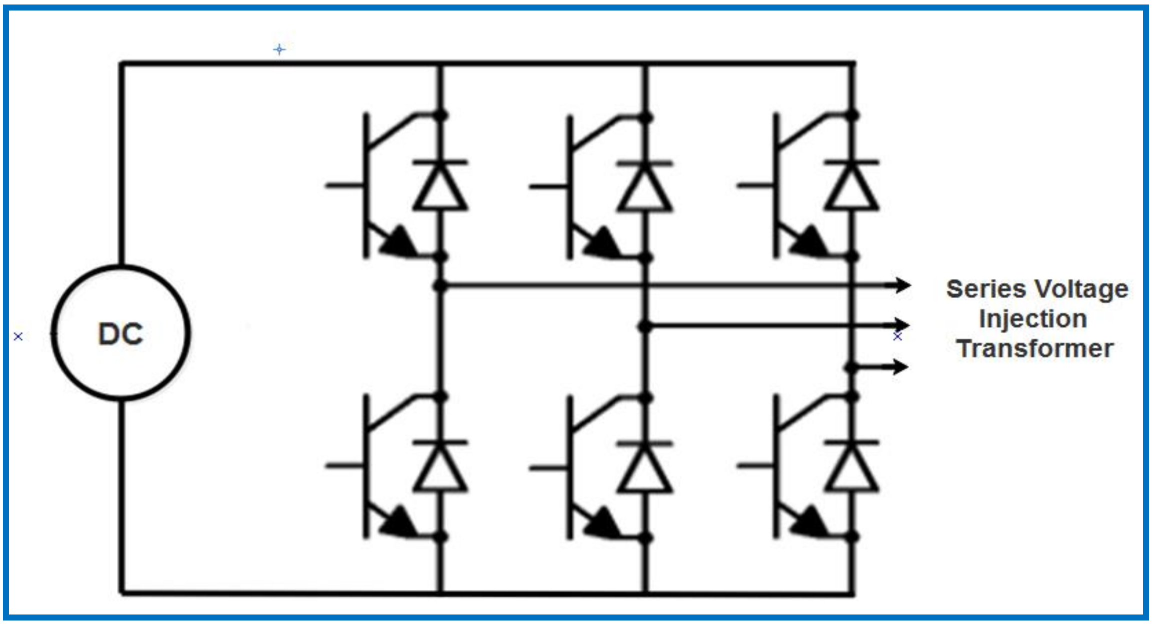


Figure 5.7: Circuit diagram of three phase voltage source inverter

5.3.4 Energy Storage

In the event of PQ disturbances in DN, real power is needed by DVR system to mitigate the voltage disturbances such as unbalanced voltage, voltage variation, voltage fluctuation studied in this research. The DVR employed in this study is a storage topology type. A storage component is employed to generate the needed voltage to the series VSI in order to generate a sinusoidal voltage that is supplied to the distribution grid via injection transformer in the cause of voltage disturbances in the distribution grid. Different energy storage element exists in the market today, such as: superconductors, capacitors, flywheel energy storage, electrochemical cells, hydraulic accumulators, ultra-battery and thermal energy storage. The super-electrical storage element used in this research can be charged from the source side or the load side. The rating of the energy storage used was 400 V. The maximum line voltage from the series voltage source inverter was calculated using equation (5.10).

$$V_{LL\,r.m.s} = \frac{m}{2} * \frac{\sqrt{3}}{\sqrt{2}} * Vdc$$

$$= m * 0.612 * Vdc \tag{5.10}$$

$$V_{LL\,r.m.s} = 220\,Volts$$

Where, m is modulation index 0.9 is used; Vdc the voltage of the storage element is 400 Volts. The 220 Vr.m.s output line to line voltage which is the nominal voltage of the phase to phase of the distribution system under study.

5.4 The Control Circuit of DVR

The control circuit as depicted in Figure 5.8 comprises; the dq0 Park's transformation controller, the proportional and integral controller, pulse width modulation generator and phase-locked loop controller.

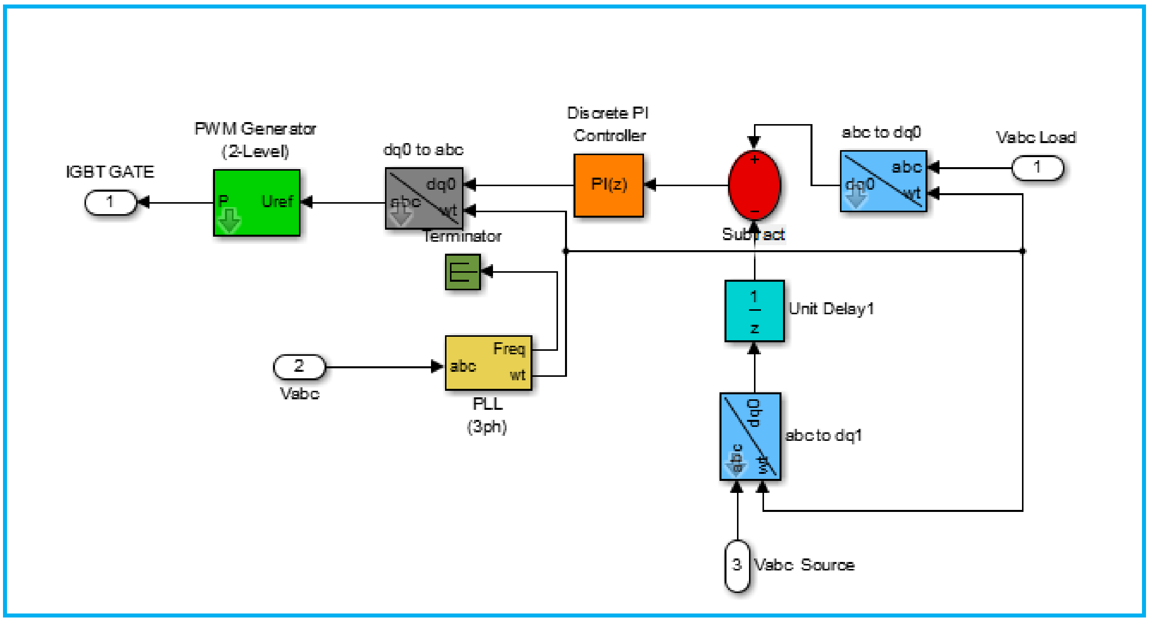


Figure 5.8: proposed Simulink model of DVR controller

5.4.1 The *DQ0* Park's Transformation Controller

The dq0 park transformation controller is utilized in this research to convert the three-phase load voltage sinusoidal wave shape to direct current signals. This was done to make the calculations on the three phase sinusoidal elements less complicated or easier to understand. Thus enabling processes and analysis to be carried out in a simplify way before inverse transformation is performed in order to return the three phase voltage (*abc*) to its real state three phase sinusoidal (*AC*) outputs. The primary advantage of dq0 park transformation is that it reduces complexity of calculations associated with the three phase *abc* system. It is easier to design and control since dq model deals with direct current values. The *dq0* park transformation single matrix is given by equation (5.11).

$$K_{Park} = \begin{bmatrix} \cos \omega t & \sin(\omega t) & 0 \\ -\sin \omega t & -\cos(\omega t) & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad (5.11)$$

Where, ωt is equal to θ is the angle between the rotating and fixed coordinate system at each time.

$$\theta = \cos^{-1}\left(\sqrt{\frac{2}{3}}\right) \tag{5.11a}$$

The abc to dq0 park transformation controller relies on the direct and quadrature axis (dq) frame alignment at time equals to zero. The location of the turning motion frame is given as $\omega.t$ (*w* represents the direct and quadrature frame rotation speed). The following connections are established when turning dq frame in correct position with A axis: as given in equations (5.12) and (5.13).

$$\begin{aligned} V_s &= V + jV_q = V_s = V_d + jV_q = \left(V_a + jV_\beta\right) * e^{-j\omega t} \\ &= \frac{2}{3} * \left(V_a + V_b e^{\frac{-j2\pi}{3}} + V_c e^{\frac{j2\pi}{3}} \right) * e^{-j\omega t} \end{aligned} \tag{5.12}$$

Where, V_a, V_b and V_c are voltage on the phases and V_d and V_q are direct voltages signal

The dq0 transform (called Park transform) is a space vector transformation of three phase time domain signals from a stationary phase coordinate system (abc) to a ratating coordinate system (dq0). The transform applied to time domain voltages in the natural frame of (V_a, V_b and V_c) is given in equation 5.13

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\omega t & \cos\left(\omega t - \frac{2\pi}{3}\right) & \cos\left(\omega t + \frac{2\pi}{3}\right) \\ \sin\omega t & \sin\left(\omega t - \frac{2\pi}{3}\right) & \sin\left(\omega t + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} V_d \\ Vq \\ V_0 \end{bmatrix} \tag{5.13}$$

The dq0 inverse park transformation is given in equation (5.14).

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\omega t & \sin(\omega t) & 1 \\ \cos\left(\omega t - \frac{2\pi}{3}\right) & \sin\left(\omega t - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\omega t + \frac{2\pi}{3}\right) & \sin\left(\omega t + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{5.14}$$

Where, V_a, V_b and V_c are three phase AC quantities and V_d, V_q and V_0 are direct current signals. The Vd and Vq are two phase quadrature voltage along the stationary frame, the 0 component is zero.

Likewise, the following connections are established when turning dq frame aligned at right angles behind A axis, equations (6.15) and (6.16) are established.

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \sin \omega t & \sin\left(\omega t - \frac{2\pi}{3}\right) & \sin\left(\omega t + \frac{2\pi}{3}\right) \\ \cos \omega t & \cos\left(\omega t - \frac{2\pi}{3}\right) & \cos\left(\omega t + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} \tag{5.15}$$

The inverse rotating the dq frame when aligned at right angles behind A axis is given in equation (5.16).

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = \begin{bmatrix} \sin \omega t & \cos(\omega t) & 1 \\ \sin\left(\omega t - \frac{2\pi}{3}\right) & \cos\left(\omega t - \frac{2\pi}{3}\right) & 1 \\ \sin\left(\omega t + \frac{2\pi}{3}\right) & \cos\left(\omega t + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{5.16}$$

In a situation where the dq0 elements of three phase balanced signals aligns with the rotating frame at time equals to zero, equation (5.17) is employed by the dq0 Park controller.

$$\begin{aligned} V_a &= \sin \omega t; \\ V_b &= \sin\left(\omega t - \frac{2\pi}{3}\right); \\ V_c &= \sin\left(\omega t + \frac{2\pi}{3}\right) \end{aligned} \tag{5.17}$$

5.4.2 Proportional and Integral Controller

This PI control system is a feedback that performs a specific task extensively employed in power distribution control systems and other applications that need continuous modulated control. The PI controller employed in this research is purposely designed to continuously estimate error values as the difference between a reference voltage desired point and an output voltage measured in the system. The PI controlling system is applied because of its capability to provide accurate and fast responsive solution and correction to a control function, the absence of derivative function which is set at zero produces a much stable steady state system.

Mathematically, PI controller is given as in equations (5.18), (5.19) and (5.20).

$$U = K_P e + K_I \int e d\tau \tag{5.18}$$

$$U = K_P e + \frac{1}{\tau_N}\int e\,d\tau \qquad (5.19)$$

$$U = K_P\left(e + \frac{1}{\tau_N}\int e\,d\tau\right) \qquad (5.20)$$

Where,

K_P is the proportional gain factor, K_I is the integration gain factor, τ_N is the reset time and e is the error given in equation (5.21).

$$e(t) = R_V - L_V \qquad (5.21)$$

Where,

R_V is the reference voltage and L_V is the load voltage, e (t) is the error.

The PI is modelled without difficulty in MATLAB/Simulink with Laplace operators as given in equation (5.22).

$$C = \frac{G(1+\tau s)}{\tau s} \qquad (5.22)$$

Where,

$G = K_P$ is the proportional gain factor

$G/\tau s = K_I$ is the integral gain factor

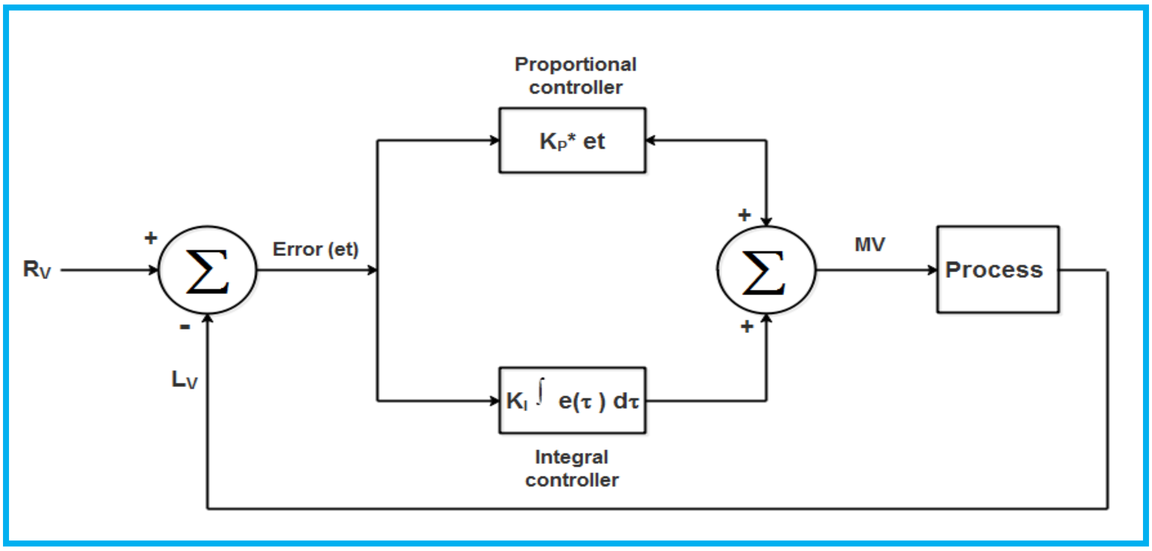


Figure 5.9: PI controller basic block diagram

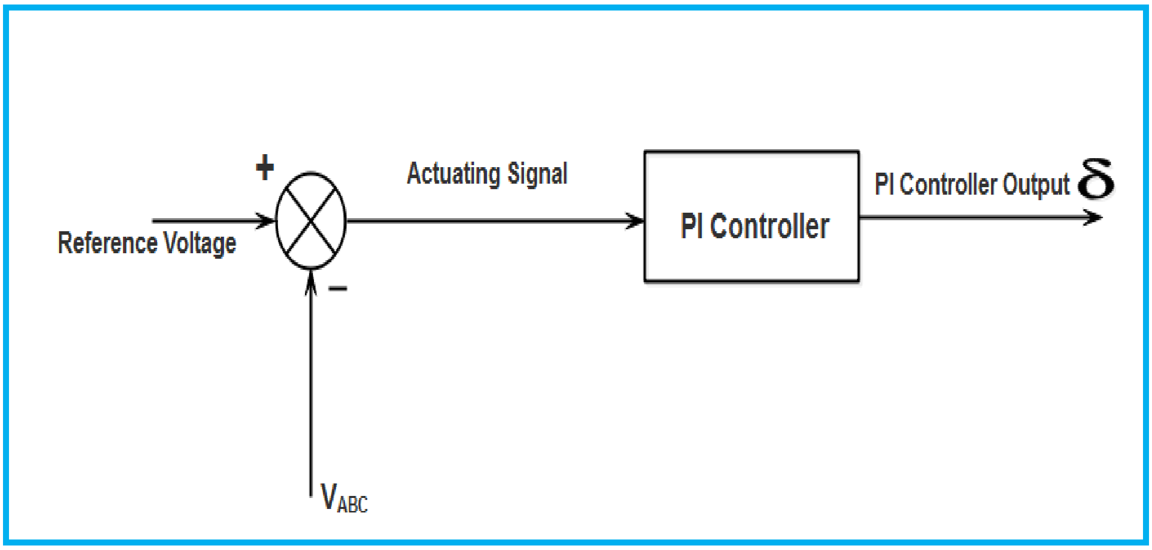


Figure 5.10: Simplified Typical Model of a Controller

5.4.3 Pulse Width Modulation Generator

The primary function of PWM technique is the comparison of two signals. A low frequency reference signal and a high frequency carrier signal. Typically, the reference signal represents the standard output one desires to have from the voltage source inverter. Therefore, it is employed to modulate the carrier signal in order to make the carrier signal take after its shape. Figure 5.11 shows the generated pulsing signal from the pulse width modulation generator for the primary purpose of providing an excellent means of controlling a voltage source inverter to produce an AC power from the DC power in this study. The PWM generator is employed to gate the voltage source inverter in order to inject the needed AC voltage to compensate the unbalanced voltage, low voltage profile and voltage variation experienced in distribution network. The primary merit of PWM is that it has a very low power loss in the switching devices. It also has almost no current when the switch is put off and on with voltage drop across the switch practically zero. The duty cycle is set without experiencing any difficulty, due to the on and off nature of PWM. It works satisfactorily well when it performs digital control.

The mode of operation of PWM generator is that it receives the modulated angle δ from the secondary side of the proportional and the integral controller. This is directed to the PWM generators in phase A demonstrated in mathematical expression in (5.24). The remaining phase B and C are shifted by 120^0 and – 120^0as presented in equations (5.25) and (5.26), respectively. Accordingly, the voltage amplitude is used as the return part of the output measurable quantity in the control system. For satisfactory performance of PWM generator, the primary parameter is needed for AC PWM system the frequency modulation index Mq of the carrier signal and the magnitude modulation index. The modulation magnitude index Mm is fixed at 1.0 p.u, so as to get the highest basic voltage element at the output of the controller as given by equation (5.27).

The modulated 3-phase voltages are given in equations (5.24), (5.25) and (5.26).

$$V_a = \sin(\omega t + \delta) \tag{5.24}$$

$$V_b = \sin\left(\omega t + \delta + \frac{2\pi}{3}\right) \tag{5.25}$$

$$V_c = \sin\left(\omega t + \delta + \frac{4\pi}{3}\right) \tag{5.26}$$

$$Mm = \frac{The\ peak\ magnitude\ of\ the\ signal}{The\ peak\ magnitude\ of\ the\ triangular\ signal} = \frac{V_C}{V_T} = 1\ p.u \tag{5.27}$$

Where;

V_C is the peak magnitude of the signal and the V_T is the peak magnitude of the triangular signal.

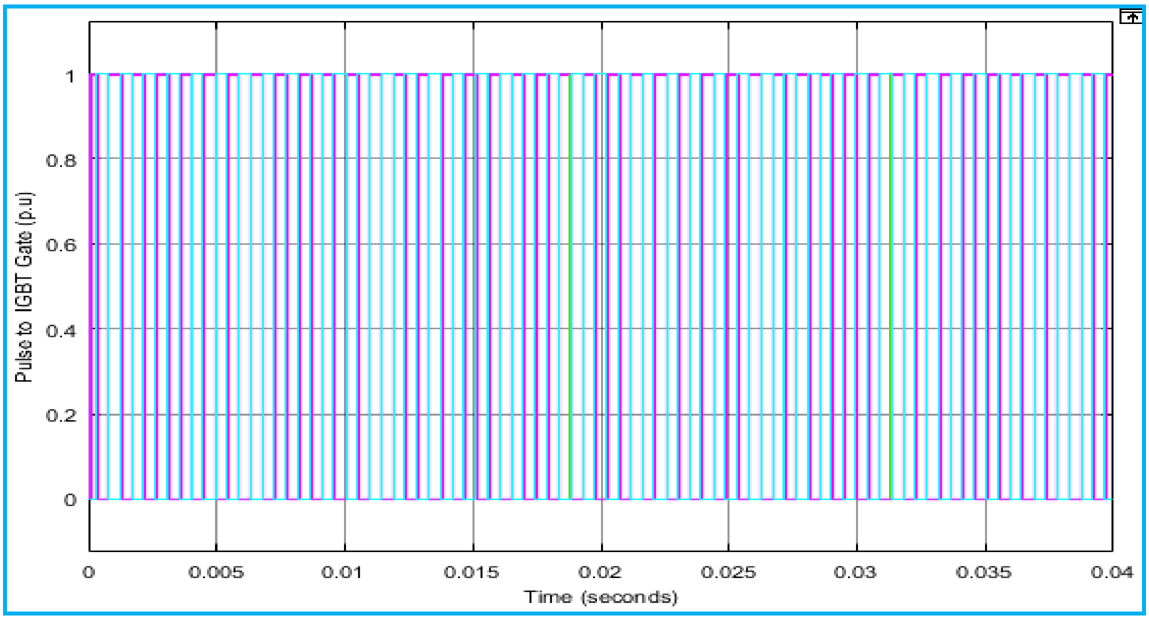


Figure 5.11: Pulses generated by discrete *PWM* generator

5.4.4 Phase-Locked Loop Controller (PLL)

The primary purpose of a PLL controller in this research work is to ensure the output of the phase and that the frequency values are maintained with the reference value. This is achieved by the use of phase shift detector and frequency oscillator made of feedback system in the PLL controller. This is to maintain phases and frequencies matched of the reference signals and the output signals. A PLL block diagram is depicted in Figure 5.12.

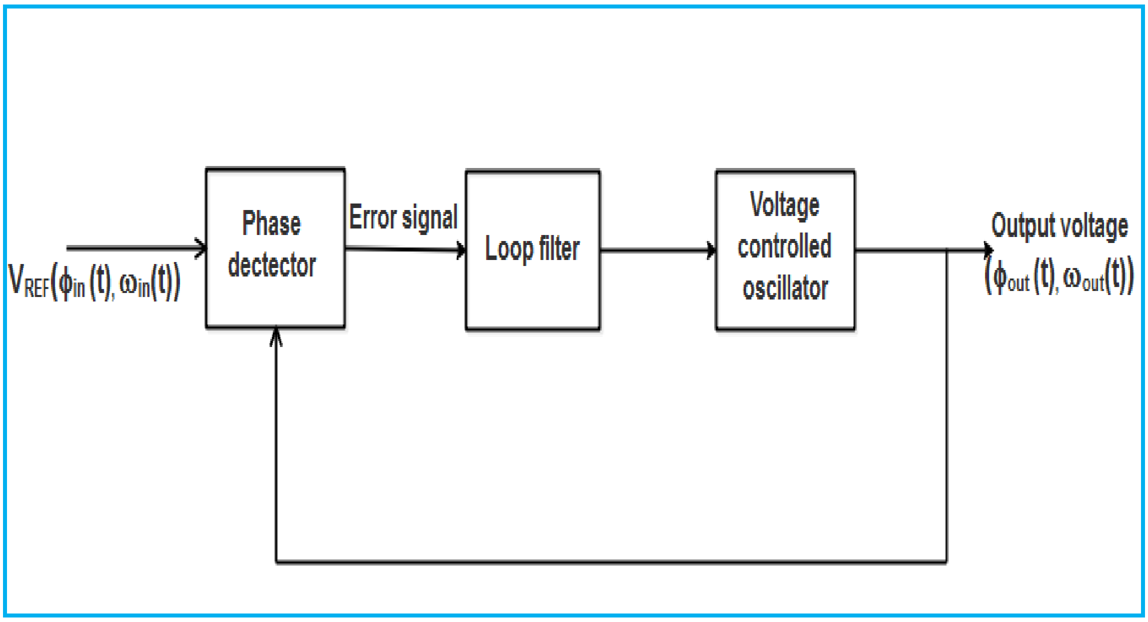


Figure 5.12: PLL controller Block diagram

The interrelationship between frequency and phase are shown by equations (5.28) and (5.29).

$$\omega(t) = \frac{d\phi}{dt} \tag{5.28}$$

$$\phi(t) = \phi(0) + \int_0^t \omega(t')\,dt' \tag{5.29}$$

5.5 The DVR Control Strategy

The primary objective of DVR control strategy is to keep the load voltage magnitude constant and balanced under any conditions. In this study the following control scheme is proposed for improvement DVR operation. The control system of a *DVR* performs a significant role, as shown in Figure 5.13. It has a requirement of fast a response when voltage unbalanced, variation/fluctuation occurs. In the process of voltage disturbances, the *DVR* reacts as fast as possible and injects an appropriate *AC* voltage to the network. The *DVR* detects the voltage disturbances by sensing the three-phase load voltage (Vabc) and transferred it through *abc/dq0* Park’s controller, which convert the three-phase load voltage sinusoidal wave shape to direct current signals. The magnitude of the three-phase load voltage is compared with the reference voltage (V_{REF}) in dq0 frame. This done to make the calculations, processes and analysis to be carried out in a simplify way.

The PI controller helps to continuously estimate an error value as the difference between a reference voltage desired point and a load voltage measured in the system, after which inverse transformation is performed to convert to three phase voltage (Vabc) to its real state three phase sinusoidal (AC) outputs using dq0/abc inverse Park's controller before injected to PWM generator. PWM generator received the modulated angle δ from the secondary side of the proportional and the integral controller, the PWM provides an efficient way of controlling an inverter to produce AC power from the DC power, the PWM helps to obtain the standard output sinusoidal voltage, that is the reference signal needed from the inverter, so as to modulate the carrier signal, in order word to make the carrier signal take on it shape. The PWM generator control system is applied to the voltage source inverter switching so as to generate a three-phase 50 Hz sine wave voltage at the load ends. The voltage source IGBT inverter is controlled by the PI controller in order to keep 1. 0 p.u voltage at the load terminal. The merit of using a PI controller is that its integral term offers the steady state error to be zero for a step input.

The PI controller input is an actuating signal which is the difference between the reference voltage and the three-phase load voltage. The output of the PI controller to the PWM generator controller is of the form of angle, which presents extra phase-lead/lag in the three-phase voltages. The output of error detector is the difference between the reference voltage (V_{REF}) and the load measured voltage (Vabc) that is V_{REF}-Vabc. Where, the V_{REF} is equal to 1.0 p.u and the Vabc in p.u at the load terminals. The PI controller output when compared at the PWM signal generator produces the expected firing sequence. The phase-locked loop (*PLL*) is employed to maintain phases and frequencies matched of output signals with the reference, this is made possible through the use of phase shift detector and frequency oscillator made of feed-back system in the PLL controller. The DVR control scheme is presented in Figure 5.13 and the flowchart in Figure 5.14 presents the main algorithm, which explained the gradual process of the DVR implementation.

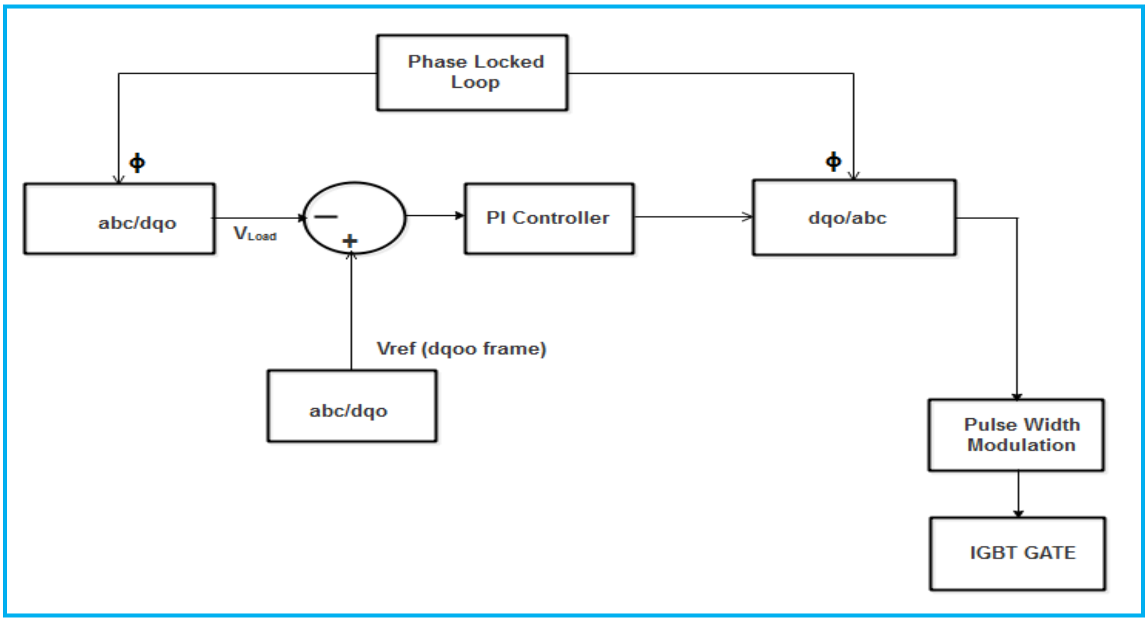


Figure 5.13: Proposed the DVR control scheme.

The control circuit of the DVR can be summarized from the control algorithm of DVR with PI controller, in order to make it simple:

- The 3-phase load voltage (abc) is converted to dq0 frame components, and the reference voltage is well compared in dq0 frame components;
- The PI controlling system provides accurate and fast responsive solution and correction to a control function. The error signal generated due to the difference between the measured load voltage profile and the reference voltage values and the controller will be active to process the needed voltage required for the mitigation of the voltage disturbance detected. The error signal generated will derive the proportional integral controller, which regulates the system operation depending on the actuating error signal;
- The output from the proportional integral controller which is in *dq0* frame is directed to the two level discrete pulse width modulation generator;
- The two level pulse width modulation (*PWM)* generator produces the needed pulses to fire the *PWM* inverter with the desire triggering sequence. The pulse width modulation generator method is utilized on voltage source inverter to modulate the carrier signal to produce a 3-phase 50 cycles-per-second sine wave output sine wave voltage which is the same with the reference voltage;
- The storage device produces a 400 V DC power to the voltage source inverter to be converted to 220 V AC power by the inverter;
- The line filter is utilized at the output of the inverter to eliminate the harmonics presents in the converted compensating AC voltage;
- The *PLL* circuit is employed in *DVR* to keep the phase and frequencies of output signals in track with the reference signal. The phase *A* is 0˚, while the angle of phase *B* and *C* are shifted by 120˚ and 240˚as shown in equations (5.24), (5.25), and (5.26) respectively; and
- The 50Hz *AC* output sinusoidal voltage from the inverter is injected to the step up series voltage boosting transformer matched in series with the 3-phase electrical secondary distribution network.

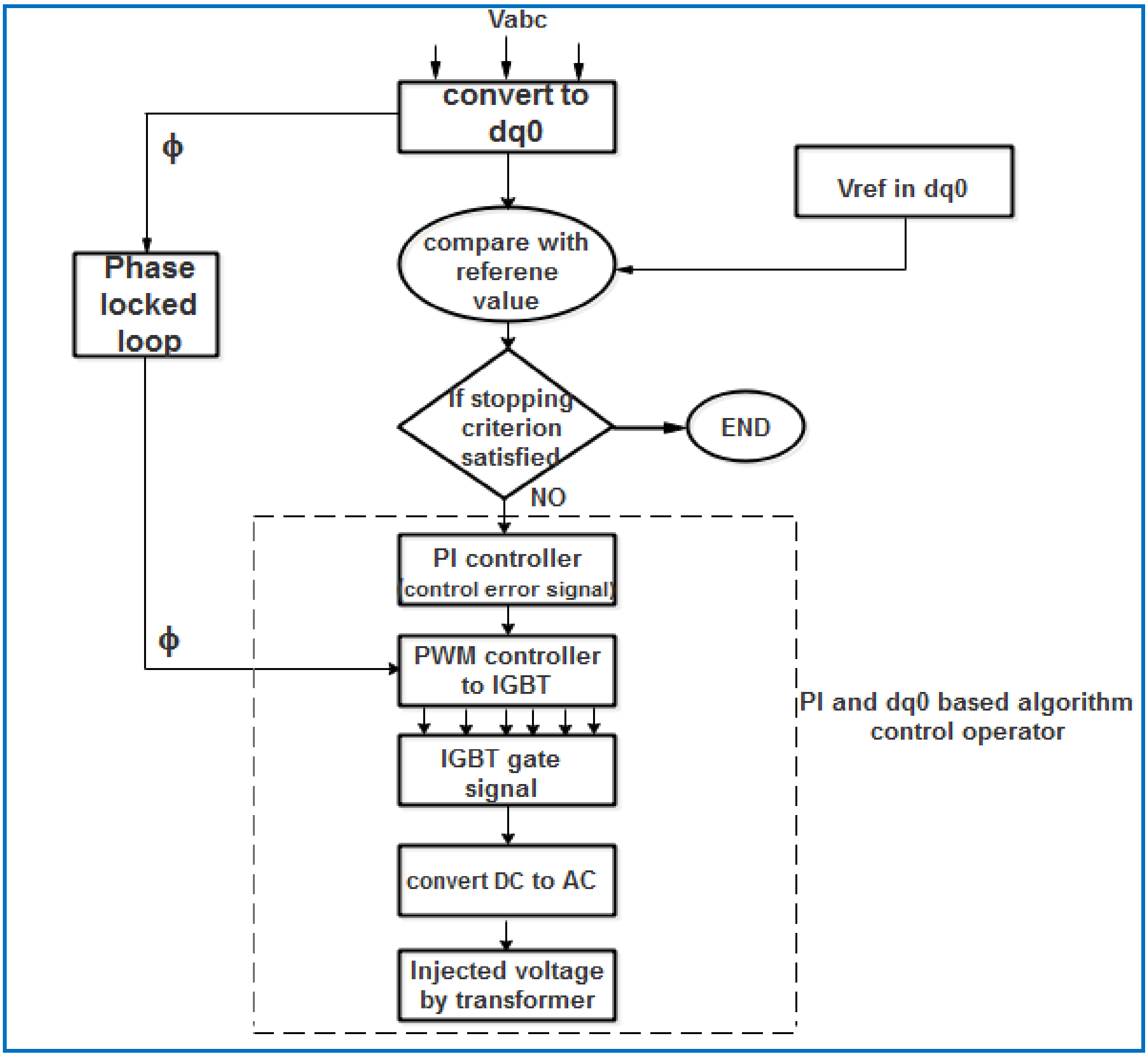


Figure 5.14: proposed Control algorithm of DVR with PI controller

5.6 The DVR Test System Parameters

The distribution system used for this study is 11 kV overhead distribution network is supplying energy to various distribution transformers of voltage rating 11 kV/ 400 V. The study network is radial secondary with distribution transformer of capacity 500 kVA, 0.4 kV residential distribution feeder is examined, the overall power demand is 360 kW at 0.9 pf at 80 % transformer rating. The electric poles are positioned at a length of 50 meters from one another. The network supply offices, residential buildings, and small business centres. It is assumed that the loads on each phase for balanced DN is 120 kW each and for unbalanced system the loads on each phase A, B, and C during the period of study is 150 kW, 110 kW and 80 kW, respectively. The test system is utilized to bring out the simulation in respect to the DVR actuation. The system is composed of 11 kV, 50 Hz distribution system, step down to 0.4 kV through a two winding transformer connected in Δ/Y 11/0.4 kV. The software simulation parameters for balanced and unbalanced distribution network is depicted in Table 5.1.

Table 5.1: System and DVR Software Simulation Parameter for Balanced and Unbalanced DNs

Parameter	Value
Distribution Transformer	11/0.4 kV, 500 kVA, Δ/Y grounded.
MV Feeder	Three Phase 11 kV radial, overhead line.
LV Feeder	3–phase 4-wire, 400 V, overhead all-aluminum conductors 100 mm^2
Balanced DN	Phase A, B and C Load are 120 kW each at 0.9 pf 80 % transformer rating.
Unbalanced DN	Red phase load is 150 kW, Blue phase load is 110 kW Yellow phase is 80 kW at 0.9 pf 80 % transformer rating.
Line impedance (Ω)	L = 1 mH, R= 0.01 Ω
Line frequency (Hz)	50
Load phase voltage (V)	220
DC supply Voltage (V)	400
Injection transformer turns ratio	1:1
PI controller	Sample time=50 µs, K_P=0.5, K_I=50
Inverter specification	Three arms IGBT based, six pulse, sample time 50 µs, carrier frequency 1080 Hz
Linear Transformer	5 kVA, 100/400 V
Filter inductance	7 mH
Filter capacitance	10µF

5.6.1 Single Line Diagram of DVR Test System

In this test system the generating unit is 11 kV, 50 Hz. The test system is used to perform the simulation about the DVR actuation. The output voltages from the load side are fed to the controller system. The power circuit generates the needed AC output voltage through the DC power system. The PI controller with the help of PMW generator is employed in the control section.

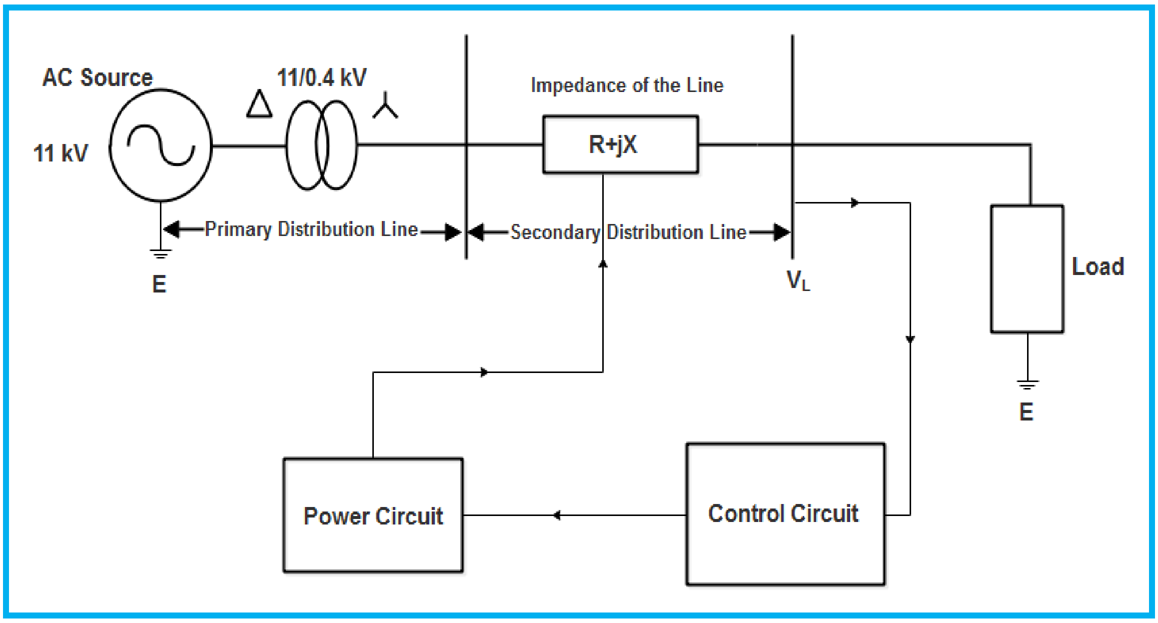


Figure 5.15: Proposed Block model of DVR Test System.

5.7 Simulink Model of the DVR Test System

In this Simulink model, the DVR is linked in series with DNs for successful compensation. The DVR system is joined to the DN through a series voltage injection transformer. The control system comprises of the dq0 frame Park’s transformation controller, the PI controller, the PWM generator and the PLL controller, they are used for the control purposes.

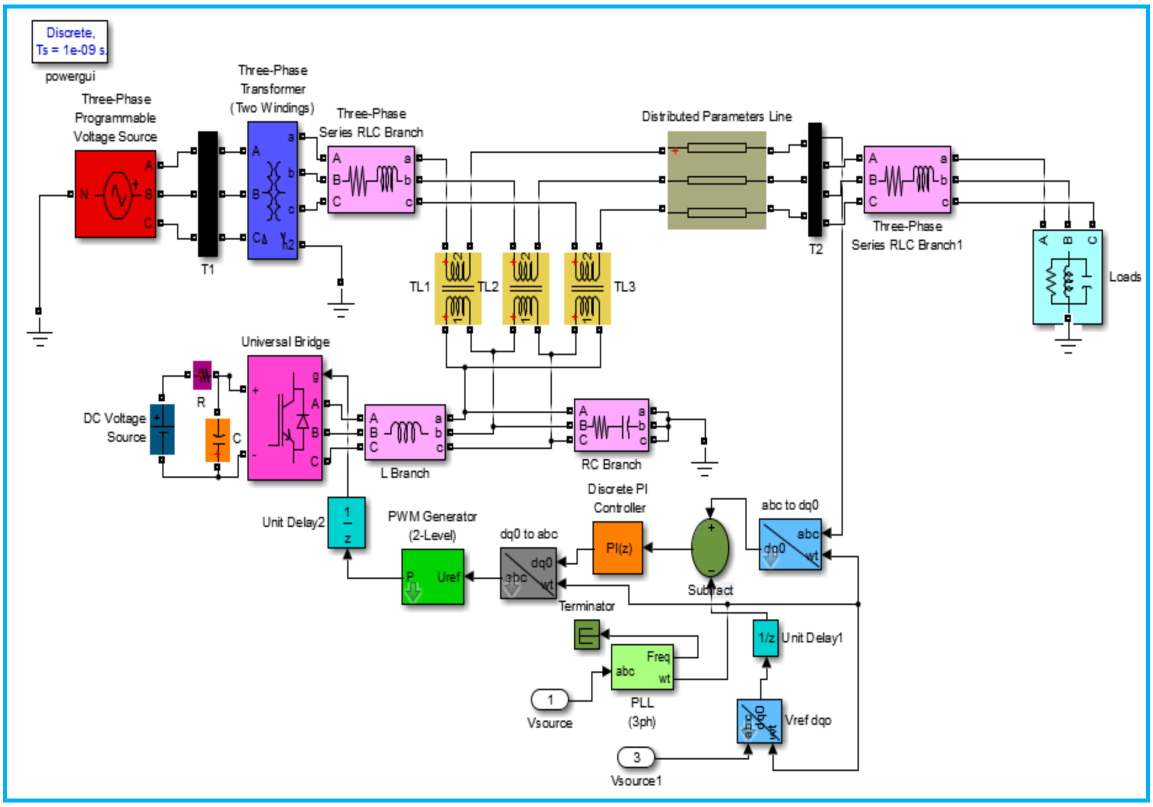


Figure 5.16: proposed MATLAB/Simulink model of the proposed DVR system

The amplitude of AC source voltages is calculated using equation (5.30).

$$V_S = \frac{2}{3}\left((V_{sa})^2 + (V_{sb})^2 + (V_{sc})^2\right)^{0.5} \tag{5.30}$$

The expected three-phase load voltage in the absence of disturbance or when the distribution line has been compensated using a DVR is given in Figure 5.17.

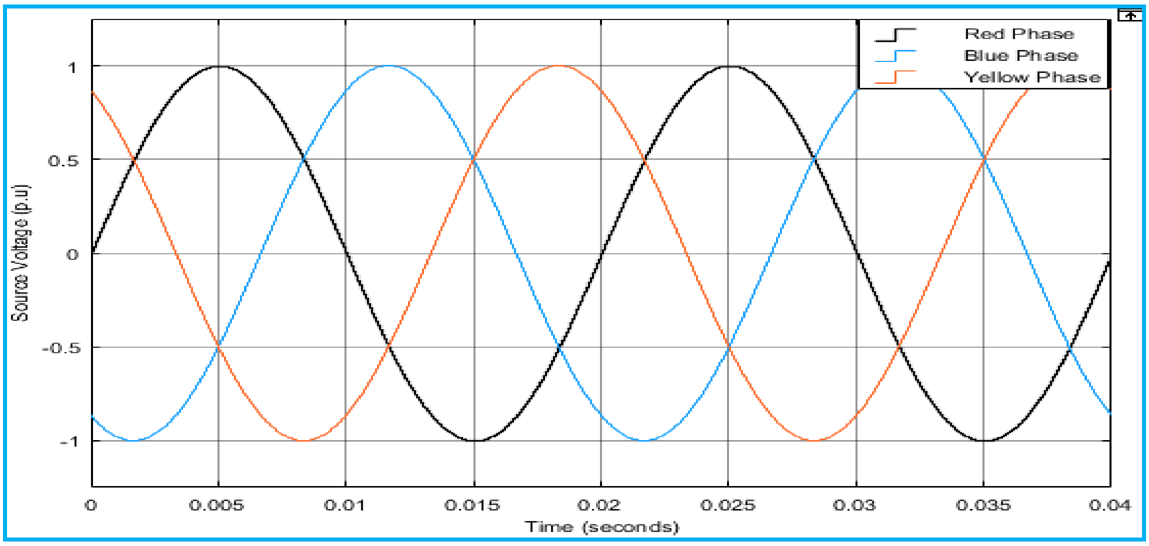


Figure 5.17: 3-phase voltage waveform in the absence of voltage disturbance

5.8 Results and Discussion

5.8.1 VV and Low VP Compensation for Balanced DN with DVR

The simulation results of the investigated system with low voltage profile, voltage variation and voltage fluctuation disturbances observed in the investigation which was carried out on the secondary distribution system in chapter three of this thesis. The results of load voltage profile, voltage drop and percentage voltage deviation in the absence of DVR system presented in Figures 3.14, 3.27 and 3.28 respectively show that the distribution network feeder is operating less than specified nominal value which is an unacceptable performance. Therefore, there is need for compensation for the optimum performance in terms of correct voltage profile, minimum voltage-drop and absence of phase voltage imbalances for all the distribution networks from 0.8 km to 5 km. The simulation results show eleven cases studied with *DVR* connected to secondary electric power distribution network are shown in Figures 5.18 to 5.28. Figure 5.29 shows the compensated load voltage profile curve for balanced distribution network and Table 5.2 shows the summary of the compensated load voltage profile readings recorded on balanced secondary electric power distribution network at steady state conditions. From the analysis of the results, it is obvious that the compensated per-unit load VP for EPDN feeder lengths of 0.5 km, 0.8 km, 1 km, 1.5 km, 2 km, 2.5 km, 3 km, 3.5 km, 4 km, 4.5 km and 5 km are: 1 p.u, 1 p.u, 1 p.u, 1 p.u, 1 p.u, 0.9999 p.u, 0.9999 p.u, 0.9998 p.u, 0.9998 p.u, 0.9997 p.u, and 0.9997 p.u respectively at the feeder end. All the voltages measured are within the standard statutory voltage limit of 0.99 p.u to 1.05 p.u of the specified nominal system voltage value, hence, it is admissible to all consumers load. Also, the voltage drop on the distribution network are within the standard acceptable minimum voltage drop of – 5% of the nominal voltage value and percentage voltage deviation are within the acceptable standard limit of ± 5 % of the rated voltage value as shown in Table 5.3 and Figure 5.30 respectively. This is made possible due to the effectiveness and efficiency of the DVR to supply the appropriate required voltage in series to the balanced 3-phase neutral connected electric distribution network feeder without any delay during disturbances on the network.

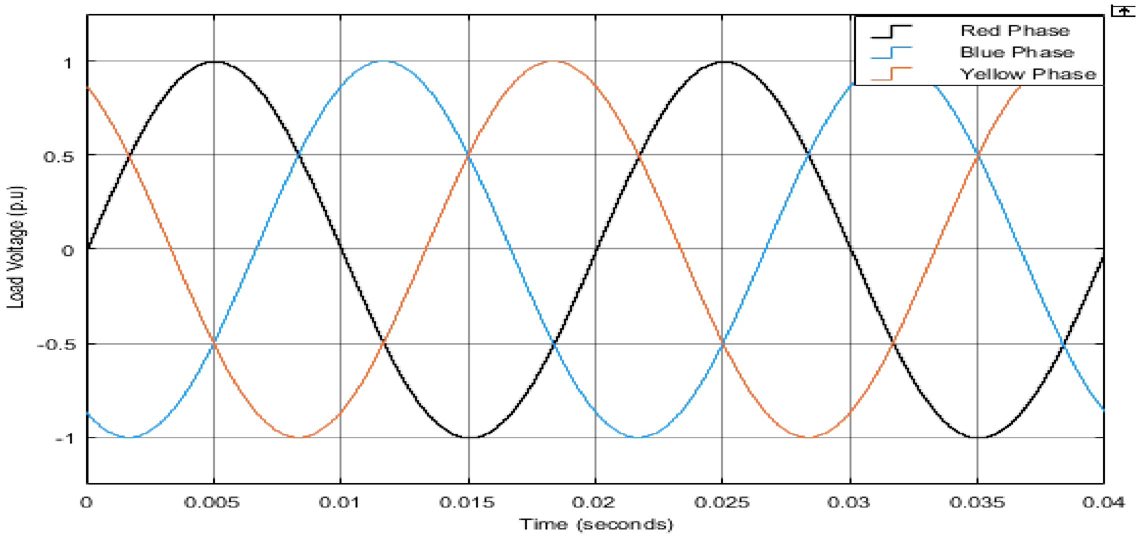


Figure 5.18: Per-unit load VP at 0.5 km of compensated balanced DN

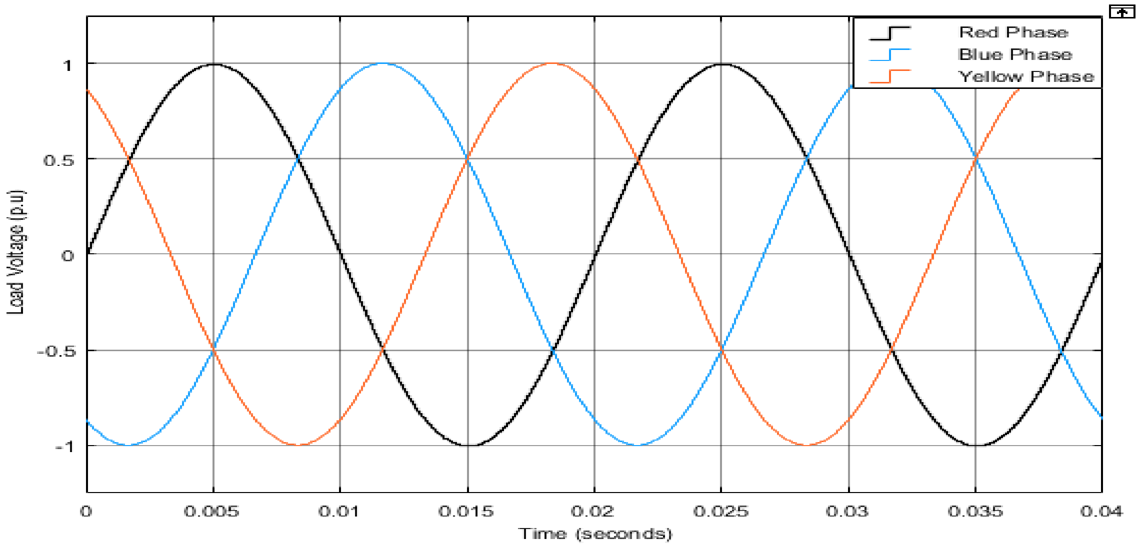


Figure 5.19: Per-unit load VP at 0.8 km of compensated balanced DN

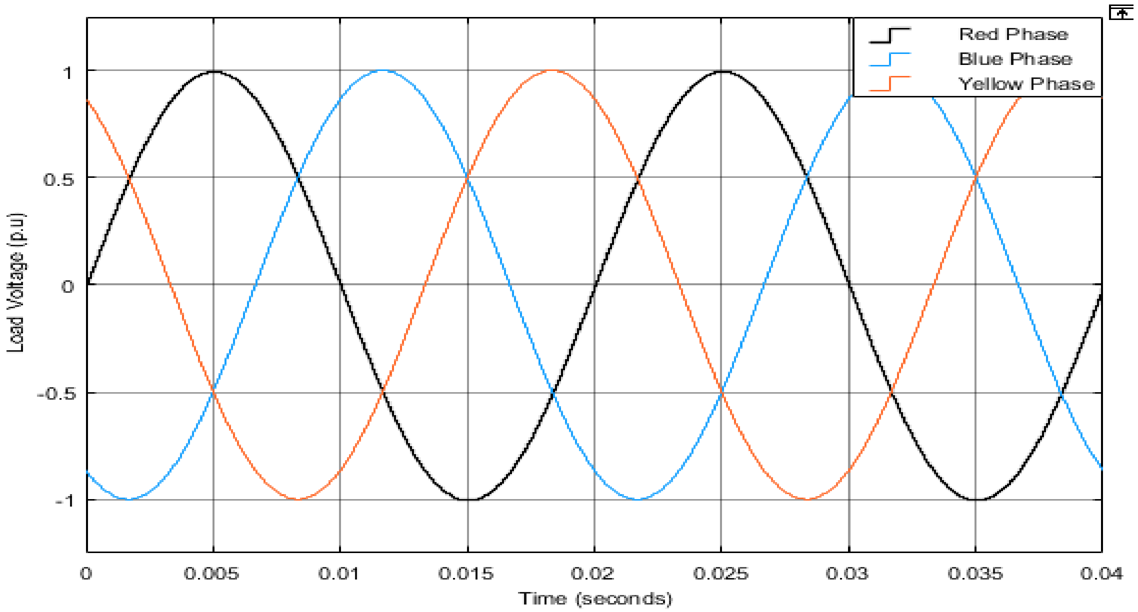


Figure 5.20: Per-unit load VP at 1 km of compensated balanced DN

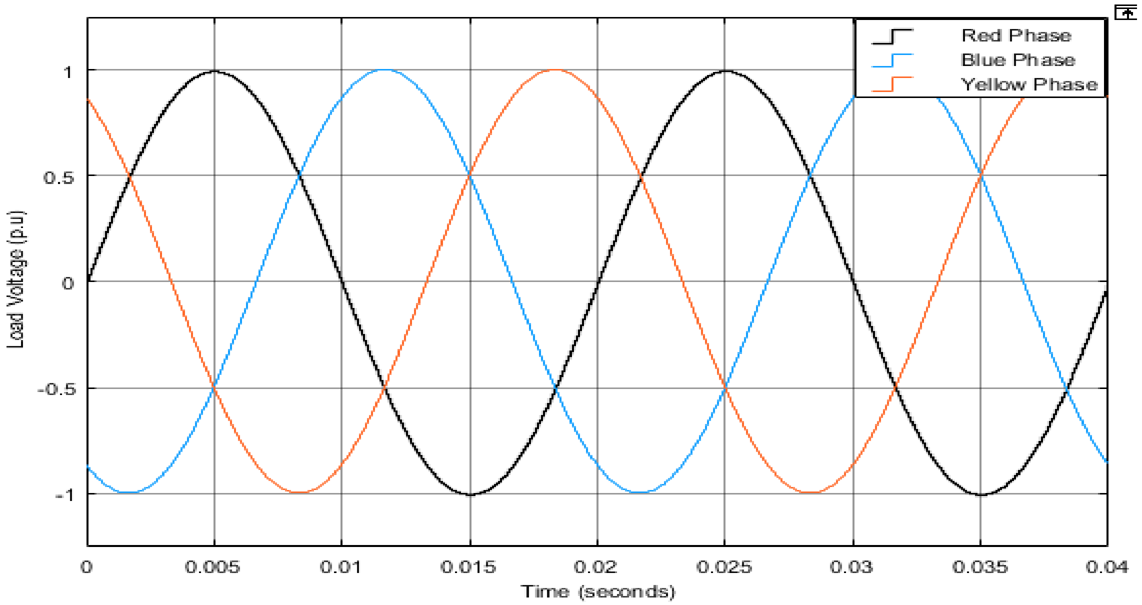


Figure 5.21: Per-unit load VP at 1.5 km for compensated balanced DN

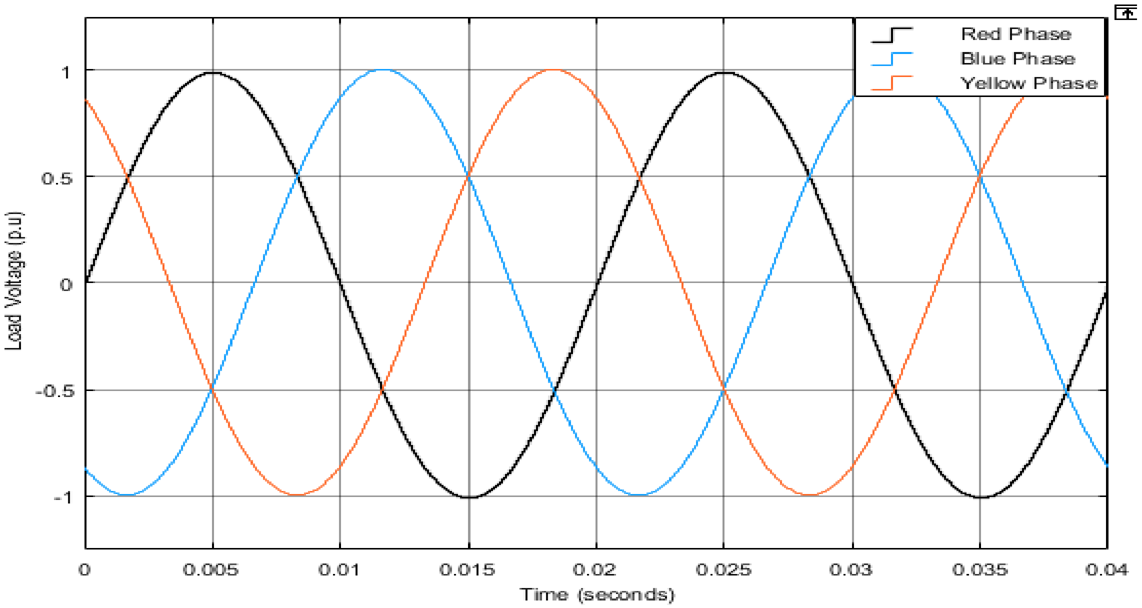


Figure 5.22: Per-unit load VP at 2 km for compensated balanced DN

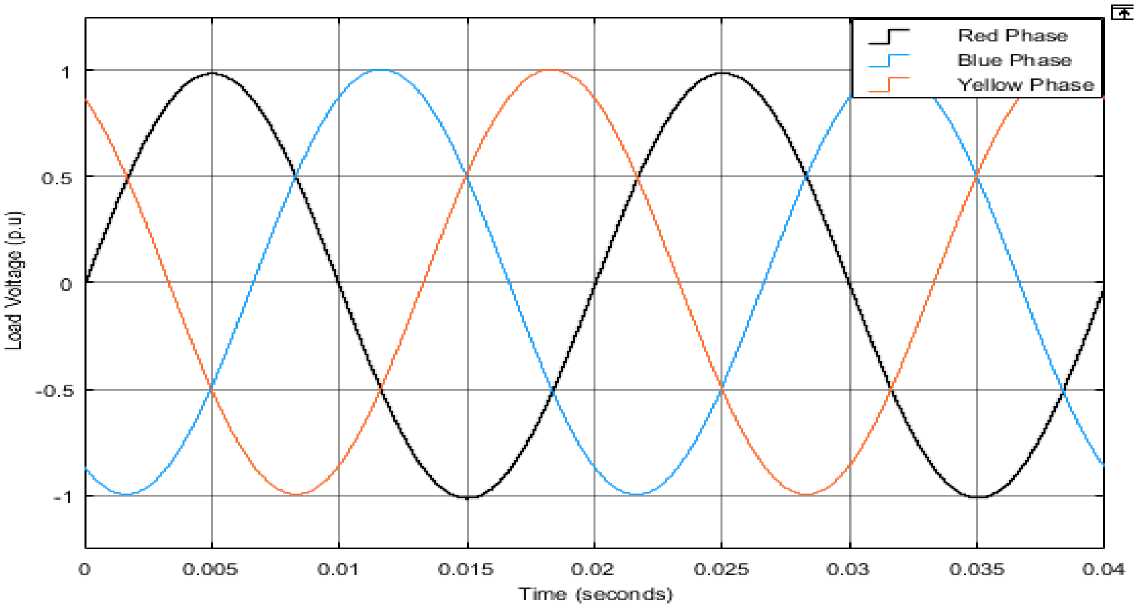


Figure 5.23: Per-unit load VP at 2.5 km for compensated balanced DN

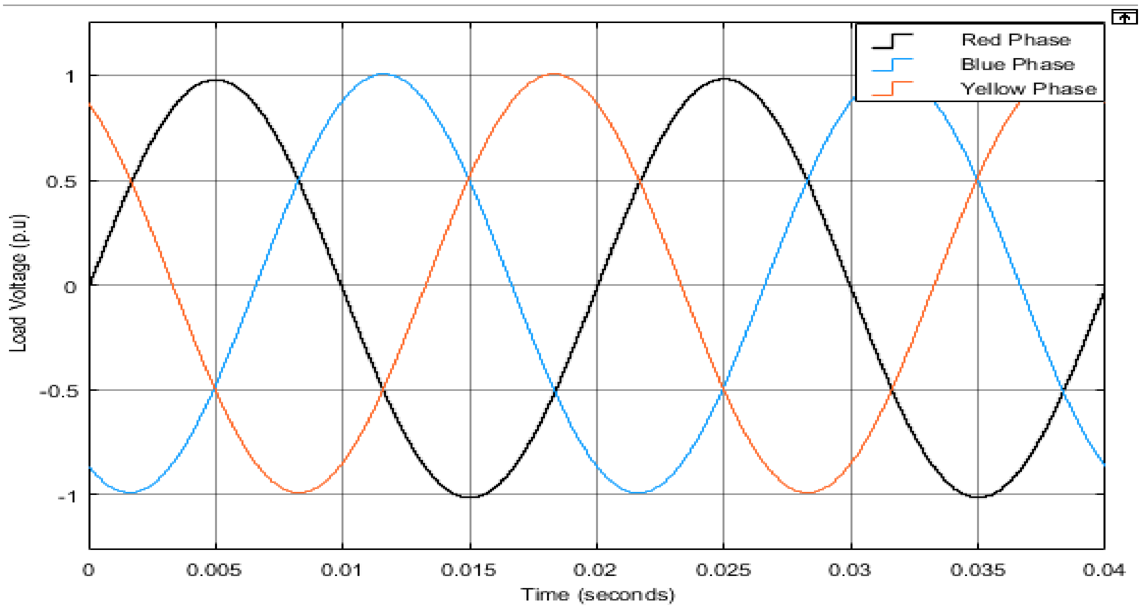


Figure 5.24: Per-unit load VP at 3 km of compensated balanced DN

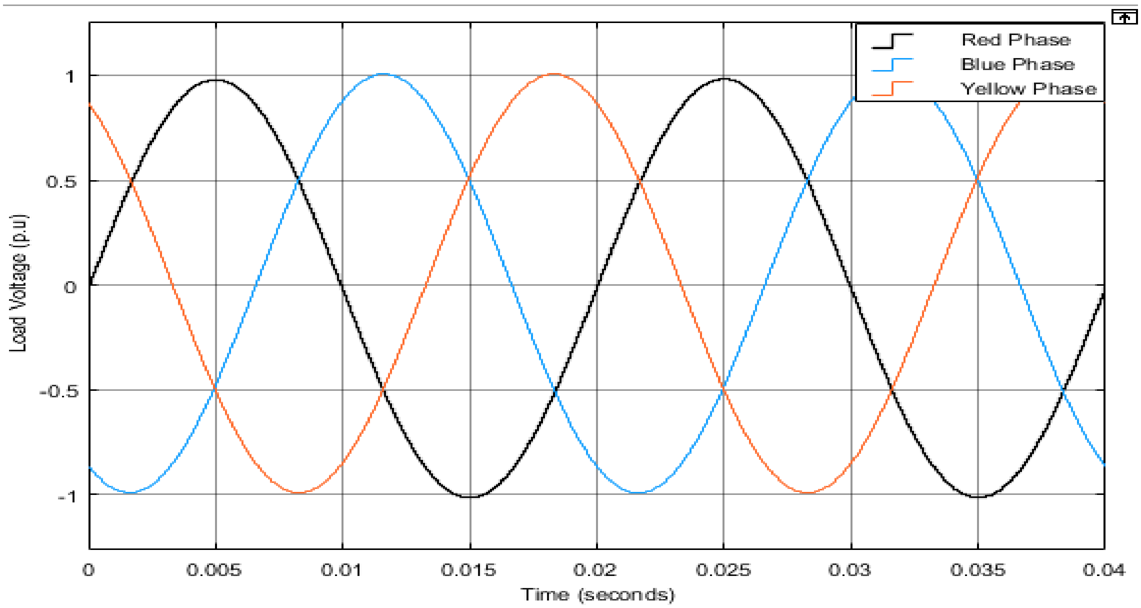


Figure 5.25: Per-unit load VP at 3.5 km of compensated balanced DN

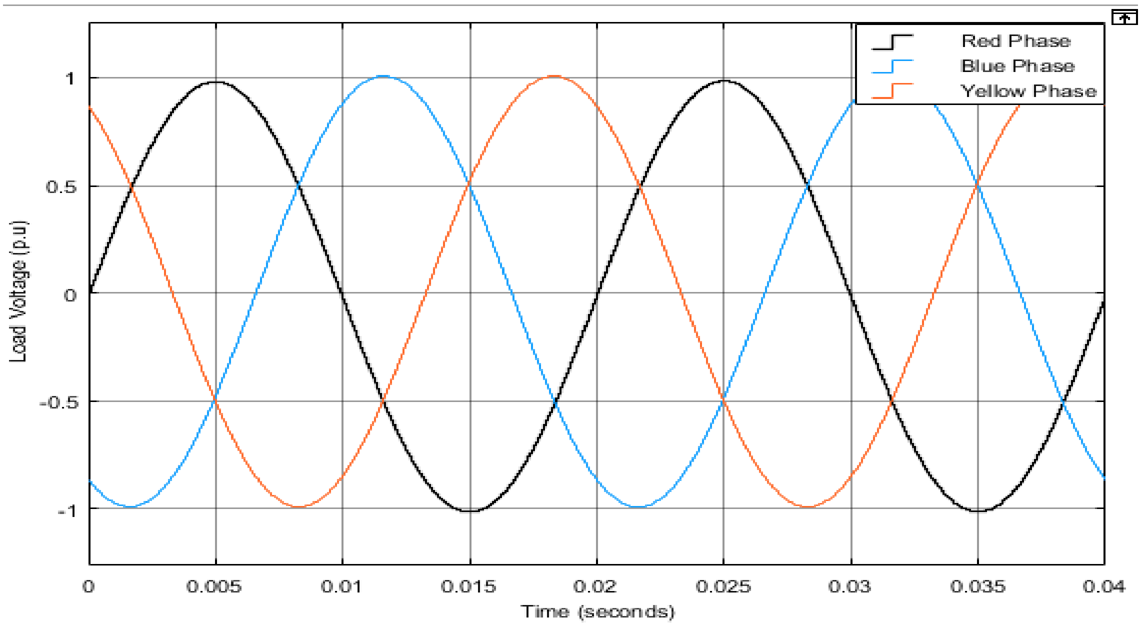


Figure 5.26: Per-unit load VP at 4 km of compensated balanced DN

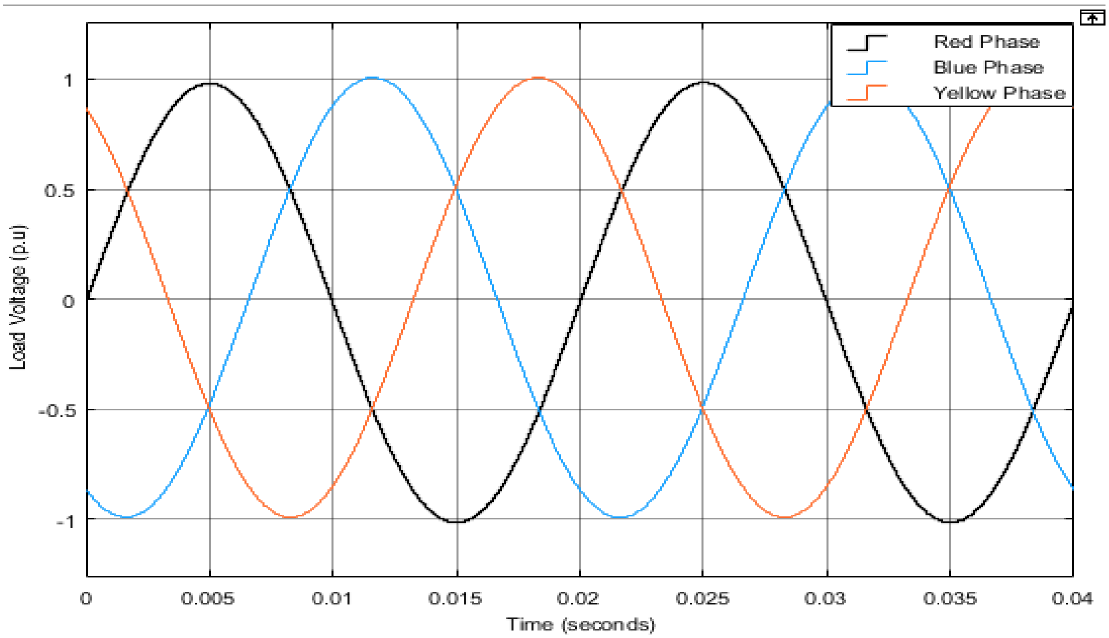


Figure 5.27: Per-unit load VP at 4.5 km of compensated balanced DN

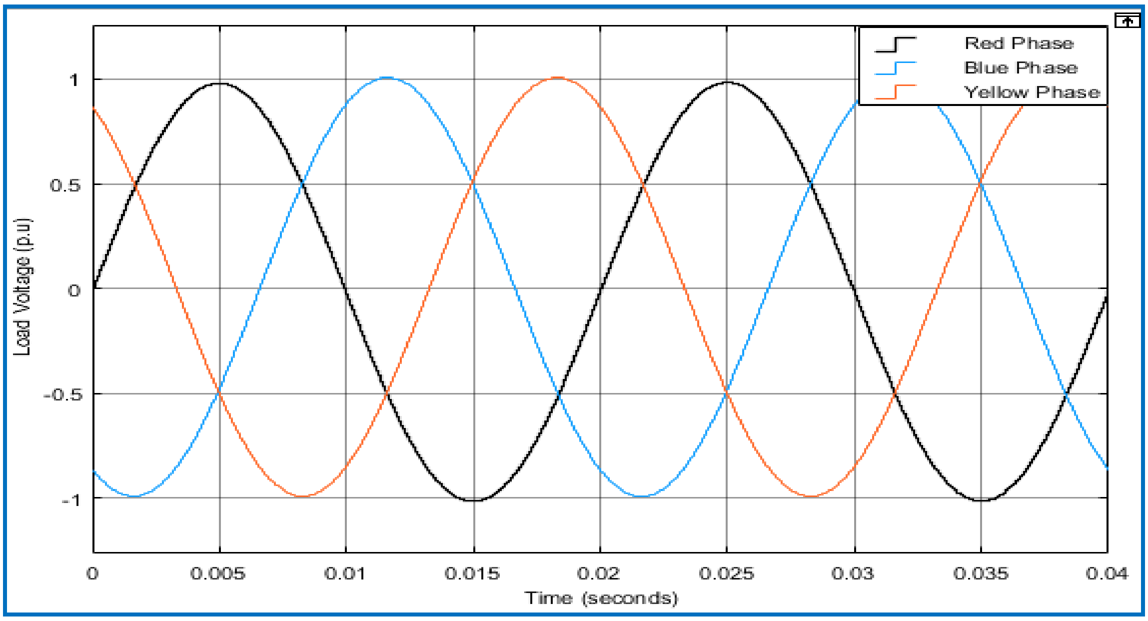


Figure 5.28: Per-unit load VP at 5 km of compensated balanced DN

Table 5.2: Per-Unit Measurement of VP of Compensated Balanced DN

Network length, (km)	Load voltage profile(p.u)
0.5	1.0
0.8	1.0
1.0	1.0
1.5	1.0
2.0	1.0
2.5	0.9998
3.0	0.9998
3.5	0.9997
4.0	0.9997
4.5	0.9996
5.0	0.9996

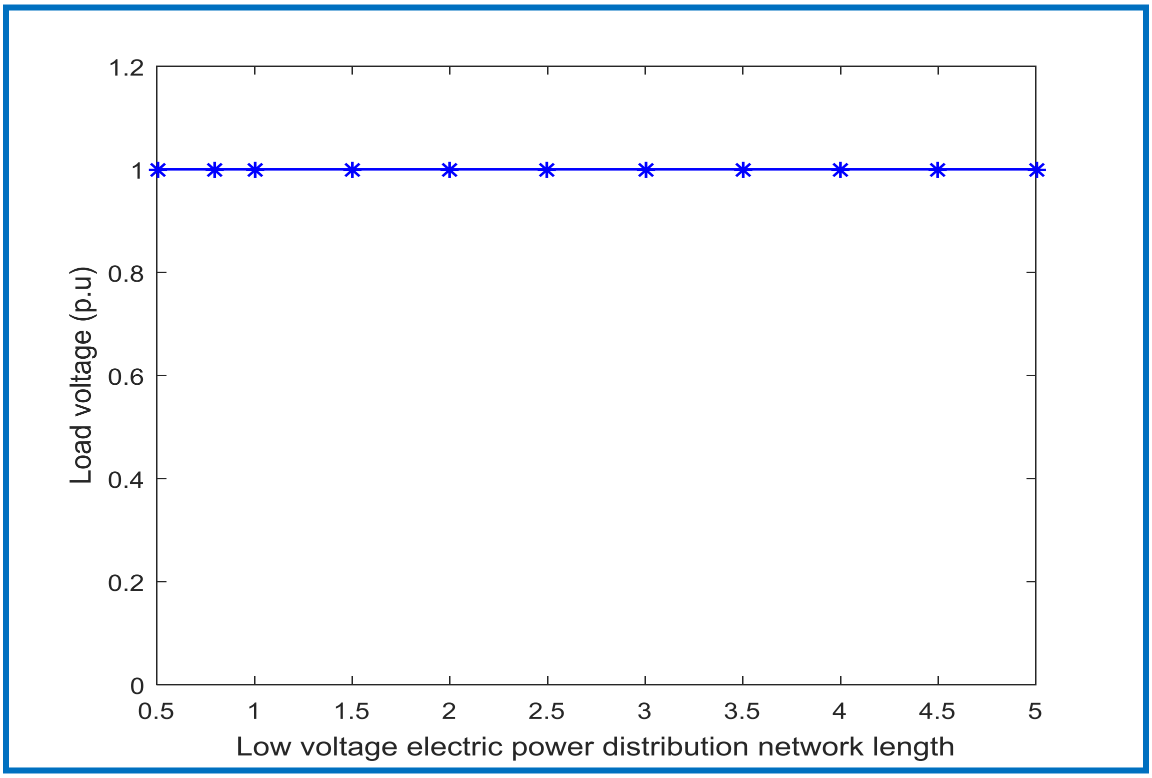


Figure 5.29: Curve of per-unit load VP of compensated balanced DN

Table 5.3: **Computation of VD (ΔUdev), PVD (Δudev, %) and VDr (Δu) For Compensated Balanced DN**

L, (km)	Vs (p.u)	VL phase A, B & C(p.u)	ΔUdev, (p.u)	ΔUdeV, %	ΔU, (V)	Load Voltage (V), Phase A, B & C	ΔUstd. min and max %
0.5	1.0	1	0	0	0	220	± 5 %
0.8	1.0	1	0	0	0	220	± 5 %
1	1.0	1	0	0	0	220	± 5 %
1.5	1.0	1	0	0	0	220	± 5 %
2	1.0	1	0	0	0	220	± 5 %
2.5	1.0	0.9998	0.0002	0.02	0.044	219.96	± 5 %
3	1.0	0.9998	0.0002	0.02	0.044	219.96	± 5 %
3.5	1.0	0.9997	0.0003	0.03	0.066	219.93	± 5 %
4	1.0	0.9997	0.0003	0.03	0.066	219.93	± 5 %
4.5	1.0	0.9996	0.0004	0.04	0.088	219.91	± 5 %
5	1.0	0.9996	0.0004	0.04	0.088	219.91	± 5 %

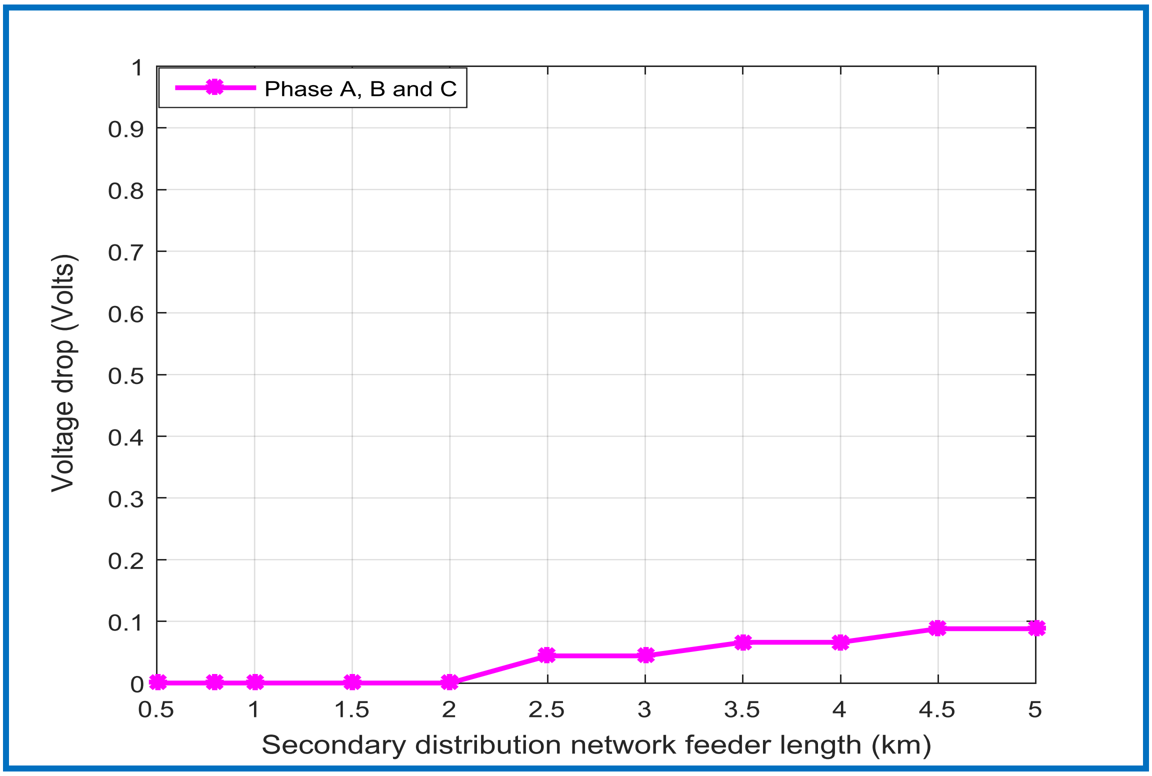


Figure 5.30: Curve of voltage drop of compensated balanced DN

Figures 5.31a shows the combined uncompensated and compensated balanced voltage profile of secondary distribution networks**.**

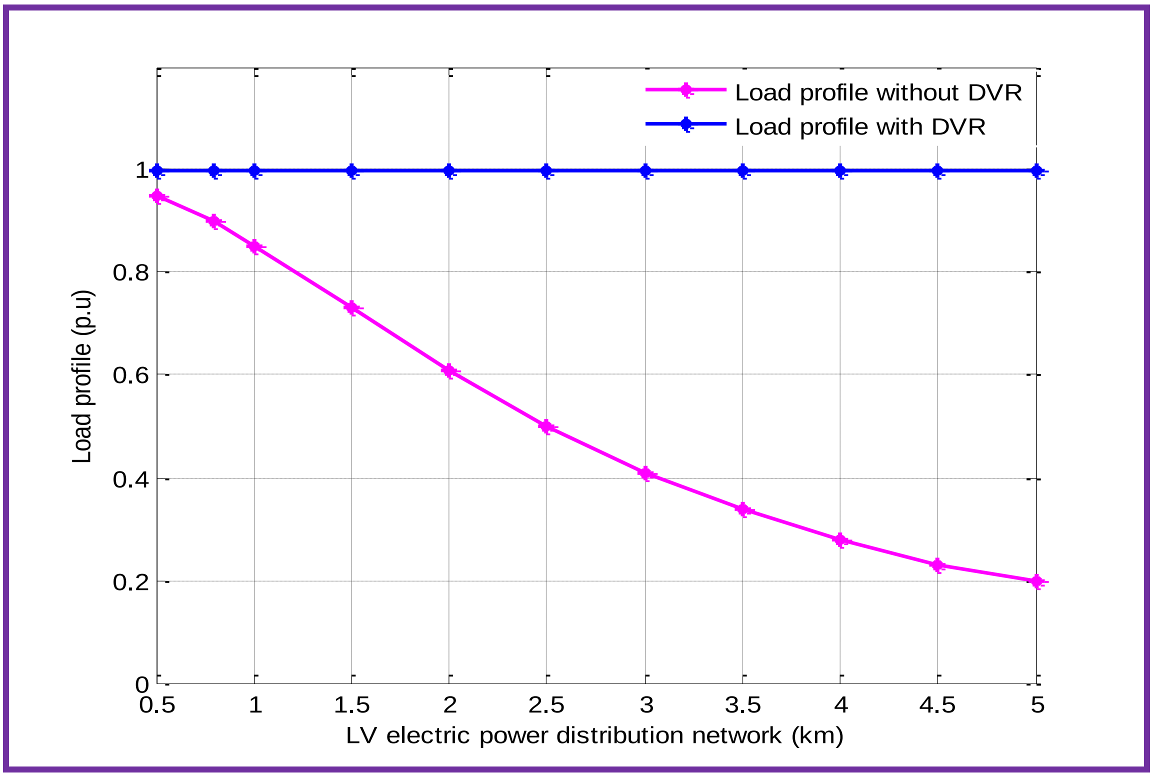


Figure 5.31a Curve of combined per-unit load VP of uncompensated and compensated balanced DN

Figure 5.31b shows the combined uncompensated and compensated balanced voltage drop of the secondary distribution network**.** This shows the effective performance of DVR in enhancing voltage profiles, mitigating voltage variation and fluctuation, reducing voltage drop and improving the power quality to the end users in the secondary distribution system within the statutory limits.

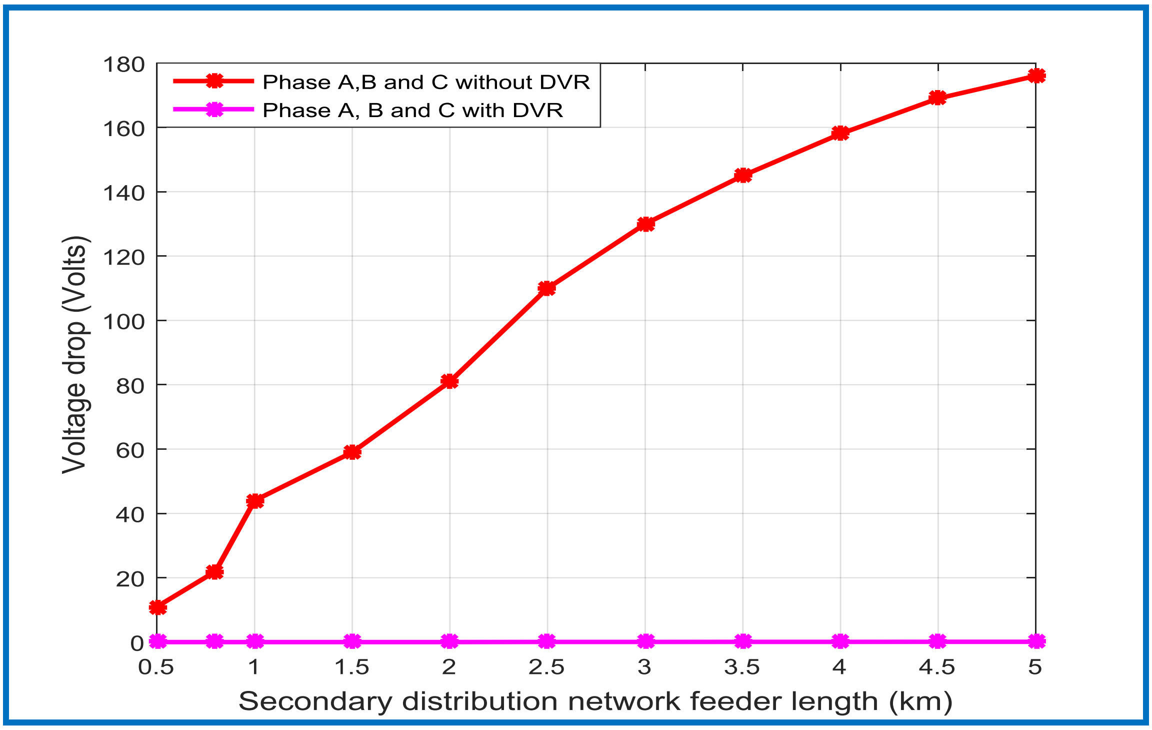


Figure 5.31b Curve of combined VDr of uncompensated and compensated balanced DN

5.8.2 UV Correction and Low VP Enhancement with DVR in Unbalanced Secondary DN.

The simulation results of the suggested system with voltage unbalance, low voltage profile, and voltage fluctuation disturbances observed in an unbalanced investigation which was carried out on the secondary distribution system in chapter three of this thesis are presented. The results of load voltage profile, percentage voltage deviation, voltage drop and percentage voltage unbalance in the absence of compensation device (DVR system) shown in Figures 3.26, 3.29-3.31, 3.32 and 3.33 respectively, show that the distribution network is operating less than specified standard rated value. Therefore, there is a need for compensation of the distribution network for optimum performance in terms of correct voltage profile, minimum voltage drop, smooth voltage curve wave-form and absence of phase voltage imbalances for the entire distribution feeder from 0.8 km to 5 km.

The simulation results show eleven cases studied with compensating device (*DVR)* connected to secondary electric power distribution network as shown in Figures 5.32 to 5.42. Figure 5.43 shows the compensated load voltage profile curve for unbalanced distribution network and Table 5.4 shows the summary of the compensated load voltage profile readings recorded in unbalanced secondary electric power distribution network feeder at steady state conditions. From the analysis of the results, it is shown that the compensated per-unit load VP for unbalanced EPDN feeder lengths of 0.5 km, 0.8 km, 1 km, 1.5 km, 2 km, 2.5 km, 3 km, 3.5 km, 4 km, 4.5 km and 5 km are: 1 p.u, 1 p.u, 1 p.u, 1 p.u, 1 p.u, 0.9999 p.u, 0.9999 p.u, 0.9998 p.u, 0.9998 p.u, 0.9997 p.u, and 0.9997 p.u respectively at the feeder end. All the voltages measured are within the standard statutory voltage limit of 0.95 p.u to 1.05 p.u of the nominal voltage value; hence, it is admissible to all consumers load.

In addition, the percentage voltage unbalance is all less than 2 %, which is the standard permissible voltage unbalance in distribution network. The voltage drop on the distribution network within the acceptable minimum voltage drop of – 5 % of the nominal system voltage and percentage voltage deviation are all within the standard permissible range of ± 5%, of the nominal system voltage value. These are show in Tables 5.5, 5.6, and Figures 5.44 and 5.45 respectively. The optimum performance of the secondary distribution network under investigation was achieved with the use of an effective, a fast responsive, dynamic, efficient and cost effective compensating device (DVR) which injected an appropriate needed voltage in series to the unbalanced distribution system feeder without delay in the event of disturbances.

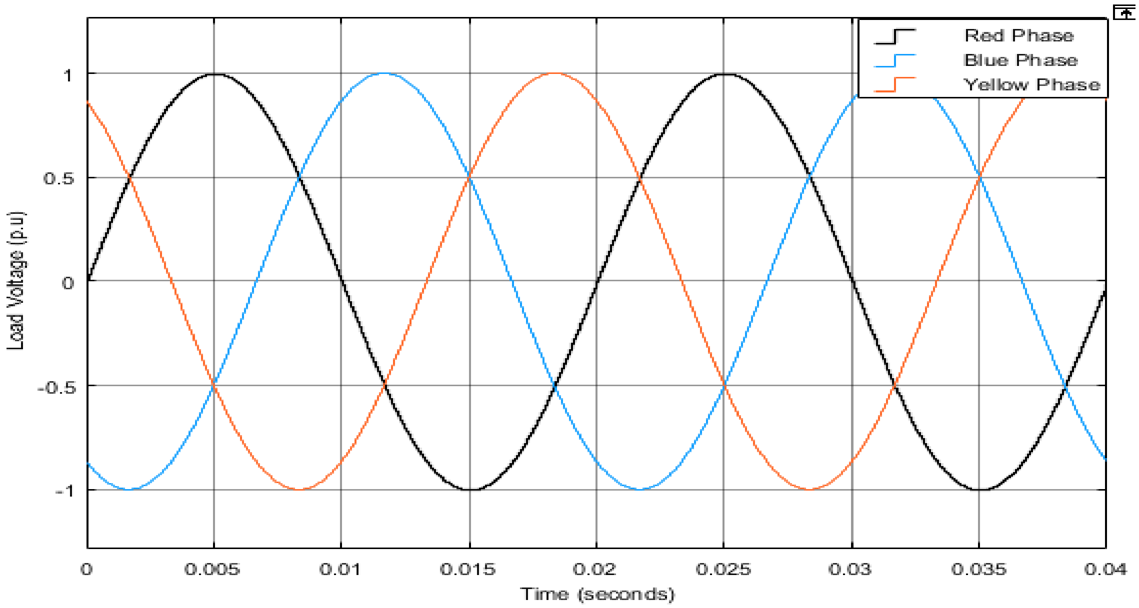


Figure 5.32: Per-unit load VP at 0.5 km of compensated unbalanced DN

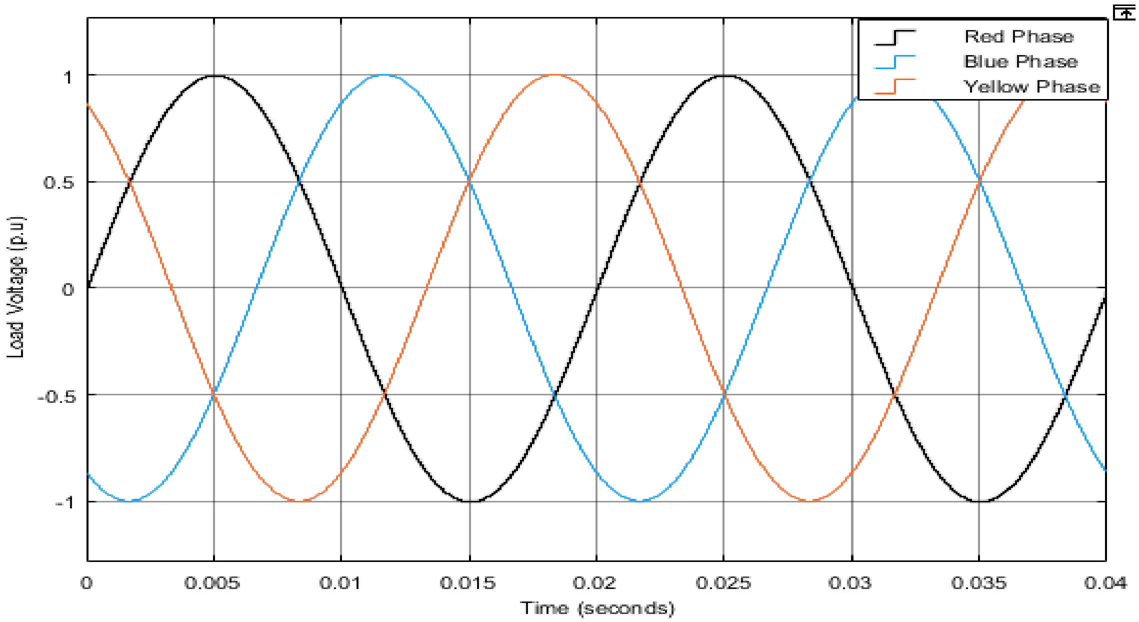


Figure 5.33: Per-unit load VP at 0.8 km of compensated unbalanced DN

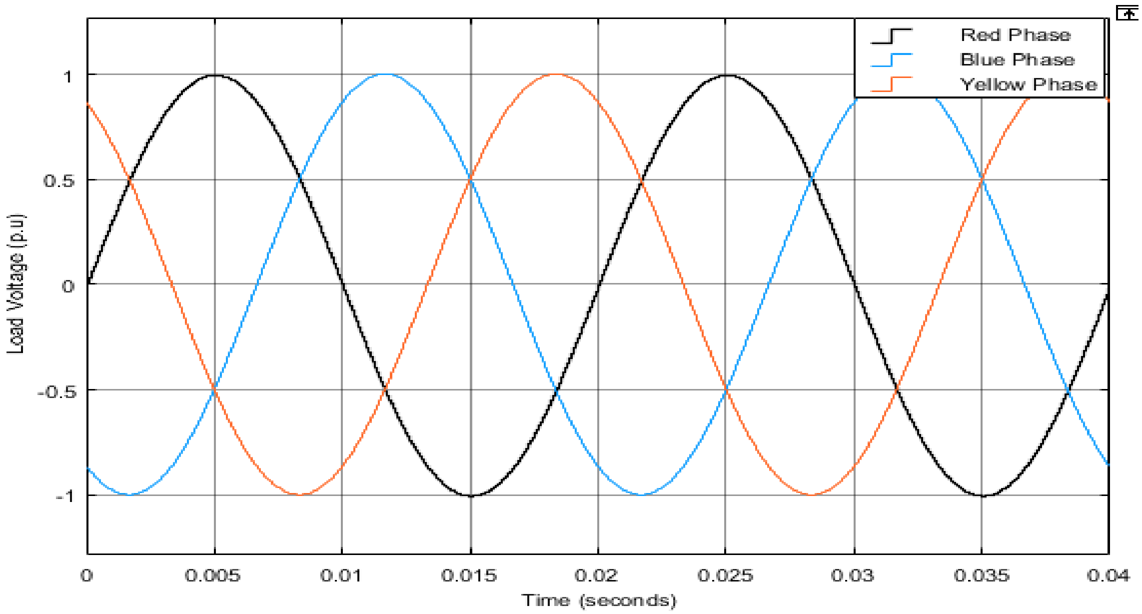


Figure 5.34: Per-unit load VP at 1 km of compensated unbalanced DN

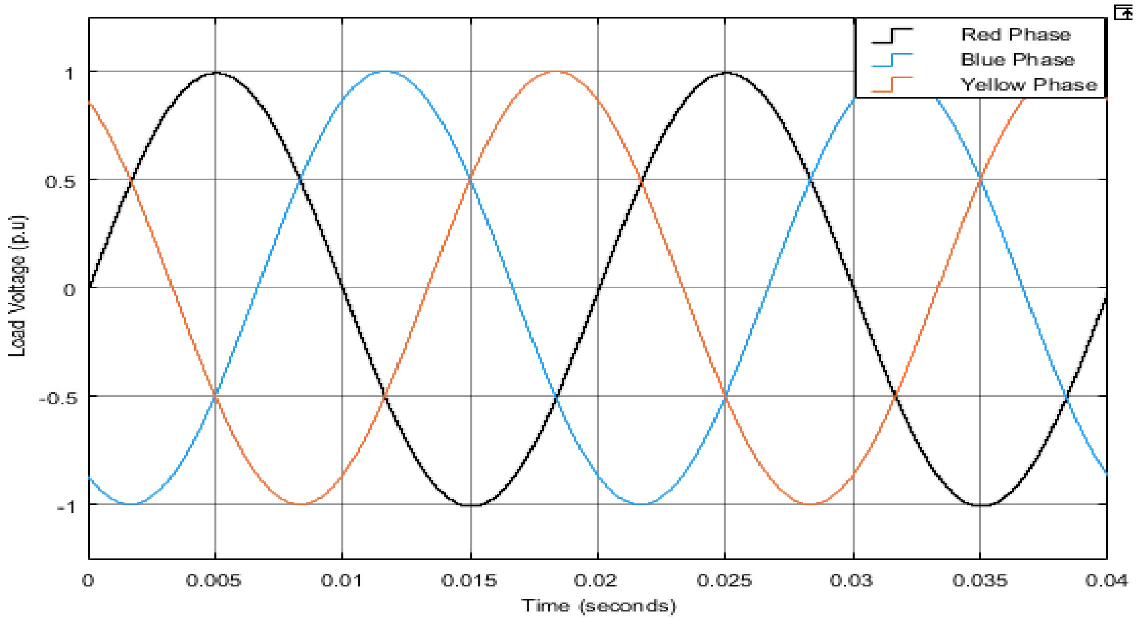


Figure 5.35: Per-unit load VP at 1.5 km of compensated unbalanced DN

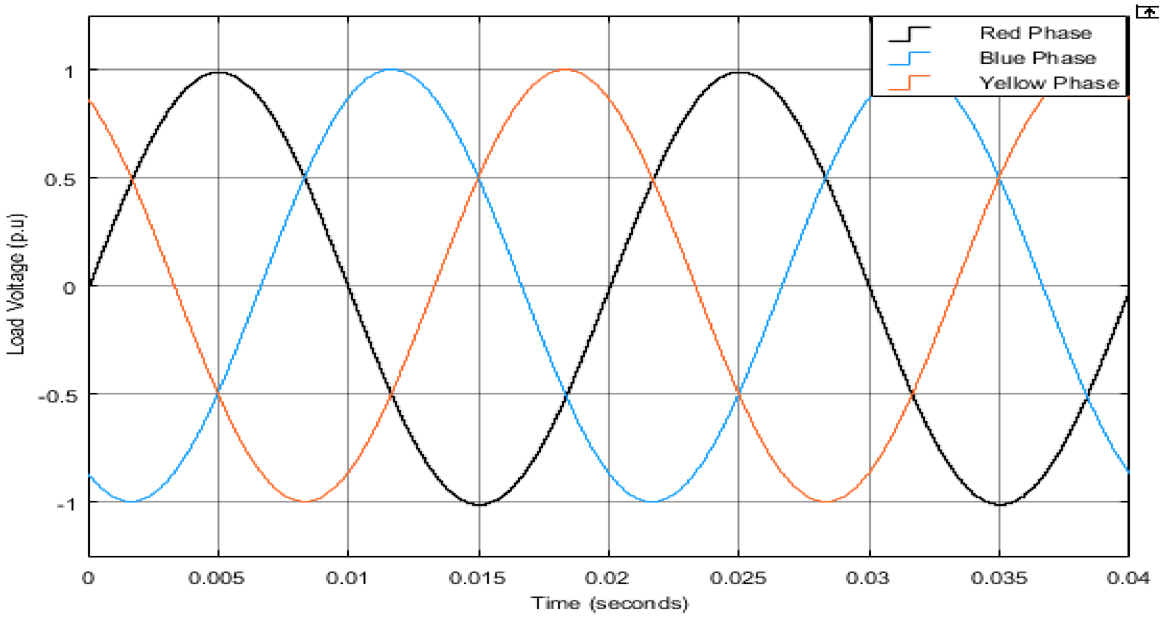


Figure 5.36: Per-unit load VP at 2 km of compensated unbalanced DN

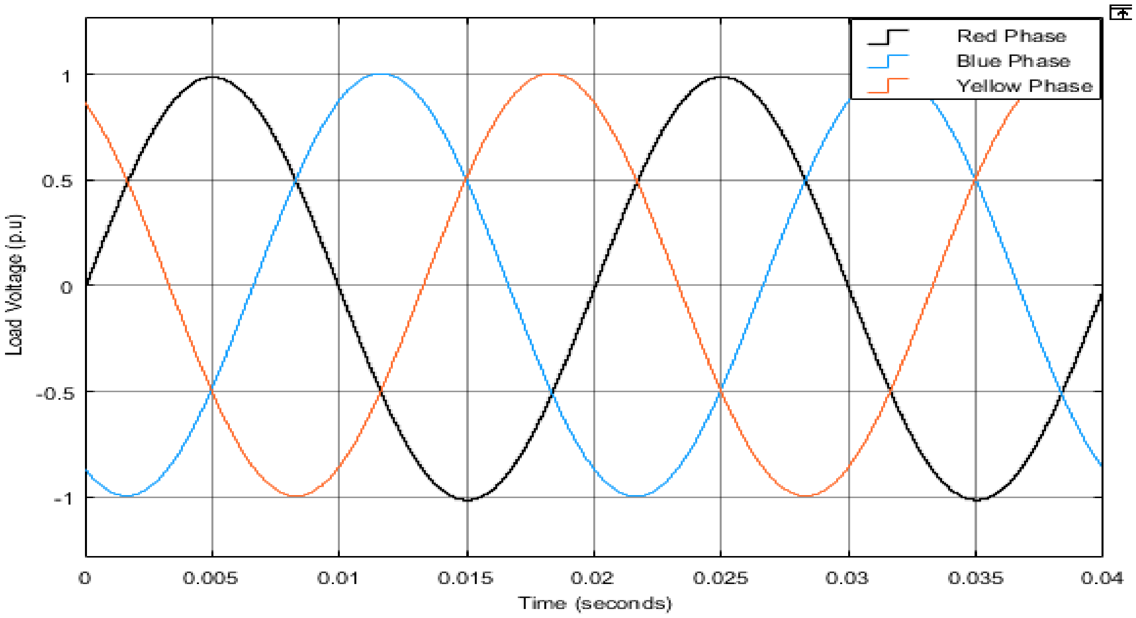


Figure 5.37: Per-unit load VP at 2.5 km of compensated unbalanced DN

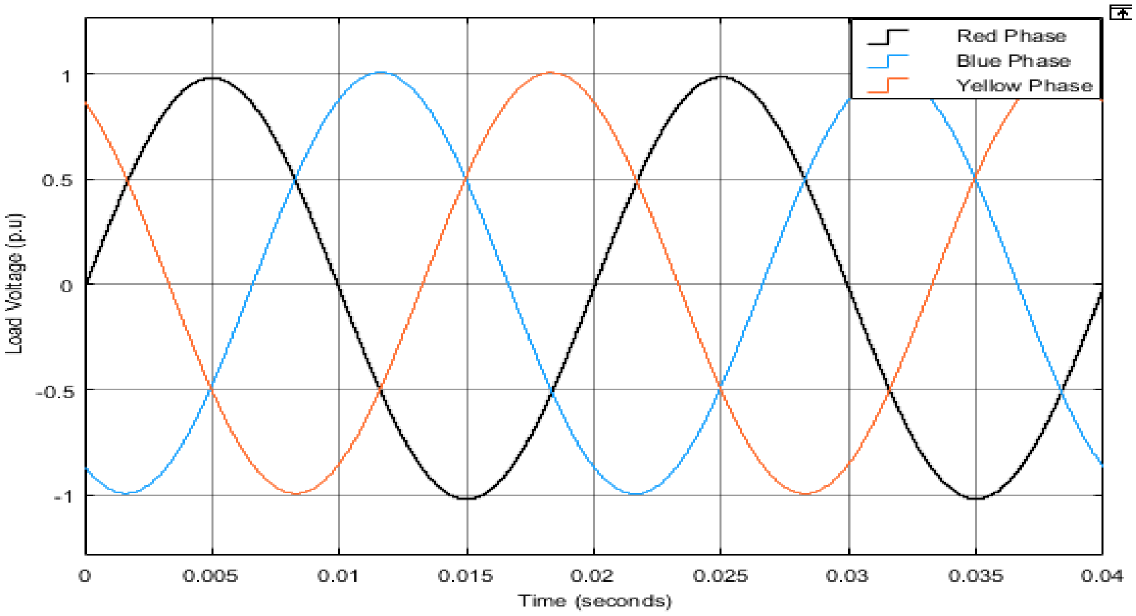


Figure 5.38: Per-unit load VP at 3 km of compensated unbalanced DN

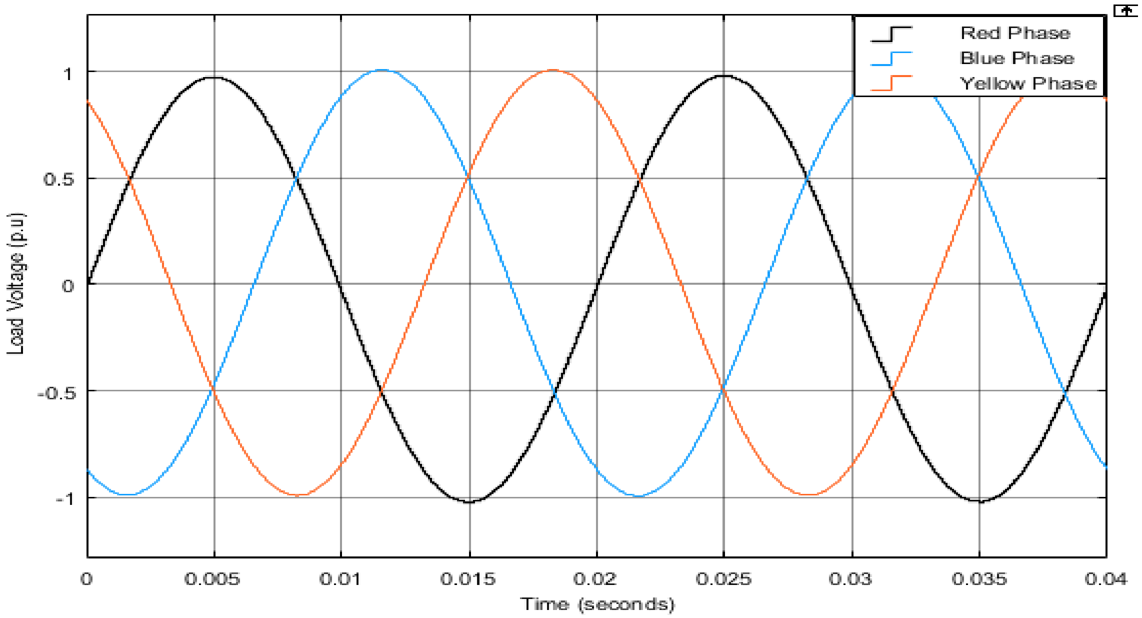


Figure 5.39: Per-unit load VP at 3.5 km of compensated unbalanced DN

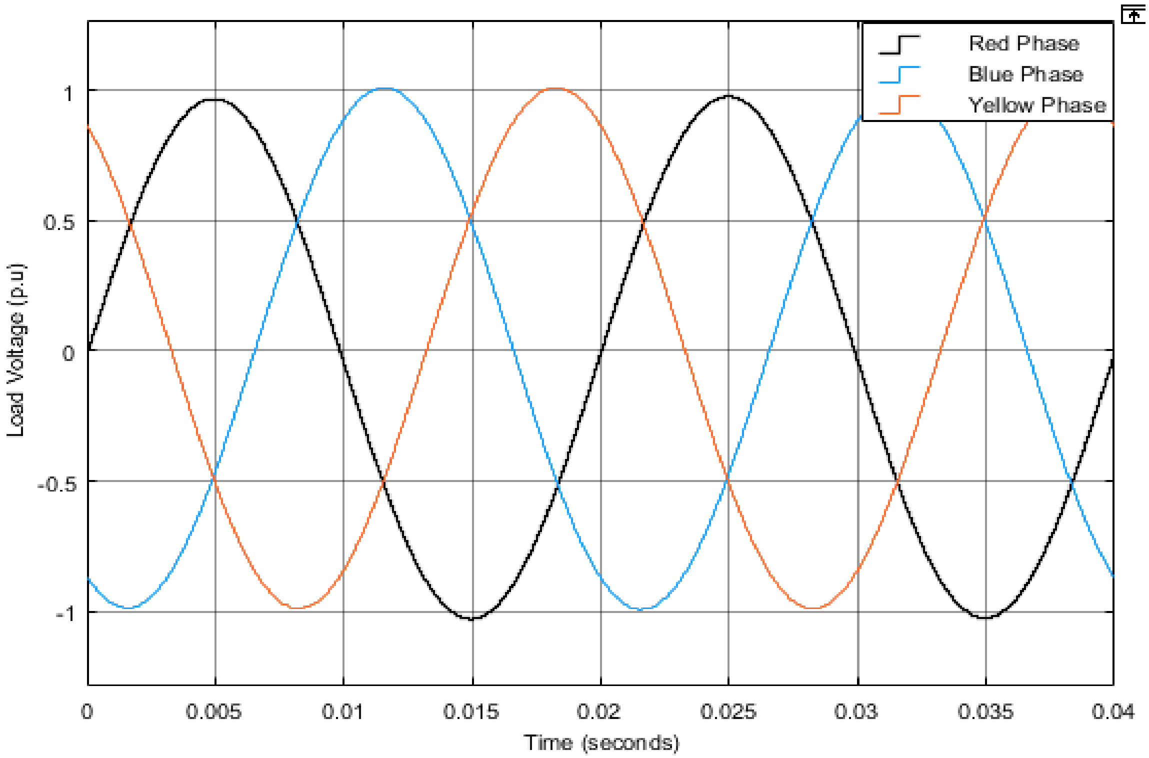


Figure 5.40: Per-unit load VP at 4 km of compensated unbalanced DN

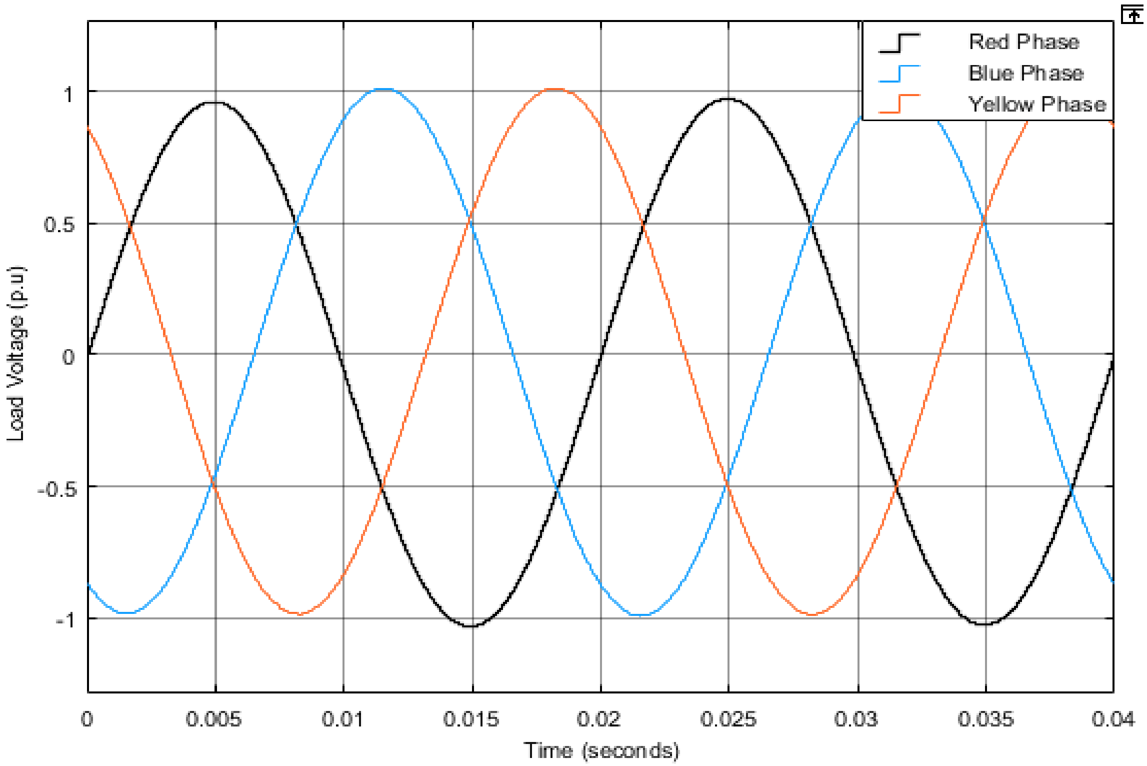


Figure 5.41: Per-unit load VP at 4.5 km of compensated unbalanced DN

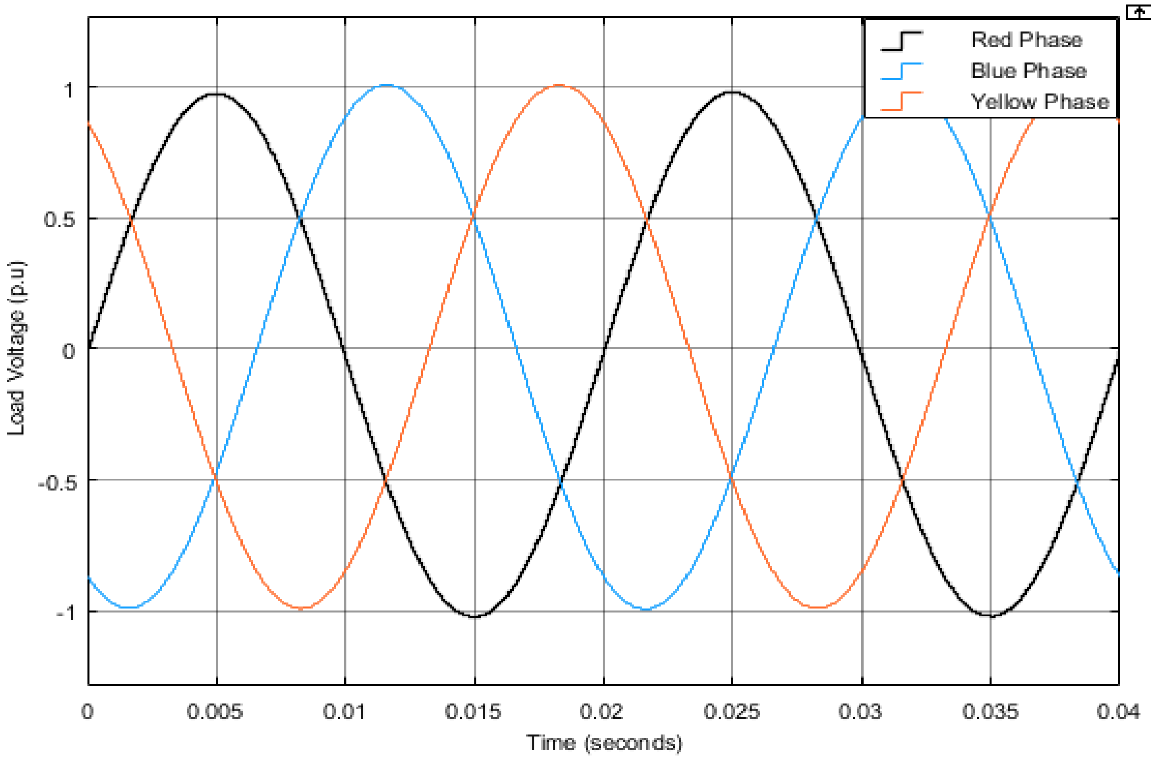


Figure 5.42: Per-unit load VP at 5 km of compensated unbalanced DN

Table 5.4: Per-Unit Measurement of VP for Compensated Unbalanced DN

L, (km)	VP Phase A (p.u)	VP, Phase B (p.u)	VP, Phase C (p.u)
0.5	1	1	1
0.8	1	1	1
1.0	1	1	1
1.5	1	1	1
2.0	1	1	1
2.5	0.9998	0.9998	0.9998
3.0	0.9998	0.9998	0.9998
3.5	0.9997	0.9997	0.9997
4.0	0.9997	0.9997	0.9997
4.5	0.9996	0.9996	0.9996
5.0	0.9996	0.9996	0.9996

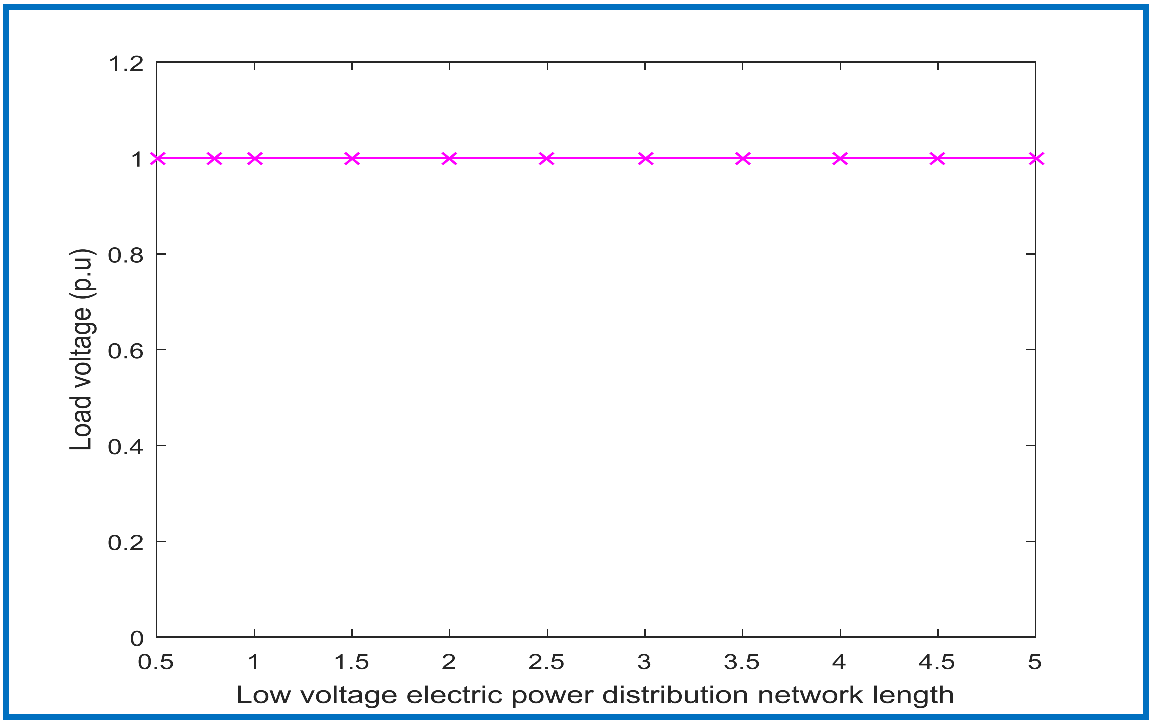


Figure 5.43: Curve of per-unit load VP of compensated unbalanced DN

Table 5.5: Computation of PVU of Compensated Unbalanced DN

L, (km)	VP, Phase A (p.u)	VP, Phase B (p.u)	VP, Phase C (p.u)	Ave (A, B % C (p.u)	P_{VUM}, %
0.5	1	1	1	1	0
0.8	1	1	1	1	0
1.0	1	1	1	1	0
1.5	1	1	1	1	0
2.0	1	1	1	1	0
2.5	0.9998	0.9998	0.9998	0.9998	0
3.0	0.9998	0.9998	0.9998	0.9998	0
3.5	0.9997	0.9997	0.9997	0.9997	1.67E-14
4.0	0.9997	0.9997	0.9997	0.9997	1.67E-14
4.5	0.9996	0.9996	0.9996	0.9996	0
5.0	0.9996	0.9996	0.9996	0.9996	0

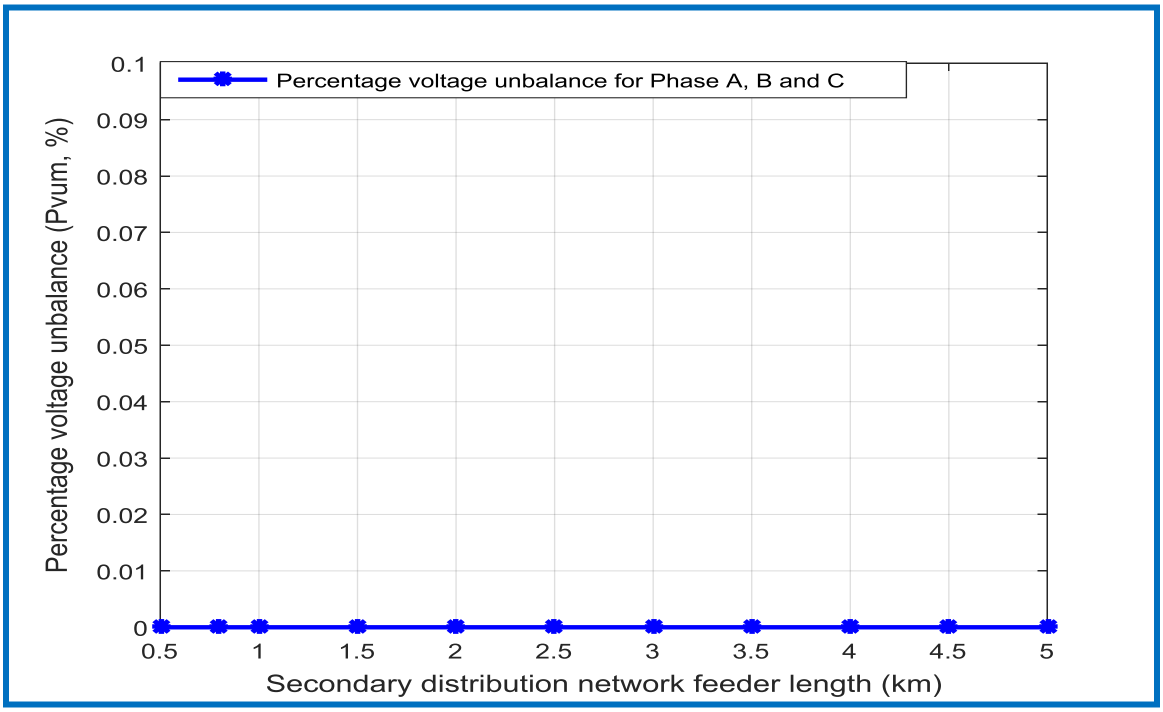


Figure 5.44: Curve of PVU for compensated unbalanced DN

Table 5.6: **Computation of VD (Δudev), PVD (Δudev, %) and VDr (Δu) for Compensated Unbalanced DN**

L, (km)	Vs (p.u)	VL Ph. A, (p.u)	VL Ph. B, (p.u)	VL Ph. C, (p.u)	ΔUdev, (p.u) Ph. A, B & C	Δudev %, Ph. A, B & C	ΔU, (V), Ph. A, B & C	VL (V), Ph. A, B & C	ΔUstd. min and max %
0.5	1.0	1	1.0	1.0000	0	0	0	220	± 5 %
0.8	1.0	1	1.0	1.0000	0	0	0	220	± 5 %
1	1.0	1	1.0000	1.0000	0	0	0	220	± 5 %
1.5	1.0	1	1.0000	1.0000	0	0	0	220	± 5 %
2	1.0	1	1.0000	1.0000	0	0	0	220	± 5 %
2.5	1.0	0.9998	0.9998	0.9998	0.0002	0.02	0.044	219.96	± 5 %
3	1.0	0.9998	0.9998	0.9998	0.0002	0.02	0.044	219.96	± 5 %
3.5	1.0	0.9997	0.9997	0.9997	0.0003	0.03	0.066	219.93	± 5 %
4	1.0	0.9997	0.9997	0.9997	0.0003	0.03	0.066	219.93	± 5 %
4.5	1.0	0.9996	0.9996	0.9996	0.0004	0.04	0.088	219.91	± 5 %
5	1.0	0.9996	0.9996	0.9996	0.0004	0.04	0.088	219.91	± 5 %

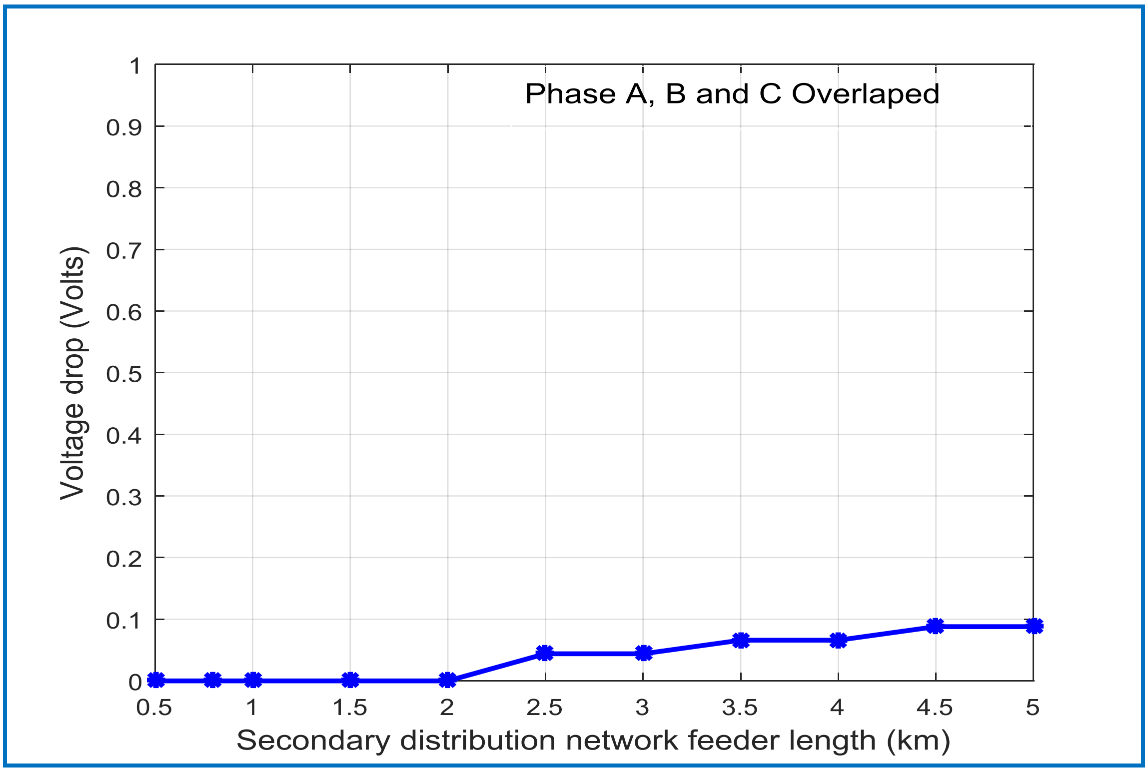


Figure 5.45: Curve of voltage drop on compensated unbalanced DN

Figure 5.46 shows the combined uncompensated and compensated voltage profile for unbalanced secondary distribution network**.** Figure 5.47 shows the combined uncompensated and compensated voltage drop for unbalanced secondary DN network. Also Figure 5.48 shows the combined uncompensated and compensated percentage voltage unbalance for unbalanced secondary distribution network. These results validate the optimal performance of DVR in enhancing voltage profiles, mitigation unbalance phase voltages, reducing voltage drops and improving security of supply to the end users in the secondary electric power distribution system within the specified statutory limits.

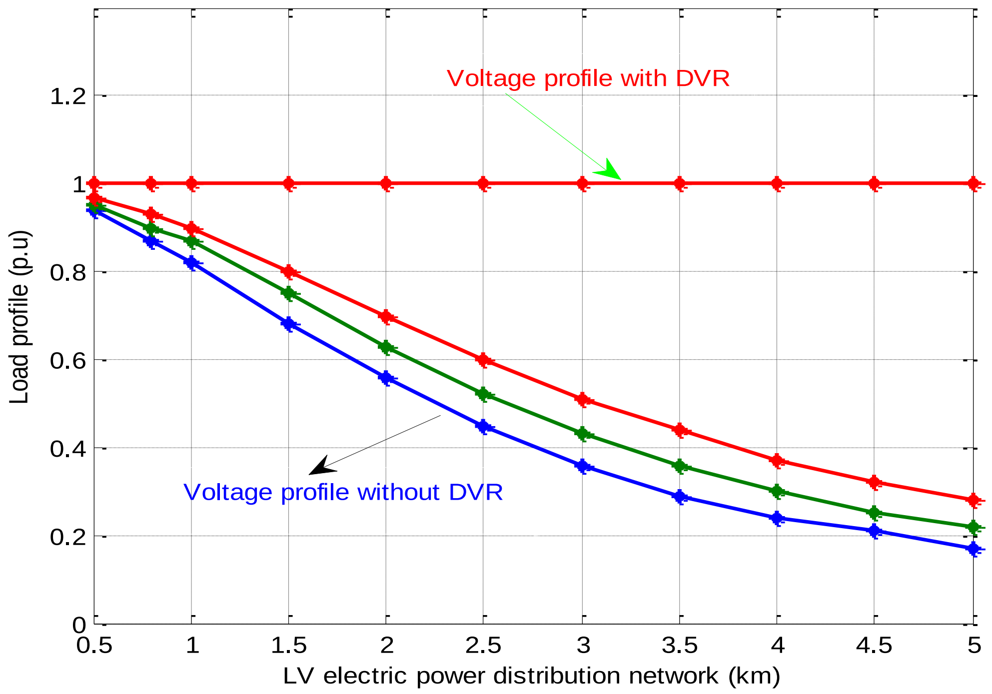


Figure 5.46: Curve of combined per-unit load VP of compensated and uncompensated unbalanced DN

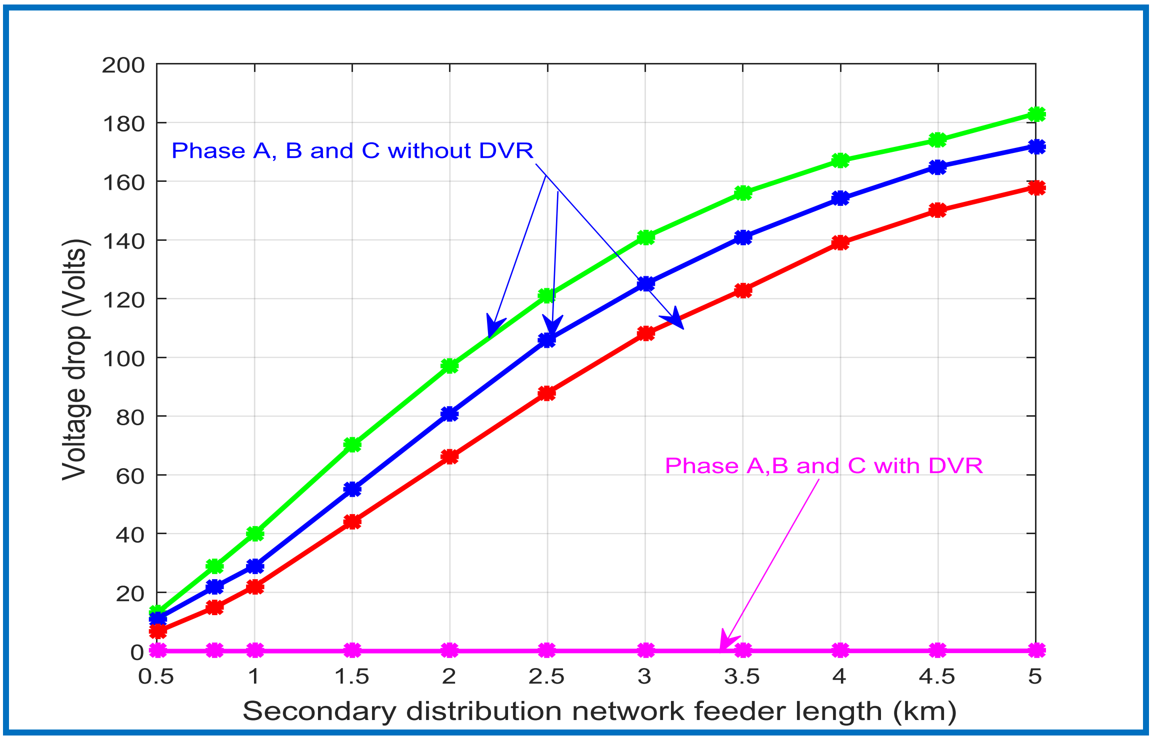


Figure 5.47: Curve of combined VDr of compensated and uncompensated unbalanced DN

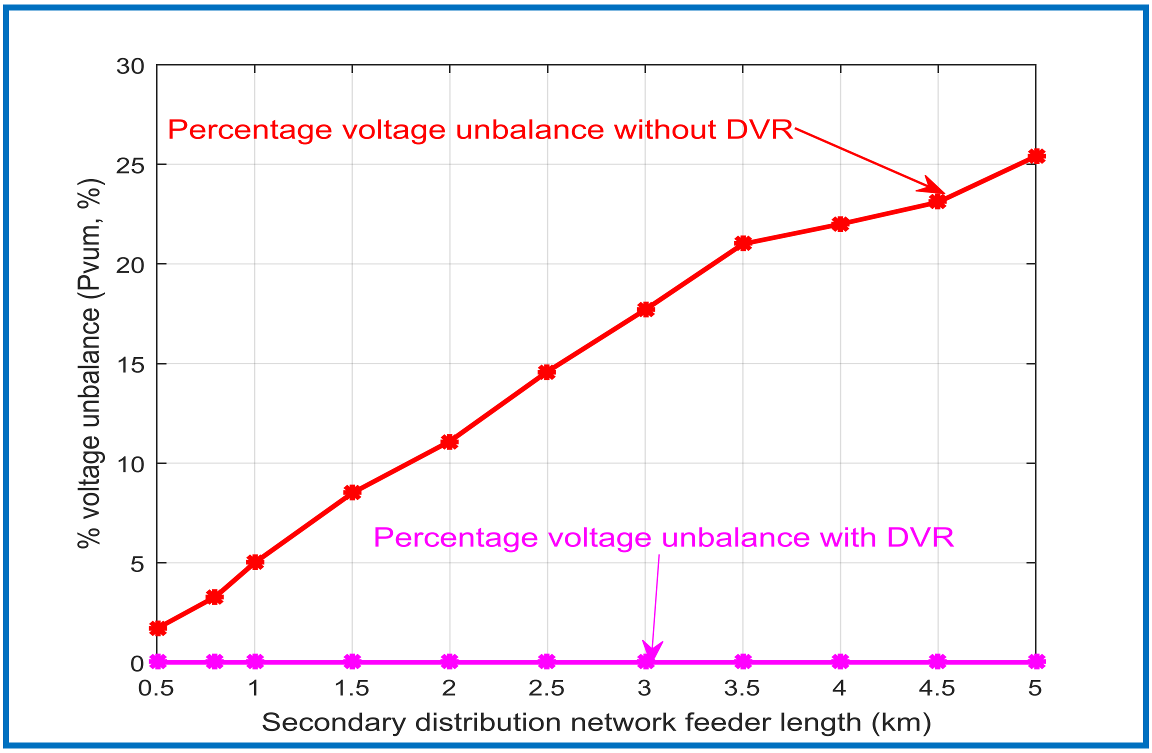


Figure 5.48: Curve of combined PVU of compensated and uncompensated unbalanced DN

5.9. Analysis for Improving the Performance of Secondary Electric Power Distribution Networks

Tables 5.3, 5.6 and Figures 5.30, 5.45 show that with the introduction of custom power device known as dynamic voltage restorer to short and long, balanced and unbalanced distribution networks feeder length of 0.5 km to 5 km, the voltage deviation (U_{dev}, %) fall within the normal permissible range, implying good voltage quality reaching end users: all values of U_{dev}, %, fall within standard minimum of – 5 % and + 5 % allowable voltage drop for all the distribution network feeder length.

Table 5.5 and Figure 5.44 Show that with the introduction of *DVR* to short and long, unbalanced distribution networks feeder length of 0.5 km to 5 km, the voltage unbalance falls within the normal permissible range of less than 2 %, meaning good and balance voltage reaching the end users: all the values of *PVU*, % falls within the standard minimum of less than 2 % allowable voltage unbalance for all unbalanced distribution network feeder length.

Tables 5.2, 5.4 and Figures 5.29, 5.43 show that the introduction of *DVR* to short and long, balanced and unbalanced distribution networks feeder length of 0.5 km to 5 km, the voltage profiles falls within the normal permissible range for all the distribution feeder length, implying good voltage profile reaching the end users: all values of voltage profile falls within the standard voltage range of 0. 95 p.u and 1.05 p.u of the specified nominal system voltage value.

5.10 Summary

In this chapter, the use of DVR was investigated for unbalance voltage mitigation, voltage variation/fluctuation correction and low voltage profile improvement in secondary distribution system. It has been shown that a DVR is more efficient, has dynamic fast response, easy to maintain, simple and effective for unbalance voltage correction, voltage variation/fluctuation mitigation and voltage profile enhancement in caparison with other custom power devices found in literature. Furthermore, a DVR has a much smaller rating than other custom power devices used for the same purpose in distribution networks. This makes DVR cheaper and smaller in size to other CPDs. The stochastic analysis established that for unbalance voltage, voltage variation, voltage fluctuation and low voltage profile in secondary distribution under steady operating conditions, the discussed technique recorded significant achievement in mitigating unbalance voltage, correction of voltage variation/fluctuation, voltage drop minimazation and enhanced voltage profile to standard acceptable limits. Through broad assessment, analysis, close examination and simulation performed with MATLAB/Simulink in Sim System Power tool box, the effectiveness of the techniques discussed is verified.

CHAPTER SIX
CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusion

The following conclusions were drawn from the investigation carried out on 11/0.4 kV secondary electric power distribution networks with and without DVR.

6.1.1. Balanced Distribution Network without DVR

The research reveals that:

(a.) From the result of load voltage profile, it is shown that at distribution feeder length of 0.5 km, 0.95 p.u voltage profile was measured which met the minimum standard statutory limit of voltage expected by customers in secondary distribution system of ±5 % of the specified nominal system voltage value;

(b.) It is shown that the load VP measured in DN feeder length of 0.8 km to 5 km for balanced EPDNs from the start to the end of the feeder is less than minimum statutory limit of -5 %, or 0.95 p.u of the nominal voltage value. Hence, there is a need to improve the voltage profile to acceptable permissible limit. The distribution feeder's phase voltage must be enhanced to a minimum -5 % of the nominal voltage value. therefore, the distribution feeder's source voltage must be enhanced to acceptable standard of 11x1.05 kV at the primary feeding substation;

(c.) From the result of voltage drop on the distribution network, 11 Volts were estimated for 0.5 km feeder, this is within the minimum –5 % voltage drop expected on the network, whereas, the voltage drop on distribution feeder length of 0.8 km to 5 km, are more than the statutory voltage drop value of -5 % of the specified nominal system voltage value. There is an urgent need to compensate for the voltage drop on the distribution feeder length of 0.8 km to 5 km; and

(d.) From the result of percentage voltage deviation assessment, it was observed that there is a need for voltage booster device to mitigate the distribution feeder of 0.8 km to 5 km which are above specified allowable voltage deviation of ±5 % of the specified nominal system voltage value of distribution network for optimum performance.

6.1.2. Unbalanced Distribution Network without DVR

(a.) Based on the result of percentage voltage unbalance evaluation, it was observed that acceptable minimum of less than 2 % was attained at 0.5 km distribution feeder length, whereas, for the distribution feeder length of 0.8 km to 5 km, the percentage voltage unbalance range from 3 % to 25 % respectively. Because of this, there is a need to correct the voltage unbalance in order for the distribution network to operate optimally.

(b.) From the result of load voltage profile investigation, it was noticed that the voltage profile for phases A, B and C at 500 meters for unbalanced distribution network are 0.97 p.u, 0.96 p.u, and 0.95 p.u respectively. This reveals that the voltage profile measured at the nodes is within statutory limits of ±5 % of the nominal voltage value permissible on distribution system.

(c.) From the result of voltage drop assessment, it was shown that the acceptable voltage drop of – 5 % of the specified nominal system voltage value was achieved on the distribution feeder length of 0.5 km, while at the EPDN feeder length of 0.8 km to 5 km, the voltage drop estimated was far above the maximum voltage drop of -5 % of the specified nominal system voltage value for distribution network.

(d.) Unacceptable percentage voltage deviation was observed in the unbalanced distribution feeder length of 0.8 km to 5 km which ranges from 12 % to 55 % in contrast to the distribution network specified standard acceptable percentage voltage deviation of ± 5%, of the nominal voltage value. It becomes necessary to compensate the distribution feeder length of 0.8 km to 5 km in order to keep to standard acceptable minimum percentage voltage deviation, so as to ensure distribution system operate effectively.

In summary, from the result of the assessment carried out on balanced and unbalanced secondary distribution systems, it is observed that the load voltage profile, percentage voltage deviation, percentage and voltage loss of 0.5 km feeder length are all within statutory limits of ± 5%, 0,95 p.u and 1.05 p.u and – 5% of specified nominal system, voltage value respectively. Similarly, the percentage voltage unbalance for unbalanced distribution at 0.5 km length is within statutory limit of < 2 %. However, It was shown that for the balanced and unbalanced secondary distribution system the load voltage profile, percentage voltage deviation, voltage drop for EPDN length of 0.8 km to 5 km are not within acceptable permissible limits of ± 5%, 0,95 p.u and 1.05 p.u, and – 5% of the specified nominal system voltage value respectively. In a similar way, the percentage voltage unbalance for unbalanced distribution feeder length of 0.8 km to 5 km are also not within standard permissible limit of < 2%. Hence, there is an urgent need to enhance the deficiencies observed in the studied secondary distribution network so as to make the distribution network to operate optimally.

To make EPDNs function with minimum optimum performance implies:

- Statutory voltage limits of ±5 % and frequency limit of ±1 %;
- Phase and frequency shift correction to acceptable value;
- Complete absence of phase voltage imbalances;

- Acceptable minimum voltage drop to specified standard value of -5 % of nominal voltage value; and
- Enhances voltage profile for short and long, balanced and unbalanced feeder length to specified standard voltage within ±5 % of the nominal rated system voltage.

6.1.3. Balanced Distribution Network with DVR

From the result of voltage profile, percentage voltage deviation, and voltage drop mitigation of balanced secondary distribution network, it was observed that for distribution feeder lengths of 0.5 km to 5 km, the voltage profiles are all within 0,95 p.u and 1.05 p.u standard distribution statutory limit, the percentage voltage deviations are all within ± 5 % acceptable voltage deviation for distribution network and the voltage drops on the feeder networks are all less than – 5 % of minimum voltage drop permissible in secondary distribution network. This shows the efficaciousness and efficiency of DVR to inject the appropriate missing voltage in series with electric power distribution networks.

6.1.4. Unbalanced Distribution Network with DVR

From the result of PVU, VP, voltage drop and percentage voltage deviation mitigation of unbalanced secondary distribution feeder lengths of 0.5 km to 5 km, with DVR connected to the DS model, it was shown that the percentage voltage unbalance is less than 2 % acceptable minimum for all the distribution networks. The voltage profiles are within the statutory voltage limits of 0,95 p.u and 1.05 p.u of the nominal voltage value for all the distribution feeder, the voltage drop is less than – 5 % minimum permissible voltage drop for the entire distribution feeder network and the percentage voltage deviation is within the standard allowable of ± 5 % of the rated voltage value for the entire distribution network under investigation. In summary, the optimum performance of secondary distribution system was only achieved at 500 meters or 0.5 km feeder length for uncompensated balanced secondary distribution network. Implies that correct voltage profile of 0.95 p.u is within statutory limit of ±5 %, voltage drop minimization of – 5 %, is within acceptable minimum voltage drop, and the absence of voltage and current phase imbalances on the distribution network.

Furthermore, for uncompensated unbalanced secondary distribution network, the optimum performance of the secondary distribution system was achieved at 0.5 km of the distribution feeder length, meaning that correct voltage profile of 0.97 p.u, 0.96 p.u and 0.95 p.u for phase A, B and C respectively reaching the customers node. These voltages are within statutory voltage limit of ±5 %. The percentage phase voltage unbalance (%P_{UNM}) is 1.7 % is less than 2 % acceptable standard for optimum operation of electrical and electronic equipment in distribution system. Minimum voltage drop on phase A, B and C respectively were estimated, which is less than the -5 % acceptable voltage drop on secondary electric power distribution network. Increment in the distribution feeder length beyond 0.5 km or 500 meters, as the distribution network must be provided with a compensating device such as DVR system which is employed to improve quality of power and security of supply and also to mitigate all types of disturbances in secondary distribution system. The DVR employed in this research is a solid state advanced power electronic which helps to mitigate voltage unbalance, decrease voltage drop, enhance low voltage profile and voltage variation/fluctuation correction experience in the distribution feeder to specified acceptable standard limits for balanced and unbalanced star connected distribution system.

In addition to effectively improving the voltage profile, minimizing voltage drop, correction of voltage unbalance for balanced and unbalanced, short and long distribution networks. DVR also performs phase angle shift correction and harmonics generated is reduced to minimum acceptable. The DVR is very simple, efficient, cost effective, small size and has a dynamically fast response, easy to maintain when compared to other custom power devices that are utilized for same purposes in secondary distribution system such as DSTATCOM and UPQC which as a drawback of large size, high cost and difficulty in maintenance.

6.2 RECOMMENDATIONS

For necessary improvement in the optimum performance of the secondary electric power distribution network, the following are recommended:

(i) For optimum performance of secondary distribution system, the distribution feeder length MUST not exceed 500 meters or 0.5 km for both balanced and unbalanced systems;

(ii) In the event of urgent energy demand by the customers which may necessitate increasing the distribution feeder length beyond standard acceptable feeder length of 500 meters, the distribution companies and the customers MUST ensure that the DVR is installed to compensate for: voltage drop; unbalance phase voltages; voltage deviation; voltage variation and fluctuation; phase and frequency shift and; low voltage profile, from the beginning of the network to the end to standard statutory limits;

(iii) Furthermore, electricity companies must provide voltage boosting at the feeder bus of 11/0.4 kV transformer to boost supply voltage to a standard +5% nominal voltage. This will eliminate the problem of critical voltage drops in the network;

(iv) In addition, the power distribution companies must provide standard routine and planned practice and quick response of personnel to repair within the shortest possible time. Preventive and routine maintenance of power supply facilities must cover elements and exercises such as transformers, circuit breakers, relays, lines and protection equipment, regular bush clearing and felling of trees within falling distance from overhead lines, replacement and up-rating of inferior, ageing and overloaded equipment, extensive re-conductoring of overhead lines with conductors of appropriate size and quality to eliminate wire cuts associated with inferior, overaged, and thin conductors. This will mitigate failure rate;

(v) It has been obviously acknowledged that there is a need for consistency in making measurements of power quality parameters and reliable guidance should be provided to all electricity industries and end users of electricity categories;

(vi) The industrial and commercial customers should compensate their power factor and should install filtering technologies

The following recommendation is proposed for the effective performance of DVR systems and distribution networks under steady state operating conditions:

(i) The extension of the secondary distribution network should not exceed 2.5 km or 2500 meters for any reason. This is to enable the DVR inject the needed voltage effectively without adversely affecting the DVR performance;

(ii) The DVR MUST be safeguarded from injecting 100 % voltage to the distribution network. This is achieved by installing a protective device that will automatically disconnect the DVR system from the network in the event of zero or less than half of the nominal voltage value being supplied from the source;

(iii) The DVR system MUST be protected from fault current which can damage the DVR system, this is accomplished by positioning a by-pass switch at the point of coupling of the DN and the DVR systems;

(iv) The DVR storage device and the rating of the series voltage injection transformer settings MUST be carefully calculated and selected for efficient and effective operation of DVR systems; and

(v) The controllers which are the heart of the DVR system MUST be painstakingly chosen in order to enhance better compensating and mitigating operation of the DVR system.

6.2.1 Recommendation for Future Research Study

The following research areas are recommended for future study:

- In this research, only the steady state response of balanced and unbalanced, short and long secondary distribution system was carried out for voltage variation, low voltage profile and voltage unbalance studies. Notwithstanding, the investigation of the enhancement techniques were investigated in detail except that the dynamic response was not dealt with in this study and this can be a subject of investigation for future studies;

- In addition, this investigative study proposed only a voltage control technique for short and long, balanced and unbalanced secondary distribution systems. This can be continued for secondary distribution system with renewable energy sources such as photovoltaic cells and wind turbine with balanced and unbalanced loads. Therefore, voltage control strategy for secondary distribution system with renewable energy sources connected to balanced and unbalanced distribution networks can be point of a future research studies;
- Investigation of DVR can be established for active loads for renewable energy sources and the effectiveness of multi-level DVR can be carried out in both medium and secondary voltage distribution networks;
- The use of Artificial Neural Network (ANN) and Adaptive Neutral Fuzzy Inference System (ANFIS) controllers can also be employed in the DVR mitigating techniques for dynamic and steady state conditions;
- Optimum performance of DVR can be established for wind turbine with active loads connected; and

Finally, the DVR technique can be generically extended further to other distribution feeder systems and feeder load configurations

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