JIMMA UNIVERSITY

JIMMA INSTITUTE OF TECHNOLOGY

FACULTY OF ELECTRICAL AND COMPUTER ENGINEERING

POWER QUALITY STUDY AND MITIGATION TECHNIQUES:

CASE STUDY ON ADDIS CENTER DISTRIBUTION SUBSTATION

A thesis Submitted to the Jimma Institute of Technology, School of Graduate studies Jimma University in partial fulfillment of the Requirements for the degree of MASTER OF SCIENCE IN ELECTRICAL POWER ENGINEERING (POWER ENGINEERING)

By: NEME TOLERA

Advisor: Dr.-Ing. GETACHEW BIRU WORKU

October, 2021

Jimma, Oromia, Ethiopia

JIMMA UNIVERSITY

JIMMA INSTITUTE OF TECHNOLOGY

FACULTY OF ELECTRICAL AND COMPUTER ENGINEERING

POWER QUALITY STUDY AND MITIGATION TECHNIQUES:

CASE STUDY ON ADDIS CENTER DISTRIBUTION SUBSTATION

By: NEME TOLERA

APPROVAL BY BOARD OF EXAMINERS

________________________	______________________
Chairman, school of Electrical And computer Engineering	Signature
Dr.-Ing Getachew Biru Advisor	______________________ Signature
____________________ Internal Examiner	_________________________ Signature
_________________________ External Examiner	___________________________ Signature

DECLARATION

I, the undersigned, declare that this M.Sc. thesis is my original work and has not been presented for a Degree in this and other Universities, all sources and materials used for the thesis work have been fully acknowledged.

Name: Neme Tolera

Signature ___________

Place: Jimma Institute of Technology, Jimma University, Jimma

Date of Submission October. 29/10/2021

This thesis has been submission for examination with my approval as a university advisor

Dr.-Ing Getachew Biru Signature__________________

ACKNOWLEDGEMENTS

First and above all, I would like to thank the almighty God for providing me this opportunities, for helping me through this difficult and granting me the capability to proceed successfully the completion of this M.Sc. thesis.

Secondly, I wish to express my deepest gratitude to my supervisor Dr.-Ing Getachew Biru for his patience, guidance, encouragement and support in shaping the outlook of this work. It could not possible for me to bring out this thesis without his help and constant encouragement. I am grateful to his motivation for the timely completion of the thesis and his dynamic suggestions for solutions to any challenges during the total work of this thesis.

Most important of all, I would like to express my thankfulness to my wife, my son, my brothers and all those cooperate during data collection Addis center distribution substation staffs.

Finally, I would like to thank all my friends in Gilgil Gibe 2 hydropower plant; those helped me through the course of my studies, discussed ideas about my thesis and made my life enjoyable.

Thank you all!

Neme Tolera

Jimma, Ethiopia

Table of Contents

LIST OF FIGURES

LIST OF TABLES

ACRONYMS AND ABBREVIATIONS

IEEE	Institute of Electrical and Electronics Engineers
IEEE Std	Institute of Electrical and Electronics Engineers Standard
ASD	Adjustable speed drives
EEU	Ethiopia Electric Utility
PQ	Power quality
DSTATCOM	Distribution Static Compensator
RMS	Root-mean-square (effective value)
TVSS	Transient voltage surge suppressor
ANSI	American National Standards Institute
CBMA	Computer Business Manufacturers Association
CBEMA	Computer Business Equipment Manufacturers Association
ITIC	Information Technology Industry Council
SEMI	Semiconductor Equipment and Materials International
SAIFI	System Average Interruption Frequency Index
CAIDI	Customer Average Interruption Duration Index
SAIDI	System Average Interruption Duration Index
ASAI	Average Service Availability Index
NEMA	National Electrical Manufacturers Association
THD	Total harmonic distortion
THD_V	Voltage Total Harmonic Distortion
THD_I	Current Total Harmonic Distortion
IDD	Current demand distortion
VDD	Voltage demand distortion
DPF	Displacements Power actor
PCC	Points of Common Coupling
CFL	Compact fluorescent lamps

UPS	Uninterruptable power supply
DVR	Dynamic Voltage Restorer
UPQC	Unified Power Quality Conditioner
APF	Active power filter
SVR	Static VAR compensators
VSC	Voltage source converters
ADC	Addis Center
AC	Alternative current
DC	Direct current
HV	High Voltage
MV	Medium Voltage
LV	Low Voltage
PEF	Permanent Earth Fault
PSC	Permanent Short circuit
TEF	Transient Earth fault TSC
TSC	Transient Short circuit
MG	Motor-Generator
GTO	Gate Turn-Off thyristor
IGBT	Insulated Gate Bipolar Transistor
PWM	Pulse Width Modulation
PFC	power factor correction

ABSTRACT

Distribution systems deliver power from bulk power systems to customers. A stable and reliable electric power supply system serve customer loads without interruptions. Electric power system interruption in Addis Center (ADC) distribution substation is becoming a day to day phenomenon, even there are time that electric power interruption occurs several times a day at ADC distribution substation systems.

Currently power quality problem is an issue to the end user. As a result, many of the residential, commercial and industries in our country faced with the problem of power quality, having various causes. In this thesis the study of power quality problems of ADC distribution substation and its mitigation techniques will be study. The study focuses on evaluating and identifying the major power quality problems of the ADC distribution substation as per IEEE standards.

The data required for the study is collected from the ADC using model–8335 Power Quality Analyzer and from recorded data. Based on the data have been recorded, oscillatory transient that reaches two times as much the standard voltage, voltage sags which is less than 90% of the RMS voltage, sustained power interruptions for 4-5 hrs. Per week, voltage unbalance of 2.4% and current distortions of (THD_I) value that reach 25.10%.

The collected data have been analyzed and simulations are done using MATLAB/SIMULINK model to show the effectiveness of mitigation techniques. In this thesis pre-insertion resistor and inductor are used to mitigate the problem of oscillatory transient and the result indicates that the transient voltage reduced from 25kV to 15kV. For the problem of voltage sag, dynamic voltage restorer is as a solution and the results shows that the device restores the voltage for the three phases from 13.02kV, 13.025kV, and 13.026 kV, respectively to 15kV. Third order high-pass filters that are 5th and 7th harmonic filters are designed and simulated for the mitigation of harmonic distortion and the filters are filtered out the harmonics and reduces the THD_I value from 25.10% to 3.05%. D-STATCOM system is also designed and simulated as a solution to harmonic distortion from 33.93 to 3.93 and for the problem of voltage unbalance redistribution of single phase loads equally among the three phases is taken as a mitigation technique.

Keywords: power quality, power quality problem, harmonic distortion, MATLAB SIMULINK software, power interruption and mitigation techniques.

CHAPTER ONE

1. INTRODUCTION

1.1 Background

Power quality is one of the big issues to be considered in Ethiopian power system Generation, Transmission and Distribution. Currently, it is building a number of power station and industry in various parts of the country. In Ethiopia electric power distribution substation system is labeled as Low Voltages are 45kV, 33kV and 15kV. Mostly 33kV and 15kV overhead conductors are used for feeding up and step down transformers on each of 33kV and 15kV feeder. The voltage reaches to the customer further reduced to 380 volts three-phase or 220 volts single-phase by step down distribution transformers. These distribution substations monitor and adjust circuits within the system. This capacity of power generation in the country is increase with installing latest technological electronic devices for improving their productivity because the demand of power is very high. This indicates that loads are changing from being linear to non-linear. Industrial processes have electronic equipment and computing devices. These electronic devices are highly sensitive to disturbance and causes power quality problems. Power quality is related to fluctuations in the electrical supply. For example momentary interruption, voltage sags or swells, transients, harmonic distortion, electrical noise, and flickering lights etc. due to those power quality problems utility. Distribution substation networks, sensitive industrial loads and critical commercial operations area all suffer various types of outages and interruptions which become financial cost and power loss [1][2][3].

The IEEE defines power quality as the ability of a system or an equipment to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment [4][5]. Power quality mainly deals with continuity of the supply and quality of the voltage. Poor power quality generally mean there is sufficient deviation in the power supply to cause process misoperation or failure. Good power quality means that the power supply is sufficient for the process to operate satisfactorily. The reasons for the increased interest in power quality is poor power quality can result in equipment downtime and/or damage resulting in a loss of productivity. Poor power quality can affect the accuracy of utility and it can causes protective equpments to malfunction. Whenever the issue of power quality is raised, the Ethiopian electric utility has the responsibility to produce good quality voltage sine waves; whereas, end-use customers have the responsibility to limit the harmonic currents their electric loads inject into the utility system. The utility should be supply to customers with a certain quality of electric power, while end users should on their parts limit the power quality disturbances they inject into the power system [1].

Modern industrial processes have large number solid-state power converters which are widely used in applications such as Adjustable speed drives (ASD) and Static power supplies. The electronic devices are very sensitive to disturbances hence it affects the power quality and thus industrial loads become less tolerant to power quality problems such as voltage dips, voltage swells, and harmonics. Voltage dips and harmonics are considered one of the most severe disturbances to the industrial equipment. Those semi-conductor devices are involved in power conversion, which is either AC to DC or from DC to AC. This power conversion contains lot of switching operations which may introduce discontinuity in the current. Due to this discontinuity and non-linearity, harmonics are present which affect the power quality delivered to the end user [4].

Power quality is the set of parameters defining the properties of the power supply as delivered to the user in normal operating conditions, in terms of the continuity of voltage and voltage characteristics.

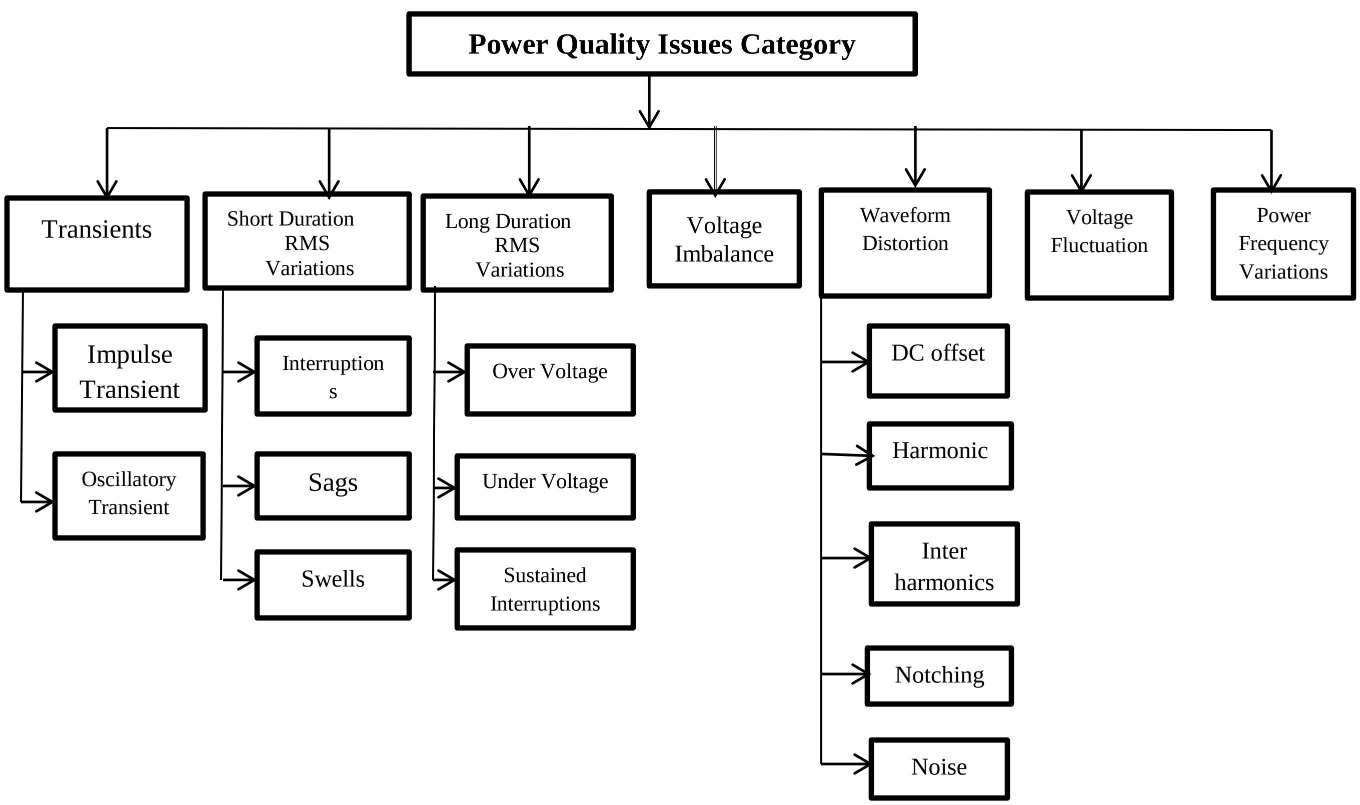


Figure 1.1 Categories and characteristics of power system electromagnetic phenomena (IEC).

1.2. Statement of the Problem

There are a lot of indications that shows the electric power quality is very low in Ethiopia. The issue of power quality is great concern in our daily life. Since Addis Ababa is the capital city of the country and a preferred location for most of the industries, considerable share of the electric power supply is directed towards the city. Due to this fact, Addis Ababa has been the load center of Ethiopian electric power system. Addis Center distribution substation is one of the distribution substations found in Addis Ababa that face distribution inefficiency, repetitive and sporadic power interruptions and power quality problems.

The people in the capital city and different towns in Ethiopia are facing problems. All residential, commercial and industrial customers are victims of the problem. Especially for factories and industries, it is really challenging to tolerate power interruption since it causes much revenue loss within hours of interruption. The effects of power quality problems in distribution substation are failure of motor drives, tripping of circuit breakers, over heating of motors, poor power factor problem, fuse blowing, contactor burn outs, and insulation cables failure [1].

The major problems in the power system that need a mitigation of quality up gradation are termed as power quality events. Power quality provides the solutions to all these power quality problems in a very efficient and optimized way. These problems, if not mitigated would cause heavy economic as well as technical disturbances. So the root cause of this problem should first be identified and evaluate and the possible solution should be investigate.

Thus, the study focuses on identifying and evaluating EEU's Addis Centre distribution substation power quality problems and their mitigation options and techniques.

1.3. Objectives

1.3.1. General objectives

The main objective of this thesis is to identify and evaluate the major power quality problems in Ethiopian Electric utility's Addis center distribution substation and assess appropriate potential mitigation techniques.

1.3.2. Specific objectives

The specific objectives of this are:

- Study the power distribution Substation system and the loads of the distribution Substation.
- Investigate the power distribution substation problems that arise from both the customer side and the electric utility side, at selected distribution
- To identify and evaluate the major power quality problems and possible solutions to the power quality problems in existing in EEU's ADC distribution substation.
- Model the distribution system by integrating possible PQ mitigation devices (Ex. DSTATCOM) and simulate and analyze the designed mitigation techniques to validate their impact on PQ.
- Draw relevant conclusions and recommendations which can help to improve the power quality problem.

1.4. Scope of the study

The main scope of this study is to deal with evaluating the power quality problem of the ADC distribution Substation network in Ethiopian Electric Utility. The study starts from the root causes analysis of power quality problems in the distribution substation and collecting the necessary data using the harmonic analyzer. Then the collected data is analyzed and compared with standard values and remedy mitigation techniques will be then studied for their impact.

1.5. Significance of the Study

The quality of power can have a direct economic impact on many industrial consumers. Both electric utilities and end users of electrical power are becoming increasingly concerned about the quality of electric power.

The thesis result will bring benefits which include:

- Improvement of electric power quality, minimizing of economic impact, increase efficiency and performance.
- Mitigation of power quality problems to have a clean power delivery to sensitive loads.
- Reduction of factory down time or service interruption

1.4. Methodology

To conduct this study data will be collected using different types of data collecting techniques.

These include observation, measurement, interview, finding recorded data and analyzed in different methods. To successfully complete this study the works to be done the following activities will be conducted:

Data Collection

Primary data will be collected during field survey from recorded data of currently operation ADC distribution and secondary data will be collected through direct measurement of voltage, current and power. During this study measures power quality using the device of power quality analyzer to identify the type of power quality problems in existing system.

This power quality analyzer has the ability to measure high speed voltage quality parameter, rms voltage quality parameters, Power quality parameters like three phase quality parameters, harmonic quality parameters like harmonic voltage, current and power, inter-harmonic voltage and current, harmonic voltage and current phase angle.

Data analysis

Analyze the output measured value of existing system with general classes of power quality problem and compare with power quality standards.

Design and Modeling

In this design and modeling of existing devices established to further study of its performances then contrast with the modeling and design of the new device. The system design and model will be analyzed, in terms of its technical application, economic benefits, performances (losses, efficiency, quality and reliability and others). Simulate the design of existing and the new model using software like MATLAB/SIMULINK or other as required

The general methodologies used in this thesis are as shown below.

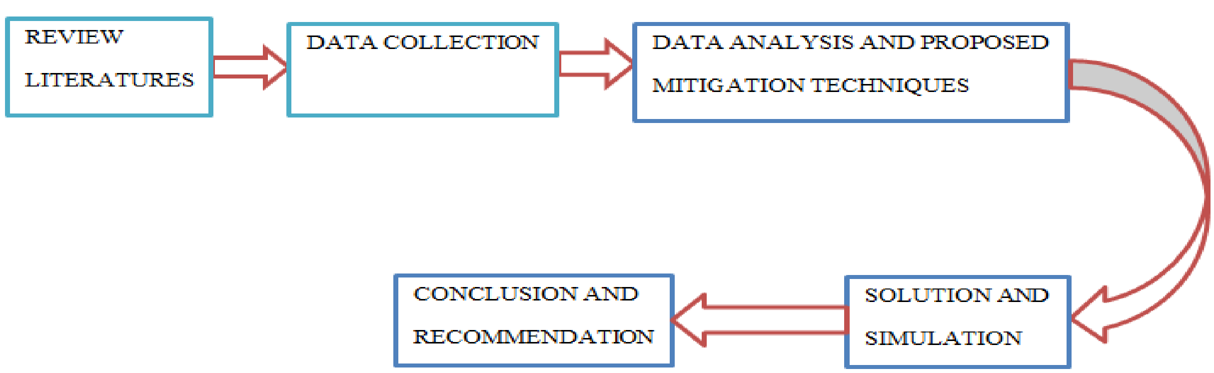


Figure 1.2 Methodology process diagram

The work of different authors haven been reviewed under the topic called literature review and it has been considered one of the methodology used to do this Thesis.

The total task of data collection is accomplished through; direct measurement: using power quality analyzer, from recorded data and equipment specifications, by interviewing people working in the factory and through prepared questionnaires.

Power quality analyzer is utilized for measurement. The device can measure average three-phase RMS voltage and current, power, power factor, reactive and apparent power, frequency, active and reactive energy consumption, Individual and total harmonic distortion. The figure above is which shows the process power quality analyzer used to get the data.

Data collection also includes the study from network, websites and other historical and documentary records relevant for the study.

Figure 1.3: Power quality analyzer model - 8335

Next to this, data analysis method has been employed to identify the type and level of the problem found in the factory. When the level of the problem identified is beyond the limit of the IEEE standard; then mitigations model are designed and simulated to observe its impact.

1.7. Organization of the Thesis

The thesis is organized into five (5) chapters, namely: introduction, Power Quality problems assessments, data collection, Analysis of Power Quality problems and proposal mitigation techniques to the existing power quality problems, simulation results and discussions and the last one is conclusion and recommendation.

Chapter 1 discusses the introduction in which the background, statement of the problem, objective (general and specification objective), and scope of study, Significance of study, methodology and organization of thesis are included.

Chapter 2 presents about the theoretical part for power quality problems assessment. This chapter discusses the power quality evaluation procedures and the seven types of power quality problems categorized by IEEE Standard 519-1995 in conjunction with their causes and adverse effects on the power system.

Chapter 3 the presents that data collection, analysis and proposed mitigation solutions. Under this chapter; collected data are analyzed, the problems are identified and respective solution and mitigation techniques are discussed.

Chapter 4 presents simulation studies and discussion of results. In this part, the designed solutions are simulated using simulating software to see their effects and the level of mitigation techniques. Simulation results are put and discussed in the fourth chapter of this thesis. Proposed solutions are simulated using MATLAB /Simulink, the results are discussed and cost analysis has been presented.

Chapter 5 discussed conclusions, recommendations and suggestions for future work. The conclusions drawn from the research work, recommended solutions and areas of study suggested for further research are included in this chapter.

CHAPTER TWO

POWER QUALITY PROBLEMS ASSESSMENT AND LITERATURE REVIEW

2.1. Introductions

Power quality problems encompass a large number of electrical and electromagnetic phenomena. Each phenomenon is caused by different situation and has degrees of negative impacts on the utility system and/or end-user equipments. The first sign of a power quality problem is a deviation in the voltage waveform of the power source from sine wave in amplitude from an established reference level or a complete interruption. The disturbance can be caused by harmonics in the current or by events in the main voltage supply system. The disturbance can go for a fraction of a cycle (milliseconds) to great durations (seconds to hours) in the voltage supplied by a source [6].

In an electrical power system, not only there are various kinds of power quality disturbances. They are classified into different categories and their descriptions are important in order to classify measurement results and to describe electromagnetic phenomena, which can cause power quality problems.

The power quality problems study concentrates on of Addis center distribution substation located in Addis Ababa city and the possible causes of these problems with possible solution. To study the Power Quality problems a general purpose power quality evaluation (assessment) procedure is followed [6] [7].

2.2. Power Quality Evaluation Procedure

Power quality assessment procedure provides a general framework that contains all the possible elements that may be needed for power quality study. From a general purpose power quality assessment, all the major disturbances associated with the power system are investigated in this thesis. The investigation emphasizes only on the existing power quality problems.

The power quality evaluation procedure followed in this thesis includes the following general steps [8].

2.2.1. Identification of Power Quality Problems

Identification of the power quality problem is the first and basic step in the task of power quality assessment. The specific power quality problems that need to be evaluated will be different from customer to customer. A review of the types of equipment used by the customer, process requirements and economic impacts of problems will lead to a list of problems that need to be studied. They can include possible problems with both the utility distribution system and the customer facilities [8] [9].

The electrical characteristics and durations of the power quality events that a conventional power system encounters, the following power quality phenomena are considered in this thesis, as categorized by IEEE Standard 519-1995. However, the IEEE Standard 1159-1995, classifies the power quality problem into seven major categories described as follows [6].

1. Voltage Transient
    - Impulsive transient
    - Oscillatory transient
2. Short duration voltage variation
    - Interruption
    - Sag
    - Swell
3. Long duration voltage variation
    - Under voltage
    - Over voltage
    - Sustained interruption
4. Voltage unbalance
5. Voltage fluctuation
6. Waveform Distortions

- DC offset
- Harmonics
- Inter harmonics
- Notching
- Noise

7. Frequency deviation

2.2.1.1. Voltage Transients

Transients are undesirable momentary changes in voltage and/or current signals in the power system. There are many causes due to which transients are produced in the power system. The main sources of transients are lightning strokes, Arcing between the contacts of the switches, sudden switching of loads, poor or loose connections, capacitor switching, energizing transformers, power electronic converters and other switching phenomena within end-user systems [10] [11].

Transients caused by lightning strokes are often dangerous and result in a severe equipment damage unless proper protection systems are installed. However, capacitor switching usually results in non-dangerous transients. Switching of grounded-wye transformer banks may also result in unusual transient voltages in the local grounding system due to the current surge that accompanies the energization [11].

Adjustable-speed motor drives are adversely affected by the transient as they need a certain quality of power for the accurate adjustment of the motor drive. Insulation flashover, equipment overheating and damage are other undesirable effects of transient.

Depending on their electrical natures, transients can be classified into two categories, impulsive and oscillatory [10].

I. Impulsive Transient

An impulsive transient is a sudden, unipolar and non-power frequency change in the steady state condition of voltage and current. It is characterized by its amplitude, rise time and decay time, which can also be revealed by its spectral content. The spectral contents of impulsive transients are of mainly high frequency, due to its non-periodic nature of occurrence. Because of the high frequency spectral contents, the shape of impulsive transients can be changed quickly by circuit components and may have significantly different characteristics when viewed from different parts of the power system. They are generally not conducted far from the source of where they enter the power system. Impulsive transients can excite the natural frequency of the power system circuits and produce oscillatory transients [6].

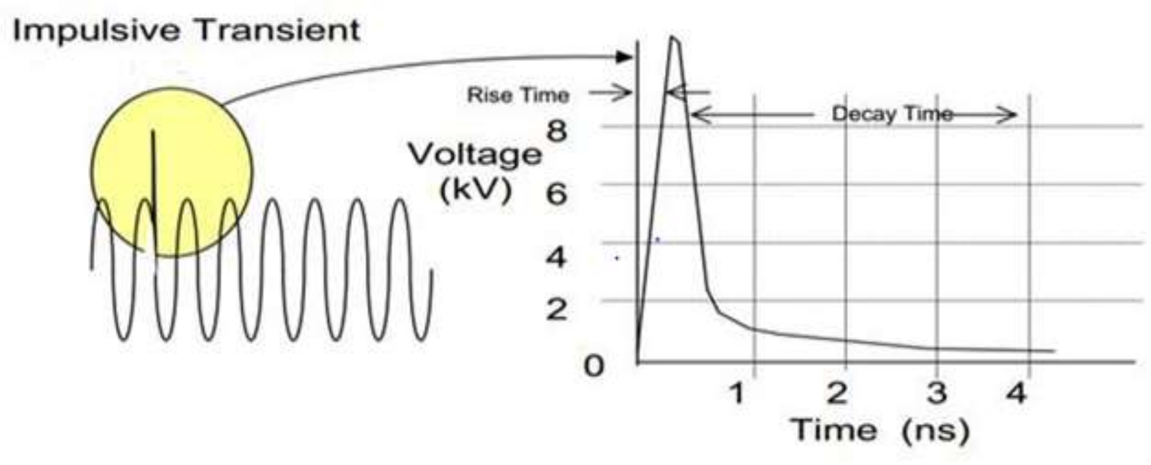


Figure 2.1 Typical positive impulsive voltage transient [12].

The most common cause of impulsive transients is lightning. An impulsive transient due to lightning strokes can occur because of a direct strike to a power line or from magnetic induction or capacitive coupling from strikes on adjacent lines [13].

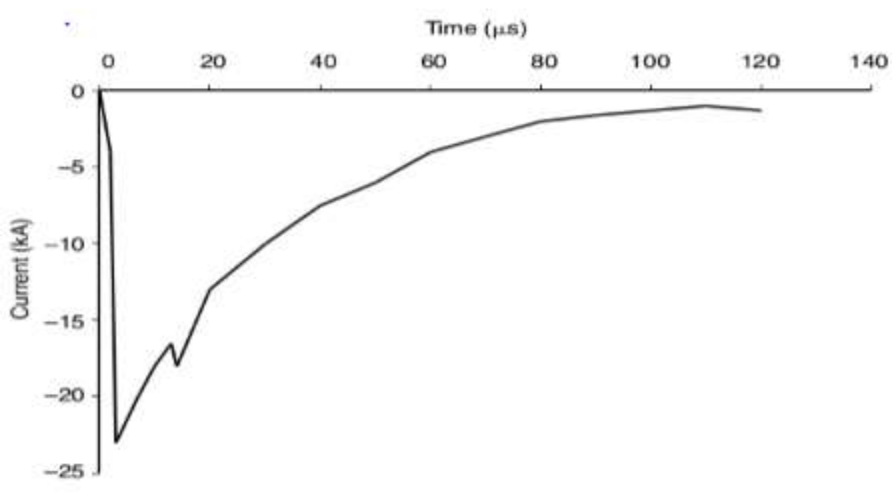


Figure 2.2 lightning stroke current impulsive transient [14] [15]

The frequency and amplitude of lightning-induced transients vary geographically depending on the rainy nature of the area, vulnerability to lightning strokes and relative height of the system.

II. Oscillatory Transient

An oscillatory transient is a sudden, non-power frequency change in the steady state condition of voltage, current or both that includes both positive and negative polarity values. It is described by the frequency at which the oscillation takes place, the duration of the transient before it dies out, and its magnitude.

The commonly occurring oscillatory transients are categorized into subclasses of high frequency, medium frequency and low frequency oscillatory transients.

The frequency ranges for these classifications are chosen to coincide with common types of power system oscillatory transient phenomena [12].

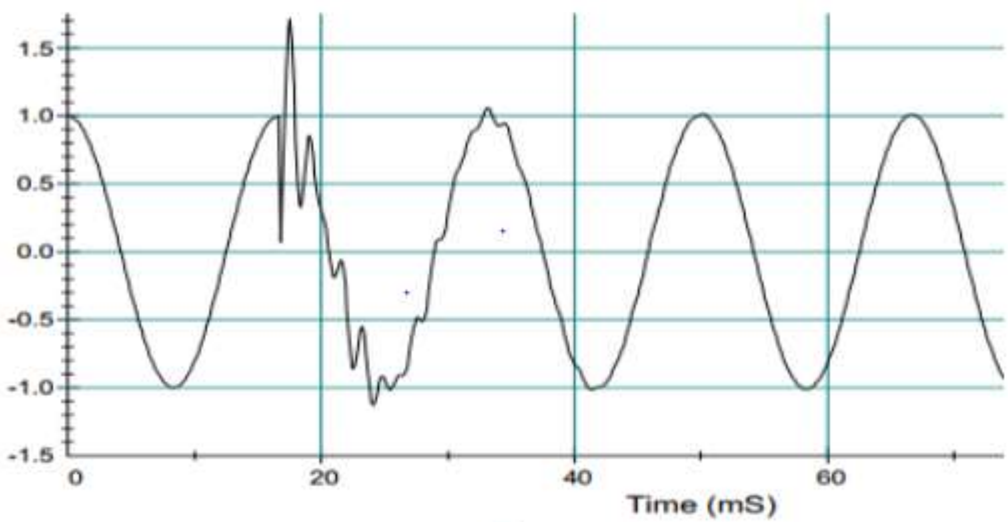


Figure 2.3: Oscillatory Transient [11]

a) High Frequency Transients

High frequency transients are oscillatory transients with a primary frequency component greater than 500 kHz and a typical duration measured in microseconds. These are often the result of a local system response to an impulsive transient. The transients can be in the high kilohertz range, last a few cycles of their fundamental frequency, and have repetition rates of several times per 50 Hz cycle (depending on the pulse number of the device) and magnitudes of 0.1 pu (less the 50 Hz component) [12].

b) Medium Frequency Transients

These are with a primary frequency component between 5 and 500 kHz with duration measured in tens of microseconds. Back-to-back capacitor energization results in oscillatory transient currents in the tens of kilo hertz. This phenomenon occurs when a capacitor bank is energized in close electrical proximity to a capacitor bank already in service. The energized bank sees the deenergized bank as a low impedance path (limited only by the inductance of the bus to which the banks are connected, typically small) [10]. Cable switching results in oscillatory voltage transients in the same frequency range. Medium frequency transients can also be the result of a system response to an impulsive transient.

c) Low Frequency Transients

Low frequency transients are transients with a primary frequency component less than 5 kHz and duration of from 0.3 to 50 milliseconds. These are frequently encountered on utility sub transmission and distribution systems and are caused by many types of events.

Capacitor bank energization results in an oscillatory voltage transient with a primary frequency between 300 and 900 Hz. The peak magnitude can reach 2.0 per unit, but is typically 1.3 to 1.5 per unit with duration of between 0.5 and 3 cycles depending on the system damping [10].

Oscillatory transients with principal frequencies less than 300 Hz can also be found on the distribution system. These are associated with transformer energization [10].

Due to the high frequency spectral contents of the oscillatory transients, they have undesirable effects of electromagnetic interference. High magnitude oscillatory transients can also damage electrical and electronic equipment due to the over voltage condition.

Voltage Variation

Electrical Power Quality is the degree of any deviation from the nominal values of the voltage magnitude and frequency. Power quality problems concerning voltage magnitude deviations can be in the form of voltage fluctuations, especially those causing flicker. The other voltage problems are the voltage sags, short interruptions and transient over voltages. Table 2.1 describes the demarcation of the various power quality issues defined by IEEE Std. 1159-1995 [18][17]. Tabular indication of voltage magnitude variation verses duration shown in the Table 2.1 below.

Table 2.1: Definition of voltage disturbance [source IEEE 1159:1195]

Event magnitude

	Transient	Swell		High Voltage
110%	Normal operating Voltage			
90%	transients	Voltage Sag		Under voltage
10%		momentary	temporary	Sustained interruption
		0.5 cycle	3 sec	1 minute

Event duration

2.2.1.2. Short-Duration Voltage Variation

This category encompasses RMS-voltage variations at power frequencies for a period of less than 1-minute. Short-duration voltage variations are caused by faulty conditions, energization of large loads, or intermittent loose connections in power wiring. The impact on the voltage during the actual fault condition is of the short-duration variation until protective devices operate to clear the fault [9].

Depending on the type of fault and the system conditions, the short duration voltage variation may be either a voltage sag (dip), voltage rise (swell), or interruption.

I. Voltage Sag

Voltage sag is a decrease to between 0.1 and 0.9 PU in RMS- voltage or current at the power frequency for durations of 0.5 cycles to 1 minute [19].

Voltage sags are usually caused by system faults, energization of heavy loads, or starting of large motors that draw very large amount of current during startup (an induction motor will draw 6 to 10 times its full load current during start-up). Possible effect of voltage sags would be system shutdown or reduce efficiency and life span of electrical equipment, particularly motors

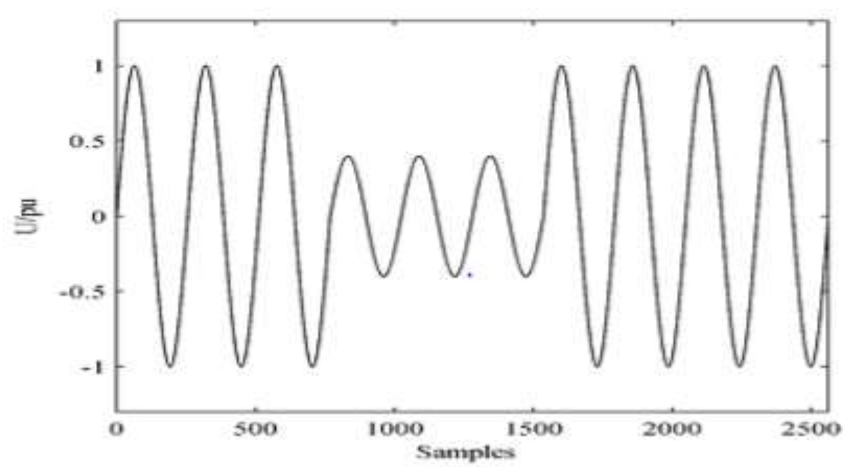


Figure 2.4: Voltage sag [12]

II. Voltage Swell

It is defined as an increase in RMS voltage or current to between 1.1 and 1.8 pu at the power frequency for durations of 0.5 cycle to 1 minute [19].

As with sags, swells are usually associated with system fault conditions such as the temporary voltage rise on the un-faulted phases during a single line-to-ground fault. Swells can also be caused by switching off a large load or energizing a large capacitor bank. Incorrect positions of transformer tap-changers may also introduce a short duration over voltage condition at times of light system loadings [15].

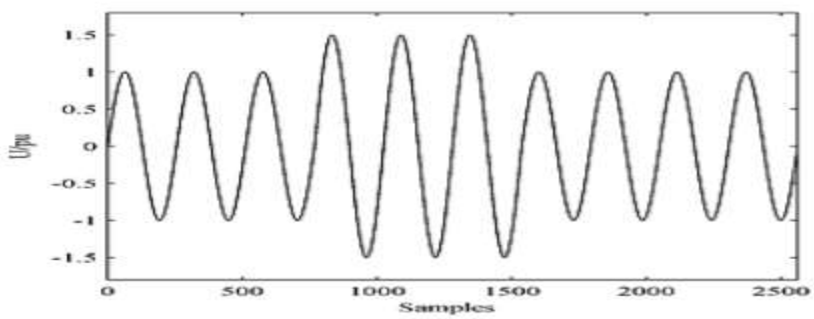


Figure 2.5: Voltage Swell [12]

III. Short Duration Interruption

An interruption occurs when there is a reduction of the supply voltage or load current to less than 0.1 PU for a duration not exceeding 1 minute [19].

Interruptions are the result of equipment failures, power system faults and control malfunctions. The interruptions are measured by their duration since the voltage magnitude is always less than 10 percent of nominal. The duration of an interruption due to a fault on the utility system is determined by the operating time of utility protective devices. Delayed reclosing of the protective device may cause a momentary or temporary interruption. The duration of an interruption can be irregular when it is due to equipment malfunctions or loose connections.

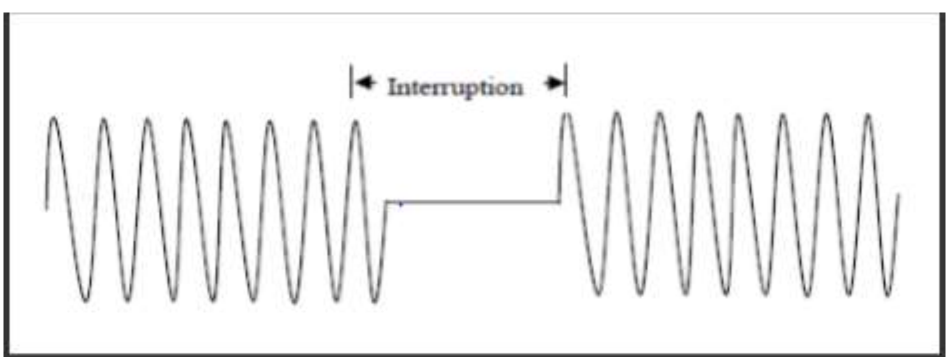


Figure 2.6 Short Duration Interruption [12],[15]

2.2.1.3. Long Duration Voltage Variation

Long duration voltage variations encompass root-mean-square (RMS) deviations at power frequencies for longer than 1 minute. ANSI C84.1 specifies the steady state voltage tolerances expected on a power system [11]. A voltage variation is considered to be long duration when the ANSI limits are exceeded for greater than 1 minute.

The voltage variations, which may be either of short duration or long duration, are deviations of the voltage magnitude which last for more than half a cycle. Those deviations can be characterized using graphs of magnitude versus duration. A lot of curves are developed among which the CBMA, ITIC, and SEMI curves are the major ones. The Computer Business Equipment Manufacturers Association (CBEMA) developed the chart, showing computer equipment sensitivity to sags and swells in curves of acceptable sag/swell amplitude versus event duration. The Information Technology Industry Council (ITIC) curve was later developed by a working group of CBEMA. In recent years, the ITIC curve has replaced the CBEMA curve in general usage for single phase 120V equipments. The SEMI curve on the other hand is developed for semiconductor processing equipment. The long duration voltage variation may be either of an under voltage, over voltage or sustained interruption as discussed below [8].

I. Under voltage

An under voltage is a decrease in the RMS ac voltage to less than 90% at the power frequency for a duration of longer than 1 minute. Under voltage is the result of switching on a load, a capacitor bank switching off or overloaded circuits.

The root cause of most problems of under voltage is that there is too much impedance in the power system to properly supply the load [20]. Therefore, the terminal voltage drops too low under heavy load due to the weak power system (high voltage drop on the transmission line). Conversely, when the source voltage is boosted to overcome the impedance, there can be an over voltage condition when the load drops too low.

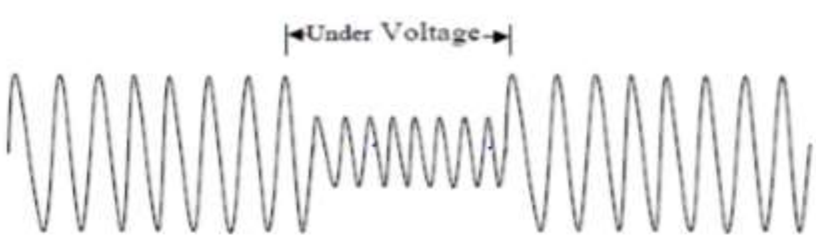


Figure 2.7 under voltage [12]

Undesirable effects of under voltage are mainly:

- Malfunctioning of certain equipment
- Equipment operation at reduced efficiency
- Reduced performance at the lower voltage
- Equipment damage due to intensified undesirable effects

II. Overvoltage

An over voltage is an increase in the RMS AC voltage greater than 110% at the power frequency for a duration longer than 1 minute.

It is generally not a result of system faults, but is caused by load variations on the system and system switching operations, such as switching off a large load, energizing a capacitor bank, and incorrect tap settings on transformers. Over voltages result because either the system is too weak for the desired voltage regulation or voltage controls are inadequate. The position of the transformer tap-changer can also be a cause of over voltage during light load conditions.

The major undesirable effects of over voltage are burning of customer equipment, insulation flashover of utility equipment, exceeding breakdown voltage in capacitors and increased power loss due to higher shunt current between transmission lines of the three phases.

The range of solution lies in either of the utility transmission and/or distribution system or end use customer system. Highly sensitive and expensive equipment of the end user may be provided with an over voltage protective device at the end use customer system.

However, it is both economical and inclusive to provide a reliable voltage regulation system at the utility transmission and/or distribution system. It is also the task of the utility to avoid over voltage conditions beyond some tolerable limits, so that the solution of that condition lies in the utility system.

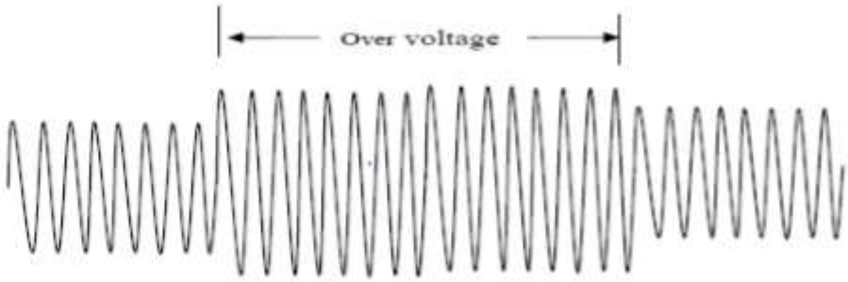


Figure 2.8: Over voltage [12]

III. Sustained Interruption

When the supply voltage drops to less than 10% of the nominal value for a period of time in excess of 1 minute, the long-duration variation is considered a sustained interruption. Interruptions can result from control malfunction, faults, or improper breaker tripping. Interruptions have their own impacts in the economic and social activities of a society and the country at large. Different industries and factories, public institutions and the likes are forced to stop their jobs due to electric power interruptions. The country's attractions for foreign investors are also affected by the electric power reliability and the consequent cost for power usage.

Interruption, which may be either of short duration or sustained, is characterized and quantified by the major reliability indices that are computed as follows:

Let C_i - Number of customer interruption

I_d - Duration of interruption

C_T - Total number of costumer interruption for a given time

r_i - Number of interruption within given time

SAIFI: System average interruption frequency index indicates how often the average customer experiences a sustained interruption over a predefined period of time [11]. It is the ratio of total customer interruptions to total number of customer served.

$$SAIFI = \frac{\sum_i C_i * r_i}{C_T} \quad \text{.......... (2.1)}$$

SAIDI: System average interruption duration index shows the total duration of interruption for the average customer during a predefined period of time [11]. It is commonly measured in customer minutes or customer hours of interruption.

$$SAIDI = \frac{\sum_i C_i * r_{id}}{C_T} \quad \text{.......... (2.2)}$$

CAIDI: Customer average interruption duration index represents the average time required to restore service [11].

$$CAIDI = \frac{\sum_i C_i * r_i}{\sum_i C_i} \quad \text{.......... (2.3)}$$

ASAI: Average system availability index represents the fraction of time (often in percentage) that a customer has received power during the defined reporting period [11].

$$ASAI = \frac{H_{ea}}{H_{ed}} * 100\% \quad \text{.......... (2.4)}$$

Whereas:

H_{ca} - Customer hour's service availability

H_{cd} - Customer hour's service demand

2.2.1.4. Voltage Unbalance

Voltage unbalance (voltage imbalance) is non-equalization of the three phase voltages. It is defined by the National Electrical Manufacturers Association (NEMA) as 100 times the absolute value of the maximum deviation of the line voltage from the average voltage on a three-phase system, divided by the average voltage [12].

Figure 2.9 phase unbalance [13]

Voltage unbalance (%) = $\frac{Vmax - Vav}{Vav} * 100$ …………………………….. (2.5)

Whereas:

V_{av} - Average three phase voltages

V_{max} - Voltage magnitude of extreme phase

Unbalance is more rigorously defined in some standards using symmetrical components as the ratio of either the negative or zero sequence components to the positive-sequence component. The most recent standards specify that the negative-sequence method be used. It is recommended that the voltage unbalances at the motor terminals not exceed 1%.

Common causes of voltage unbalance include:

- Unevenly distributed single-phase loads on the same power system
- Unidentified single-phase to ground faults
- An open circuit on the distribution system primary
- Unbalanced or unstable utility supply
- Faulty operation of power factor correction equipment
- Unbalanced transformer bank supplying a three-phase load that is too large for the bank.

Voltage unbalance degrades the performance and shortens the life of a three-phase motor [12]. Voltages unbalance at the motor stator terminals causes phase current unbalance far out of proportion to the voltage unbalance. Unbalanced currents lead to torque pulsations, increased vibrations and mechanical stresses, increased losses, and motor overheating, which results in a shorter winding insulation life.

Unbalanced voltage inputs decrease the efficiency of a motor that it results in wastage of energy and in turn money. A motor will run hotter when operating on a power supply with voltage unbalance. The additional temperature rise is calculated with the following equation [12]:

$$Percent\ additional\ temperature\ rise = 2 * (\%voltage\ unbalance)^2 \quad (2.6)$$

Winding insulation life is reduced by one-half for each 10°C increase in operating temperature.

2.2.1.5. Voltage Fluctuation

Voltage fluctuations are periodic variations of the voltage envelope or a series of random voltage changes that generally not exceed 10 percent of the nominal value.

Higher power loads that draw current which bears continuous and rapid variations in its magnitude can cause voltage fluctuations. The term flicker is derived from the impact of the voltage fluctuation on lamps such that they are perceived by the human eye to flicker. Although voltage fluctuation and flicker are often used interchangeably, strictly speaking, voltage fluctuation is an electromagnetic phenomenon while flicker is an undesirable result of the voltage on the humans' sense of seeing. One of the most common causes of voltage fluctuations on utility transmission and distribution systems is an arc furnace. On the other hand, during Ferro resonance the voltage magnitude may fluctuate wildly. End users at the secondary circuit may actually see their light bulbs flicker. Some electronic appliances may be very susceptible to such voltage excursions. Prolonged exposure can shorten the expected life of the equipment or may cause immediate failure.

Voltage flicker is measured with respect to the sensitivity of the human eye. Typically, magnitude as low as 0.5 percent can results in lamp flicker if the frequency is in the range of 6 to 8 Hz [3]. The simplest and generally most effective technique for compensating for existing or potential flicker is to provide a sufficiently stiff source of power so that the effect is negligible at the point where the flicker source is tapped off from the rest of the power distribution system. Compensatory methods are also used to emulate the stiff source. Series capacitors, thyristor switching of inductors with shunt capacitors (static var control), saturating shunt inductors and thyristor switched shunt capacitors may be used to maintain a relatively steady voltage at the tie point [11] [21].

A common solution to flicker-causing loads is to apply devices that are commonly called static VAr compensators. These can react within a few cycles to maintain a nearly constant voltage by rapidly controlling the reactive power production. Such devices are commonly used on arc furnaces, stone crushers, and other randomly varying loads where the system is weak and the resulting voltage fluctuations are affecting nearby customers.

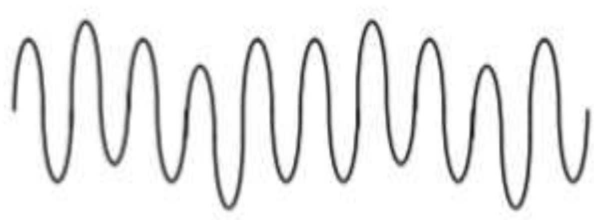


Figure 2.10: Voltage fluctuation [12]

2.2.1.6. Waveform Distortion

Waveform distortion is defined as any steady-state deviation of the voltage and/or current waveform from an ideal sine wave of the power frequency. The waveform distortion is principally characterized by its spectral contents which are investigated using a Fourier transform, expressed as [22].

$$F(t) = F_o + \sum_{h=2,4,6,\dots}^{\infty} (F_h \cos(h * \omega_o\, t + \emptyset_h)) + \sum_{h=1,2,3,\dots}^{\infty} (F_h \sin(h * \omega_o\, t + \emptyset_h)) \dots\dots (2.7)$$

Whereas:

F (t) - Voltage/Current waveform

F_O - Dc-component

F_h - spectral content

h - Harmonic number

ωo - Fundamental angular frequency and

$\emptyset h$ - Phase shift of the spectral content.

The effect of the harmonic contents on the distortion of the sinusoidal waveform can be observed from the above equation (2.7).

Usually, the voltage waveform has negligible harmonics that it can be assumed to be pure sinusoidal at the fundamental frequency. In that case, if the current drawn by the load has harmonics, the active power of the load is consumed only at the fundamental component of the load current. The remaining harmonics generate a reactive power. There are five primary forms of waveform distortion of which one or more events occur in a distorted voltage or current waveform.

I. DC Offset

DC offset is the dc voltage or current component of the spectral contents in an AC voltage or current. This occurs mainly as the result of a geomagnetic disturbance or asymmetry of electronic power converters, such as half-wave rectification.

Mathematically, DC offset of a voltage or current waveform F (t) is expressed as follows [23]:

$$\text{DC Offset} = \frac{1}{T}\int_0^T F(t)\,dt \quad \text{......} \quad (2.8)$$

Whereas:

T - Period of the voltage/current waveform and

F (t) - Voltage/Current waveform as a function of time, t

Direct current in ac networks can have a detrimental effect by biasing transformer cores so they saturate in normal operation. This causes additional heating and loss of transformer life.

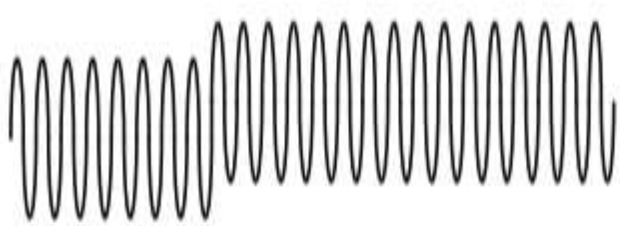


Figure 2.11: DC-offset wave forms [13]

II. Harmonics

Harmonics is defined as a sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency usually 50Hz or 60Hz. Harmonics is a growing problem for both electricity suppliers and users. Distorted waveforms can be decomposed into a sum of the fundamental frequency and harmonics. Harmonic distortion originates in the nonlinear characteristics of devices and loads on the power system [19].

Harmonics are sinusoidal voltage or current components of the waveform. They have frequencies that are integer multiples of the fundamental frequency. They are mathematically given as follows [24]:

$$H_n = \frac{1}{T}\int_0^T\{F(t)\cos(h\omega_o t + \varphi_n)\, dt \qquad (2.9)$$

Whereas:

H_n - n^{th} harmonic

T - Period of the voltage/current waveform

F (t) - Voltage/Current waveform as a function of time t

n - Harmonic number

ω_0 - Fundamental angular frequency

φ_n -Phase angle of the n^{th} harmonic

Harmonics originate from the nonlinear characteristics of devices and loads that require currents other than a sinusoid on the power system. The most common of these loads are static power converters, although several other loads are also non-sinusoidal, such as the following [10]:

- Arc furnaces and other arc-discharge devices, such as fluorescent lamps
- Resistance welders (impedance of the joint between dissimilar metals is different for the flow of positive vs. negative current)
- Magnetic cores, such as transformer and rotating machines that require third harmonic current to excite the iron
- Synchronous machines (winding pitch produces fifth and seventh harmonics)
- Adjustable speed drives used in fans, blowers, pumps, and process drives

- Solid-state switches that modulate the current-to-control heating, light intensity, etc.
- Switched-mode power supplies, used in instrumentation, PCs, televisions, etc.
- Static var compensators
- Electronic phase controllers
- High-voltage DC transmission stations (rectifiers of AC to DC and DC to AC invertors)
- Photovoltaic invertors converting DC to AC

Harmonic distortion levels are described by the complete harmonic spectrum with magnitudes and phase angles of each individual harmonic component. It is also common to use a single quantity, the total harmonic distortion (THD), as a measure of the effective value of harmonic distortion.

Mathematically, THD values of voltage and current, THDV and THDI respectively, are given as follows [11].

$$THD_V = \frac{\sqrt{\sum_{h=2}^{h} V_h^2}}{V_1} \quad \text{... (2.10)}$$

$$THD_I = \frac{\sqrt{\sum_{h=2}^{h} I_h^2}}{I_1} \quad \text{.. (2.11}$$

Whereas:

I_h - RMS of harmonic current components

I_1 - RMS current at the fundamental frequency

V (h) - RMS of harmonic spectral components and

V_1 - RMS voltage at the fundamental frequency

Total Demand Distortion (TDD) is another commonly used harmonic index used to quantify current distortion. It is similar to the THD concept except that the distortion is expressed as a percentage of some rated or maximum load current magnitude, rather than as a percentage of the fundamental current. It is expressed as follows [10].

$$TDD_1 = \frac{\sqrt{\sum_{h=2}^{h} I_h^2}}{I_L} \text{ ……………………………………………………….. (2.12)}$$

$$THD_V = \frac{\sqrt{\sum_{h=2}^{h} V_2^2}}{V_L} \text{……………………………………………………….. (2.13}$$

Whereas:

I_L - rated load-current.

V_L - RMS voltage at load terminal

Individual demand distortion can be expressed as follows:

$$IDD_h = \frac{I_h}{I_L} \text{ ………………………………………………………… (2.14)}$$

$$VDD_h = \frac{V_h}{V_L} \text{ …………………………………………………………(2.15)}$$

The degree to which harmonics can be tolerated is determined by the susceptibility of the load or utility equipment to harmonics. The least susceptible type of equipment is that in which the main function is in heating, as in an oven or furnace [11]. In this case, the harmonic energy generally is utilized and hence is quite completely tolerable. The most susceptible type of equipment is that whose design or constitution assumes a perfect (nearly) sinusoidal fundamental input. This equipment is frequently in the categories of communication or data processing equipment. A type of load that normally falls between these two extremes of susceptibility is the motor load.

Harmonic currents in a motor can give rise to a higher audible noise emission. On the other hand, the harmonics can result in mechanical oscillations in a turbine-generator combination or in a motor-load system, produce a resultant flux distribution in the air gap, which can cause or enhance phenomena called cogging (refusal to start smoothly) or crawling (very high slip) in induction motors [11].

A major effect of harmonic voltages and currents in rotating machinery (induction and synchronous) is increased heating due to iron and copper losses at the harmonic frequencies [18]. The harmonic components thus affect the machine efficiency and can also affect the torque developed. On transformers, current harmonics cause an increase in copper losses and stray flux losses, and voltage harmonics cause an increase in iron losses. The overall effect is an increase in the transformer heating. The transformer losses caused by both harmonic voltages and harmonic currents are frequency dependent. The losses increase with increasing frequency and higher frequency harmonic components can be more significant than lower frequency components in causing transformer heating. Current harmonics also result in increased audible noise of the transformer.

Harmonics have a degrading effect on the performance of power transmission cables, capacitors, electronic equipment communication system, utility metering, and switch gear and relaying.

On the load itself, harmonics have the undesirable impact of decreasing the power factor. Therefore, power factor is composed of two components [25] [21]. The first component is due to the phase shift between the sinusoidal input voltage and current at the power frequency induced by the inductive or capacitive nature of the load and is referred to as the Displacements Power actor (DPF).

$$Displacement\ power\ factor = \cos(\varphi) \quad (2.16)$$

The second component is due to non-linear characteristics of the load and is referred to as the distortion factor.

$$Distortion\ Factor = \frac{1}{\sqrt{1+THD^2}} \quad (2.17)$$

The load's power factor is therefore the product of its distortion factor and its displacement power factor given as follows:

$$PF = \frac{1}{\sqrt{1+THD^2}}\cos(\varphi) \quad (2.18)$$

Whereas:

P.F - Load's power factor

φ - The displacement angle between the fundamental current and voltage

THD - Total current distortion of load current.

Increased neutral current in 3-phase wye connected distribution networks is another undesirable effect of harmonics. In a 3-phase wye connected system, the neutral current is dominated by any dc-component and odd tripled harmonics which is expressed as (2.17):

$$I_{h(rms)} = \sqrt{I_o + \sum_{k=3,9,12,....}(I_K^2)} \text{ .... (2.19}$$

Whereas:

(rms) - RMS current of the neutral wire

I_O - Dc-component of the phase current

I_k - Tripled harmonic

III. Inter harmonics

Inter harmonics are defined as voltage and/or current components having frequency that are not integer multiples of the frequency at which the supply system is designed to operate (fundamental frequency). They can appear as discrete frequencies or as a wideband spectrum. Inter harmonics are generally the result of frequency conversion activities. The main sources of inter harmonics are static frequency converters, cyclic- converters, induction furnaces, and arcing devices. Power line carrier signals can also be considered as inter harmonics.

Inter harmonic currents can excite resonances on the power system as the varying inter harmonic frequency becomes coincident with natural frequencies of the system. The higher frequency inters harmonic signals affect the power-line-carrier signaling. They can also induce visual flicker in fluorescent lamps and other arc lighting as well as in computer display devices [9].

IV. Notching

A periodic voltage disturbance caused by normal operation of power electronic devices when current is commutated from one phase to another is notching. It tends to occur continuously and can be characterized through the harmonic spectrum of the affected voltage [19].

Notching is a drop in voltage as close to zero as permitted by system impedance caused by a momentary short circuit between two phases, during current commutation in the normal operation of power electronic devices. Figure 2.9 shows an example of voltage notching occur when the current commutates from one phase to another of the notches from a three-phase converter that produces continuous dc current [12].

Figure 2.12: Notch wave forms [12].

Notching can ordinarily be characterized by its notch-depth and total notch area. Since notching occurs periodically, it can also be characterized through the harmonic spectrum of the affected voltage. However, the frequency components associated with notching are generally quite high and may not be readily characterized with measurement equipment normally used for harmonic analysis.

V. Noise

Noise is defined as unwanted electrical signals with spectral content lower than 200 kHz superimposed upon the power system voltage or current in phase conductors, or found on neutral conductors or found on neutral conductors or signal line

Noise in power systems can be caused by power electronic devices, control circuits, arcing equipment, loads with solid-state rectifiers, and switching power supplies. Noise problems are often exacerbated by improper grounding that fails to conduct noise away from the power system. Basically, noise consists of any unwanted distortion of the power signal that cannot be classified as harmonic distortion or transients. Noise disturbs electronic devices such as microcomputer and programmable controllers. The problem can be mitigated by using filters, isolation transformers, and line conditioners [19].

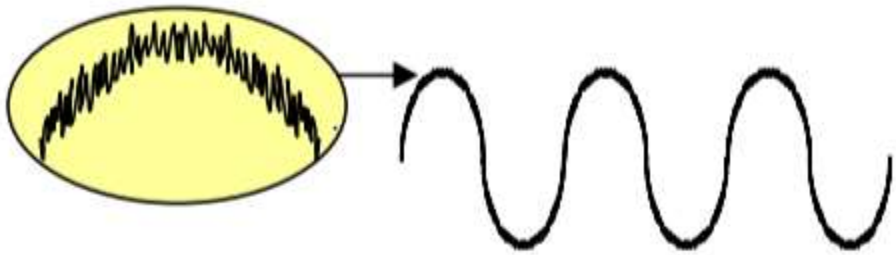


Figure 2.13: Noise waveform [12]

2.2.1.7. Power Frequency Variation

Power frequency variations are deviations of the power system fundamental frequency from it specified nominal value. The power frequency of a power system is directly related to the rotational speed of the generators supplying the system. Frequency variations occur as the dynamic balance between load and generation changes. The size of the frequency deviation and its duration depend on the load characteristics and the response of the generation control system to load changes.

Frequency variations that go outside of accepted limits for normal steady-state operation of the power system can be caused by faults on the bulk power transmission system, a large block of load being disconnected or a large source of generation going off-line. On modern interconnected power systems, significant frequency variations are rare.

Frequency variations of consequence are much more likely to occur for loads that are supplied by a generator isolated from the utility system. In such cases, governor response to abrupt load changes may not be adequate to regulate within the narrow bandwidth required by frequency-sensitive equipment. Frequency variations may cause a motor to run faster or slower to match the frequency of the input power [26].

As a solution to the problem of a constantly changing power frequency, each generating unit of the country should utilize effective governor control mechanisms to maintain the power frequency within the permissible range.

Figure 2.14: Power frequency variations [12]

2.2.2. Power Quality Problem Characterization

Electrical characteristics of the problems are discussed along with the system response at different conditions at this step. The problems listed above can be described further by listing appropriate characteristics. For steady-state phenomena, the following characteristics can be used to describing the power quality problem:

- Amplitude
- Frequency
- Spectrum
- North depth and
- Notch area.

For the non-steady state phenomena, the following characteristics are required for describing the power quality problem.

- Rate of rise
- Amplitude
- Frequency
- Spectrum
- Duration and
- Rate of occurrence [8].

Moreover, all the potential causes of the power quality problems are identified including their natures of occurrence and levels of severity. It is also that impacts of the power quality disturbances on utility and end-user equipments are discussed.

2.2.3. Collection and Measurement of Data

Having identified the nature of causes of the power quality problems, the point that from where and when to take measurements are decided at this step.

The power quality monitoring period should capture a complete power period, an interval in which the power usage pattern begins to repeat itself. Measurements are also taken while all the machines of the industry are working at the same time, to see the cumulative characteristics of the industrial loads. For instance, an industrial plant may repeat its power usage pattern each day, or each specified period depending on the largeness of the plant and the time-pattern of operation of its machines. The task of data collection is accomplished through direct measurement, from recorded data and equipment/ wiring specifications, and by asking the personnel who is in charge.

To assess the quality of electric power supplied to industrial plants and power quality disturbances of the industries entering into the electric power system, monitoring will typically be performed at the service entrance points of the industry. The Points of Common Coupling (PCC) are the tapping points on the 15 kV feeders to the plant. However, as the distance, and in turn the line impedance, from the tapping point to the primary of the service transformers is negligible, the primaries of service transformers are taken as points of common couplings. The monitoring locations and PCC are shown in the figure 2.3 [8].

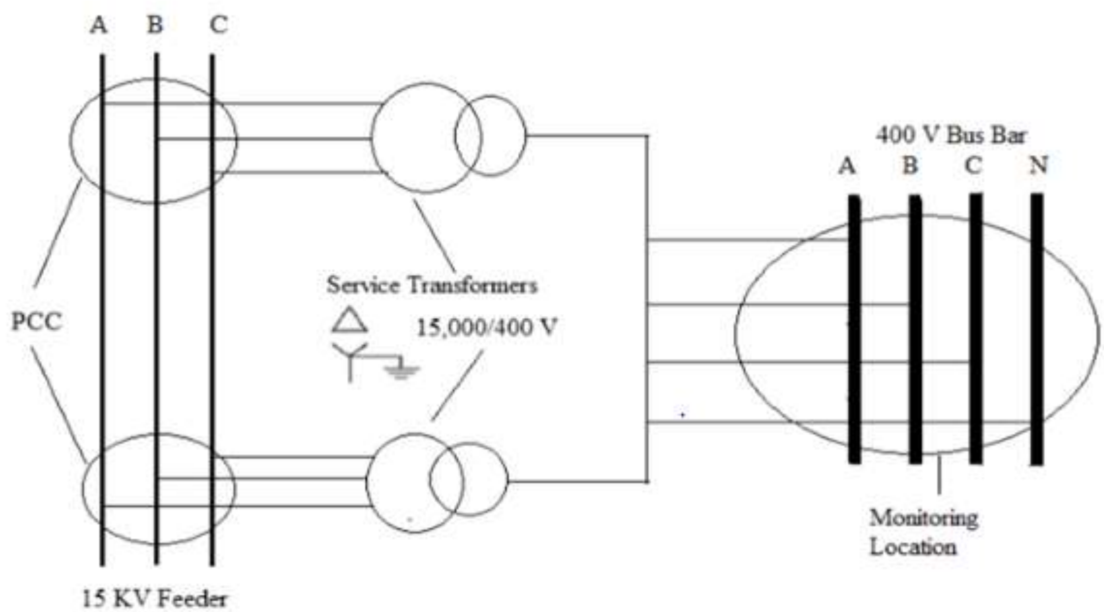


Figure 2.15 Monitoring location and point of common coupling [9][15].

2.2.4. Data Analysis and Comparison with Standard Values

Data obtained through measurements and from recorded sources are analyzed. Having made suitable analysis, the data obtained are computed and compared with permissible values set by some standards such as IEEE recommended practice for power quality monitoring, IEEE recommended practice for harmonic control, National Equipment Manufacturers Association (NEMA) and American National Standards Institute (ANSI) [11].

The computed values above are utilized to benchmark the result of the power quality assessment with a standard tolerable value. The benchmarking process is made with the Computer Business Equipment Manufacturers Association (CBEMA) or Information Technology Industry Council (ITIC) curves for voltage variation, the harmonic voltage and current limits of IEEE Std. 5191992, the voltage fluctuation curves, and the derating curve for unbalanced operation [11].

2.2.5. Solutions to the Power Quality Problems

Once the cause and electrical characteristics of a certain power quality problem are identified, the solution to those power-quality-problems will be discovered. At this step, the technical feasibility of alternative solutions is also investigated through electrical modeling and simulation to see how much the problem is solved and the system performance at different working conditions. Once the range of technical solutions are identified, economic analysis need to be performed to decide whether or not application of the specific solution has economic advantage. However, when regulatory limits are violated, solutions are recommended to the plant not to enable the plant to earn economic advantages but to meet regulations.

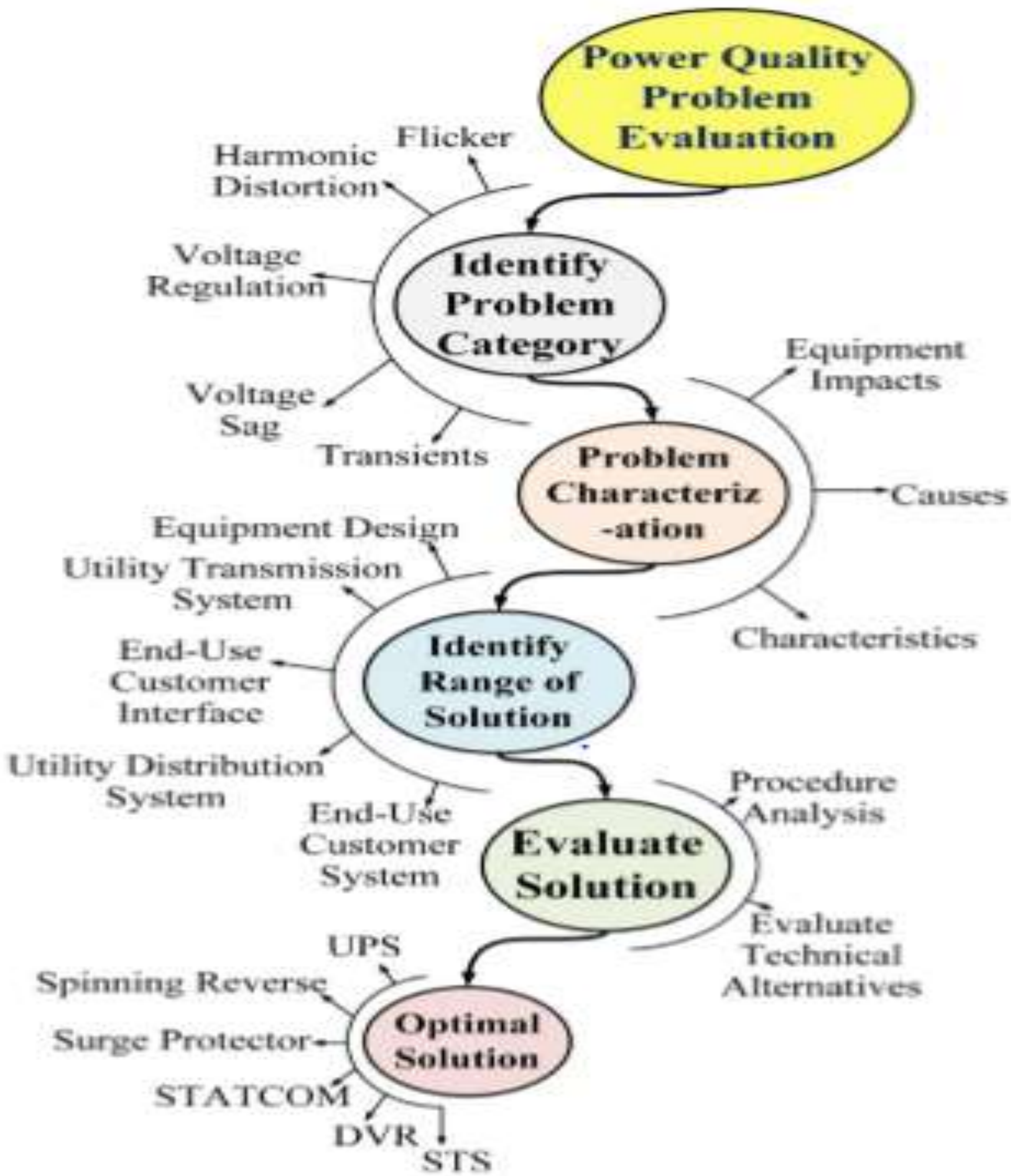


Figure 2.16 Flow diagrams for evaluation of power quality problems, solution of a problem comes through a process starting with identification of the problem category [27].

2.3. LITERATURES REVIEW

Power quality is a set of electrical boundaries that allows a piece of equipment to function in its intended manner without significant loss of performance. In other words, power quality problem is any power problem manifested in voltage, current, or frequency deviations that result in failure or mis-operation of customer equipment. IEEE Standard 1159 defines power quality as the concept of powering and grounding sensitive equipment in a manner that is suitable for the operation of that equipment [1].

According to IEEE100-1992, an interruption to service is the isolation of an electrical load from the system supplying that load, resulting from an abnormality in that system. The abnormality in the system can either be a malfunction of a system component, a fault or a system operation due to maintenance or repair. Interruptions, independent from the cause, are generally undesired, as they leave energy unnerved and customers without service. Most of the time, interruptions occur because the system is reacting to a fault. A fault or short-circuit is defined by IEEE100-1992 as an abnormal connection of relatively low impedance, whether made accidentally or intentionally, between two points of different potential [28] [29]. Over-loading, earth fault and short circuits are the major cause of interruptions in distribution system

There are many principal causes of electrical failure; such as dust and dirt accumulation, moisture, lose connections, and friction of moving parts, aging of conductors, clearance from trees and limbs and structures, equipment over loading, frequency and so on. An effective maintenance program should aim to minimize these effects by keeping equipment clean and dry, keeping connections tight [30].

Now-a-days the customers use large number of devices at their installations that consist of power electronics. The residential customers use different domestic appliances such as televisions, video cassette recorders, microwave ovens, personal computers, heating-ventilation-air conditioning equipments, dishwashers, dryers etc. The business and office equipments include workstations, personal computers, copiers, printers, lighting etc. On the other hand, the industrial customers use programmable logic controllers (PLC), automation and data processors, variable speed drives, soft starters, inverters, computerized numerical control tools and so on. Presently, many customers use compact fluorescent lamps (CFL) for lighting their installations. Many of these devices are quite sensitive to power quality disturbances [3].

The studies and surveys in different countries around the world have been done to estimate the impacts of poor power quality to the customers. Manufacturers of electrical and electronic equipments and end users of electric power are challenging utilities to upgrade the quality of their electric power supplies. Utilities on the other hand, are forcing end-users to mitigate the quality of electric current they draw. Disturbances like transients, short duration voltage variations (sags and swells), voltage unbalance and harmonics were monitored [1]. The significant change in components of power systems from being largely linear to partially nonlinear has meant that sensitivity of equipment to disturbances has increased. Power quality problems can be caused by electrical system design, improper grounding techniques, harmonics or simply just load interactions. Some symptoms caused by power quality problems include malfunction of equipments, high failure rate of electronic systems, over heating of transformers, motors and capacitor bank failures, inaccuracy of testing and measuring equipments and lights dimming or blinking.

Table 2.2 summery of power quality variation categories [31]

Power Quality Variations	Method of Characterizing	Typical Causes	Example Power Conditions Solutions
Impulsive Transients	Peak magnitude, Rise Time, Duration	Lighting, Electro-Static Discharge, load Switching	Surge Arrestors, Filters, Isolation Transformers
Oscillatory Transients	Waveforms, Peak Magnitude, Frequency Components	Line/cable Switching, Capacitor Switching, load Switching	Surge Arrestors, Filters, Isolation Transformers
Sags/Swells **Interruption**	RMS vs. Time, Magnitude, Duration Duration	Remote System Faults System protection (Breakers, Fuses), Maintenance	Ferroresonant Transformers, Energy Storage Technologies, UPS, Energy Storage Technologies, UPS, Backup Generators
Under voltages/ over voltages	RMS vs. Time, Statistics	Motor Starting, Load Variations	Voltage Regulators, Ferroresonant Transformers
Harmonic Distortion	Harmonic Spectrum, Total Harm. Distortion, Statistics	Nonlinear Loads, System Resonance	Filters(active or passive), Transformers(cancellation or zero sequence components)
Voltage Flicker	Variation Magnitude, Frequency of Occurrence, Modulation Frequency	Intermittent Loads, Motor Starting, Arc Furnaces	Static Var Systems

The term power quality refers to the characteristics of the voltage, frequency and current at a given time and location on a power system. Power quality is the measure, analysis and improvement of bus voltage, usually a load bus voltage to maintain that voltage to sinusoidal at rated voltage and frequency.

Harmonic distortion exists due to the nonlinear characteristics of devices and loads on the power system. Harmonic distortion levels can be characterized by the complete harmonic spectrum with magnitudes and phase angles of each individual harmonic component. Harmonic currents result from the normal operation of nonlinear devices on the power system. Current distortion levels can be characterized by a total harmonic distortion. For instance, many adjustable speed drives will exhibit high total harmonic distortion values for the input current when they are operating at very light loads.

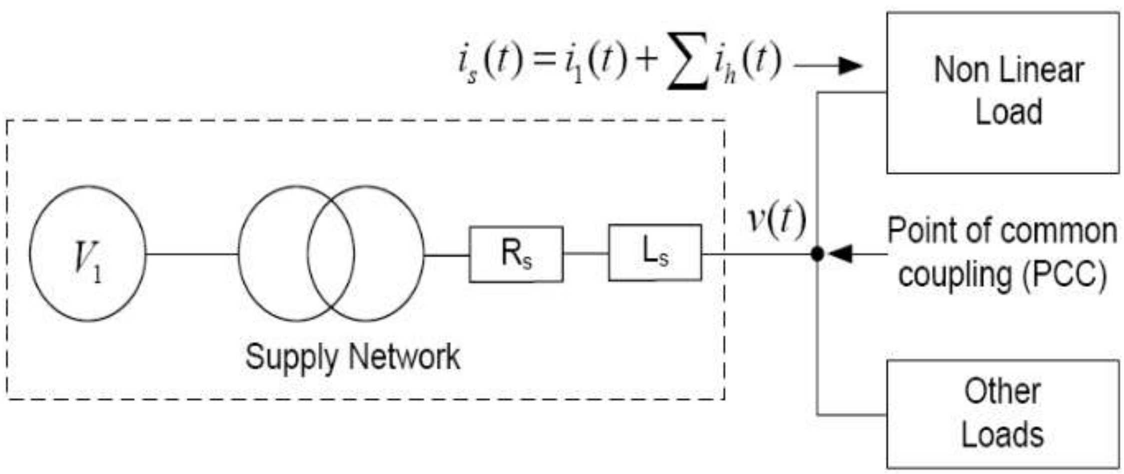


Figure 2.17 Harmonic distortion

The power system frequency is directly related to the rotational speed of the generators on the system. At any instant, the frequency depends on the balance between the load and the capacity of the available generation. Frequency variations that go outside of accepted limits for normal steady state operation of the power system are normally caused by faults on the bulk power transmission system, a large block of load being disconnected, or a large source of generation going off-line. Frequency variations that affect the operation of rotating machinery, or processes that derive their timing from the power frequency, are rare on modern interconnected power systems. Power factor is a way to measure the amount of reactive power required to supply an electrical system and an end-user's facility. Inductive loads require reactive power and constitute a major portion of the power consumed in industrial plants. Motors, transformers, fluorescent lights, arc welders, and induction heating furnaces all use reactive power. Nonlinear loads often shift the phase angle between the load current and voltage, require reactive power to serve them, and cause low power factor. Apparent power or demand power is the total power needed to serve a load. It is the vector sum of reactive and active power. A poor power factor due to inductive loads can improved by the addition of power factor correction equipment, but a poor power factor due to a distorted current waveform requires a change in equipment design or the addition of harmonic filters. The problem with low power factor exceeds the commonly known consequences, such as power, energy, and voltage losses. Along with these consequences, the active power produced will decrease. Since the current is inversely proportional to the power factor, it can be proved that power losses are inversely proportional to the square of the power factor.

$$P_{loss} = I^2 R \qquad \text{...(2.20)}$$

To overcome the problem related to the power quality custom power device is introduced. A number of power quality problem solutions are providing by custom devices. The fast response of D-STATCOM makes it efficient solutions or improving the power quality in distribution system. Under the heavy load conditions, a significant voltage drop may occur in the power system. The main application of D-STATCOM exhibit high speed control of reactive power to provide voltage stabilization in power system. The D-STATCOM protect the distribution system from voltage sags, flicker caused by reactive current demand [22] [32].

DSTATCOM is to suppress voltage variation and control reactive power in phase with system voltage. It can compensate for inductive and capacitive currents linearly and continuously.

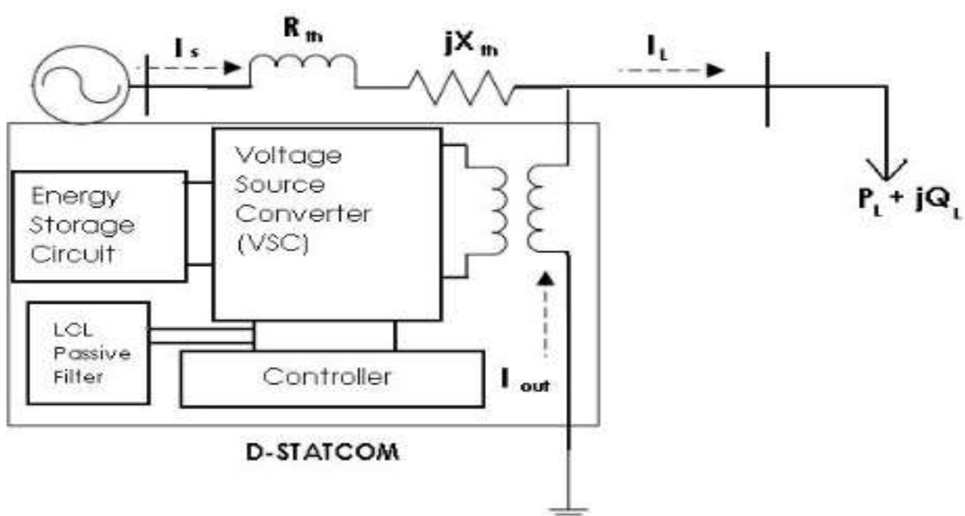


Fig 2.18 Schematic diagram of D-STATCOM

Advantages of DSTATCOM are the response is much faster to changing system conditions, does not contribute to short circuit current, has a symmetric lead-lag capability, has no moving parts and hence the maintenance is easier and it has no problems of loss of synchronism under a major disturbance. Disadvantage of DSTATCOM is it has a high cost level due to complex system setup. The applications of DSTATCOM area power factor improvement, current harmonic compensation, load current balancing and flicker effect compensation. The Other methods to overcome the power quality problem are as follows:-

1. Uninterruptible Power Supply (UPS)

UPS is the most common solution for all types of RMS voltage variations (sags, swells, under voltage, overvoltage, and interruptions). A UPS uses stored energy in a battery to provide load power when the normal power supply falls outside a defined voltage range. There are three major UPS topologies each providing different levels of protection:

- Off-Line UPS (also called Standby)
- Line-Interactive UPS
- True On-Line UPS

I. Off-Line UPS (Standby)

Low cost solution for small, less critical, stand-alone applications such as PLC, PC and peripherals. Off-line UPS systems supply the load directly from the electrical utility with a limited conditioning. The unit provides power to the load from the battery during sags, swells and power interruptions. They have some noise suppression through a filter/surge suppressor module [33].

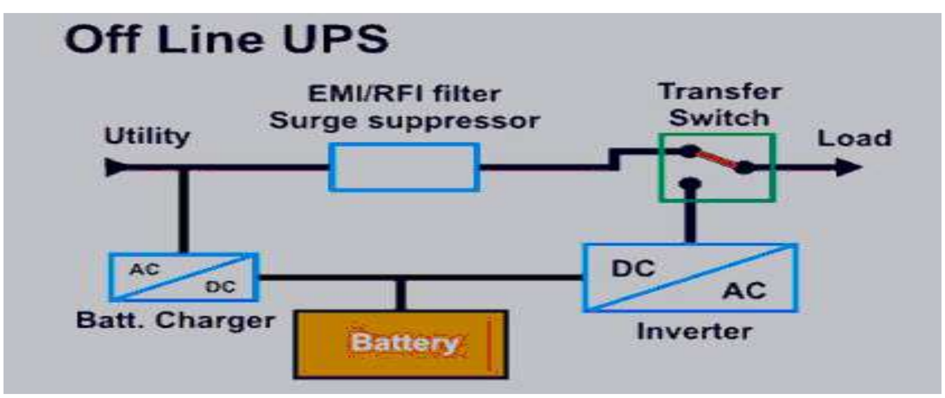


Figure 2.19 Block Diagram of Off-Line UPS

Advantages of off-line UPS are high efficiency, low cost and high reliability. The main disadvantage is that protection from high and low voltages is limited by the battery capacity. It also, poor output voltage regulation and noticeable transfer time. To keep unit cost low, most off-line units utilize step-sine wave outputs when on battery power [33].

II. Line-Interactive UPS

Line-Interactive UPS provides highly effective power conditioning plus battery back-up. These units are ideal in areas where voltage fluctuations are frequent. The defining characteristic of line-interactive models is they can regulate output voltage without depleting the battery.

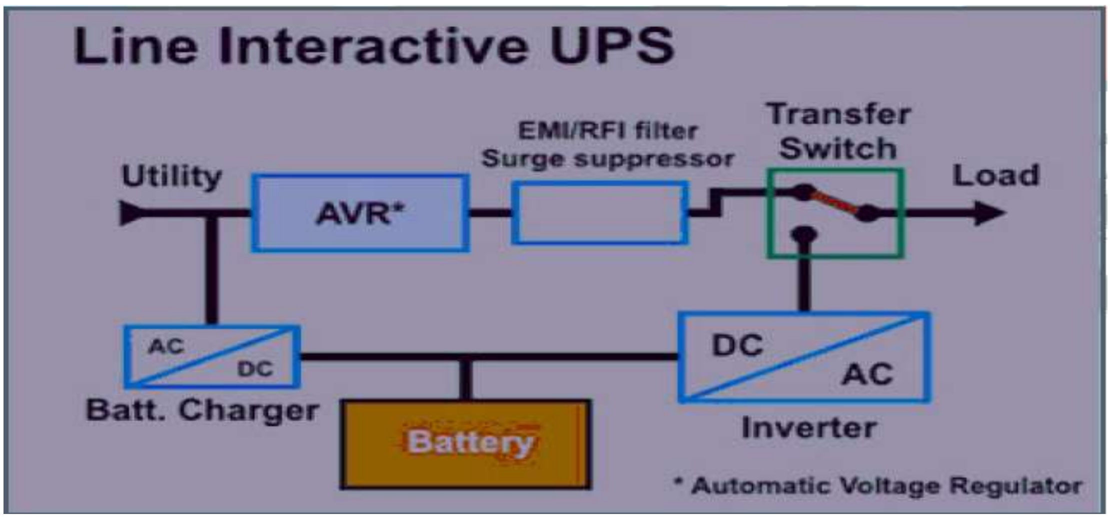


Figure 2.20 Block Diagram of Line-Interactive UPS

Advantages are good voltage regulation and high efficiency. Disadvantages are noticeable transfer time and difficulty in comparing competing units. The output waveform can be either a sine wave or step-sine wave depending on the manufacturer and model [33].

III. True On-Line UPS

True On-Line UPS provides the highest level of power protection, conditioning and power availability. True on-line technology, also called double conversion is unique in that the power is converted from AC utility to DC for battery charging and to power the inverter. The DC is then converted back to AC to power the critical load [33].

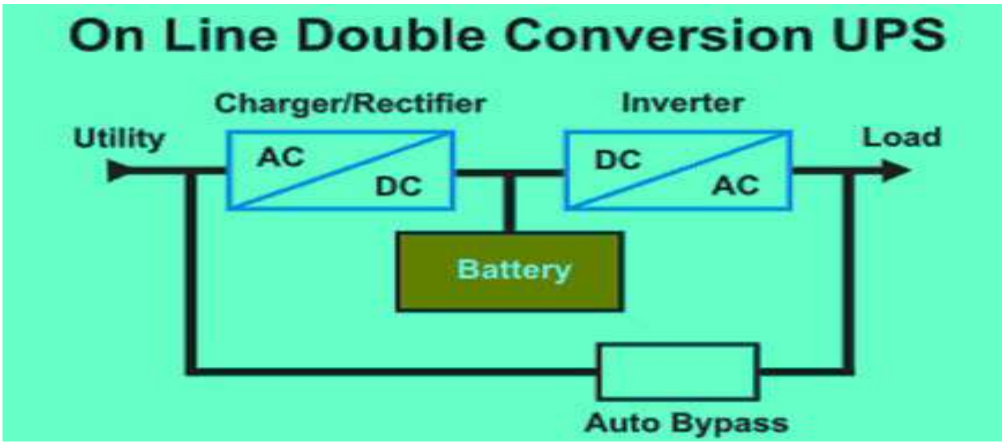


Figure 2.21 Block Diagram of True On-Line UPS

Advantages of the On-line UPS include the elimination of any transfer time and superior protection from voltage fluctuations. Voltage regulation is achieved by continuously regenerating a clean sine wave. Disadvantages are lower efficiency and higher audible noise[33].

2. Static Series Compensator

Commercially, static series compensator is known as Dynamic Voltage Restorer. It is a high-speed switching power electronic controlling device. It also, known as series voltage booster. DVR is a series connected custom power device, designed to inject a dynamically controlled voltage in magnitude and phase in to distribution line via coupling transformer to correct load voltage [33].

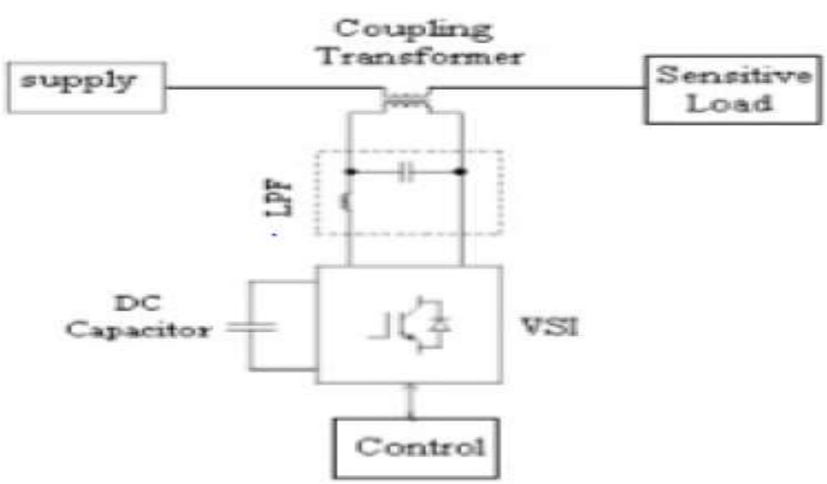


Figure 2.22 Generalized block diag. of DVR

It consists of an energy storage device, a boost converter (dc to dc), voltage source inverter, ac filter and coupling transformer, connected in series. Here dc capacitor bank is used as energy storage device, which is interface by a boost converter. The boost converter regulates the voltage across the dc link capacitor that uses as a common voltage source for the inverters. The inverter generates a compensating voltage, which is inserted into distribution system through series matching transformer. In the case of voltage regulation, the DVR controllers generate a reference voltage, and compare it with source voltage and inject synchronized voltage to maintain the load voltage constant. The energy storage devices provide the required power to synchronized injected voltage. The ac filter overcomes the effects on winding of coupling transformer and switching losses of control signal generating techniques for VSI [33]. Therefore, DVR is supposing as an external voltage source of controlled amplitude, frequency, and phase angle. The aim of using DVR is to maintain the amplitude, and phase angle of fixed load voltage.

3. Unified Power Quality Conditioner (UPQC)

UPQC is an equipment which is used for compensate for voltage distortion and voltage unbalance in a power system. Also, it is used to compensate for load current harmonics. UPQC is a combination of a Shunt Active power filter and Series Active power filter. Here Shunt Active power filter (APF) is used to compensate for load current harmonics and make the source current completely sinusoidal and free from harmonics and distortions. The Series APF is used to mitigate for voltage distortions and unbalance which is present in supply side and make the voltage at load side perfectly balanced, regulated and sinusoidal.

4. Static VAR compensators (SVR)

Static VAR compensators use a combination of capacitors and reactors to regulate the voltage quickly. Solid-state switches control the insertion of the capacitors and reactors at the right magnitude to prevent the voltage from fluctuating. The main application of SVR is the voltage regulation in high voltage and the elimination of flicker caused by large loads (such as induction furnaces) [33].

5. Voltage source converters (VSCs)

Voltage source converters generate a sinusoidal voltage with the required magnitude and phase, by switching a dc voltage in a particular way over the three phases. This voltage source can be used to mitigate voltage sags and interruptions [33].

CHAPTER THREE

3. DATA COLLECTION, ANALYSIS OF POWER QUALITY PROBLEMS AND PROPOSED MITIGATION TECHNIQUES

3.1. Introduction

In chapter two background of different power quality problems and Literatures have been discussed. The major causes of problems and options to reduce them are highlighted on the bases of Literature Review. Under this chapter, data which has been collected and is being analyzed. After analysis of the data, mitigation solutions have been proposed for further assessment. The collected data have been analyzed and the levels of the disturbances have been compared to international standards.

The schematic diagram of Addis Center distribution substation is shown below in figure 3.1. This distribution substation has only one 132kV radial incoming feeder from Kality substation and there are six (6) number of 15kV outgoing feeder. The six (6) outgoing feeders in the Addis center distribution substation are namely, ADC-4, ADC-5, ADC-7, ADC-8, ADC-11, and ADC-15. Data have been collected at Addis center substation from the secondary winding of transformer with respective ratings of 50000KVA, 15/0.4KV and tapping impedance.

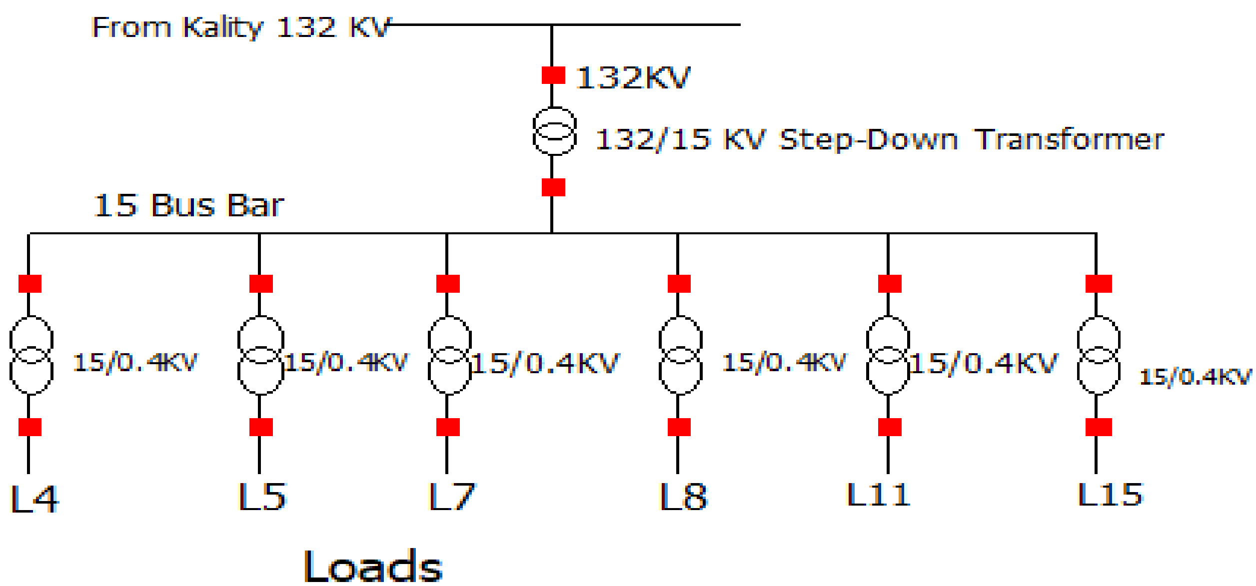


Figure 3.1 outgoing loads of Addis Center distribution substation

3.2. Data Collection and Analysis

3.2.1. Data Collection and Analysis from Addis Center Substation

In this sub topic only data collected from Addis Center distribution substation is considered. The incoming feeders are connected in radial fashion. This distribution substation has only one 132kV radial incoming feeder from Kality substation and there are six (6) number of 15kV outgoing feeder of loads with outgoing lines CB shown in figure 3.2, 3.3 and 3.4 below. The substation has one power transformer having 50MVA with 132/15kV substation loads. The voltage is then further reduced by distribution transformers to the utilization voltages of 400/380 volts three-phase or 220 volts single-phase supply required by most users. Once the voltage has been lowered at the distribution substation, the electricity flows to industrial, commercial, and residential centers through the distribution system. Conductors called feeders reach out from the distribution substation to carry electricity to customers. At key locations along the distribution system, voltage is lowered by distribution transformers to the voltage needed by customers or end-users. The Figure 3.2 shows below 132KV incoming from Kality substation line.

Figure 3.2 the 132KV in coming from Kality substation.

Figure 3.3 the Outgoing lines of Addis Center distribution substation.

Figure 3.4 the Addis Center distribution substation 6 outgoing lines CBS.

The figure 3.5 below shows approximately the distance of outgoing lines from the Addis Center distribution substation. Previously, eleven Express ways were designed out from ADC substation, but five of them are not in service currently due to the damage caused during the construction work of LRT (Figure 3.5). Therefore, supply lines from ADC are mainly conducted with conventional outgoing lines of feeders.

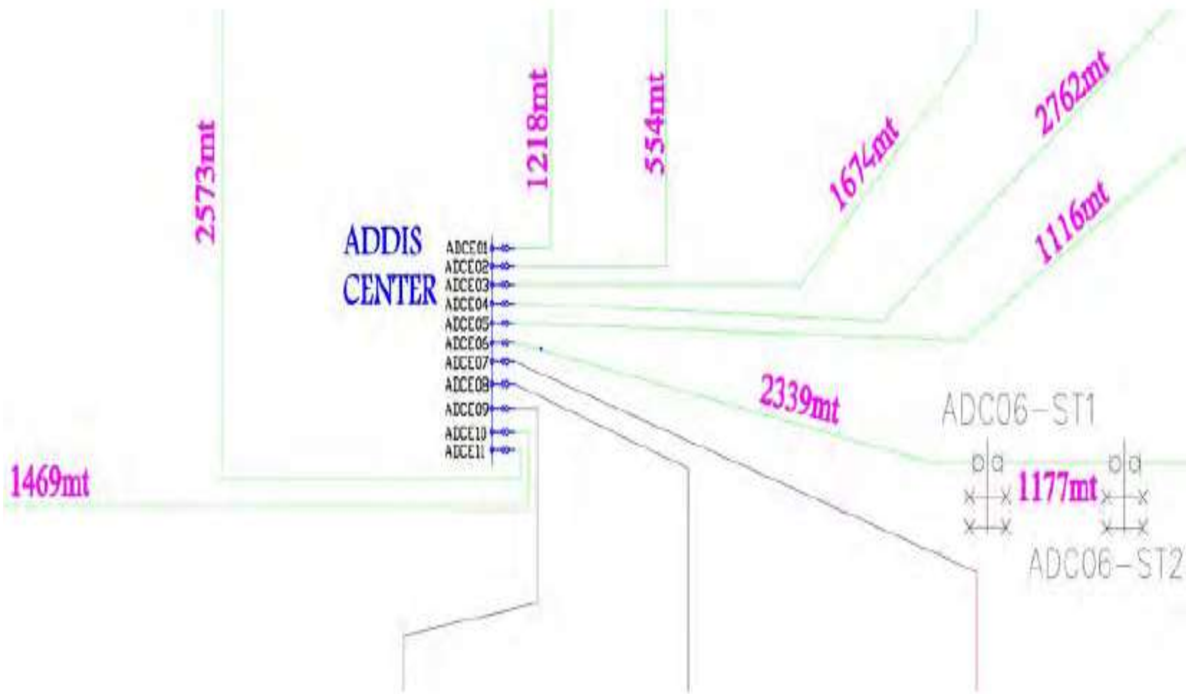


Figure 3.5 Status of Expressway draw from Addis Center distribution substation.

Data collected from ADC distribution substation are shown in Table 3.1, 3.2, 3.3, 3.4, 3.5, 3.6 and 3.7 respectively. The substation has 6 feeders as shown in the above one line diagram and the data for the substation is given in Table 3.1 shown below [34].

Table 3.1 Data for Addis Center Distribution Substation.

Name of substation	Lines			Transformer Quantity	Voltage level (KV)	Transformer capacity (MVA)	Total substation capacity (MVA)
	HV	MV	LV				
Addis Center	2	0	4	1(one)	132/15	50	50

Table 3.2 Addis Center Distribution Substation and feeders data.

No	Name of substation	Feeder name	Voltage level (KV)	Feeder load (A)	Feeder load (MW)	Feeder load (MVAr)	Feeder load (MVA)	Number of customers
1	Addis center	ADC-4	15/0.4	166	5.31	2.88	6.47	8428
2	Addis center	ADC-5	15/0.4	115	2.99	1.69	5.18	5746
3	Addis center	ADC-7	15/0.4	186	6.83	3.35	7.37	10343
4	Addis center	ADC-8	15/0.4	59	2.53	1.49	3.66	8428
5	Addis center	ADC-11	15/0.4	184	5.78	3.3	7.28	10343
6	Addis center	ADC-15	15/0.4	186	4.83	3.35	6.37	6512
Total				898	28.27	16.01	36.33	49,800

Table 3.2 above shows the share of load and number of customers connected to the feeders of Addis Center substation.

Table 3.3 Data profile at peak and minimum load recorded in September 2019

BAY LINE	Peak Load				Minimum Load			
	Power (MW)	Current (A)	Date	Time	Power (MW)	Current (A)	Date	Time
Kality I Incoming Line	14	70	6/9/2019	10:00PM	4	25	13/9/2019	04:00AM
Transformer I		1015	11/9/2019	10:00PM		330	13/9/2019	04:00AM
15 KV outgoing line(capacity 50MW)								
Line-4	7.24	285	11/9/2019	10:00AM	4.32	65	13/9/2019	04:00AM
Line-5	4.86	65	18/9/2019	9:00AM	2.65	20	13/9/2019	04:00AM
Line-8	7.24	239	16/9/2019	09:00AM	4.56	92	18/9/2019	03:00AM
Line-11	8.01	277	11/9/2019	10:00M	4.45	80	18/9/2019	04:00AM
Line-15	5.34	201	18/9/2019	10:00PM	3.24	40	1/9/2019	02:00AM

The Table 3.3 above shows the Power (MW) and Current (A) data incoming from Kality and 15 kV outgoing lines. The load Current at pear and minimum load data recorded in September 2019 with date and time indicated correspondingly.

Table 3.4 Data profile at peak and minimum load recorded in October 2019

BAY LINE	**Peak Load**				**Minimum Load**			
	Power (MW)	**Current (A)**	**Date**	**Time**	**Power (MW)**	**Current (A)**	**Date**	**Time**
Kality I Incoming Line	15	65	22/10/2019	11:00PM	4	18	6/10/2019	04:00AM
Transformer I		940	11/9/2019	11:00PM		308	6/10/2019	05:00AM
15 KV outgoing line (Capacity 50 MW)								
Line-4	7.35	240	11/10/2019	11:00AM	4.91	70	6/10/2019	05:00AM
Line-5	5.60	68	28/10/2019	11:00AM	3.68	2	19/10/2019	02:00AM
Line-8	7.91	231	17/10/2019	09:00AM	5.01	74	10/9/2019	05:00AM
Line-11	5.01	250	18/10/2019	12:00M	3.84	85	29/9/2019	04:00AM
Line-15	5.98	182	15/10/2019	9:00PM	3.69	70	14/10/2019	04:00AM

The Table 3.4 above shows the Power (MW) and Current (A) data incoming from Kality and 15 kV outgoing lines. The load Current at peak and minimum load data recorded in October 2019 with date and time indicated correspondingly.

Table 3.5 Data profile at peak and minimum load recorded in November 2019

BAY LINE	Peak Load				Minimum Load			
	Power (MW)	Current (A)	Date	Time	Power (MW)	Current (A)	Date	Time
Kality I Incoming Line	15	65	1/11/2019	11:00PM	4	19	16/11/2019	04:00AM
Transformer I		946	2/11/2019	12:00PM		220	24/11/2019	03:00AM
15 KV outgoing line (capacity 50MW)								
Line-4	7.58	239	21/11/2019	11:00AM	6.5	47	27/11/2019	04:00AM
Line-5	5.89	65	26/11/2019	10:00AM	4.01	2	24/11/2019	11:00AM
Line-7	7.01	249	28113/2019	12:00AM	6.54	92	30/11/2019	03:00AM
Line-8	7.25	230	30/10/2019	13:00:AM	4.25	15	16/11/2019	03:00AM
Line-11	7.96	256	26/11/2019	11:00AM	6.01	50	30/11/2019	02:00AM
Line-15	6.12	195	25/11/2019	13:00PM	2.35	30	9/10/2019	24:00:AM

The Table 3.5 above shows the Power (MW) and Current (A) data incoming from Kality and 15 kV outgoing lines. The load Current at pear and minimum load data recorded in November 2019 with date and time indicated correspondingly

Table 3.6 Data profile at peak and minimum load recorded in December 2019

BAY LINE	Peak Load				Minimum Load			
	Power (MW)	Current (A)	Date	Time	Power (MW)	Current (A)	Date	Time
Kality I Incoming Line	13	60	14/12/2019	11:00PM	5	20	28/12/2019	02:00AM
Transformer I		910	14/12/2019	12:00PM		292	300/11/2019	03:00AM
15 KV outgoing line (Capacity 50MW)								
Line-4	8.01	180	23/11/2019	11:00AM	4.06	46	31/11/2019	04:00AM
Line-5	5.4	66	9/11/2019	10:00AM	2.65	18	23/11/2019	04:00AM

Line-7	6.01	242	25/11/2019	19:00AM	2.35	2	13/11/2019	11:00AM
Line-8	7.90	198	30/12/2019	11:00AM	4.75	20	4/11/2019	03:00AM
Line-11	5..86	202	6/11/2019	11:00AM	3.0	2	13/12/2019	19:00:AM
Line-15	4.52	245	14/12/2019	13:00PM	2.01	67	28/12/2019	05:00AM

The Table 3.6 above shows the Power (MW) and Current (A) data incoming from Kality and 15 kV outgoing lines. The load Current at peak and minimum load data recorded in December 2019 with date and time indicated correspondingly.

Table 3.7 Data profile at peak and minimum load recorded in January 2020

BAY LINE	**Peak Load**				**Minimum Load**			
	Power (MW)	**Current (A)**	**Date**	**Time**	**Power (MW)**	**Current (A)**	**Date**	**Time**
Kality I Incoming Line	12	60	28/1/2020	11:00PM	5	24	5/12/2020	04:00AM
Transformer I		902	16/1/2020	11:00PM		305	4/1/2020	03:00AM
15 KV outgoing line(Capacity 50 MW)								
Line-4	7.81	174	30/1/2020	15:00AM	4.15	44	4/1/2020	03:00AM
Line-5	5.23	157	25/1/2020	11:59AM	2.13	26	4/1/2020	14:00:AM
Line-7	6.01	246	20/1/2020	10:00AM	3.21	100	3/1/2020	05:00AM
Line-8	6.98	58	23/1/2020	10:00AM	3.68	22	13/1/2020	04:00AM
Line-11	5.69	196	4/1/2020	18:00AM	2.94	41	8/1/2020	04:00AM
Line-15	5.6	226	4/1/2020	11:00PM	2.36	40	24/1/2020	05:00AM

The Table 3.7 above shows the Power (MW) and Current (A) data incoming from Kality and 15 kV outgoing lines. The load Current at pear and minimum load data recorded in January with date and time indicated correspondingly

3.2.2. Transients at ADC

Transients are disturbances that occur for a very short duration. The main sources of transients are lightning strokes (Impulsive Transients) and switching events (Oscillatory Transients) at utilities and/or end-use customers [12]. During the period of monitoring, impulsive transients are not seen because lightning protection systems are installed at Addis Center distribution substation, the 132 kV incoming overhead line, and distribution transformers. At the substation, 120 kV, 10 kA surge arresters are also installed at each phase of the primary side of the transformers to absorb the transient over voltages which may enter the power line past the lightning protection systems.

Three surges that exceed 120 kV with respect to ground (157.5% of nominal voltage) are recorded to occur at the substation since February 18, 2008 for the last 12 years. This gives the failure rate of the lightning protection system at Addis center substation to be 0.2727 per year. The significance of this figure of failure rate depends on the level of protection desired to save expensive equipments from lightning strokes. Therefore, there is no single maximum value of failure rate not to be exceeded, set by standards.

The installation of surge arresters in addition to the lightning protection system has protected the system well from lightning strokes that no damage has occurred in the substation for the last 12-years. However, neither harmonic filters nor power factor correctors are installed at Addis Center Substation and all the selected industries of study except National Tobacco Enterprise. National Tobacco Enterprise, the power factor correctors are subdivided into 12-smaller units, so that the capacitor switching is less vulnerable to dangerous transients. As a result, significant oscillatory transients are not discovered by the measurements [9].

3.2.3. Types of Faults in Addis Center Outgoing Feeders

This distribution substation has only one 132kV radial incoming feeder from Kality substation. There is one power transformers having 50 MVA with 132/15kV, approximately around 49,800 customers (i.e. industrial, commercial and residential). Again for this substation there are no feeders dedicated for industrial, commercial and residential customers separately.

3.2.3.1. Interruption Data from September 2019 to January 2020

Among the different types of power system faults, frequently occurring faults at ADC substation include permanent and transient earth fault, permanent and transient short circuit, and interruptions request duet to operation/maintenance. Table 3.6 shows the duration and frequency of these different types of faults such as permanent Earth Fault (PEF), Permanent Short circuit (PSC), Transient Earth fault (TEF) and Transient Short circuit (TSC) [30].

Table 3.8 -3.12 shown below the collected data recorded interruptions that includes a peak load, type of fault, frequency and duration of interruption of the faults occurred on each of the six outgoing feeders. An interruption occurs when there is a reduction of the supply voltage or load current to less than 0.1 PU in duration of that time. The collected sample data taken is a recorded data for five selected months. A sample average evaluation for frequency of different faults and duration of interruption for the five months from September 2019 to January 2020 has been considered based on the number of interruptions is tabulated in table 3.8, 3.9,3.10,3.11,3.12 respectively with graphs.

Table 3.8 Different types of fault and duration of interruption in September

LINE/ FEEDER	PEAK LOAD (A)	INTRRUPTION					
		Operation	Over Load	Short Circuit	Earth Fault	Under Frequency	Duration of Interruption in (Hrs.)
132 KV incoming	70	0	0	0	0	0	0
ADC -4	285	2	0	4	11	0	3:51:00AM
ADC -5	65	0	0	1	0	0	3:22:00AM
ADC -8	239	0	0	0	0	0	0
ADC -11	277	4	0	1	5	0	17:05:00PM
ADC -15	201	7	0	6	11	0	01:17:00AM

The Table 3.8 shows different duration of interruptions in hours due to short circuit, earth fault, over load and operation for the months of September 2019 for the six feeders' of Addis Center distribution substation.

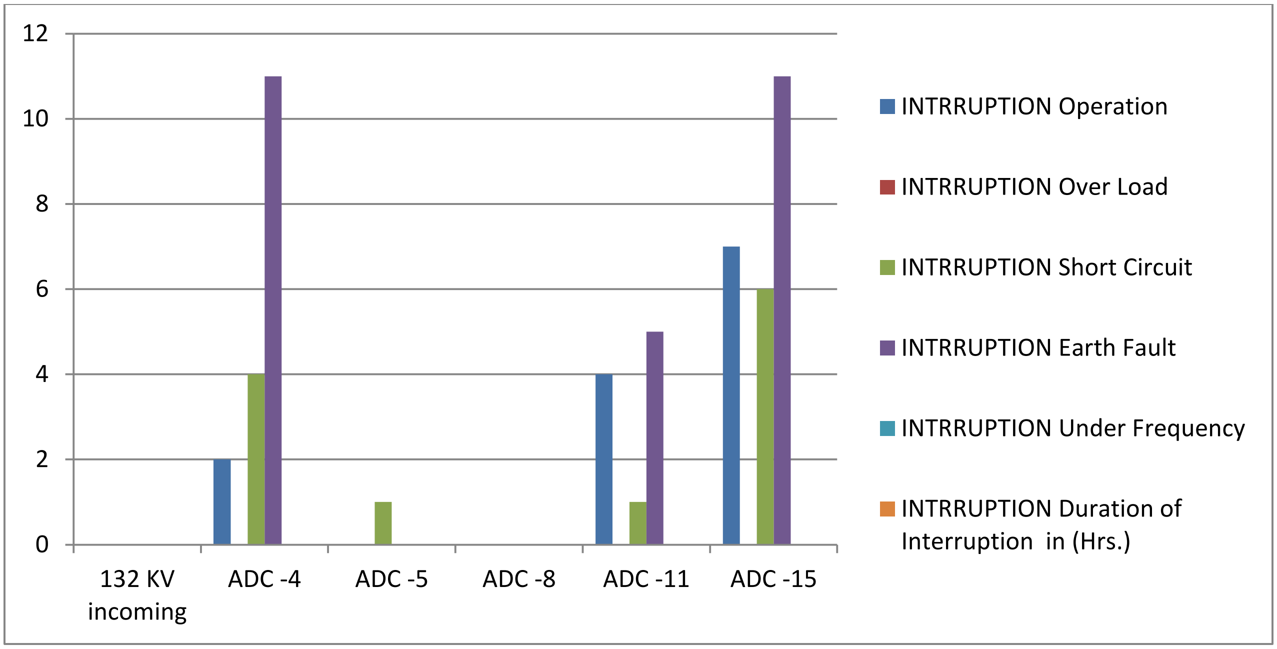


Figure 3.6 Average frequency fault and duration of interruption in September

Figure 3.6 shows the average frequency and duration of interruptions for the months of September 2019 for the six feeders' of Addis Center distribution substation.

Table 3.9 Different types of fault and duration of interruption in October.

LINE/ FEEDER	PEAK LOAD (A)	INTRRUPTION					
		Operation	Over Load	Short Circuit	Earth Fault	Under frequency	Duration of Interruption in Hrs.
132 KV incoming	65	0	0	0	0	0	0
ADC -4	240	2	0	6	7	0	04:16:00AM
ADC -5	68	0	0	1	1	0	00:40:00AM
ADC -8	231	2	0	1	1	0	06:41:00AM
ADC -11	250	0	0	1	21	0	09:16:00AM
ADC -15	182	8	0	2	6	0	06:03:00AM

The Table 3.9 shows different duration of interruptions in hours due to short circuit, earth fault, over load and operation for the months of October 2019 for the six feeders' of Addis Center distribution substation.

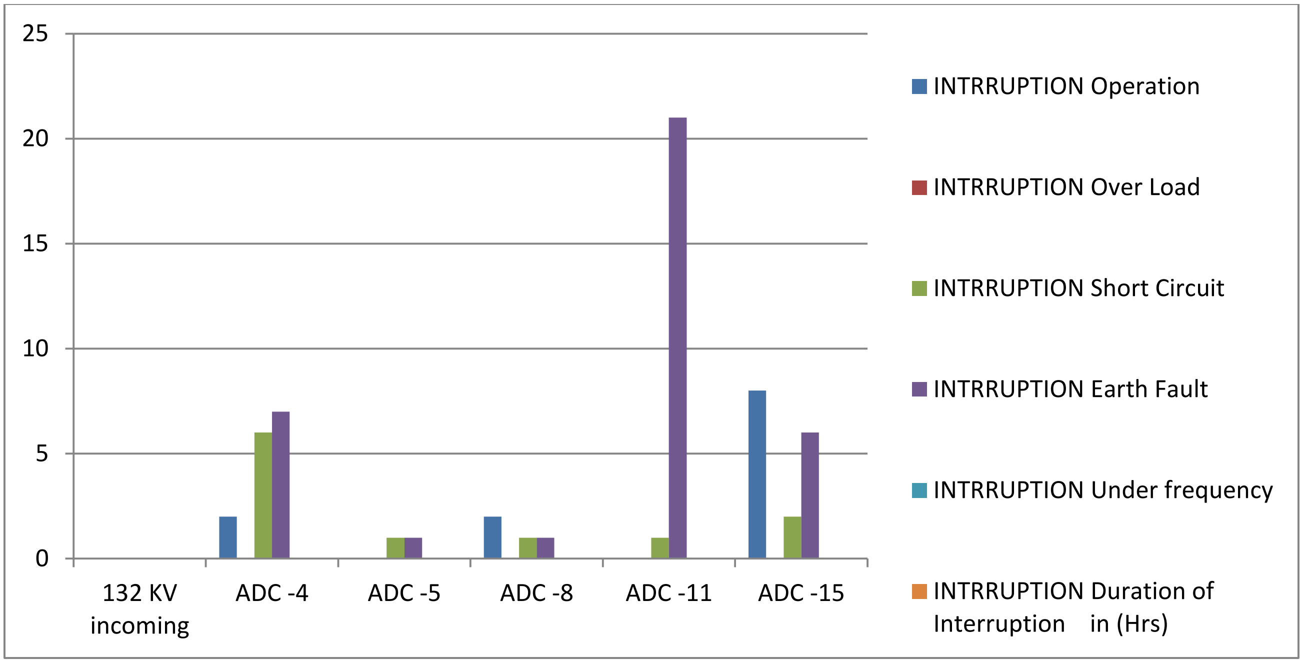


Figure 3.7 Average frequency fault and duration of interruption in October.

Figure 3.7 shows the average frequency and duration of interruptions for the months of October 2019 for the six (6) feeders' of Addis Center distribution substation.

Table 3.10 Different types of fault and duration of interruption in November.

LINE/ FEEDER	PEAK LOAD (A)	INTRRUPTION					
		Operation	Over Load	Short Circuit	Earth Fault	Under frequency	Duration of Interruption in (Hrs.)
132 KV incoming	65	0	0	0	0	0	0
ADC -4	240	2	0	6	7	0	04:16:00AM
ADC -5	68	0	0	1	1	0	00:40:00AM
ADC -8	231	2	0	1	1	0	06:41:00AM
ADC -11	250	0	0	1	21	0	09:16:00AM
ADC -15	182	8	0	2	6	0	06:03:00AM

The Table 3.10 shows different duration of interruptions in hours due to short circuit, earth fault, over load and operation for the months of November 2019 for the six feeders' of Addis Center distribution substation.

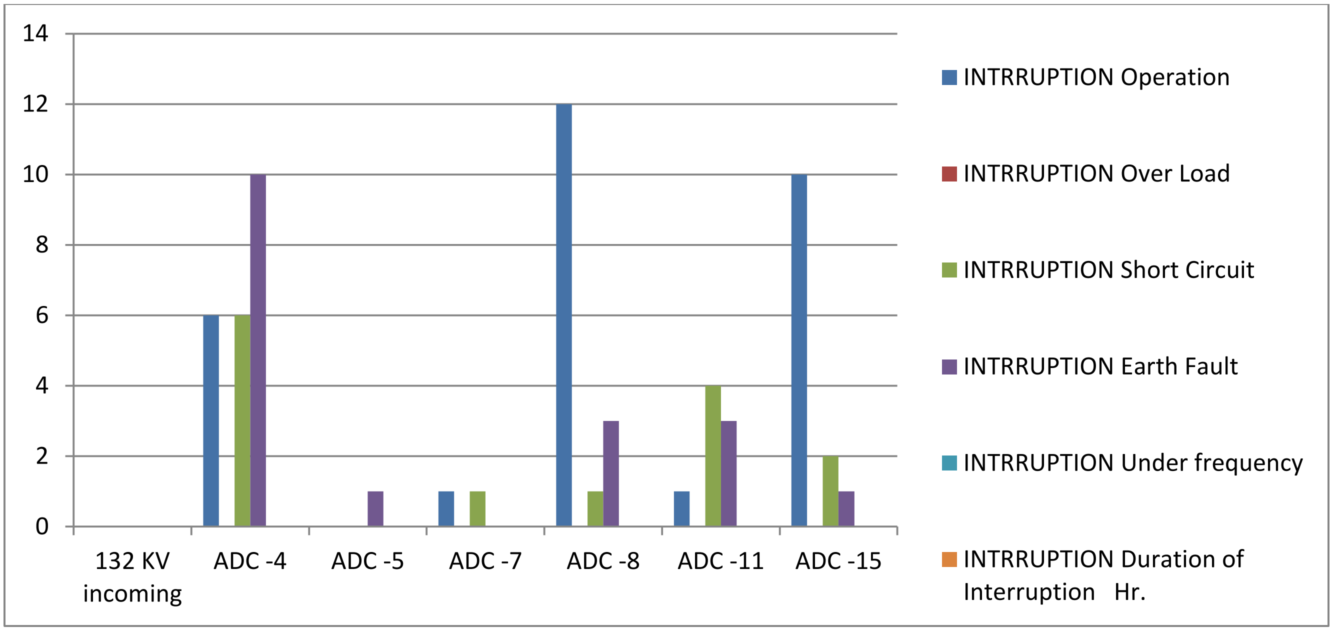


Figure 3.8 Average frequency fault and duration of interruption in November.

Figure 3.8 shows the average frequency and duration of interruptions for the month of November 2019 for the six feeders' of Addis Center distribution substation

Table 3.11 Different types of fault and duration of interruption in December.

LINE/ FEEDER	PEAK LOAD (A)	INTRRUPTION					
		Operation	Over Load	Short Circuit	Earth Fault	Under frequency	Duration of Interruption in (Hrs.)
132 KV incoming	60	0	0	0	1	0	0:11:00AM
ADC -4	174	3	0	2	6	0	7:02:00AM
ADC -5	157	1	0	0	0	0	0:19:00AM
ADC -7	246	4	0	0	5	0	09:42:00AM
ADC -8	58	4	0	0	3	0	01:04:00AM
ADC -11	202	3	0	2	5	0	08:42:00AM
ADC -15	245	3	0	0	5	0	05:54:00AM

The Table 3.11 shows different duration of interruptions in hours due to short circuit, earth fault, over load and operation for the month of December 2019 for the six feeders' of Addis Center distribution substation.

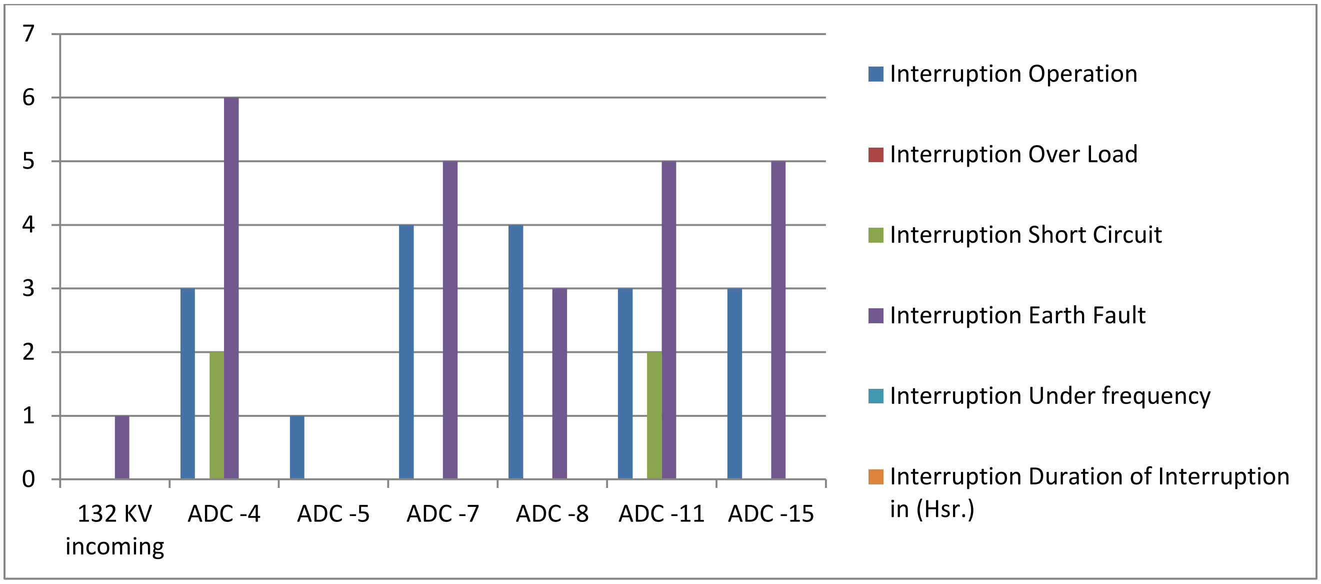


Figure 3.9 Average frequency fault and duration of interruption in December.

Figure 3.9 shows the average frequency and duration of interruptions for the month of December 2019 for the six feeders' of Addis Center distribution substation

Table 3.12 Different types of fault and duration of interruption in January.

LINE/ FEEDER	PEAK LOAD (A)	INTRRUPTION					
		Operation	Over Load	Short Circuit	Earth Fault	Under Frequency	Duration of Interruption in (Hrs.)
132 KV incoming	60	0	0	0	0	0	0
ADC -4	174	9	0	3	4	0	7:32:00AM
ADC -5	157	1	0	0	3	0	01:22:00AM
ADC -7	246	0	0	0	1	0	0:05:00AM
ADC -8	58	3	0	1	3	0	03:12:00AM
ADC -11	196	2	0	4	2	0	12:40:00PM
ADC -15	226	12	0	5	6	0	01:03:00AM

The Table 3.12 shows different duration of interruptions in hours due to short circuit, earth fault, over load and operation for the month of January 2020 for the six feeders' of Addis Center distribution substation

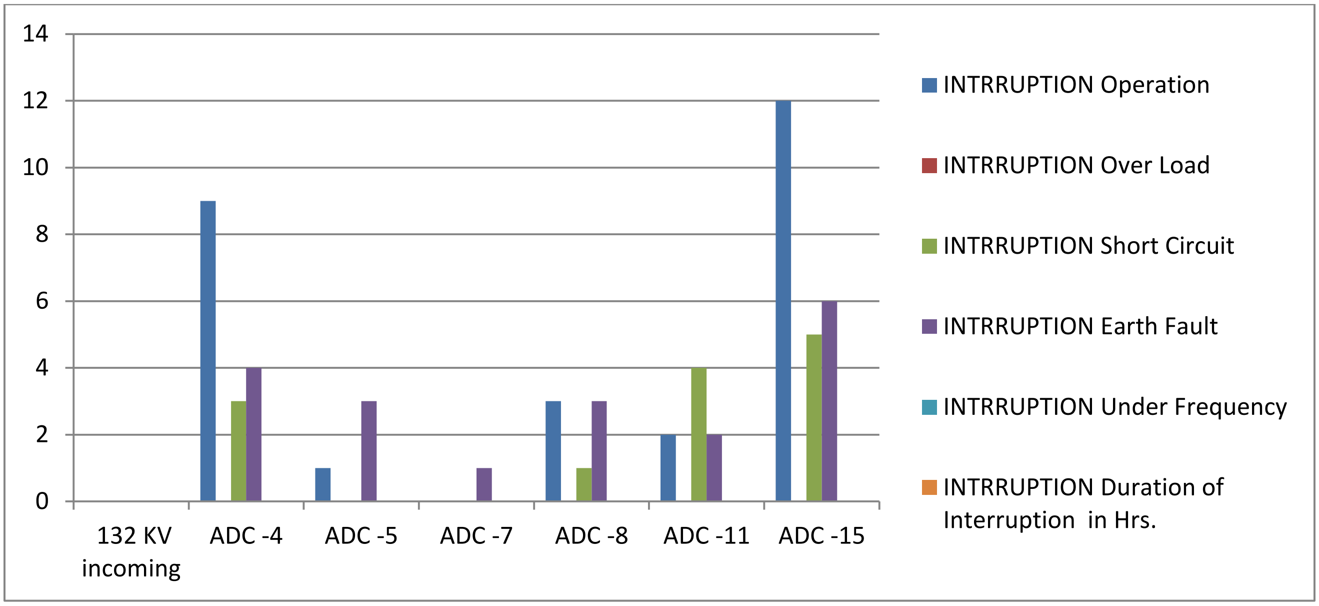


Figure 3.10 Average frequency fault and duration of interruption in January.

Figure 3.10 shows the average frequency and duration of interruptions for the months of January 2020 for the six feeders' of Addis Center distribution substation.

3.2.3.2. Major Interruption Causes of ADC Substation

The major faults occurring can either temporary or permanent type. Permanent or Sustained interruptions are long-duration interruptions which last longer than five minutes whereas interruptions with duration of less than five minutes are termed momentary interruptions [19]. Many of the distribution problems are temporary and mainly caused by tree, animal contact, and whether condition. They can easily solve with little or no intervention from the system. By simply reclosing, the system will be re-energizing. But permanent faults can't be restored by simple re-energizing. Permanent faults can be caused by Equipment malfunction, cable failure, down line or persistent tree contact [21].

Permanent (Sustained) interruptions can be classified as Planned and Unplanned Interruptions [19]. Planned interruptions (operational outages) occur mainly for the purpose of construction, preventative maintenance or repair. A planned interruption occurs at a selected time less inconvenient for the customers and the customers have notified before of the interruption. If the occurrence time of the interruption has not been selected, then the interruption is unplanned. Unplanned interruption occurs due to fault clearing, unwanted operation of the protection system or due to inadvertent initiation of opening operation of a switching device.

In Addis Center distribution substation, major faults occurring frequently are short circuit, earth fault, overload, Blackout, under frequency and there are planned outages for operational and maintenance purpose. The Table 3.13 below shown indicated that date, duration and reason of interruption, type of fault, operational and maintenance at Addis Center distribution substation in January 2020.

Table 3.13 the type of fault, date and duration and reason interruption in January 2020 at ADC.

No	Interruption date	Duration of interruption (Hrs.)	Type of fault	Reason of interruption
1	10/1/2020	04:56-10:16	Earth & short circuit fault	Line no 8 CB tripped due to double fault.
2	"	09:59-10:16	Operation	Line no 11 CB switch off for maintenance to safety
3	"	09:59-10:16	Operation	Line no 5 CB switch off maintenance to safety
4	11/1/2020	07:09-07:15	earth fault	Line no 5 CB tripped due to earth fault
5	13/1/2020	06:10 -09:29	Earth & short circuit fault	Line no 11 CB tripped out due to double fault
6	"	17:00 -17:37	Earth & short circuit fault	Line no 15 CB tripped out due to double fault
7	14/1/2020	08;01 -11:21	Earth & short circuit fault	Line no 15 CB tripped out due to double fault
8	15/1/2020	16:41 -16:45	Earth fault	Line no 4 CB " due to earth fault
9	16/1/2020	15:52 -17:35	Overcurrent	Line no 15 CB tripped due to excessive current fault
10	"	16:33 -16:52	Maintenance	Line no 4 CB opened for maintenance and safety of line no 15 outgoing line work.
11	18/1/2020	06:00 -09:50	Overcurrent	Line no 15 CB tripped due to over current fault.

12	"	09:57 -10:27	Maintenance	Line no 4 CB opened for maintenance due to cable burned.
13	"	13:12 -13:30	Maintenance	Line no 4 CB opened to tapping changing transformer
14	"	20:50 -21:05	Short circuit	Line no 4 CB tripped due to short circuit and Auxiliary CB measurement line out
15	19/1/2020	16:54 16:58	Earth fault	Line no 11 CB tripped out due to earth fault
16	"	20:35 -20:45	Maintenance	Line no 15 CB switch off for maintenance.
17	20/1/2020	17:39 -18:10	Maintenance	Line no 4 CB opened for maintenance of broken transmission wire
18	21/1/2020	08:18 -08:20	Earth fault	Line no 4 CB tripped due to earth fault.
19	22/1/2020	14:54 -15:12	Maintenance	Line no 4 CB switch off for maintenance to connect transformer.
20	24/1/2020	14:42 -15:43	Earth fault	Line no 5 CB tripped due to earth fault.
21	26/1/2020	07:54 -07:57	Earth fault	Line no 4 CB tripped due to earth fault.
22	27/1/2020	06:38 -06:43	Earth fault	Line no 15 CB tripped due to excessive current fault.
23	28/1/2020	16:13 -16:54	Maintenance	Line no 15 CB opened for maintenance of defected cable.
24	29/1/2020	12:34 -12:34	Earth fault	Line no 15 CB tripped due to excessive current fault.
25	"	13:48 -15:00	Operation	Line no 4 CB switch off for maintenance to close the line
26	30/1/2020	14:58 -16:08	Earth fault	Line no 11 CB tripped out due to earth fault
27	31/1/2020	08:00 -08:26	Overcurrent	Line no 4 CB tripped out due to excessive current fault
28	"	08:38 -08:41	Overcurrent	Line no 7 CB tripped out due to excessive current fault
29	"	10:22 -15:57	Maintenance	Line no 15 CB switch off for maintenance to fill concrete.

The Table 3.14 below shown indicated that date, duration (Hrs.) and reason of interruption, type of fault, operational and maintenance at Addis Center distribution substation in February 2020.

Table 3.14 the type of fault, date and duration and reason interruption in February 2020 at ADC.

No	Interruption date	Duration of interruption (Hrs.)	Type of fault	Reason of interruption
1	1/2/2020	09:16 -09:18	Earth fault	Line no 7 CB tripped due to earth fault
2	"	13:43 -15:38	Overcurrent	Line no 11 CB tripped due to excessive current fault.
3	3/2/2020	08:34 -08:35	Earth fault	Line no 7 CB tripped out due to earth fault
4	5/2/2020	07:12 -09:12	Overcurrent	Line no 11 CB tripped out due to excessive current.
5	8/2/2020	06: 35 -06:36	Earth fault	Line no 4 CB tripped out due to earth fault.
6	"	11:04 -11:07	Earth fault	Line no 7 CB tripped out due to earth fault.
7	"	11:38 -11:40	Earth fault	Line no 11 CB tripped out due to earth fault.
8	"	12:58 -14:25	Overcurrent	Line no 15 CB tripped due to excessive current fault.
9	"	13:05 -13:08	Overcurrent	Line no 11 CB tripped due to excessive current fault.
10	"	13:09 -13:11	Overcurrent	Line no 7 CB tripped due to excessive current fault.
11	"	13:11 -14:25	Maintenance	Line no 4 CB switch off for maintenance
12	"	13:58 -19:48	Overcurrent	Line no 4 CB tripped out due to excessive current.
13	"	15:28 -22:48	Overcurrent	Line no 11 CB tripped out due to excessive current.
14	"	18:47 -19:09	Maintenance	Line no 15 CB switch for maintenance.
15	10/2/2020	08:30 -08:32	Earth fault	Line no 15 CB tripped due to earth fault.
16	"	09:58 -09:59	Earth fault	Line no 11 CB tripped due to earth fault.
17	11/2/2020	08:30 -08:31	Earth fault	Line no 7 CB tripped out due to earth fault.
18	"	20:09 -20:29	Maintenance	Line no 15 CB opened for maintenance of outgoing line fire light.
19	"	20:09 -20:29	Maintenance	Line no 4 CB opened safety for maintenance due to line no 15 CB opened
20	14/2/2020	06:34 -09:47	Short circuit	Line no 11 CB tripped out due to short circuit fault.
21	"	08:45 -08:49	Earth fault	Line no 7 CB 7 tripped out due to earth fault.
22	"	15:12 -15:15	Short circuit	Line no 11 CB tripped out due to short circuit fault.
23	"	16:20 -16:50	maintenance	Line no 11 CB switch off for maintenance to connect cable.

24	16/2/2020	08:39 -08:41	Earth fault	Line no 4 CB tripped out due to earth fault.
25	17/2/2020	09:05 -09:06	Earth fault	Line no 15 CB tripped out due to earth fault
26	"	11:41 -11:42	Earth fault	Line no 4 CB tripped out due to earth fault.
27	18/2/2020	14:05 -14:44	Operation	Line no 4 CB switch for maintenance for drop out phase.
28	19/2/2020	14:21 :15:33	Operation	Line no 4 CB switch for maintenance for broken line.
29	"	14:24 -15:33	Operation	Line no 15 CB switch for maintenance for safety.
30	"	16:00 -16:37	Maintenance	Line no 4 CB switch for maintenance.

From above Tables 3.13 and 3.14 shown the different fault, duration and reason of interruption and frequently happened in Addis Center distribution substation permanents interruptions that sample taken in January and February 2020 are the following faults:

A. **Short Circuit analysis at ADC**

Short Circuit Analysis is performed to determine the currents that flow in a power system under fault conditions. It also, helps to ensure that personnel and equipment are protected by establishing proper interrupting ratings of protective devices.

Short circuit occurs when an electric current travels along a path that is different from the intended one in an electrical circuit. When this happens, there is an excessive electric current which can lead to circuit damage, fire, and explosion [20]. It also occurs when the insulation of the wiring used breaks down, an external conducting material (such as water) that is introduced accidently into the circuit, electric motors are forced to operate when the moving parts are jammed and Dust are lead to short circuits and power failures.

The data collected in the Table 3.13 and 3.14 above shown interruption for further fault analysis of short circuits happened at Addis Center distribution substation in January and February 2020. Here short circuits occur many times due to double fault (double line to ground fault), insulation breakdown (insulation failure due to air pollution, water, and ice), circuit damage (including mechanical failure, accidents, and excessive internal and external stresses), flashover, human error, winds and earth fault. According to ADC substation short circuit fault with double fault occurs when any two phases connected together and then to ground or between live conductors in one or more phases. This double fault short circuit frequently happened on outgoing lines of ADC-8, ADC-11, ADC-15 and sometimes outgoing line ADC-4 are occurred in January and February 2020. It also, the insulation breakdown (due to the insulation in the connection degrades, the insulation properties are lost and flashover between phases or to ground,), failure measurement, human error, winds and circuit damage frequently occurs on substation outgoing lines in January and February 2020 at ADC. In addition, there are short circuits fault which happened at substation not only a sample taken both the months at Addis Center distribution substation.

B. Earth fault analysis at ADC

Earth fault occurs is an inadvertent fault between the live conductor and the earth. When earth fault occurs, the electric system gets short circuited and the short circuited current flows through the system. The fault current returns through the earth or any electrical equipment, which damages the equipment.

The Tables 3.13 and 3.14 shown above are described some of the interruption earth fault found at Addis center distribution substation in January and February 2020. The earth fault occurs at substation due to insulation loss between phases and exposed conductive, subsequent impact to the cables sheath, broken of transmission wires (cables), burned cables and short circuit. Those faults most of time happened at ADC substation on the outgoing lines of ADC-4, ADC-7, ADC-11, ADC-15 and sometimes on the outgoing lines of ADC-5 and ADC-8 occurs in both January and February 2020 thoroughly the months. In addition, there is earth fault which happened at substation not only a sample taken both the months at Addis Center distribution substation.

C. Overcurrent fault analysis at ADC

An overcurrent occurs when the current exceeds the rated amperage capacity of that circuit or of the connected equipment on that circuit. An overcurrent can be caused by overloading the circuit or by short circuit, incorrect design, excessive, ground fault, or an arc fault.

From the Tables (3.13) and (3.14) above shown, the interruption of the overcurrent fault occurs due to the short circuit, excessive current and earth fault on the outgoing lines ADC-11, ADC-15 and sometimes ADC-4, ADC-7 both in January and February 2020 thoroughly the months at

Addis Center distribution substation. In addition, there are overcurrent occurs in another months at the substation not only a sample taken both months at Addis Center distribution substation.

D, Maintenance and Operation analysis at ADC

Operations and maintenance typically includes the day to day activities necessary for the building/built structure, its systems and equipment and occupants/users to perform their intended function and repairing it, for the further working order.

From the Tables (3.13) and (3.14) above shown, the interruption of the operation and maintenance are occurs due maintenance of safety, burned of cables, for transformer tap change, filling concrete, broken of transmission wire/line and broken line on the outgoing lines ADC-4, ADC-5, ADC-11 and ADC-15 both in January and February 2020 thoroughly the months at Addis Center distribution substation. In addition, there are operations and maintenance occurs in another the months at the ADC substation not only in sample taken those months.

3.2.3.1 Voltage Fluctuation analysis

Selected distribution of study consumes power that does not have 1-7% fluctuation at low frequency. As a result, voltage fluctuations that reach 1-10% and of frequency around 5 Hz are not discovered at ADC distribution substation. Even though, voltage fluctuations of 1 to 7% at low frequency are not discovered during the measurement, the power line impedance is not a guarantee to voltage fluctuation. It is due to absence of high power loads drawing a fluctuating current that flicker is not observed.

3.2.4. Sustained Interruption Data Analysis

The distribution substation has six feeders of 15kV customer side voltage rating. This voltage is stepped down to 380V by factory service transformers. Since the industry is supplied directly from 15kV line, it is better to study the electric power interruption of the feeder from the substation. From the monthly average interruption and average duration of interruption data shown in the Table 3.15, the reliability indices are computed use of equations 2.1 to 2.4.

Table 3.15: Reliability indices of 15 kV outgoing feeders at Addis center distribution Substation.

No	Feeders	Monthly average No of interruption	Monthly average duration of interruption	SAIFI	SAIDI	CAIDI	ASAI
1	ADC-L4	16.2	5.254	13.71	4.45	0.32	0.9974
2	ADC-L5	1.8	1.008	1.04	0.58	0.56	0.99942
3	ADC-L7	2.4	2.622	2.49	2.72	1.09	0.9987
4	ADC-L8	6.8	4.276	5.75	3.62	0.63	0.9963
5	ADC-L11	11.6	10.108	12.01	0.497	0.04	0.9942
6	ADC-L15	16.8	5.456	10.98	3.57	3.64	0.9938
Total		55.6	28.724	45.98	9.85	6.24	0.9966

Table 3.16: Design target values of reliability indices on per-annum basis [35]

Target values	
Indicator	Values
SAIFI	1
SAIDI	1-1.5Hr
CAIDI	1-1.5Hr
ASAI	0.99983

Comparing the values obtained from Table 3.15 above with the design target value tabulated in Table 3.16, the following conclusions can be drawn.

When we compare the calculated SAIFI value with German standard, the system-average interruption frequency (SAIFI) of the feeders is extremely high when compared to the design target value. The target value is 1-interruption per- annum, while the monthly-average interruption frequency of the substation feeders reaches 16.8. This will become 84 per annum. The minimum SAIFI is 5.2 which occurred on feeder ADC-L5. This shows even the minimum interruption frequency is much higher than the typical interruption frequency of the design target value. As per Ethiopian Electrical Agency‘s (EEA’s) standard, SAIFI should not exceed 20 interruption per customer per year, which indicates that the current value is above the acceptable value by large margin. This clearly indicates that there is serious reliability problem in the present ADC substation.

Availability of all the feeders as observed from the ASAI values is below the typical target value, which is 99.66% available as shown in Table 3.15. However, this value is not still good enough since the ASAI value should be greater than 99.98% as per EEA's standard. These indicate that the feeder lines get interrupted for a long duration of time. .

Again from CAIDI, we can observe that all the feeders have large CAIDI value. The minimum CAIDI value is 0.04 hour per month. On yearly basis, it becomes 0.2 hour which is very less compared to the design target value (1-1.5hour). This means that the feeders require little time to restore service.

The computed values of the system average interruption duration indices (SAIDI) showed there is long duration of interruption when compared to the design target value. The minimum monthly average interruption duration is 9.85 hours. This becomes 118.5 hours of average interruption duration per annum. The permissible SAIDI value in Germany is 0.383 hours per customer per year. As per (EEA), the SAIDI value should not exceed 25 hours per customer per year. It shows that electric power is interrupted for a long period of time.

From the Table 3.15 above shown the computing interruption data of Addis Center distribution substation, does not meet the requirements set by the regulatory body that is Ethiopian Electric Agency (EEA) and German standard (international reliability indices of best experienced countries). The results clearly show that interruption data of Addis Center distribution substation is facing serious power interruption problem. In order to overcome the problem, the Addis Center distribution substation has been using standby generator as much as possible. The thesis work did not consider a better option. It is better to use the Interconnection system in case of power interruption. The analysis has been done to give recommendation for the Ethiopian Electric Utility concerning the issue of frequent power interruption.

3.2.5. Voltage variation data Analysis

The voltage variations, which may be either of short duration or long duration, are deviations of the voltage magnitude for more than half a cycle. Those deviations can be benchmarked using graphs of magnitude versus duration such as the CBEMA, ITIC, SEMI and equipment-specific curves. The graphs are suitable as they can benchmark both short duration and long duration voltage variations. Both short duration and long duration variations are discussed here in parallel. The ITIC (CBEMA) curve is shown below in Figure 3.11 [9].

The IEEE C57.12.00-1987 recommended practice gives the maximum rms over voltages that the transformer should be able to withstand at steady state to be 5% at rated load and 10% at no load.

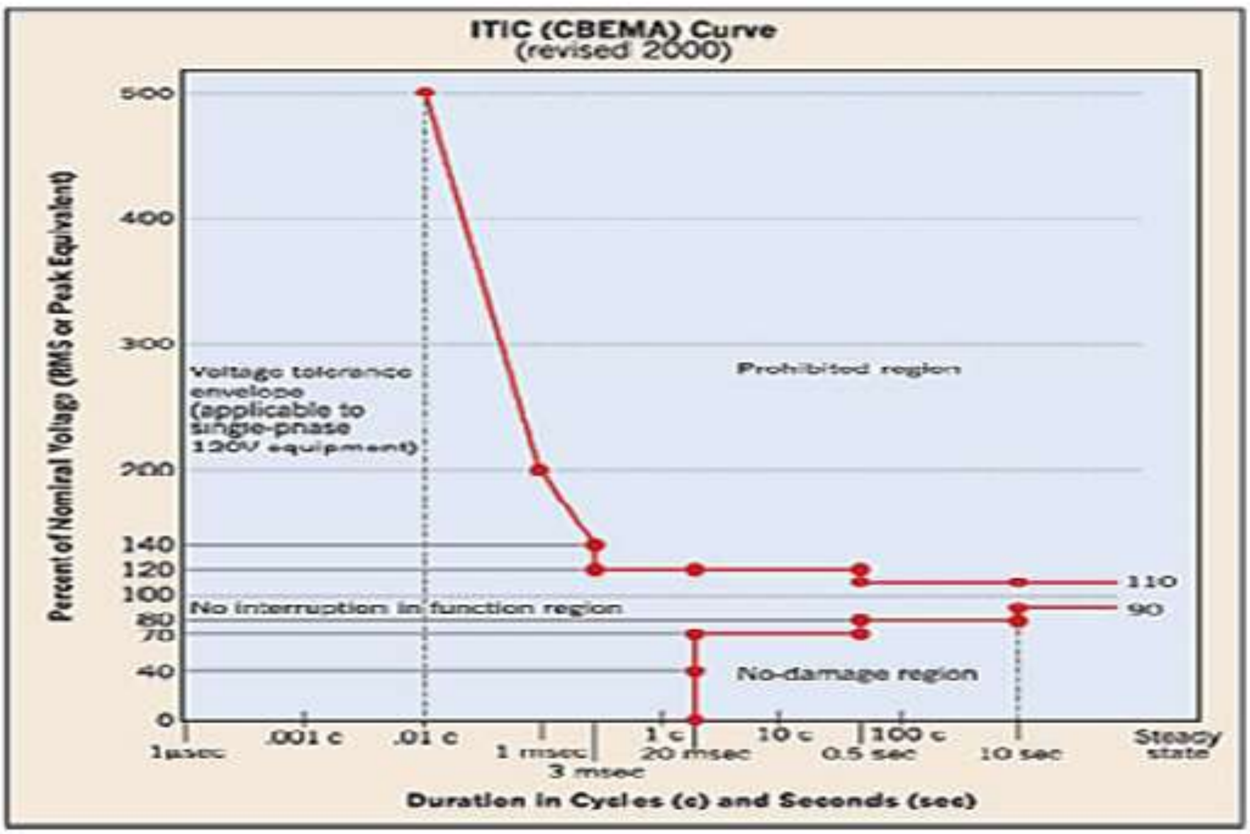


Figure 3.11 The ITIC (CBEMA) curves [19]

At Addis Center Substation, over voltages that reach 150 kV (113.64) are recorded at the 120kV primary side of the transformer, on 25th August 2010. As per IEEE C57.12.00-1987 recommended practice, this condition (13.64% over voltage) is much beyond the tolerable value which is 5% at rated load. The breaker was therefore turned off to isolate the system from that faulty condition from 8:00 Am to 12:00 Am. However, at normal operation typical voltage profile of the 132 kV line is as shown below.

Table 3.17 Typical voltage profiles of the 132 kV line at Addis center substation

Hour(AM)	1	2	3	4	5	6	7	8	9	10	11	12
P (MW)	10	12	12	13	13	12	12	11	11	11	10	8
Q (MVAR)	3	3	4	4	4	3	3	4	4	4	3	2
System Voltage(KV)	132	129	130	130	131	131	131	134	132	132	133	130

As shown on the Table 3.17 above, the voltage variation of the 132 kV line meets the IEEE requirements. However, occurrences of sever over voltages indicate that the overall system voltage variations at the substation violate the IEEE limits.

The Summary of voltage variations at Addis Centre distribution substation are contains RMS, minimum, maximum and average value of each phase on primary side of transformer. Voltage variation standard states 10% deviation is permissible. The root cause of voltage variation has been faults on the utility power distribution and poor voltage regulation at the substation.

3.2.6. Voltage and current unbalances Analysis

At Addis Center distribution substation the measured values of the voltages and currents from the secondary side of the transformer (15kV) at peak time and evaluation shown in table 3.18 below:

Table 3.18 Measurement results of maximum voltage and current at the ADC.

<table>
<tr><th colspan="2" rowspan="2">Voltage and Current</th><th colspan="2">Measured Values</th><th colspan="2">Average</th><th colspan="2">Unbalance (%)</th></tr>
<tr><th>V(kV)</th><th>(A)</th><th>V(kV)</th><th>I(A)</th><th>V</th><th>I</th></tr>
<tr><td rowspan="3">Phase to neutral</td><td>I</td><td>8.637</td><td>955</td><td rowspan="3">8.601</td><td rowspan="3">954.33</td><td rowspan="3">0.4</td><td rowspan="3">0.3</td></tr>
<tr><td>II</td><td>8.579</td><td>950</td></tr>
<tr><td>III</td><td>8.586</td><td>958</td></tr>
<tr><td rowspan="3">Phase to Phase</td><td>I</td><td>14.976</td><td>1130</td><td rowspan="3">14.689</td><td rowspan="3">1106.67</td><td rowspan="3">2.4</td><td rowspan="3">2.11</td></tr>
<tr><td>II</td><td>14.435</td><td>1110</td></tr>
<tr><td>III</td><td>14.658</td><td>1080</td></tr>
</table>

According to the NEMA (National Electrical Manufacturers Association of USA) standard voltage unbalance is defined as the maximum deviation from the average of the three-phase voltages or currents, divided by the average of the three-phase voltages or currents, expressed in percentage, which is given by the following equation.

$$\%Voltage\ unbalance = \frac{maximum\ deviation\ from\ V}{Average\ V} * 100\% \quad \ldots\ldots\ldots\ldots\ldots 3.1$$

Therefore,

$$Average\ voltage = \frac{14.976 + 14.435 + 14.458}{3} = 14.689$$

$$maximum\ deviation = 14.976 - 14.689 = 0.353$$

$$\%\ voltage\ unbalance = \frac{0.353}{14.689} * 100\%$$

= 2.4%

$$\%\ current\ unbalance = \frac{maximum\ deviation\ from\ average\ I}{Average\ I} \ldots\ldots\ldots\ldots\ldots 3.2$$

Therefore,

$$Average\ current = \frac{1130 + 1110 + 1080}{3} = 1106.67$$

$$maximum\ deviation = 1130 - 1106.67 = 23.33$$

$$\%current\ unbalance = \frac{23.33}{1106.67} * 100\%$$

=2.11%

As can be seen from the result above the percentage of voltage unbalance exceeds the accepted IEEE limit of 2 %. Therefore, appropriate mitigation method should be applied.

For benchmarking, the NEMA MG 1-1993 curve for motor derating-factor as a function of percent phase voltage unbalance, is shown below.

Figure 3.12: De-rating factor for squirrel cage induction motors due to unbalanced voltage standard ANSI/NEMA MG1[11]

The ANSI C84.1-1989 recommends that voltage and current unbalances were the maximum voltage unbalance measured under no load conditions should not exceed 3%. For voltage imbalance greater than 1% at a Customer's motor terminals, the motor derated. ANSI Standard MG-1 provides guidelines for motor de-rating to avoid excessive motor heating. Additionally, excessive current imbalance due to supply voltage imbalance can cause nuisance tripping of motor protective devices. NEMA MG-1 states that 1% of voltage unbalance can create 6-10% current unbalance. While the standards differ, motors are generally able to handle a certain amount of voltage unbalance up to 5% through derating [11].

Comparing the Table 4.18 and the derating curve on figure 3.12 above, we can see that the level of voltage unbalance in Addis center distribution substation is significant to cause the undesirable effects of motor pulsations and vibrations. The effects of voltage unbalance on overheating and drop of efficiency are functions of the level and duration of the unbalance [9]. Therefore, it needs appropriate mitigation techniques.

3.2.7. Power Frequency Variation Analysis

The electric power network is designed to operate at a specified value of frequency (50 Hz). The frequency variations are caused if there is any imbalance in the supply and demand. Large variations in the frequency are caused due to the failure of a generator or sudden switching of loads. The permissible value of power frequency variations according to the IEEE standard for normal operation is ±0.5 (49.5 Hz to 50.5 Hz at 50 Hz nominal frequency). Based on this standard the measurement result shown below in the Table 3.19 indicates that the power frequency variation from fundamental frequency and the permissible limits.

At Addis Center Substation, under frequencies that reach 49.2 are recorded. The under frequency phenomena that fall to 49.2 Hz are recorded in January 19/1/2020 Wednesday from 9:00 AM at Addis Center distribution Substation as follows in Table 3.19.

Table 3.19 Frequency variation recorded of Addis center distribution substation

No	**Times (24 Hrs. format)**	**Frequency (Hz)**	**Frequency variation (%)**
1	1:00 AM	50.2	+0.2
2	2:00 AM	50.2	+0.2
3	3:00 AM	50.2	+0.2
4	4:00 AM	50.2	+0.2
5	5:00 AM	50.1	+0.1
6	6:00 AM	50.1	+0.1
7	7:00 AM	50.1	+0.1
8	8:00 AM	49.9	-0.1
9	9:00 AM	49.2	-0.8
10	10:00 AM	49.9	-0.1
11	11:00 AM	49.9	-0.1
12	12:00 AM	50.1	+0.1
13	13:00 AM	50.0	0
14	14:00 AM	50.0	0
15	15:00 AM	50.0	0
16	16:00 AM	50.1	+0.1
17	17:00 AM	50.1	+0.1
18	18:00 AM	50.1	+0.1

19	19:00 AM	49.8	-0.2
20	20:00 AM	50.0	0
21	21:00 AM	50.0	0
22	22:00 AM	50.0	0
23	23:00 AM	50.1	+0.1
24	24:00 AM	50.1	+0.1

As it can be seen from Table 3.19 above the power frequency variation is below the 1% standard range and tolerable.

2.2.8. VOLTAGE SAG ANALYSIS

Voltage Sag is defined as a short reduction in voltage magnitude for the duration of time and commonly occurring in power quality issue. According to the IEEE defined standard (IEEE Std. 1159, 1995), voltage sag is defined as a decrease of rms voltage at the power frequency for duration of 0.5 cycles to 1 min. within range of 0.1 to 0.9 pu. Voltage sag (dip) duration are subdivided into instantaneous (0.5-30 cycles), momentary (30 cycles -3 seconds), Temporary (3 seconds-1 min.) with range of magnitude 0.1-0.9 pu [9]. Voltage sag is caused by faults on the system (single line-to-ground fault on the system), transformer energizing or heavy load switching.

Table 3.20 Voltage sag data records at ADC

Outgoing Feeders	Date and Time	Voltage sag in (kV)	Per unit
ADC-4	5/12/2019 @10:15AM	13.05	0.87
ADC-5	11/10/2019@4:45PM	13.2	0.88
ADC-7	12/12/2019@6:46PM	13.35	0.89
ADC-8	2/3/2020@9:25AM	13.02	0.87
ADC-11	1/12/2019@8:23AM	13.49	0.89
ADC-15	2/3/2020@11:55AM	13.4	0.89

At Addis Center distribution substation during the measuring process in five months duration for dips and shown events in table 3.20 above, the voltage sag is detected on feeders ADC-4, ADC-5 and ADC-8 and the voltage decreases to 13.0.5 kV, 13.2 KV, 13.02 KV for duration of 150msec, 200msec, 300msec respectively and occurred in 5/12/2019 at (10:15:00), 11/10/2019 at (4:45:00) and 2/3/2020 at (9:25:00). The problem is caused by three phase short circuit fault at the electrical system of the ADC and the occurrence of short circuit is recognized when the circuit breakers connected to the machines trip to clear the fault. The complete data for the voltage sag is obtained from annually recorded data and interview with the section head. Therefore, it is necessary to find appropriate mitigation technique to solve the problem.

3.2.9. DATA ANALYSIS ON WAVEFORM DISTORTION

The limits of allowable voltage and current harmonics distortion set by IEEE and IEC have been presented in (3.21) and (3.23) which are just based on the personal experiences and involvement of Power Quality analysts in harmonic analysis research. These standards provide guidelines for power quality usages and practices.

At Addis Center distribution substation, the harmonic voltage and current distortions are small with respect to the permissible values such that both the voltage and current distortions within tolerable limits are shown below the measurement results.

Table 3.21 voltage harmonic distortion limits, IEEE standard 519-1992.

Utility bus voltage	Maximum individual harmonic component (%)	Maximum THD (%)
<39Kv	3	5
39Kv to 137.9Kv	1.5	2.5
138Kv and above	1	1.5

The maximum individual harmonic and total harmonic voltage distortion contents of the electric power at Addis Center distribution substation when the substation is working at full load are shown in the Table (3.22) below.

Table 3.22: Voltage data from secondary side of transformer supplying at full load

No. of Measurements	V_1 RMS in (kV)	V_2 RMS in (kV)	V_3 RMS in (kV)	V_1 THD (%)	V_2 THD (%)	V_3 THD (%)	Voltage Unbalance (%)
1	14.736	14.635	14.725	2.94	2.992	3	0.25
2	14.875	14.758	14.856	2.9659	2.991	3	0.3
3	14.756	14.651	14.768	2.95	2.993	3	0.29
4	14.976	14.835	14.858	2.9779	2.982	3	0.58
5	14.867	14.735	14.843	2.963	2.9895	3	0.35
6	14.653	14.562	14.625	2.92	2.992	3	0.30
7	14.536	14.486	14.525	2.9	2.996	3	0.14
8	14.215	14.325	14.262	2.85	3	2.988	0.41
9	14.321	14.268	14.322	2.86	2.996	3	0.13

The Table 3.22 above shows the voltage distortion level and RMS value of each phase taken from the secondary side transformer of the feeder of Addis Center distribution substation processing and the measurement on individual phases. The average full load measurement shows that the THDv is 11.81%, 11.97% and 12% for the respective phases. As per IEEE standard the voltage distortion should be below 3% for individual harmonic components and below 5% for total harmonic distortion. The figure in the table implies there is sign of significant voltage distortion. Therefore, it needs mitigation techniques.

Table 3.23 Current distortion limits for general distribution systems

Maximum harmonic current distortion (% of I_L)						
Individual harmonic order (old harmonics)						
Isc/I_L	<11	11<h<17	17<h<23	23<h<35	35<h	TDD
<20*	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>100	15.0	7.0	6.0	2.5	1.4	20.0

The maximum individual harmonic and total harmonic current distortion contents of the electric power at Addis Center distribution substation when the substation is working at full load are shown in the Table 3.24 below.

Table 3.24 Current data from secondary side of transformer supplying at full load.

No. of Measurements	I_1 RMS in (A)	I_2 RMS in (A)	I_3 RMS in (A)	I_1 THD (%)	I_2 THD (%)	I_3 THD (%)	Current Unbalance (%)
1	928	925	927	1.4	2.996	3	0.14
2	1048	1045	1046	1.6	2.995	3	0.16
3	1082	1080	1079	1.68	2.995	3	0.15
4	1110	1108	1111	1.73	2.999	3	0.12
5	1130	1128	1129	1.76	2.997	3	0.09
6	962	961	960	1.498	2.997	3	0.1
7	955	953	951	1.485	2.994	3	0.21
8	989	986	980	1.54	2.988	2.997	0.4
9	965	945	935	1.478	2.95	3	1.7

The average current harmonic distortions for different reading are presented for each phases in Table 3.24 above shown. The THD_I for phase one, phase two and phase three are 21.5%, 23.4% and 25.4% respectively, RMS value of individual harmonic components for current from is taken from secondary side of transformer.

The Tables 3.23 above shows individual harmonic component limits apply to the odd harmonic components. The short circuit current and rated current of 15 kV feeder at the point of common coupling are averaged to be 10 kA and 1925 A respectively, which give Isc/IL ratio in the range of <20. As a result, the TDD values of the current harmonics exceed 5% at the point of common coupling. Current distortion which results in a dc offset is allowed. The total Demand Distortion (TDD) is computed using equation:

$$TDD = \frac{\sqrt{\sum_{h=2}^{hmax} I_h^2}}{I_L} * 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .3.1$$

$$\frac{\sqrt{\sum_{h=2}^{hmax} I_h^2}}{I_L} = \frac{312.99}{1925}$$

$$TDD = \frac{319.99}{1925} * 100$$

$$= \underline{\underline{16.21\%}}$$

So, the result of TDD is 16.21% at PCC. It is therefore necessary to install harmonic filters for filtering out the harmonics to meet the IEEE standards.

3.3. Proposed Mitigation Techniques

3.3.1. Mitigation of Oscillatory Transients

I. Pre-Insertion Resistors

The use of pre-insertion resistors involves inserting resistors into the capacitor energization circuit prior to the closure of the main set of contacts. This is done in order to reduce the magnitude of the initial inrush current into the capacitor bank. The resistor with the value of 5 Ω are kept in place for duration of about 15.5 ms once the main switch is closed at which time they are shorted out of the circuit. This is to prevent undesired voltage drop across the resistors once steady state is achieved [21].

II. Pre-Insertion Inductors

The use of pre-insertion inductors operates in a similar manner, except the inductors are not switched out of the circuit once the transient is completed. Considering that the impedance of inductors is frequency dependent, then during initial inrush of current into the bank, the frequency is quite high and hence the impedance is high. When the system returns to steady state, the frequency is lower and hence the effective impedance is reduced significantly. Therefore, the inductors do not interfere significantly with the operation of the circuit [36]. As a result, using pre-insertion resistor for the mitigation of oscillatory transient is beneficial since the resistor damps the transient and the standard voltage level is achieved [15].

3.3.2. Voltage Sag Mitigation

To prevent the occurrence of voltage sag measures can be taken at different stages. The basic and economical solution is to strengthen the sensitive devices to the power quality problems. This prevents the damage of these devices to the abnormalities in the power system. The device manufacturers use a specific curve like ITIC curve during manufacturing. This curve specifies the withstanding capability of sensitive devices like computers, PLC's, ASD's during voltage imbalance occurring in the system. Based on this curve the design is improved so that the damage of these devices is prevented.

The second basic way to prevent the occurrence of voltage sag is to analyze the causes that lead to voltage imbalance. Improving the poor wiring and weak grounding systems can prevent the damage of the sensitive equipment. The medium which causes power quality problems should be avoided to the extent possible.

The use of power conditioning equipment is the most common solution to protect the power system network from these problems. Most of the power conditioning equipment is voltage monitoring devices during faults occur in power system. These devices may be connected at the source side or in the transmission network, or at the load end. In general, these devices are connected at the point of common coupling (PCC) where the load is connected to the supply. This is done as the cost of the power conditioning device increases from load end to source side [15]. This power conditioning devices are Line-voltage regulators, M-G Sets (Motor-generator Sets), Magnetic Synthesizers, SVC (Static VAR Compensators), UPS (Uninterruptible Power Supplies), SMES (Superconducting magnetic energy storage) and Custom Power Devices.

3.3.2.1. Voltage Sag Mitigation using Dynamic Voltage Restorer

Voltage sag is one of the power quality problems which exist in distribution. So in order to overcome this problem, a device called Dynamic Voltage Restorer (DVR), which is the most efficient and effective modern power electronic device, is used in power distribution networks. DVR is a solid state power electronics switching device consisting of GTO or IGBT. The capacitor banks as an energy storage device and injection transformers. It is normally installed in a distribution system between the supply and the critical load feeder at PCC. The basic idea of the DVR is to inject a controlled voltage generated by a forced commutated converter in series to the bus voltage by an injecting transformer. A DC to AC inverter regulates this voltage by sinusoidal PWM technique. In normal operating conditions, the DVR injects only a small voltage to compensate for the voltage drop of the injection transformer and device losses. However, when voltage sag occurs in the distribution system, the DVR control system calculates and synthesizes the voltage required to preserve output voltage to the load by injecting a controlled voltage with a certain magnitude and phase angle into the distribution system to the critical loads [37].

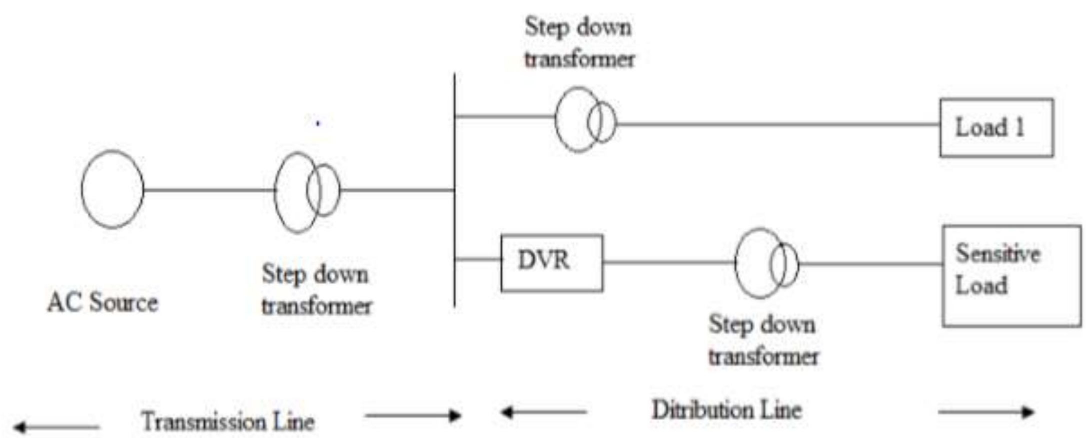


Figure 3.13: Location of DVR

The basic functions of a controller in a DVR are detection of voltage sag/swell events in the system, computation of the correcting voltage, generating of trigger pulses to the sinusoidal PWM based DC-AC inverter, correction of any anomalous (abnormality) in the series voltage injection and termination of the trigger pulses when the system has passed.

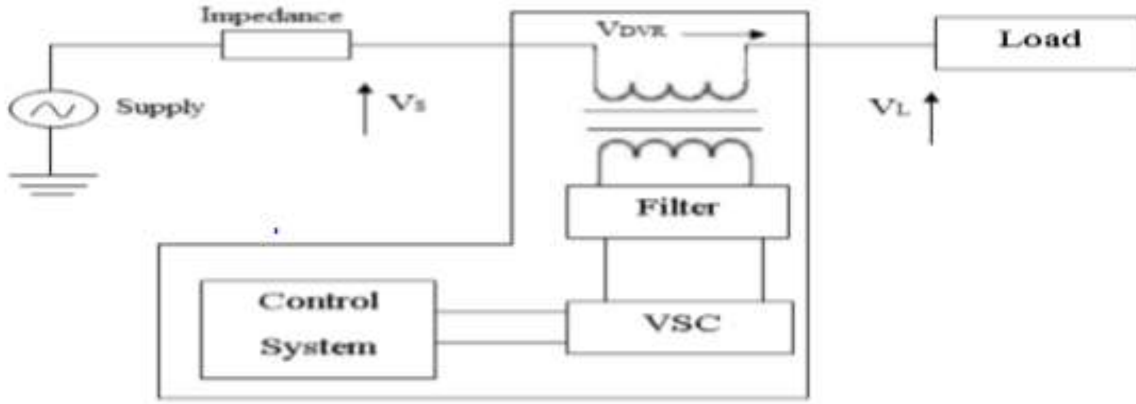


Figure 3.14 Schematic diagram of DVR [37]

3.3.3. Mitigation of Voltage Unbalance

A voltage “imbalance” is a variation in the amplitudes of three-phase voltages, relative to one another. This imbalance can be caused by different loads on the phases, resulting in different voltage drops through the phase-line impedances and due to unequal loads on distribution lines or within a facility. In other words, the negative or zero sequence voltages in a power system typically result from unbalanced loads causing negative or zero sequence currents to flow.

Voltage unbalance was harmful because the source of the problem should be thoroughly investigated and corrected. Balancing the voltage helps to save energy and money by increasing motor’s efficiency and possibly preventing expensive facility downtime due to equipment failures. For the utility, it is just a matter of repairing malfunctioning equipment or redistributing loads to reduce the unbalance. For the end-users, proper testing and communication with the utility would help locate and resolve the problems. Proper testing and communication with the utility can help to locate and resolve the problem. For the causes of voltage unbalance due to uneven distribution of single phase loads, redistributing the loads equally to the three phases improves the problem of voltage unbalance.

Adjustable speed drives can be equipped with AC-line reactors and DC link reactors to mitigate the effects of unbalance. Depending on how the ASD is configured with AC and/or DC reactors, both the magnitude of RMS currents and the percent of current unbalance can be potentially reduced.

3.3.4. Harmonics mitigation

3.3.4.1. Harmonic Mitigation using Harmonic Filters

Various harmonic-mitigation techniques have been proposed and applied in recent years. In this case, filters are designed for the distortions that exceed harmonic limits set by the IEEE Standard 519-1992. There are two types of filters used for filtering the harmonic distortions: passive filters and active filters.

a. Passive Filters

Passive filters contain inductance, capacitance and resistance elements configured and tuned to control harmonics. They are commonly used and relatively inexpensive compared with other for eliminating harmonic distortion. They are employed either to shunt the harmonic currents off the line or to block their flow between parts of the system by tuning the elements to create a resonance at a selected frequency [25].

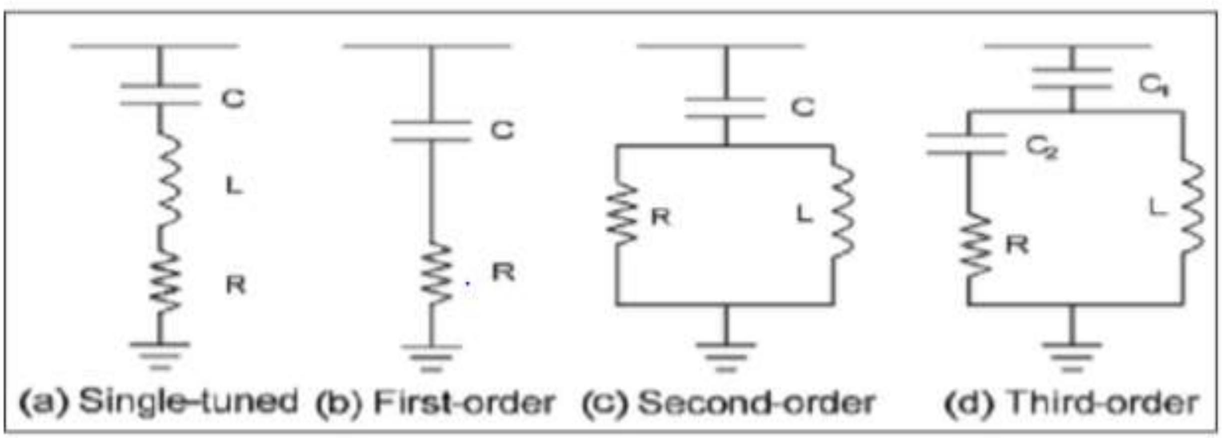


Figure 3.15 Common passive filter configurations.

The most common type of passive filter is single-tuned notch filter, shown in figure (3.15a), which is the most economical and frequently used. In the single-tuned filter circuit, a capacitor and inductor are connected in series. This filter is also known as low pass filter. The filter is single-tuned to present low impedance to a particular harmonic current. It is connected in shunt with the power system there by diverting the harmonic currents from their normal flow path on the line into the filter. Notch filter can provide power factor correction in addition to harmonic suppression [25]. The first order high-pass filter, in the figure 3.15b above, is not normally used, as it requires a large capacitor and has excessive loss at fundamental frequency. The second order high-pass filter provides the best filtering performance, but has higher fundamental frequency losses as compared with the third order. The third order high-pass filter's main advantage over second order is a substantial reduction in fundamental frequency loss, owing to increased impedance at that frequency caused by the presence of the capacitor C2. Moreover, the rating of C2 is very small compared with C1.

b. Active Filters

Active filters are relatively new types of devices for eliminating harmonics. They are based on sophisticated power electronics and much more expensive than passive filters. They are designed to inject harmonic currents to counterbalance existing harmonic components as they show up in the distribution system [25]. However, they have distinct advantage that they do not resonate with the system. They can address more than one harmonic at a time and combat other power quality problems such as flicker. They are particularly useful for large, distorting loads from relatively weak points on the power system.

Most of the time active filters are used in very difficult circumstances where passive filters cannot operate successfully because of where the parallel resonance lies. In this thesis passive filters are designed as effective solution for power system harmonic mitigation because passive filters are relatively inexpensive as compared to active filters.

c. Single-Tuned Harmonic Filters

Passive filters always provide reactive compensation to a degree dictated by the volt-ampere size and voltage of the capacitor bank used. They designed for the dual purpose of providing the filtering action and compensating power factor to the desired level. These passive filters presents very low impedance with respect to line impedance, at the tuning frequency, through which all current of that particular frequency will be diverted [38]. Despite its reactive power compensation advantage, a single tuned shunt filter can only eliminate a single current harmonic component. Therefore, for a wide range generated harmonics a single tuned filter is to be designed for each current harmonic to be suppressed individually. This multiple single-tuned filters are designed to eliminate multiple harmonics as illustrated in figure 3.16 [38].

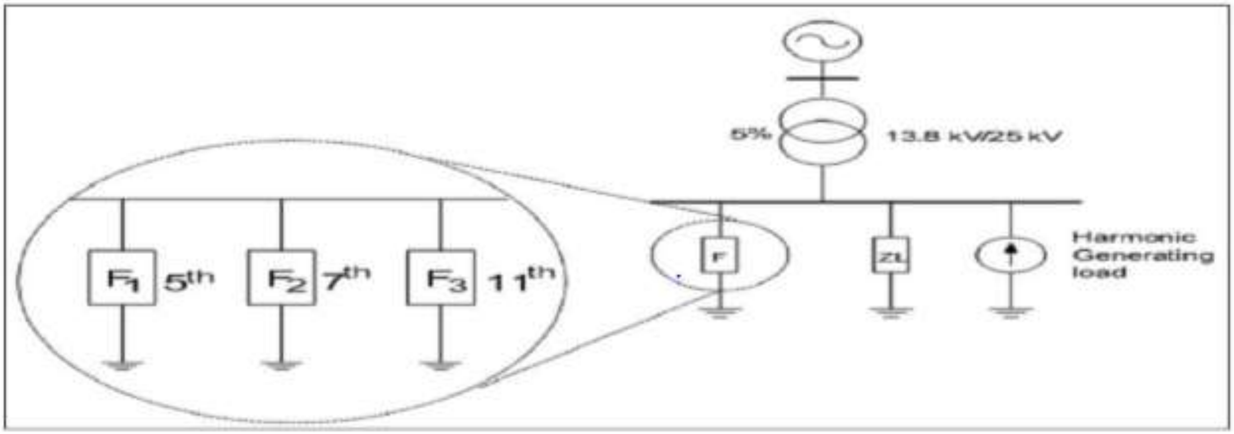


Figure 3.16 Three-branch filters

3.3.4.2. Harmonic Mitigation Using Distribution Static Compensator (DSTATCOM)

For renewable energy sources, STATCOM can be a suitable candidate for mitigating power quality issues. STATCOM is a power electronics device whose basic principle is injection or absorption of reactive current at PCC. Additional converters and power conditioning instruments are required to integrate renewable energy source with power electronic interface. The STATCOM unit is mainly designed for reactive power compensation to the load. This STATCOM unit is an inverter with DC link capacitor. It receives control pulses which are generated using modified Icosϕ algorithm, which in turn causes the STATCOM to provide real power and reactive power compensation [35]. The Icosϕ algorithm is developed to compensate harmonic, reactive and unbalance effects in a balanced or unbalanced 3-phase source/load [39]. The actual load current subtracted from the expected main current per phase equals the compensation currents (ref) for the STATCOM. Additionally, a hysteresis current controller is also used. If compensation current drops below the value of switch-off point, there lay is turned off. This pulse is then passed through a circuit block. The proportion of the gain factor decides the amount of real power supply from the mains while renewable energy sources supply the rest using STATCOM. The configuration of STATCOM interface for renewable energy source is shown in figure 3.17.

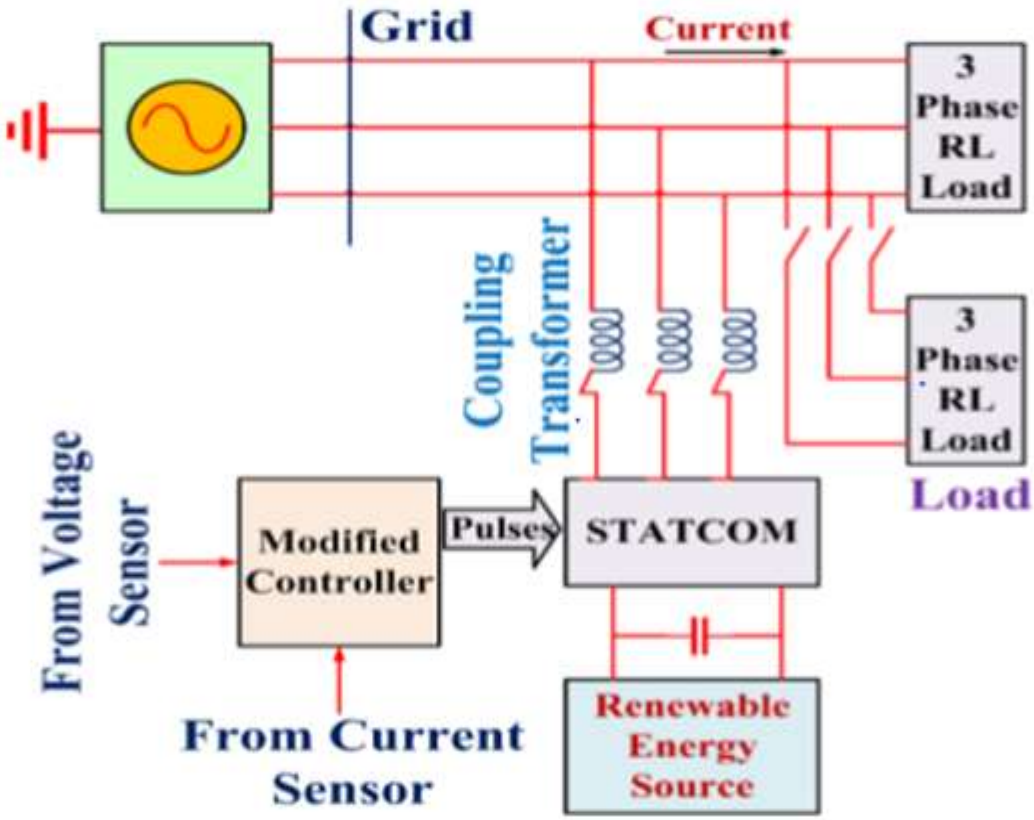


Figure 3.17 Schematic of the three-phase grid system with the STATCOM interface for renewable energy source [40] [41]

To mitigate the power quality issues in a wind power system, STATCOM can be very useful [24]. It acts as a FACTS device used in transmission system in shunt manner. In this configuration, VSC is connected to system bus through a coupling transformer. Reactive power depends on the amplitude of VSC. In overloading condition, STATCOM injects reactive power in system. If terminal voltage (VDC) is less than the system voltage, which is facing under voltage, STATCOM absorbs reactive power [40][41]. The drawbacks of using the additional circuits in STATCOM are high switching loss, increased costs, and a bulkier system. But the model described above replaces the additional converters with a STATCOM unit. There are several advantages of STATCOM. They are compensating current does not get lowered as the voltage drops. The other reasons for preferring are overall superior functional characteristics, faster performance, smaller size, cost reduction and the ability to provide both active and reactive power. It can be used to improve transient conditions and voltage fluctuations and useful to control voltage flickers and power oscillatory damping of system [35][41].

3.3.4.3. Design of shunt harmonic filter to reduce current harmonic distortion

The design procedure of single tuned shunt harmonic filter is:

1. Calculate the value of the capacitance needed to improve the power factor and to eliminate any penalty by the electric power company.
2. Choose a reactor to tune the series capacitor to the desired harmonic frequency
3. Calculate the peak voltage at the capacitor terminals and the RMS reactor current.
4. Choose standard components for the filter and verify filter performance to assure that capacitor components will operate within IEEE-18 recommended limits

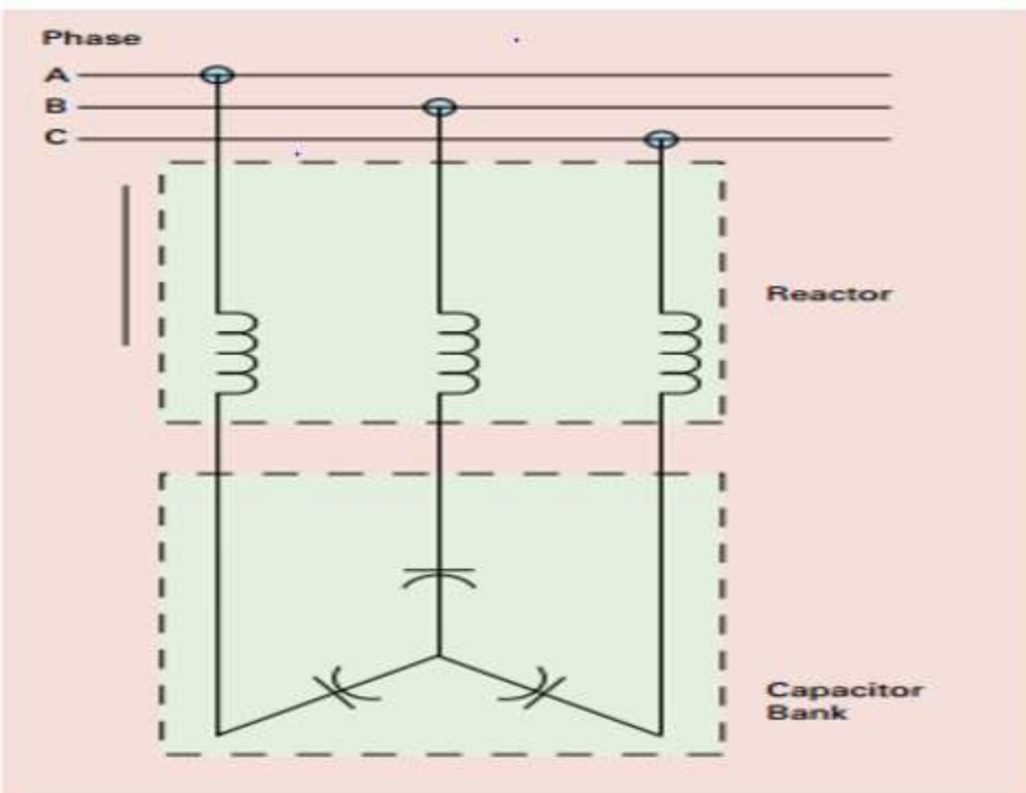


Figure 3.18: Harmonic filter and power factor correction configuration

Most harmonic flow analysis on power systems is performed using steady-state, linear circuit solution techniques. Harmonic sources, which are nonlinear elements, are generally considered to be injection current sources into the linear network models. They can be represented as current injection sources or voltage sources. For most harmonic flow studies, it is suitable to treat harmonics sources as simple sources of harmonic currents [10].

Modeling of nonlinear loads

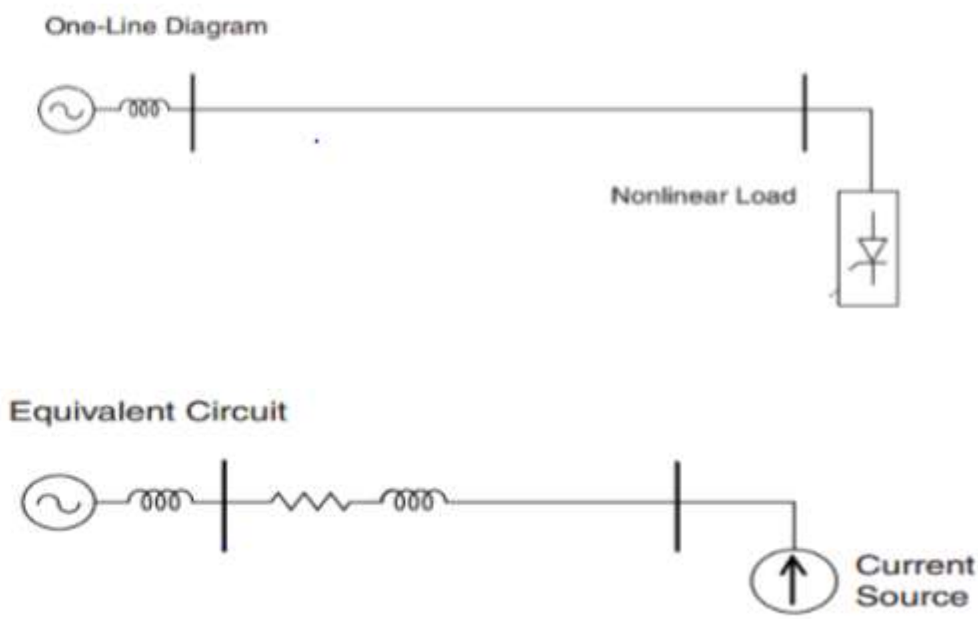


Figure 3.19: Representation of nonlinear loads as a current source for analysis [11]

3.3.4.4. Power factor correction

Power factor is defined as the ratio between the active component P and the total value of the apparent power S.

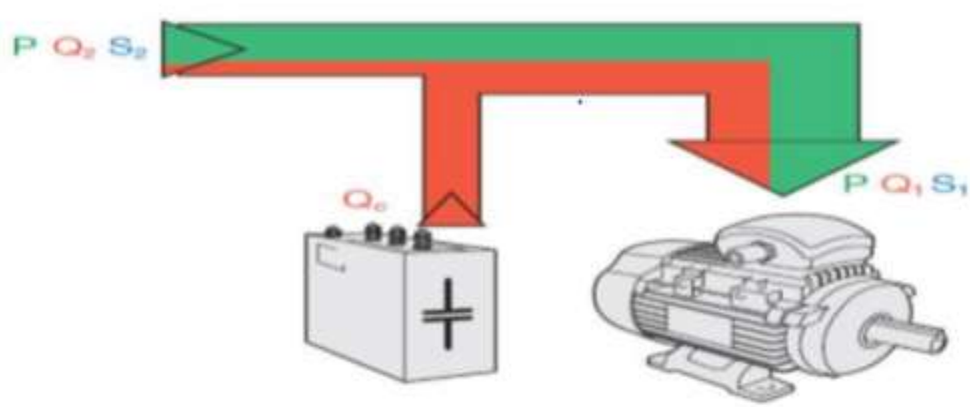
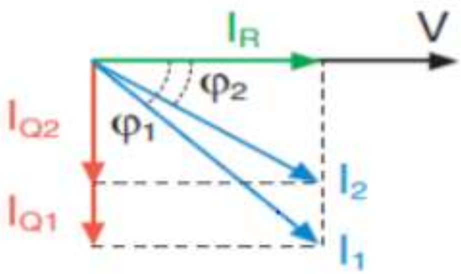
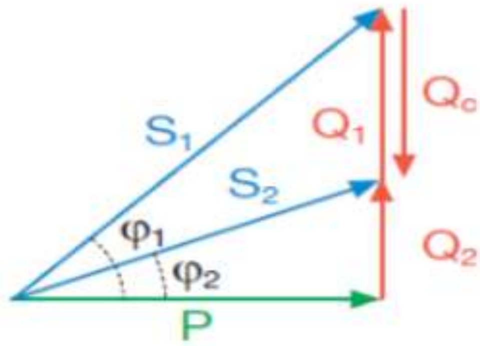


Figure 3.20: Active, reactive and apparent power diagram [20]





$\tan(\varphi_1) = \frac{Q_1}{P} \rightarrow Q_1 = P\tan(\varphi_1)$ ……………………………………………………………………………(3.2)

$\tan(\varphi_2) = \frac{Q_2}{P} \rightarrow Q_1 = P\tan(\varphi_2)$ ……………………………………………………………………………(3.3)

$Q_2 = Q_1 - Q_C \rightarrow Q_C = Q_1 - Q_2$ ……………………………………………………………………………(3.4)

$Q_C = P\,[\tan(\cos^{-1}(PF_1)) - \tan(\cos^{-1}(PF_2))]$ ………………………………………………………………(3.5)

Whereas:

P - Active power

Q_1 - Reactive power before power factor correction

φ_1 - Phase displacement angle before power factor correction

Q_2 - Reactive power after power factor correction

φ_2 - Phase displacement after power factor correction

Q_c - Reactive power for power factor correction

Some inductive loads need much reactive power from the utility supplying electric power. But this has a limit how reactive power to be sent from the utility. The rest is to be generated near to the load requiring it. This is known as power factor improvement.

Improving the power factor means taking the necessary steps to increase the power factor in a defined section of the installation by locally delivering the necessary reactive power so that the value of the current and consequently of the power flowing through the upstream network can be reduced, at the same time required output power. In this way, the lines, the generators and the transformers can be sized for a lower apparent power. Thus, this improvement of power factor is known as power factor correction (PFC). The main advantages of power factor correction can be summarized as follows:

- Better utilization of electrical machines;
- wise utilization of electrical lines;
- Reduction of losses;
- Reduction of voltage drops.

3.3.4.5. DESIGN OF HARMONIC FILTER AND POWER FACTOR CORRECTION

Capacitor banks can be used combined with inductors in order to limit the effects of the harmonics on a network. Actually, the combination capacitor-inductor constitutes a filter for harmonics. Previously it has been illustrated how, to avoid the negative effects of resonance, it is necessary to insert an inductor in series with a capacitor. By applying an analogous reasoning, it is possible to think of placing in a point of the network a combination of an inductor and a capacitor properly dimensioned in order to get the same resonance frequency of the order of the current harmonic to be eliminated. In this way, the assembly inductor-capacitor presents a very low reactance in correspondence with the harmonic to be eliminated which shall circulate in the assembly without affecting the whole network

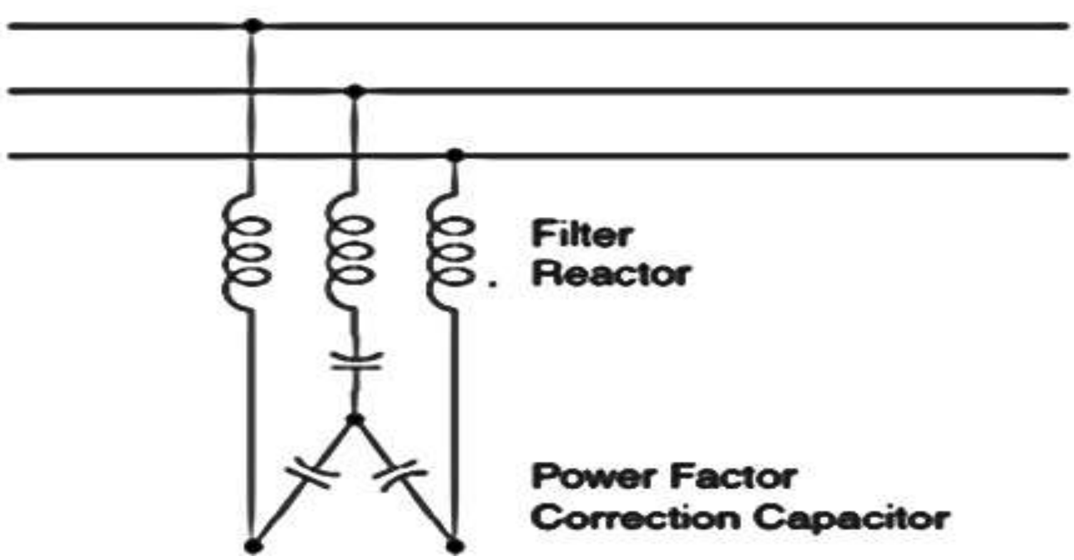


Figure 3.21 ADC Distributions Substation PFC Electrical Diagram

Table 3.25: Summarized recorded data

Measured loadings	Active power (KW)	Reactive Power (KVAr)	Apparent power (KVA)	Rated power factor
Average reading	28,270	16,010	36,330	0.87

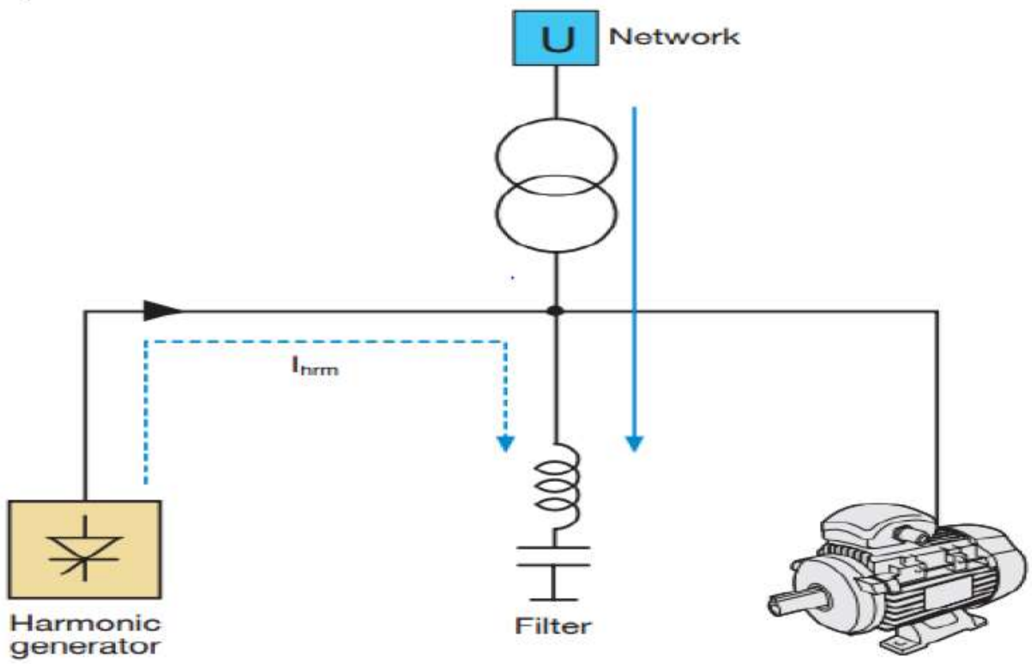


Figure 3.22: Power factor correction and filter connection of inductors and capacitor

Therefore this filter, called passive filter, consists in a capacitor connected in series with an inductor so that the resonance frequency is altogether equal to the frequency of the harmonic to be eliminated. Passive filters, which are defined on a case by case basis, according to a particular harmonic to be filtered, are cost-effective and easy to be connected and put into function.

Thus, I design a filter and power factor corrector which would improve the power factor of the loads from the existing 0.87 power factor reading to 0.98. Therefore, the net reactive power from the filter required to correct from the existing 87 to 98 percent power factor can be computed as follows:

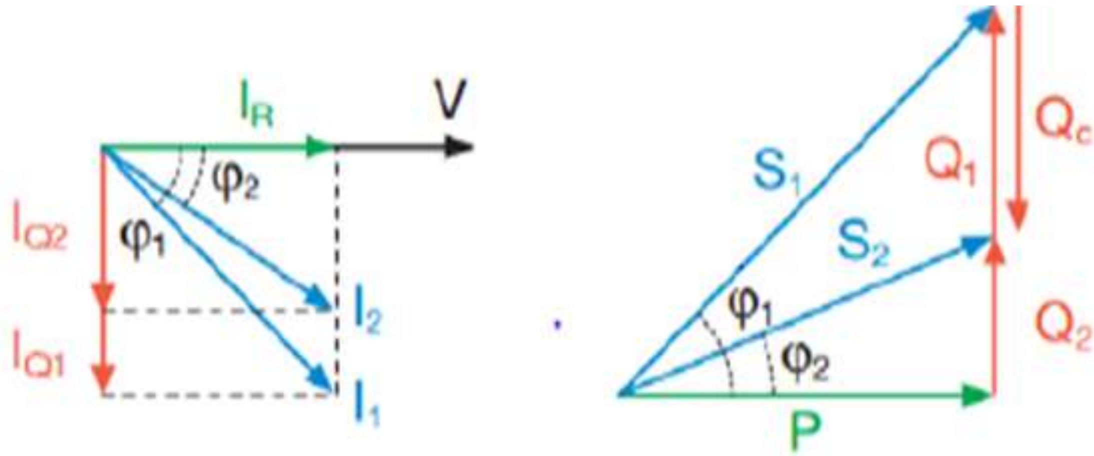


Figure 3.23 Power phasor representation of before and after power factor correction

Where:

- P is the active power;
- Q1, φ_1 are the reactive power and the phase displacement angle before power factor correction;
- Q2, φ_2 are the reactive power and the phase displacement angle after power factor correction;
- Qc is the reactive power for power factor correction

From Power factor = $\cos\varphi_1 \quad \Rightarrow \quad \varphi_1 = \cos^{-1}(\text{pf})$

$$\cos\varphi_1 = 0.87 \quad \Rightarrow \quad \varphi_1 = 29.54°$$

When the system is compensated the power factor should be

$$cos\varphi_2 = 0.98 \quad \Rightarrow \quad \varphi_2 = 11.48°$$

The reactive power demand for a PF of 0.98 is given as follows

Active and reactive power demand is related by the equation:

$$\text{P1} = \frac{\text{Q1}}{\tan(\emptyset1)} = \frac{16010KAVr}{0.5667} = 28251.28KW$$

$$\text{P2} = \frac{\text{Q2}}{\tan(\emptyset2)} = \frac{16010KAVr}{0.2031} = 78828.16KW$$

Since the active power remain same for the cases before and the power factor correction:

$$P_1 = P_2$$

$$\text{Q2} = \frac{\text{Q1}\tan(\emptyset2)}{\tan(\emptyset1)}$$

Thus, the reactive power demand for a 98 percent power factor would be

$$Q_2 = \frac{16010KAVr*0.2031}{0.5667}$$

Q_2 =5737.83KAVR

Required compensation for the filter and the power factor correction is

Compensation = Q1 – Q2 = 16010VAr – 5737.83 KVAR

Compensation = 10272.17KVAR

For a nominal 380-V system, the net wye-equivalent filter reactance (capacitive) X_{Filt} is determined by

$$X_{Filt} = \frac{kV^2 \, x \, 1000}{K_{var}} = \frac{1000 \, x \, 0.38^2}{10272.17} = 0.0141\Omega$$

X_{Filt} is the difference between the capacitive reactance and the inductive reactance at fundamental frequency:-

$$X_{Filt} = X_{Cap} - X_L \qquad \text{.......3.6}$$

For tuning at a specific harmonic point (in our case at 7th harmonic),

$$X_{Cap}=h^2X_L \qquad \text{.......3.7}$$

Where h is the harmonic order number;

Note: The filter will be tuned slightly below the harmonic frequency of concern to allow for tolerances in the filter components and variations in system impedance. This prevents the filter from acting as a direct short circuit for the offending harmonic current, reducing duty on the filter components. With this premises, let us take h = 6.8.

Combining equation (4) and (5), X_{Cap} would be formulated as:

$$X_{Cap} = \frac{X_{Filt}*h^2}{h^2-1} = \frac{0.0141*7^2}{7^2-1} = 0.1465\Omega$$

The capacitance value corresponding for the above capacitive reactance will be:

$$C_{Cap} = \frac{1}{2\pi f X_{Cap}} = \frac{1}{2*\pi*50Hz*0.1465} = 21727.64\mu F$$

Also, the reactive power rating of the capacitor will be determined by the equation:

$$K_{var} = \frac{1000*kv^2}{X_{cap}}$$

To achieve Xcap(capacitor reactance) at the given rated voltage, the capacitor has to be rate:-

$$K_{var} = \frac{1000*kV^2}{X_{cap}} = \frac{1000*(0.38)^2}{0.1465} = \frac{1000*0.1444}{0.1465} = 985.67\text{KVAR}$$

From standard tables reading, the capacitor size which is nearest to 975.7kVAR is 1000kVAr rating.

Compute filter reactor size. The filter reactor size can now be selected to tune the capacitor to the desired frequency. From step 1, the desired frequency is at the 7th harmonics. The filter reactor is computed from the wye-equivalent capacitive reactance, determined in step 2, as follows:

$$X_{Cap} = \frac{1000*kv^2}{k_{var}} = \frac{1000*0.38^2}{1000} = 0.1444\Omega$$

These are the capacitor reactance for our capacitor bank:

$$X_L = \frac{X_{cap}}{h^2} = \frac{0.1444}{7^2} = 0.00295\Omega$$

$$L = \frac{X_{L(fun)}}{2\pi f} = \frac{0.00295}{2\pi*50Hz} = \mathbf{2.39\mu H}$$

CHAPTER FOUR

4. SIMULATION STUDIES AND DISCUSSION OF RESULTS

4.1. Introduction

ADC distribution substation has only one 132kV radial incoming feeder from Kality substation and have six (6) of 15kV outgoing feeder of loads. This voltage also further is stepped down to 380V by one transformers has 50000kVA, 15/0.38 KV. The whole power quality data have been analyzed and are compared with different international standards in chapter three. In this chapter simulation studies with and without different mitigation techniques results using MATLAB/SIMULINK/software are presented.

4.2. Impulse Transients

For impulsive transients caused by lightning strokes, direct stroke shielding lightning protective systems are installed at substations and high voltage overhead transmission lines. Surge arresters are also installed at substations and distribution transformer.

4.3. Mitigation of Oscillatory Transients

Among the causes of oscillatory transient, capacitor energization is the one which occurs in the Addis Center distribution substation and has various effects on sensitive industrial equipments. Therefore, here proper mitigation technique was applied. The solutions for Oscillation transients associated with capacitor switching have been simulated using MATLAB/SIMULINK/ software. These alternative solutions for transients associated with capacitor switching are discussed below along with their electrical modeling and simulation using SimPowerSystems software. The simulation results show the effect of capacitor switching and the effectiveness of the technique used to mitigate the transients associated with capacitor switching.

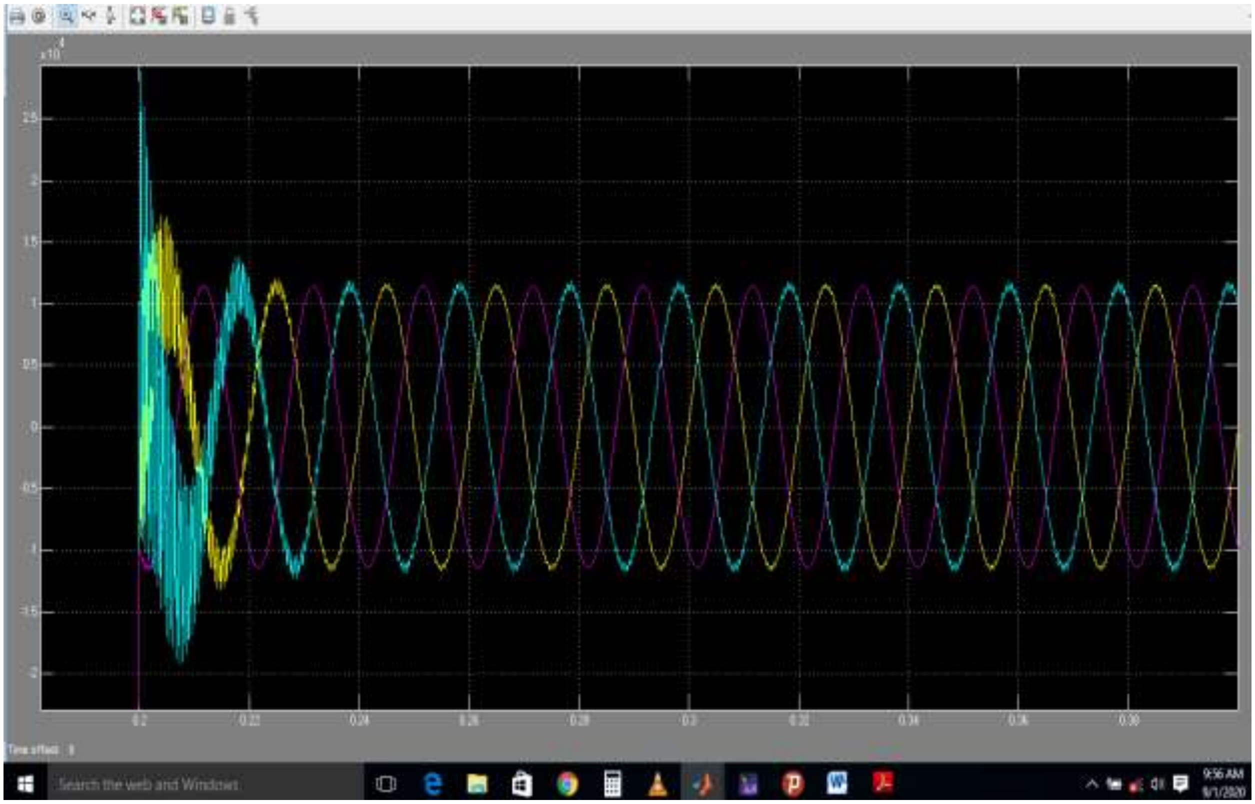


Figure 4.1 Oscillatory transient voltages waveform without pre-insertion resistor

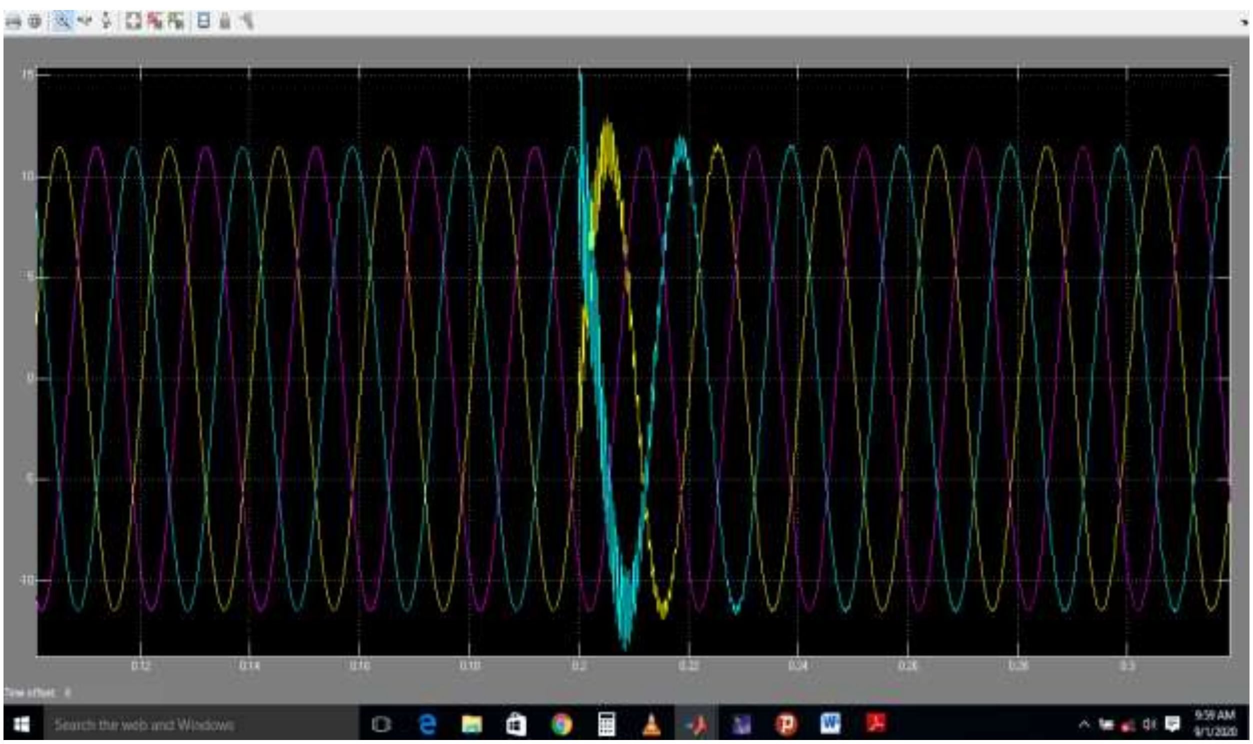


Figure 4.2 Oscillatory transient currents waveform without pre-insertion resistor

To overcome the problem of oscillatory transient overvoltage in this thesis by pre inserting resistor and inductor in simulation model which is twice as much the standard operating voltage level shown in figure 4.1 and 4.2 above causes various problems in the industry equipments such as malfunction of programmable logic controllers (PLC) and nuisance tripping of variable speed drives (VSD). As a result, pre-insertion resistor and inductor are used as mitigation. Thus, the overshoot is significantly reduced to the required standard voltage and current level. The simulation results that show the effect of transient reduction by using pre-insertion resistor and inductor are shown below in figure 4.3, 4.4 and 4.5, 4.6 respectively.

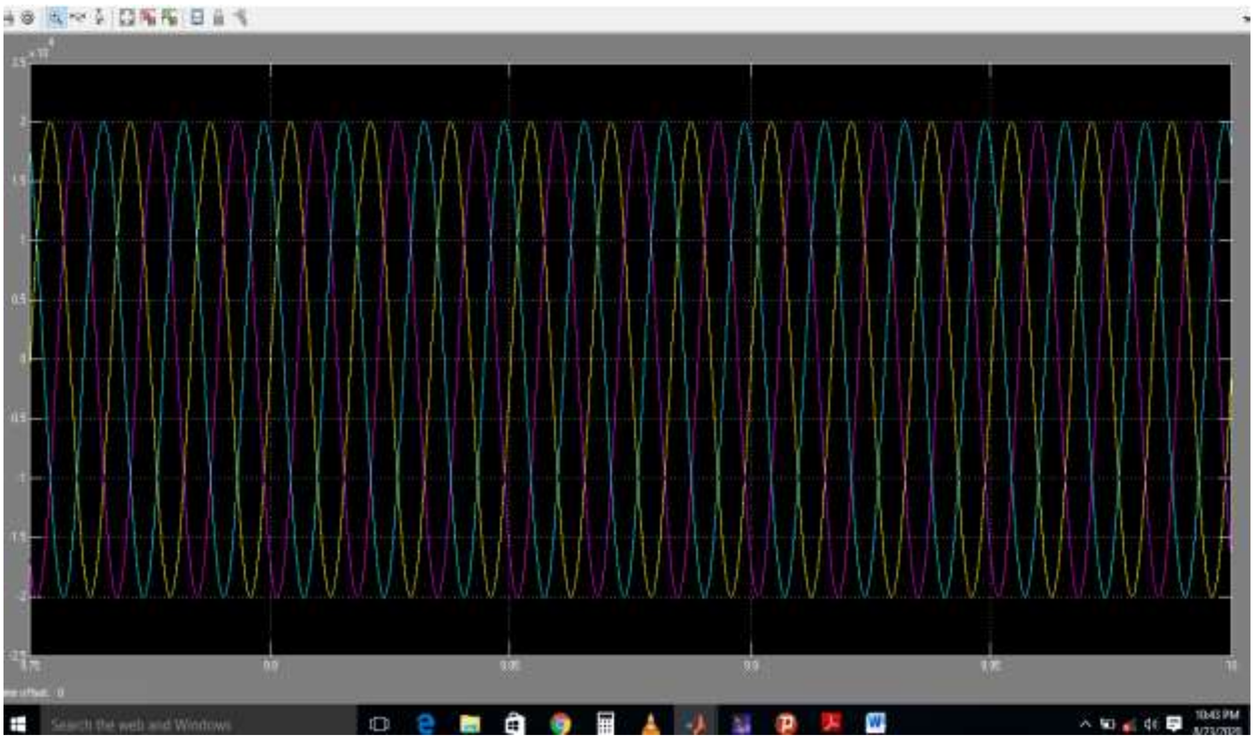


Figure 4.3 Oscillatory transient voltages waveform with pre-insertion resistor.

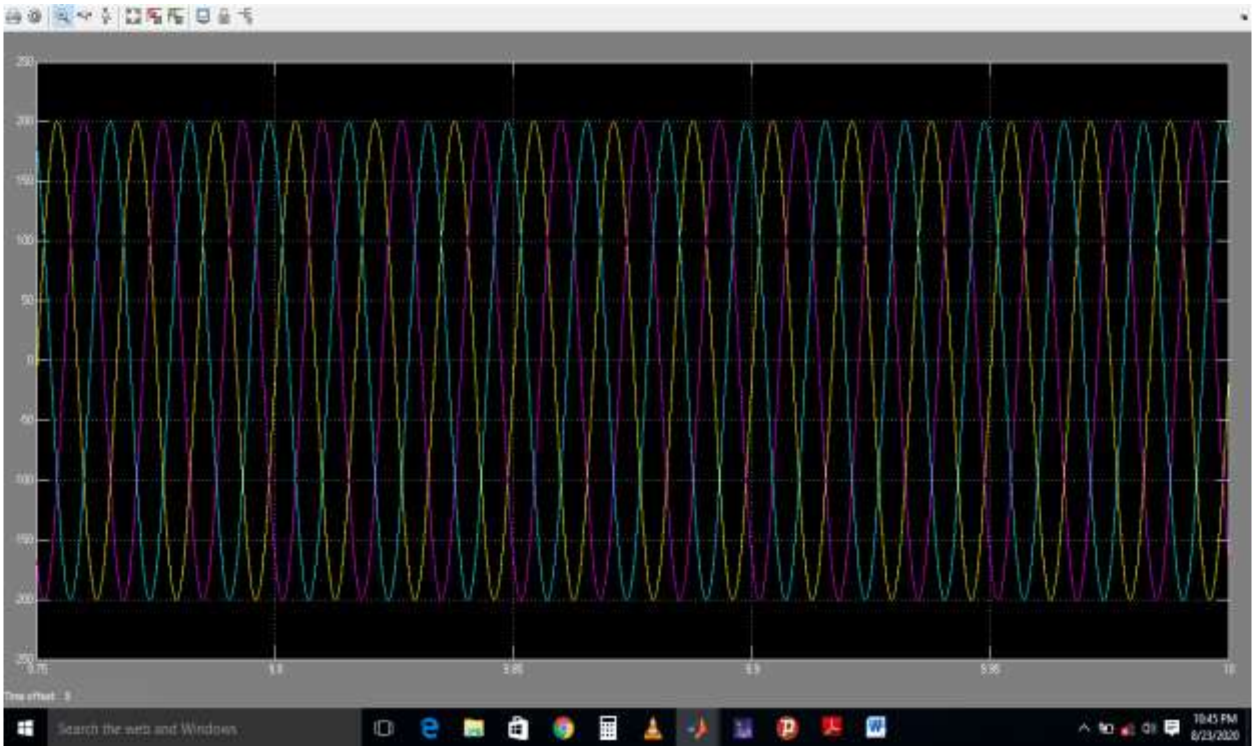


Figure 4.4 Oscillatory transient currents waveform with pre-insertion resistor.

Figure 4.5 Oscillatory transient voltages waveform with pre-insertion inductor

Figure 4.6 Oscillatory transient currents waveform with pre-insertion inductor

4.4. Mitigation of Voltage Sag Problem

The voltages sags problems caused by switching heavy loads, which happened to system faults at ADC distribution substation. Therefore, here proper mitigation technique was applied. These alternative solutions for voltage sag associated with switching heavy loads are discussed below mitigated using Dynamic Voltage Restore (DVR). The solution for voltage sag problem is modeled and simulated using MATLAB/SIMULINK/ software. The first simulation shows voltage sag problem without DVR when three phase to ground (LLLG fault) short circuit fault occurred in the system at a point with fault resistance of 1 Ω for time duration of 200 ms and the voltage is decreased to less than 90%. This voltage sag is needed to be compensated to get the desired voltage level at the load side. The simulation results that show the effect of voltage sag is shown below in figure 4.7.

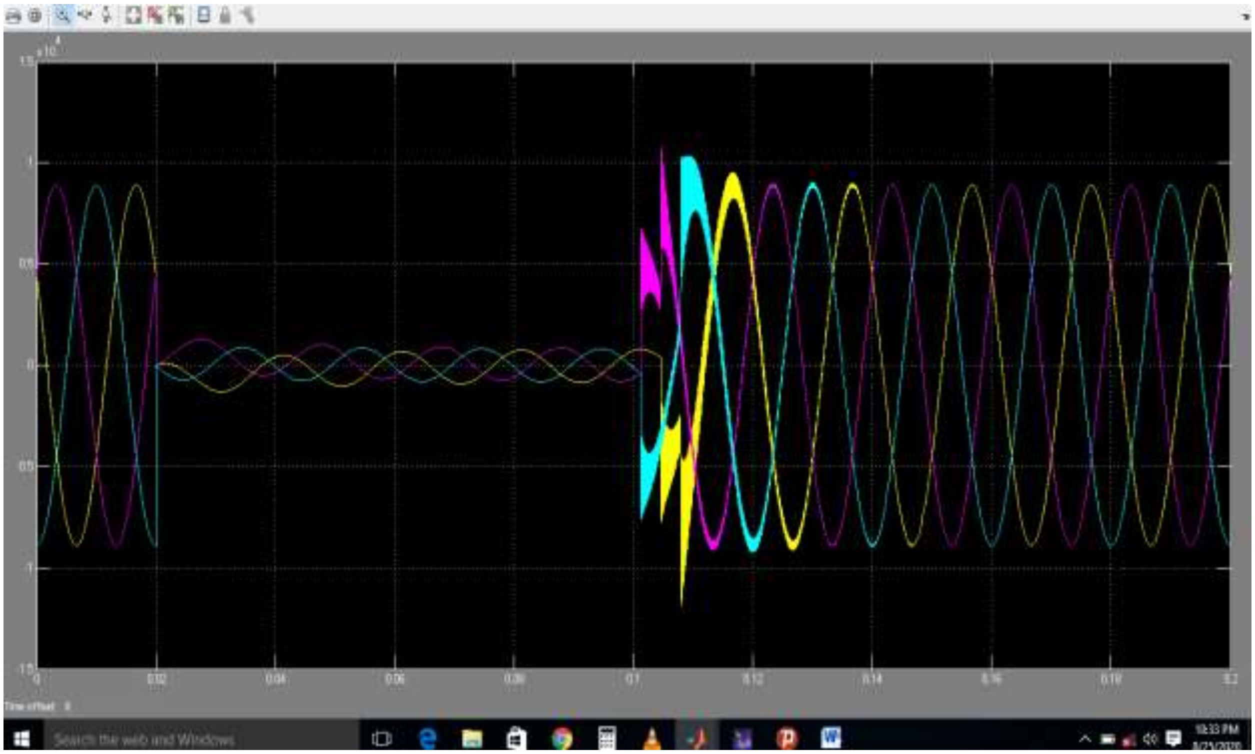


Figure 4.7 Voltage sag problem without DVR

In order to mitigate the problem of voltage sag, the simulation is carried out using the same scenario as above but a DVR is now introduced at the load side to compensate the voltage sag occurred due to the three phase to ground short circuit fault. The proposed dynamic voltage restorer responds to this sag and injects the appropriate amount of missing voltage that reaches below standard level during the sag event for compensation. When the DVR is in operation the voltage sag is compensated and the rms voltage at the load point is maintained to the standard voltage level. It is clearly observed that from simulation results the voltage waveform that is obtained after connection of DVR the voltage restores for the three phases is maintained shown below in figure 4.8. This shows that the installed DVR in distribution substation to mitigate voltage sag is working effective and efficiently.

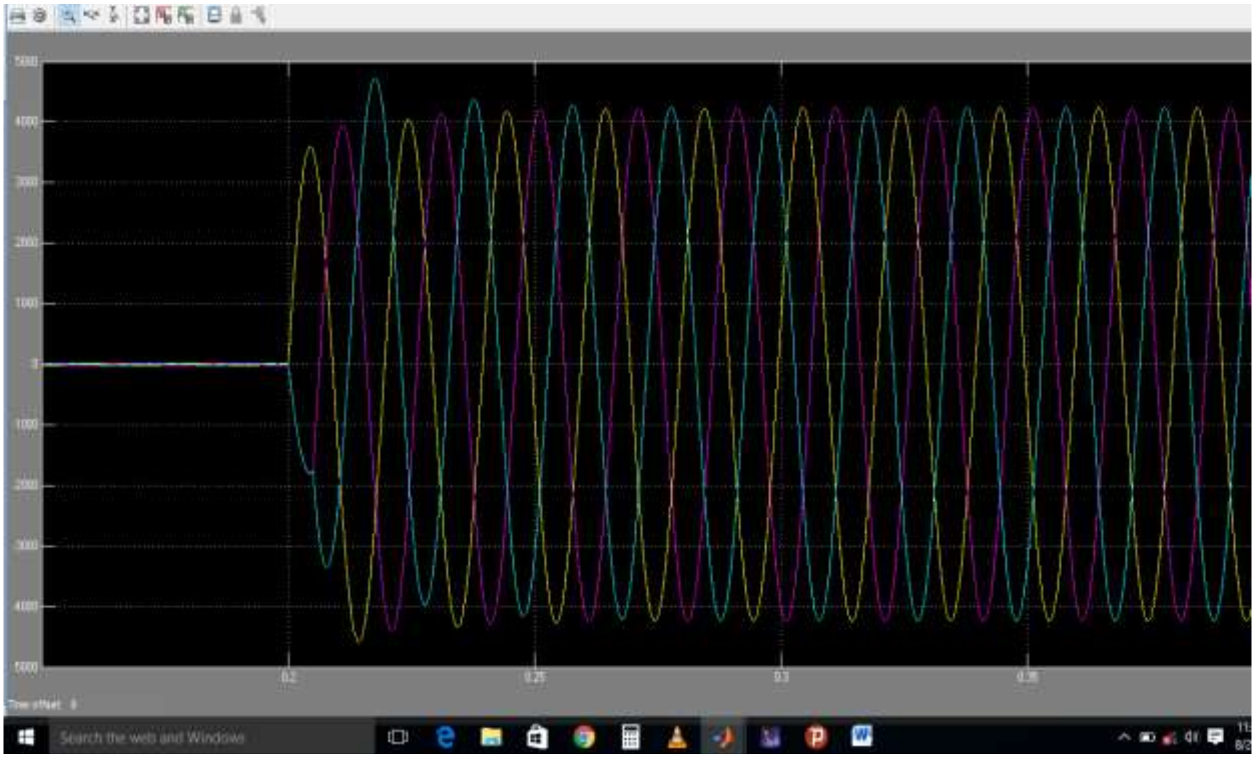


Figure 4.8 Injected voltages by DVR

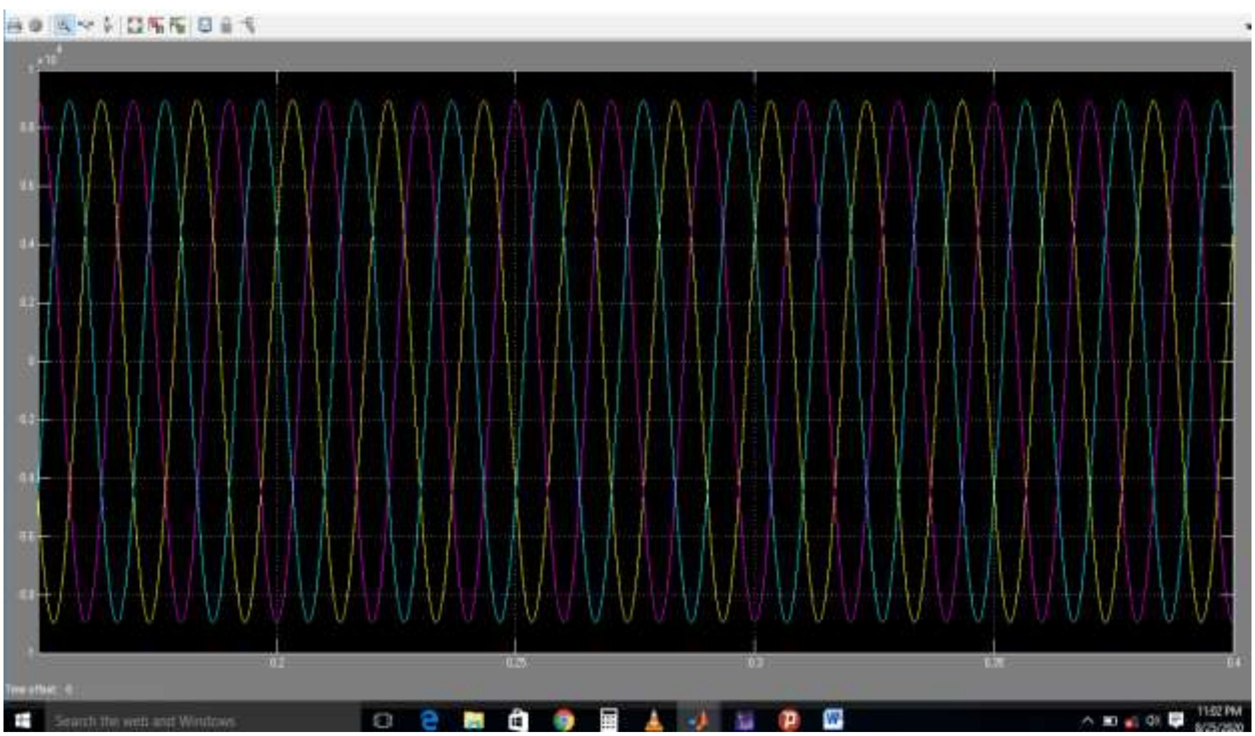


Figure 4.9 Voltage sag with DVR

4.5. Mitigation of Harmonic Problem

4.5.1. Mitigation of Harmonic by filter

The solutions for harmonic problem have been simulated using MATLAB/SIMULINK/ software. The third order high-pass filter's harmonic filters (5th and 7th harmonic filters) are simulated to effectively reduce the distortion levels to acceptable values. The current waveforms before and after filtering are presented for comparison.

Figure 4.10 Harmonic currents injected by non-linear loads

Figure 4.11 Currents waveform without filter

As we can see from figure 5.9 above shown the problem of harmonics produces a distorted waveform analysis the THD value is above the IEEE acceptable limit, i.e. 5% for this study. Therefore, to alleviate the problem, harmonic filters are used; consequently, the resulting waveform will be pure sinusoidal

Figure 4.12 Currents waveform and THD with filter

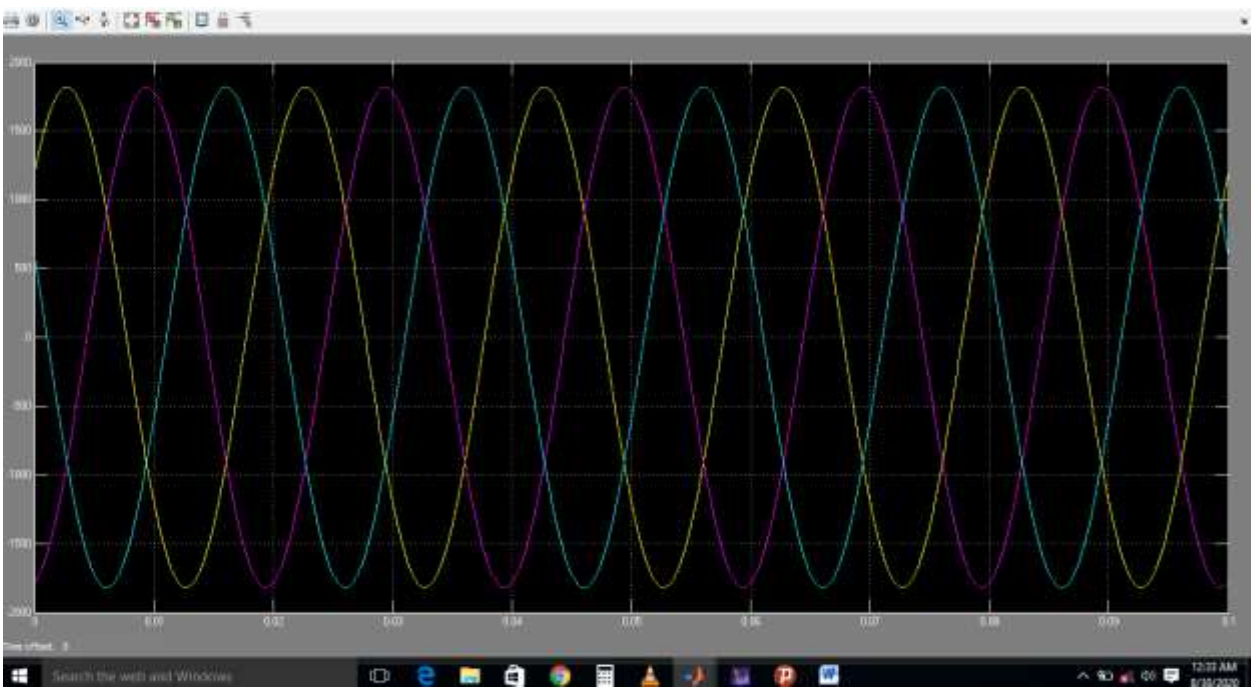


Figure 4.13 Currents waveform with filter

The results obtained in figure 5.11 above shown the third order high-pass filter's harmonic filter has significantly reduced the harmonic currents that appear at the secondary terminal of the transformer. The current THD level is reduced from above the IEEE acceptable limit to below 5% due to the compensation provided by the third order high-pass filter's harmonic filter. It is clear that the filters effectively reduce the distortion level to the acceptable magnitude, i.e. less than 5%.

4.5.2. Harmonic Mitigation Using DSTATCOM

The mitigation techniques using D-STATCOM for harmonic problem is modeled and simulated using MATLAB/SIMULINK/ software. The simulation figure 4.13 shows below harmonic problem without D-STATCOM when three phases (LLL fault) short circuit fault occurred in the system at a point with fault resistance of 10 Ω for time duration of 2s. This harmonic is needed to be compensated to get the desired current and voltage level at the load side. The simulation results that show the effect of harmonic is shown below in figure 4.13.

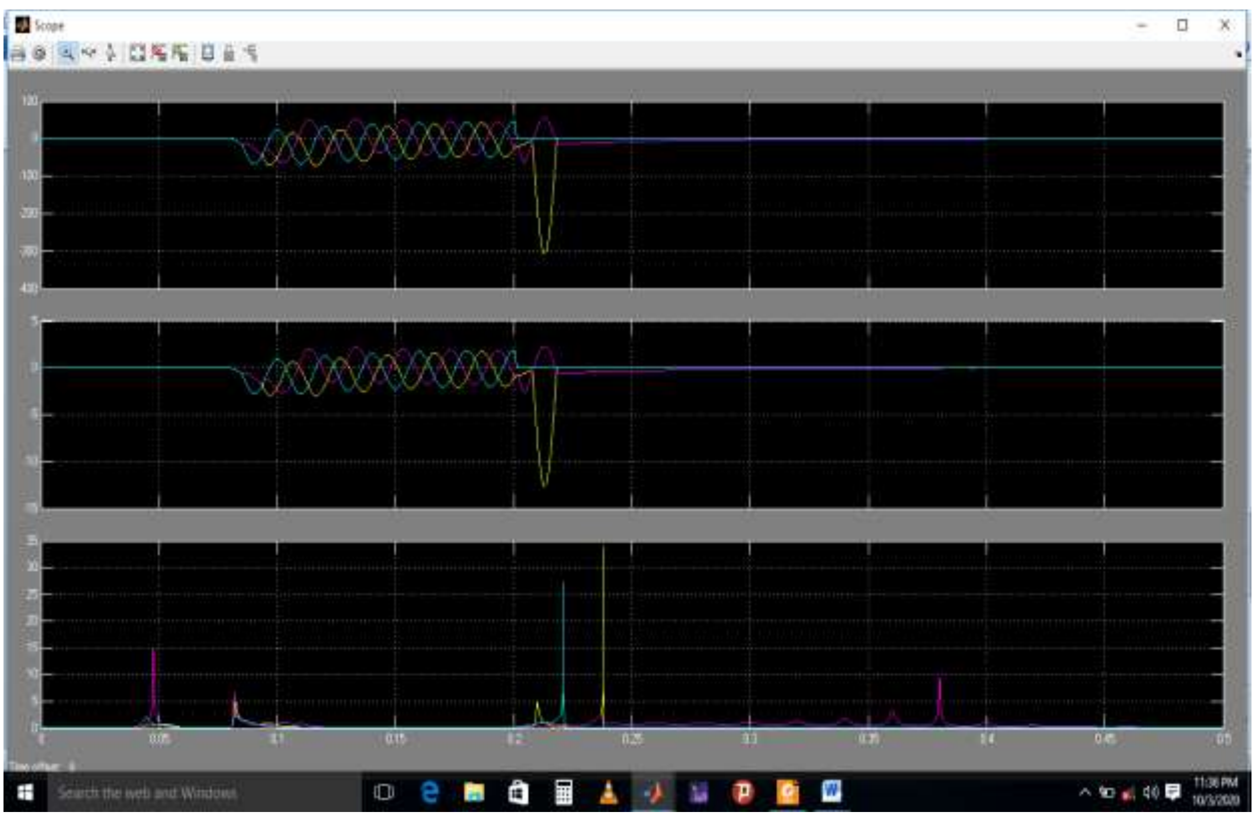


Figure 4.14.Harmonic Mitigation without DSTATCOM

The result obtained in figure 5.14 shown below the D-STATCOM has significantly reduced the harmonic currents and voltage that appear at the secondary terminal of the transformer. The current THD level is reduced from above the IEEE acceptable limit to below 5% due to the compensation provided by D-STATCOM harmonic mitigation techniques. It is clear that the D-STATCOM effectively reduce the distortion level to the acceptable magnitude, i.e. less 5%.

Figure 4.15 Harmonics Mitigation with DSTATCOM

Therefore, in order to mitigate the problem of harmonic current, the simulation is carried out using D-STATCOM is now introduced at the load side to compensate the harmonic current occurred due to the three phase short circuit fault. The proposed D-STATCOM responds to this harmonic and injects the appropriate amount of missing current and voltage that reaches below standard level during the harmonic event for compensation. When the D-STATCOM is in operation the harmonic current is compensated and the rms voltage at the load point is maintained to the standard current level. It is clearly observed that from simulation results the current and voltage waveform that is obtained after connection of D-STACOM for the three phases is maintained shown above in figure 4.14. This shows that the installed D-STATCOM in distribution substation to mitigate harmonic current is working effective and efficiently.

CHAPTER FIVE

5.CONCLUSIONS, RECOMMENDATIONS AND SUGGESTIONS FOR FUTURE WORK

5.1. Conclusions

The aim of this thesis was to study and analysis the power quality problems in the Addis Center distribution substation system, compare with standard values and propose mitigation techniques for the level exceeds the standard level. Based on the results of the power quality assessment carried out at ADC distribution substation, the following major conclusions are drawn.

Transients are disturbances that occur for a very short duration. It is impulsive transient and oscillatory transient, for impulsive transients caused by lightning strokes, direct stroke shielding lightning protective systems are installed at substations but, the oscillation is occurred at the ADC. The energization of three phase distribution switching capacitor bank which is used to improve the power factor, gives rise to oscillatory transient overvoltage. Oscillatory transient overvoltage due to capacitor switching can cause a wide range of problems, such as tripping of variable speed drives and tripping of power supplies. Therefore, pre-insertion resistors and inductor are used to mitigate the effect of the problem and reduce the oscillatory transient overvoltage from 25kV to 15kV or below acceptable limit (5%).

The short duration voltage variation, voltage sag, was occurred on the three phases to ground short circuit fault. The voltages sags problems caused by switching heavy loads, which happened to system faults at ADC distribution substation. Due to three phases to ground short circuit fault resulting in tripping of protective device and failure of sensors which check the quantity. It has also caused equipment malfunctions and ultimately equipment damage, particularly motors. So in order to overcome this problem dynamic voltage restorer is installed in ADC distribution substation system between the supply and the critical load feeder at the PCC, to restore the voltage to the normal standard voltage level. Therefore, here proper mitigation technique was applied. These alternative solutions for voltage sag associated with switching heavy loads are using mitigated using Dynamic Voltage Restore (DVR). When the DVR is in operation the voltage sag is compensated and the rms voltage at the load point is maintained. The results show that the device restores the voltage for the three phases from 13.02kV, 13.025kV and 13.026 kV, respectively to 15kV.

The problem of voltage unbalance is occurred at the ADC distribution substation. The voltage unbalance is caused by uneven single-phase load distribution among the three phases, most of the single phase loads are connected to phases 1, 2 and 3 are identified by measuring the currents in the three phases and the values are 1130 A, 1110 A and 1080 A, respectively, for the three phases. The effect of voltage unbalance is decreased motor efficiency and performance resulting in motor damage from excessive heat which affects ADC distribution profitability. So the problem should be mitigated by redistributing the loads equally to the three phases.

The ADC distribution draws a distorted current of above standard acceptable limit (5%) THD at its full load and TDD values of 16.21% which is beyond the IEEE current distortion limits, i.e. less than 5 %. Harmonic current are originated from non-linear loads, loads which draw non-sinusoidal current even when the supply voltage is perfectly sinusoidal. Specifically, 5th and 7th harmonics are the dominant harmonic frequencies caused by static power converters used in adjustable speed drives for motor control, switched mode power supplies and six-pulse static drives and the negative effects was studied. As a result, third order high-pass filter's harmonic filters were designed for the 5th and 7th harmonic current mitigation and the distortion levels were reduced from 25.10% to 3.05%. This reduction in distortion level shows how important a filter is to get rid of the ill effects, additional heating, false tripping and equipment malfunction associated with harmonics.

The harmonic current distortions also mitigate using D-STATCOM techniques at distribution substation. D-STATCOM is a shunt connected device and injects current into the system. These devices are connected to the distribution network at the point of interest to protect the critical loads. D-STATCOM requires more number of power electronic switches and storage devices for their operation. To overcome this problem, PWM switched auto-transformer is used for mitigating the harmonic current. Hence, PWM switched auto transformer, it is an efficient and economical solution for harmonic current mitigation. When the D-STATCOM is in operation the harmonic current is compensated and the rms voltage at the load point is maintained from 33.93% to 3.93%. Therefore, the installed D-STATCOM in distribution substation to mitigate harmonic current is working effective and efficiently.

5.2. Recommendations

The solutions given for the mitigation of power quality problems discovered throughout the study and complete assessment of power quality problems should be done for the distribution substation and compare with IEEE standards needed because there can be avoid the loss of money, improve productivity, profitability and for identifying those early failure of equipments in the distribution substation which causes power quality problems.

From power quality analysis, it has been seen that the distribution has been facing redundant power interruption problem which cause production interruptions. This affects the distribution substation technically and economically. The Ethiopian Electric power and Ethiopian electric utility should work a lot on the whole power system, from generation to distribution to reduce power quality problems and especial attention should be given to power interruption problem which has been a day to day problem for the end users. Therefore, Ethiopian Electric Utility should work hard concerning the electrical power interruption issue.

The industry should communicate with the utility on the alleviation of power interruptions and inspect the equipments provided by the service provider like transformers. Additionally, both the utility and the industry should also check the injection of harmonic currents by the non-linear loads to prevent damage of equipments due to harmonic distortion.

At the end, I recommend for the distribution substation and industry to keep the power quality problems measuring instrument, Power quality analyzer model - 8335 and Fluke 434/435 three phases Power Quality Analyzer properly because this device provides great help for studying problems associated to power quality issues smoothly and easily.

5.3 Suggestions for Future Work

As we know harmonic have effects on different equipments, therefore, the study and impact of harmonics on industry and equipments must be studied in detail in the future.

The following areas are the issues that need to be further studied.

- ❖ Impact assessment of the power quality problems on each and every electrical device
- ❖ Detail study power quality problems of the factory in distribution substation networks.
- ❖ Further study in Ethiopia need to assess the power quality status of their supply system and sensitivity of their equipment to solve the power quality problems.

REFERENCE

[1] An Investigation of Power Quality Problems in Distribution Network and Development of Mitigation Techniques. A Case Study of National Tobacco Enterprise Factory Ginbar Ensermu M.Sc. thesis 2012, ASTU.

[2] A. Moreno-Munoz (Ed.), “power quality mitigation technology in distribution environment”.
[3] Study and Simulation of Power Quality Improvement in Distribution Network. (Case Study: Metehara Sugar Factory) Netsanet Tadiwos M.Sc. thesis, March, 2017

[4] Voltage Quality and Power Quality Factor Improvement using Active Power Line Conditioner, by MARAVATHU NAGARJUNA Roll No.-212EE5398,2012-2014.

[5] IEEE 100, The Authoritative Dictionary of IEEE Standard Terms, seventh edition, 2000, p.234.

[6] Getu Tadesse, Studies on Power Quality Problems and Design of Mitigation Techniques: Case Study- Africa PLC (Macaroni and Pasta Factory) MSc. Thesis November 2015.

[7] Owyong Siew Leng, Simulating Power Quality Problems, School Of Information Technology and Electrical Engineering, University Of Queensland, October 2001.

[8] Dugan, Roger C., Mark McGranaghan, Surya Santoso, and H. Wayne Beaty, Electrical Power Systems Quality, McGraw-Hill Inc., 2003.

[9] Getenet Tesega, Power Quality Assessment at Selected Industrial Plants in Addis Ababa City, M.Sc. Thesis May 2011.

[10]Alexander Kusko, Sc.D, P.E. Marc T. Thompson, Ph.D. “Power Quality in Electrical Systems”, McGraw-Hill Companies, 2007.

[11] Reger C. Dugan / Mark F. McGranaghan, “Electrical power quality”, second edition, 2004.

[12] Mark Mc Granaghan, “Power quality standards”

[13] Robert G. Ellis, P.Eng.” Power System Harmonics”, Rockwell International Corporation, Canada, 2001.

[14] Surajit Chattopadhyay Madhuchhanda Mitra Samarjit Sengupta, Electric Power Quality, 2nd edition, 2010.

[15] Estifanos Dagnew, Power Quality Problems and Mitigation Techniques Case Study: National Tobacco Enterprise. M.Sc. Thesis November 2015.

[16] Tejashree G. More et al. Int. Journal of Engineering Research and Applications ISSN: 2248-9622, Vol. 4, Issue 4 (Version 4), April 2014, pp.170-177

[17] International Journal of Industrial Electronics and Electrical Engineering, ISSN: 2347-6982 Volume- 2, Issue- 1, Jan.-2014

[18] IEEE Std. 519-1992, IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems.

[19] IEEE Std 1159-1995, IEEE Recommended Practice for Monitoring Electric Power Quality, Approved June 14, 1995, IEEE Standards Board, USA.

[20] Taufik, Erin Matsumoto, and Makbul Anwari "Impact of Multiple Adjustable Speed Drive System to Power System Harmonics" 2nd IEEE International Conference on Power and Energy (PECon 08), Johor Baharu, Malaysia, 2008.

[21] Michella Weverink,"Mitigation of Voltage Sags in Industrial Power Plants with Medium Voltage DC Distribution System" Department of Electrical Power Processing Delft University of Technology February 2009.

[22] R.Sasi Kumar and P. Rajaguru "Power quality improvement in distribution system using DSTATCOM", International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering (An ISO 3297: 2007 Certified Organization) Vol. 2, Issue 12, December 2013.

[23] ABB SACE, "Power factor correction and harmonic filtering in electrical plants" Technical application papers, July 2008.

[24] Gebretsadik Teklay, Investigation and Analysis of Harmonic Pollution in Industrial and Commercial Power Systems, June, 2011.

[25] Jeff Mc Guire, Monitoring of Distribution System Power Quality, October 1999.

[26]. FRANCISCO C.DE LA ROSA, "Harmonics and power system", CRC press, 2006.

[27] Received February 1, 2018, accepted March 8, 2018, date of publication March 12, 2018, date of current version April 18, 2018.Digital Object Identifier 10.1109/ACCESS.2018.2814981

[28] Doeg Rodriguez Sanabria,Comparative Framework for Service Reliability in Electric Distribution Systems, MSc. Thesis, University Of Puerto Rico, Mayaguez Campus, 2005

[29] Tempa Dorji,Reliability Assessment of Distribution Systems, Including a case Study on Wangdue Distribution System in Bhutan, MSc. Thesis, Department of Electrical Power Engineering, Norwegian University of Science and Technology, 2009.

[30] Kiros Tesfay, Study and Evaluation of the Reliability and Design of Power Distribution System: Case Study Addis Ababa Power Distribution. M.Sc. Thesis, June 2014.

[31] An Investigation of Power Quality Problems in Distribution Network. A case study of Adama spinning Factory Milkias Berhanu M.Sc. thesis 2010, ASTU.

[32] Nipun Paroha and Vivek Anand "Power Quality Improvement in Distribution Line Using DSTATCOM" International Journal of Science and Research (IJSR) Volume 5 Issue 6, June 2016.

[33] www.ijcrt.org ©2018 IJCRT | National Conference Proceeding NCRIETS April 6-7, 2018 |
ISSN: 2320-2882 National Conference on Recent Innovation in Emerging Technology &
Science by JB Institute of Technology, Dehradun & IJCRT

[34] ABEBA DEBRU, Study of distributed generation in improving power system reliability (Case study: Addis Center Substation) M.Sc. thesis, June 2016.

[35] P. Kundur "Power System stability and control" Tata Mc-grah Hill edition' 2006.

[36] Harjit Singh Birdi, Power Quality Analysis Using Relay Recorded Data, August 2006.

[37]. Amit Kumar Jena, Bhupen Mohapatra, Kalandi Pradhan, Modeling and Simulation of a Dynamic Voltage Restorer for Mitigation of Voltage Sags, International Journal of Electrical, Computer, Electronics and Communication Engineering Vol:8 No:8, 2014.

[38]. Alexandre Nassif, "Modeling, Measurement and Mitigation of Power System Harmonics," Ph.D. dissertation, University of Alberta, fall 2009

[39] J. Schlabbach, D. Blume and T. Stephanblome, Voltage Quality in Electrical Power Systems, 2nd edition, The Institution of Engineering and Technology, 1999.

[40] H. Davudi, S. Torabzad, B. Ojaghi,"Analysis of Harmonics and Harmonic Mitigation Methods in Distribution Systems," Department of Electrical Engineering, Urmia Branch, Islamic Azad University, Urmia, Iran, 2011.

[41] C. Sankara, Power Quality, 2002.

APPENDIX A: IEEE Std. 1159-1995 Definitions of Terms

Dropout: A loss of equipment operation (discrete data signals) due to noise, sag, or interruption.

Dropout voltage: The voltage at which a device fails to operate.

Electromagnetic compatibility: The ability of a device, equipment, or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment.

Electromagnetic disturbance: Any electromagnetic phenomena that may degrade the performance of a device, equipment, or system, or adversely affect living or inert matter**.**

Electromagnetic environment: The totality of electromagnetic phenomena existing at a given location.

Electromagnetic susceptibility: The inability of a device, equipment, or system to perform without degradation in the presence of an electromagnetic disturbance**.**

Equipment grounding conductor: The conductor used to connect the noncurrent carrying parts of conduits, raceways, and equipment enclosures to the grounded conductor (neutral) and the grounding electrode at the service equipment (main panel) or secondary of a separately derived system (e.g., isolation transformer).

Failure mode: The effect by which failure is observed.

Flicker: Impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time.

Frequency deviation: An increase or decrease in the power frequency. The duration of a frequency deviation can be from several cycles to several hours.

Fundamental (component): The component of an order 1 (50 or 60 Hz) of the Fourier series of a periodic quantity.

Harmonic (component): A component of order greater than one of the Fourier series of a periodic quantity.

Harmonic content: The quantity obtained by subtracting the fundamental component from an alternating quantity.

Immunity (to a disturbance): The ability of a device, equipment, or system to perform without degradation in the presence of an electromagnetic disturbance.

Impulsive transient: A sudden non power frequency change in the steady-state condition of voltage or current that is unidirectional in polarity (primarily either positive or negative).

Inter harmonic (component): A frequency component of a periodic quantity that is not an integer multiple of the frequency at which the supply system is designed to operate operating (e.g., 50 Hz or 60 Hz).

Interruption, momentary (power quality monitoring): A type of short duration variation. The complete loss of voltage (< 0.1 pu) on one or more phase conductors for a time period between 0.5 cycles and 3 s.

Interruption, sustained (electric power systems): Any interruption not classified as a momentary interruption.

Interruption, temporary (power quality monitoring): A type of short duration variation. The complete loss of voltage (< 0.1 pu) on one or more phase conductors for a time period between 3 s and 1 min.

Momentary (power quality monitoring): A time range at the power frequency from 30 cycles to 3 s when used to quantify the duration ofa short duration variation as a modifier.

Noise: Unwanted electrical signals which produce undesirable effects in the circuits of the control systems in which they occur**.**

Nonlinear load: Steady-state electrical load that draws current discontinuously or whose impedance varies throughout the cycle of the input ac voltage waveform**.**

Notch: A switching (or other) disturbance of the normal power voltage waveform, lasting less than 0.5 cycles, which is initially of opposite polarity than the waveform and is thus subtracted from the normal waveform in terms of the peak value of the disturbance voltage. This includes complete loss of voltage for up to 0.5 cycles.

Oscillatory transient: A sudden, non-power frequency change in the steady-state condition of voltage or current that includes either positive or negative polarity value.

Overvoltage: When used to describe a specific type of long duration variation, refers to a measured voltage having a value greater than the nominal voltage for a period of time greater than 1 min. typical values are 1.1–1.2 pu.

Power disturbance: Any deviation from the nominal value (or from some selected thresholds based on load tolerance) of the input ac power characteristics**.**

Power quality: The concept of powering and grounding sensitive equipment in a manner that is suitable to the operation of that equipment.

Sag: A decrease to between 0.1 and 0.9 pu in rms voltage or current at the power frequency for durations of 0.5 cycle to 1 min. Typical values are 0.1 to 0.9 pu.

Shield: A conductive sheath (usually metallic) normally applied to instrumentation cables, over the insulation of a conductor or conductors, for the purpose of providing means to reduce coupling between the conductors so shielded and other conductors that may be susceptible to, or that may be generating unwanted electrostatic or electromagnetic fields (noise).

Swell: An increase in rms voltage or current at the power frequency for durations from 0.5 cycles to 1 min. Typical values are 1.1–1.8 pu.

Transient: Pertaining to or designating a phenomenon or a quantity that varies between two consecutive steady states during a time interval that is short compared to the time scale of interest. A transient can be a unidirectional impulse of either polarity or a damped oscillatory wave with the first peak occurring in either polarity**.**

Under voltage: A measured voltage having a value less than the nominal voltage for a period of time greater than 1 min when used to describe a specific type of long duration variation, refers to. Typical values are 0.8–0.9 pu**.**

Voltage distortion: Any deviation from the nominal sine wave form of the ac line voltage.

Voltage fluctuation: A series of voltage changes or a cyclical variation of the voltage envelope.

Voltage imbalance (unbalance), polyphase systems: The maximum deviation among the three phases from the average three-phase voltage divided by the average three-phase voltage. The ratio of the negative or zero sequence component to the positive sequence component, usually expressed as a percentage.

Waveform distortion: A steady-state deviation from an ideal sine wave of power frequency principally characterized by the spectral content of the deviation

APPENDIX B-1 THE DATA SHEET RECORDED IN JANUARY.

Hrs.	Frequency	Tap Pos.	132 KV incoming				KV	15 B/B	LV	AUX	15 KV outgoing lines currents					
			KV	A	MW	Mvar	A	V	A	A	L-4	L-5	L-7	L-8	L-11	L-15
1	50.2	11B	133	31	7	2	42	15	410	1	64	35	120	30	72	83
2	50.2	11B	133	28	6	2	40	15	388	1	60	32	116	26	70	60
3	50.2	11B	133	26	6	2	38	15	372	1	55	30	115	25	68	55
4	50.1	11B	133	24	6	2	34	15	362	1	56	30	118	25	64	55
5	50.1	11B	132	24	6	2	33	15	360	1	57	30	118	27	64	54
6	50.2	11B	132	29	6	2	38	15	370	1	60	32	125	28	70	55
7	50.1	11B	132	35	7	2	59	15	502	1	76	31	159	38	90	101
8	50.1	11B	132	45	9	3	76	15	642	1	106	34	199	45	124	130
9	50	12	131	50	10	2	83	15	710	1	131	22	205	49	147	141
10	50.1	12	131	50	10	3	83	15	718	1	134	22	197	48	150	137
11	50.1	12	131	50	10	3	83	15	715	1	135	22	195	48	150	137
12	49.9	12	131	48	10	3	79	15	670	1	122	17	202	48	143	137
13	50	12	132	45	9	3	74	15	623	1	110	20	185	47	135	123
14	50	12	132	40	8	2	70	15	592	1	105	34	163	47	126	118
15	50	12	132	40	8	1	70	15	590	1	103	34	162	47	126	118
16	50	12	132	40	8	2	70	15	590	1	102	34	163	47	126	118
17	50.1	12	132	40	8	2	70	15	590	1	100	34	165	47	125	117
18	50	12	132	45	9	2	70	15	610	1	105	39	174	43	117	125
19	50	12	132	45	9	2	70	15	600	1	103	39	174	42	117	118
20	50	12	132	45	9	2	70	15	585	1	100	38	174	40	110	115
21	49.9	12	133	40	8	2	68	15	578	1	98	38	174	38	106	113
22	49.9	12	131	40	8	2	67	15	575	1	97	38	173	38	105	112
23	50.1	12	133	35	7	2	60	15	520	1	82	34	160	38	95	85
24	50.1	12	133	35	7	2	60	15	517	1	77	33	155	35	93	85
Max	50.2	12	133	50	10	3	83	15	718	1	135	39	205	49	150	141

Hrs.	1:00	9:00	1:00	9:00	9:00	10:00	9:00	0	10:00	Hrs	11:00	18:00	9:00	9:00	10:00	9:00
Min	49.9	11B	131	24	6	2	33	15	360	1	55	22	115	25	64	54
Hrs.	12:00	1:00	9:00	4:00	2:00	1:00	5:00	0	5:00	Hrs	3:00	9:00	3:00	3:00	4:00	5:00

APPENDIX B-2 THE DATA SHEET RECORDED IN JANUARY.

Hrs.	Frequency	Tap Pos.	132 KV incoming				KV	15B/B	LV	AUX	15 Kv outgoing lines currents					
			KV	A	MW	Mvar	A	V	A	A	L-4	L-5	L-7	L-8	L-11	L-15
1	50.2	12	134	30	6	2	47	15	398	1	55	35	109	35	70	87
2	50.2	12	134	30	65	2	45	15	398	1	53	35	108	35	70	87
3	50.2	11B	134	30	5	2	45	15	392	1	52	32	105	32	68	85
4	50.2	11B	134	28	5	2	42	15	390	1	50	32	105	32	65	85
5	50.2	11B	133	28	7	2	42	15	385	1	50	32	110	32	65	80
6	50.1	12	132	35	10	2	70	15	570	1	119	42	140	40	97	110
7	50.1	12	131	45	10	3	82	15	695	1	119	42	199	45	132	147
8	50.1	12	132	50	11	3	90	15	700	1	131	45	159	47	140	155
9	50	12	132	53	11	3	97	15	832	1	154	5353	220	53	174	189
10	50	12	132	55	12	3	94	15	818	1	151	53	174	53	182	198
11	50	12	132	50	12	3	97	15	832	1	146	53	200	48	186	189
12	50	12	132	50	11	3	96	15	830	1	146	53	200	46	183	185
13	50	12	132	48	10	3	94	15	815	1	140	52	190	45	180	180
14	50	12	132	48	10	3	90	15	804	1	135	50	188	44	180	175
15	50	12	132	48	10	3	87	15	750	1	130	48	190	43	170	170
16	50	12	132	48	10	3	84	15	726	1	121	52	191	44	142	164
17	50	12	132	49	10	3	85	15	728	1	125	55	190	44	145	170
18	50	12	132	49	10	3	85	15	738	1	135	50	191	46	151	150
19	50	12	132	50	10	3	89	15	762	1	151	42	210	48	160	149
20	50	12	132	49	10	3	85	15	726	1	140	40	200	42	140	133
21	50	12	132	46	9	3	71	15	661	1	137	38	190	40	131	121
22	50.1	12	132	46	9	3	70	15	650	1	134	38	188	40	118	100
23	50.1	11B	133	44	8	3	68	15	607	1	120	36	155	36	100	93
24	50.2	11B	133	40	8	2	60	15	559	1	98	36	131	34	87	84
Max	50.2	12	134	55	12	3	97	15	832	1	154	55	210	53	186	198
Hrs.	1:00	1:00	1:00	11:00	11:00	7:00	9:00	0	9:00	all Hrs.	9:00	17:00	19:00	9:00	11:00	10:00
Min	50	11B	131	28	5	2	33	15	385	1	50	32	105	32	65	84
Hrs.	9:00	3:00	7:00	4:00	3:00	1:00	4:00	0	5:00	all Hrs.	4:00	3:00	3:00	3:00	4:00	0:00

APPENDIX C- Simulink model of simulation

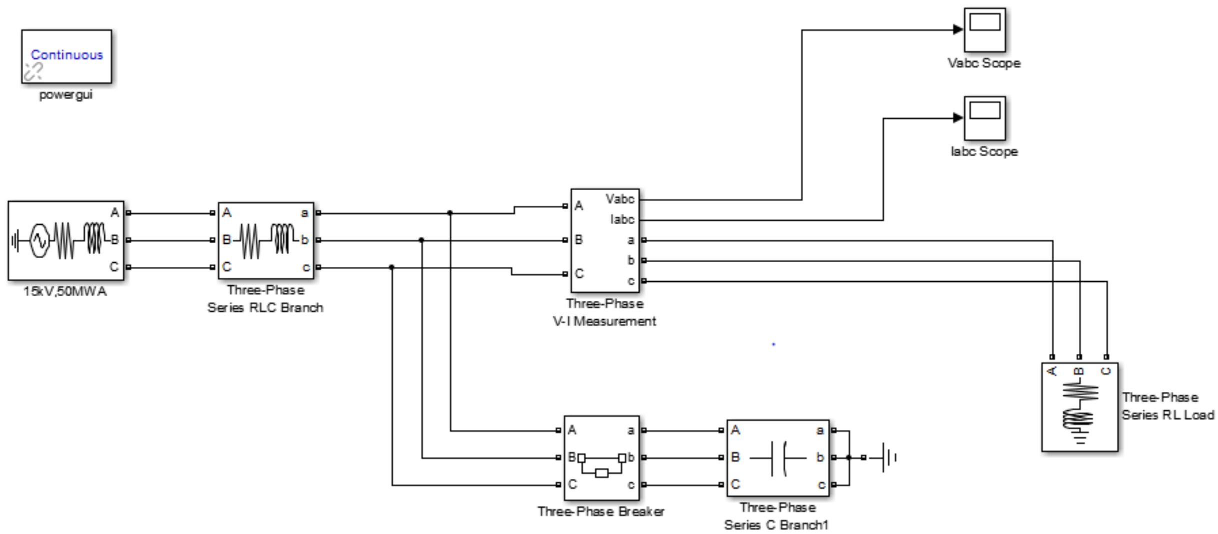


Figure C-1. Simulink model for oscillatory transient without pre-inserting

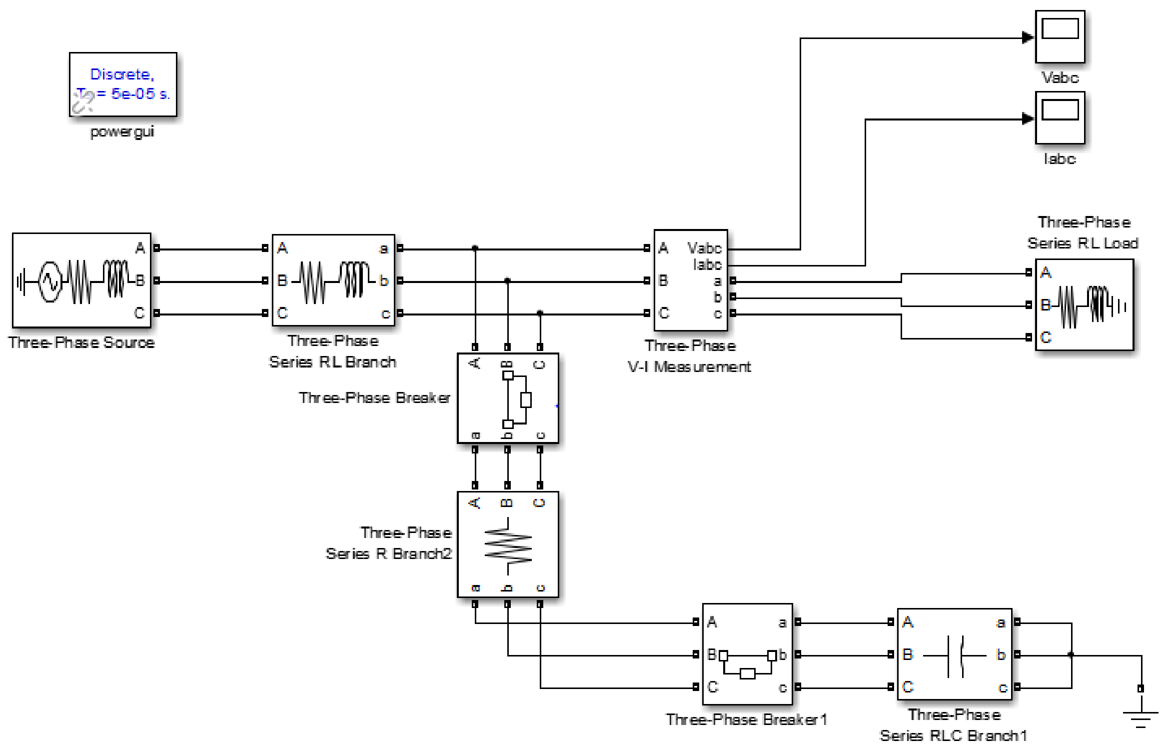


Figure C-.2. Simulink model for oscillatory transient with pre-insertion resistor

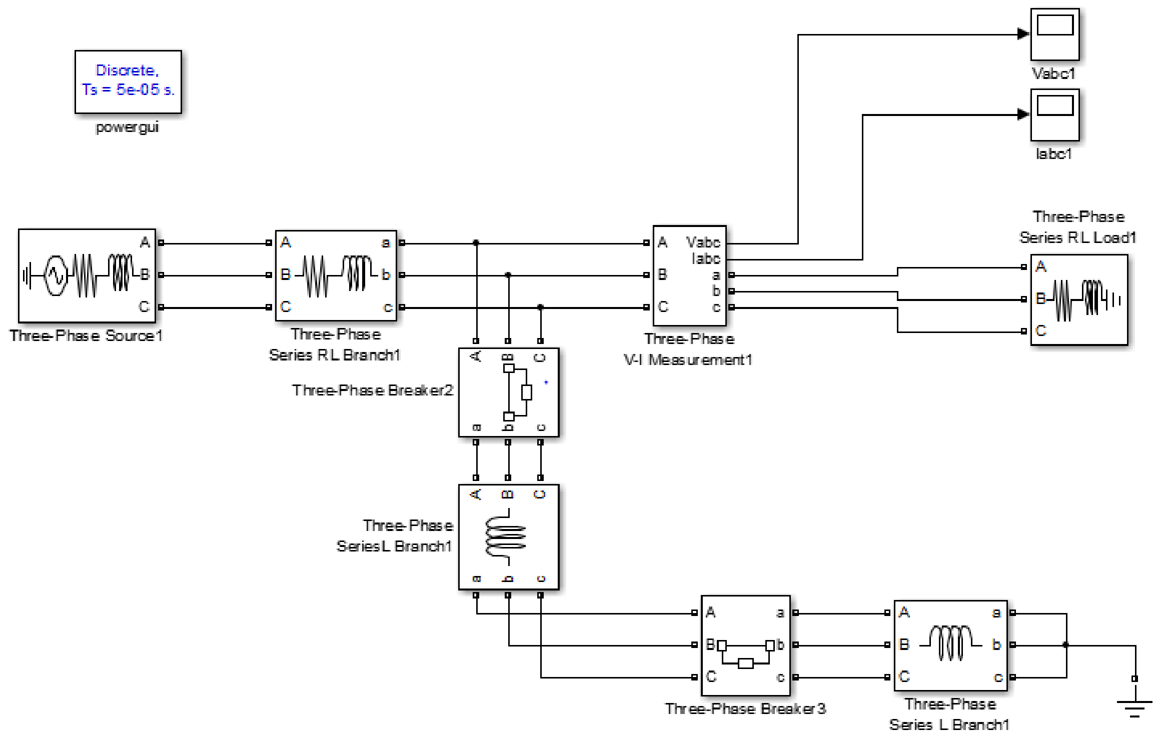


Figure C-.3. Simulink model for oscillatory transient with pre-insertion inductor

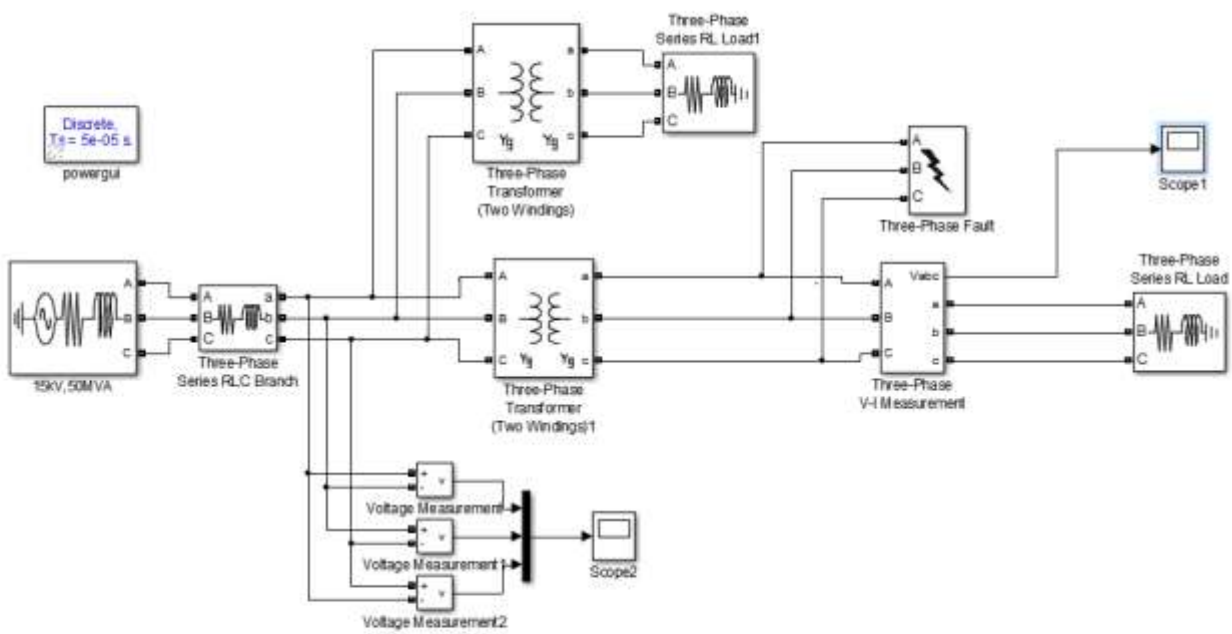


Figure C-4. Simulink model of voltage sag without DVR

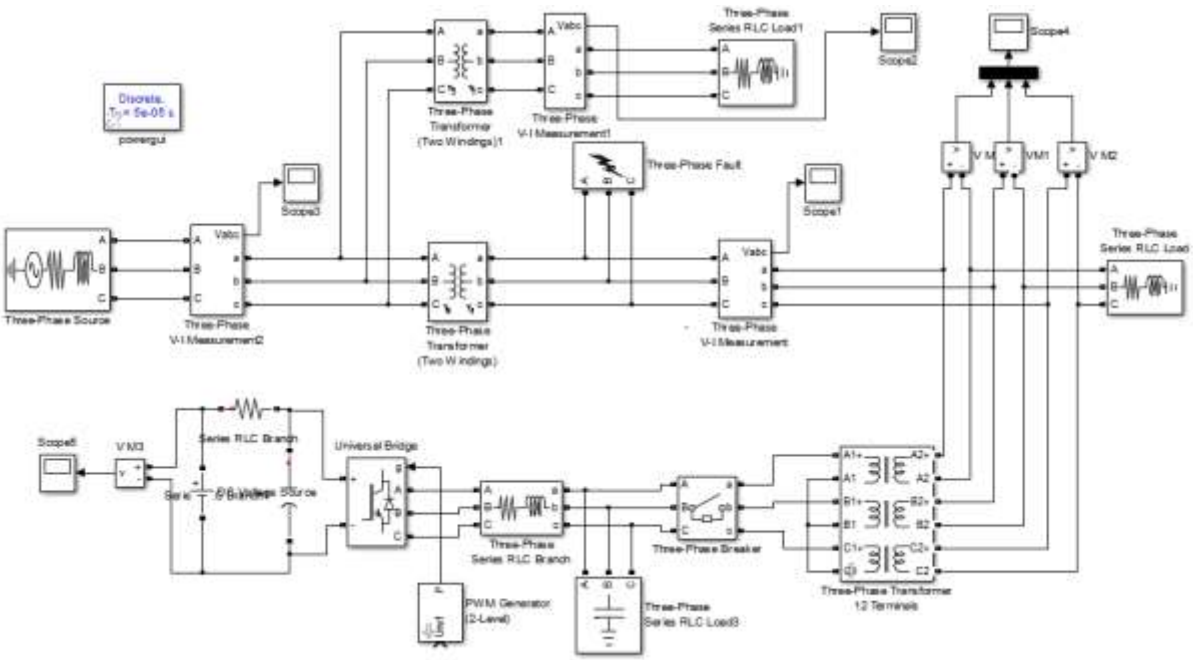


Figure C-5. Simulink model of voltage sag with DVR

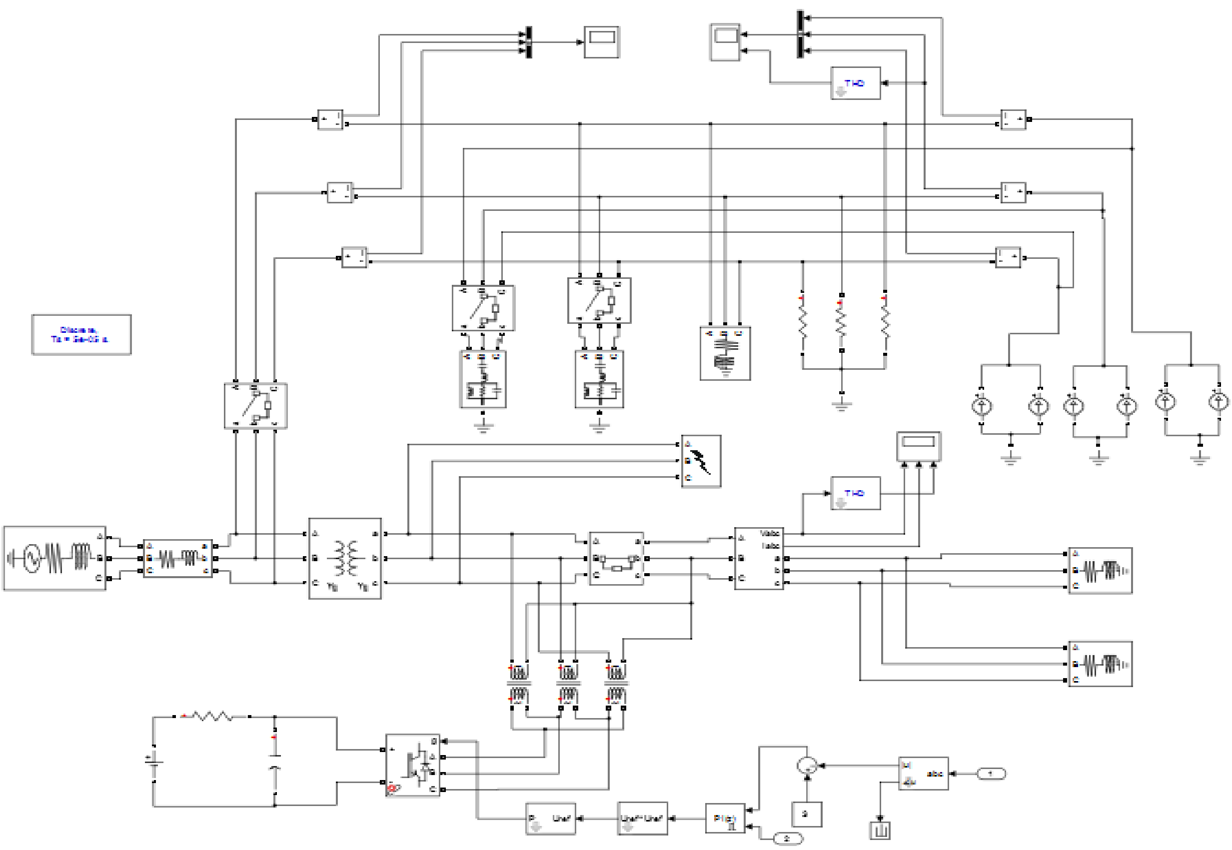


Figure C-6 simulink model harmonic mitigation with and without filter and D-STATCOM