ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING

# POWER QUALITY PROBLEMS AND MITIGATION TECHNIQUES

## CASE STUDY: NATIONAL TOBACCO ENTERPRISE

BY

ESTIFANOS DAGNEW MITIKU

A THESIS SUBMITTED TO ADDIS ABABA INSTITUTE OF
TECHNOLOGY IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE
IN
ELECTRICAL POWER ENGINEERING

ADVISOR
DR. ING. GETACHEW BIRU WORKU

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# Certification

The undersigned certify that he has read and hereby recommend for the acceptance by the Addis Ababa University a thesis entitled: **Power Quality Problems and Mitigation Techniques, under the case study of National Tobacco Enterprise**, in partial fulfillment of the requirements for the degree of Masters of Science in Electrical Power Engineering.

| | | |
|---|---|---|
| Dr.-Ing. Getachew Biru | ______________________ | ______________________ |
| Advisor | Signature | Date |

# Declaration

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

Signature: ____________________ Date: ________________________

***DEDICATED***

***TO***

***MY FATHER***

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I would like to express my sincere appreciation to my advisor Dr.Ing. Getachew Biru for his guidance, constructive comments, suggestions and encouragement from the start of the study up to the final work of the paper. He read all the drafts of my thesis and taught me to be thorough in analyzing problems and rigorous in presenting ideas. This thesis would not have been possible without his support and guidance.

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# ABSTRACT

The electrical energy is one of the easily used forms of energy and with the advancement of technology; the dependency on the electrical energy has been increased greatly. However, the quality of power being supplied is affected by various internal and external factors of the power system and the presence of power quality problems deteriorate the performance of the system.

Nowadays power quality problem is an issue to the industrial customers. As a result, many of the industries in our country faced with the problem of power quality, having various causes. In this thesis work the assessment of power quality problems of National Tobacco Enterprise which is located in Addis Ababa and its mitigation techniques have been studied. The study focuses on investigating and identifying the power quality problems of the industry as per IEEE standards.

The data required for the study is collected from the industry using Fluke 434/435 three phase Power Quality Analyzer and from recorded data. Based on the measurement the following 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 5-6 hrs per week, voltage unbalance of 2.62% and current distortions of THD value that reach 18.33%.

The collected data have been analyzed and computer simulations are done using MATLAB/SIMULINK model to show the effectiveness of mitigation techniques. In this thesis pre-insertion resistor is used to mitigate the problem of oscillatory transient and the result indicates that the transient voltage reduced from 510 V to 230 V. For the problem of voltage sag, dynamic voltage restorer is identified as a solution and the results shows that the device restores the voltage for the three phases from 202.86 V, 201.25 V, and 200.33 V, respectively to 230 V. Single-tuned multi-branch 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 value from 18.33% to 3.97%. Standalone photovoltaic system is also designed as a solution to sustained power interruptions and for the problem of voltage unbalance redistribution of single phase loads equally among the three phases is taken as a mitigation technique.

***Key Words***: *Power quality, power quality assessment, National Tobacco Enterprise, IEEE standards, Mitigation Techniques, MATLAB/SIMULINK model.*

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| | |
|---|---|
| AC | Alternating Current |
| Ah | Ampere Hours |
| ANSI | American National Standards Institute |
| ATS | Automatic Transfer Switch |
| CBEMA | Computer Business Equipment Manufacturers Association |
| DC | Direct Current |
| DOA | Days of Autonomy |
| DOD | Depth of Discharge |
| DVR | Dynamic Voltage Restorer |
| EEPCo | Ethiopian Electric Power Corporation |
| FFT | Fast Fourier Transform |
| GTO | Gate Turn-Off thyristor |
| IEC | International Electro technical Commission |
| IEEE | Institute of Electrical and Electronics Engineers |
| IEEE Std | Institute of Electrical and Electronics Engineers Standard |
| IGBT | Insulated Gate Bipolar Transistor |
| IGCT | Integrated Gate Commutated Thyristors |
| ITIC | Information Technology Industry Council |
| KV | Kilo Volt |
| KVA | Kilo volt ampere |
| KVAR | Kilo Volt ampere reactive |
| KW | Kilo Watt |
| MATLAB | Matrix Laboratory |
| MOSFET | Metal Oxide Semiconductor Field Effect Transistors |
| ms | Millisecond |
| NEMA | National Equipment Manufacturers Association |
| NTE | National Tobacco Enterprise |
| $P_{lt}$ | Long-term flicker severity |
| $P_{st}$ | Short-term flicker severity |

| | |
|---|---|
| PCC | Point of Common Coupling |
| PLC | Programmable Logic Controllers |
| PQ | Power Quality |
| PU | Per Unit |
| PV | Photovoltaic |
| RMS | Root Mean Square |
| TCF | Temperature Correction Factor |
| TDD | Total Demand Distortion |
| THD | Total Harmonic Distortion |
| $THD_I$ | Current Total Harmonic Distortion |
| $THD_v$ | Voltage Total Harmonic Distortion |
| VSC | Voltage Source Converter |
| VSD | Variable Speed drives |

# CHAPTER 1

# INTRODUCTION

## 1.1.Background

Electrical energy is the most efficient and popular form of energy and the modern society is heavily dependent on the electric supply. Today it is difficult to imagine life without supply of electricity. In recent times, electric utilities, academic and research centers, equipment manufacturers, industries and other end users of electric power are becoming increasingly concerned about the quality of electric power because it is very important for the efficient functioning of the end user equipments. Thus maintaining power quality is very essential [1].

Power quality is an issue that is becoming increasingly important to both utilities and electricity consumers at all levels of usage. The term PQ has been widely used by many industrial and commercial electricity end-users. The quality of power is affected if there is any deviation in the voltage, current or frequency values at which the power is being supplied. This affects the performance and life time of the end user equipment. So to maintain the continuity of the power being supplied, the faults should be cleared at a faster rate and for this the power system switching equipment should be designed to operate without any time lag [1].

Whenever the issue of power quality is raised, the utility has the responsibility to produce sine wave voltage; whereas, end-use customers have the responsibility to limit the harmonic currents their electric loads inject into the utility system. The utility is therefore required to supply its customers with a certain minimum quality of electric power, while end users should on their parts limit the power quality disturbances they inject into the power system. In our country, most of the electric power quality problems occur in the industries. Typical power quality phenomena include harmonics, transients, short-duration voltage variations, long duration voltage variations, voltage imbalance, voltage fluctuations, and power frequency variations.

This thesis is mainly concerned on power quality problems existing in National Tobacco Enterprise these are: oscillatory transient overvoltage, voltage sags, sustained power interruptions, voltage unbalance and harmonic pollutions. These PQ problems have significant adverse effects on the power system and equipments of the industry.

## 1.2.Statement of the Problem

An electric utility should supply electric power at a certain minimum quality standard to its customers and the customers are allowed to draw a certain permissible degree of distorted current. In most of the countries standards and regulations have developed for the attainment of the desired electric power quality. In the case of Ethiopia electric power quality problems have a huge impact on industrial plants, governmental and non-governmental organizations, business centers, commercial centers, residences and other end electric power users for the achievement of their goals.

The motivating factor to work on this thesis is the occurrence of different power quality problems in the industry. Among the PQ problems oscillatory transient overvoltage which is caused by capacitor bank energization have the effect of malfunctioning sensitive power electronic device and data corruption. Voltage sags caused by short circuit faults occurred in the industry power system resulting in failure of the breaker to trip in case of a fault detected by the protective relays due to prolonged exposure of short circuit currents, the tripping of controls to the dc drives, programmable logic controllers (PLCs) and the remote I/O units, for instance, have been found to trip which leads to a partly shut down of production for hours or even days leading to significant financial losses and reduction of efficiency and life span of electrical equipments, particularly motors.  The frequent sustained power interruptions affect the production process; causing downtimes of several machines and left labors without work as a result this costs the industry huge amount of money annually. Voltage unbalances due to uneven single-phase load distribution among the three phases. The utilization of non-linear loads is increasing by the end users and these loads inject harmonic currents into the power system. Noticeably, the harmonic currents are potentially dangerous in negatively affecting both the utility and end-users of electric power.

Thus, the study focuses on finding solutions and appropriate mitigation techniques to the existing power quality problems and improving the profitability of the industry.

## 1.3.Objectives

### General Objective

The main objective of this thesis is assessing the quality of the electrical power in National Tobacco Enterprise and based on the assessment investigating the level of power quality disturbances to the industry loads.

### Specific objective

The specific objectives of this study are to:

1. identify and examine the power quality problems that arises in National Tobacco Enterprise,
2. compare the level of those disturbances with acceptable values set by IEEE standards
3. identify the causes and adverse impacts of the identified PQ problems,
4. study and design appropriate mitigation techniques to the existing PQ problems,
5. design and simulate the impact of pre insertion resistors, dynamic voltage restore and harmonic filters for mitigation of oscillatory transients, voltage sags and harmonic distortions, respectively.
6. draw relevant conclusions and recommendation for the industry.

## 1.4.Significance of the Study

The output of the study is significant for the industry because the paper addresses the existing power quality problems and if the industry implements the solutions provided it protects their equipments from the effect of different power quality problems that result from capacitor bank switching, system faults, and injection of harmonic currents which arises from non linear loads, it increases the efficiency and performance of their equipments and it saves the money they lost due to poor power quality which causes production loss, damage to sensitive electronic devices and reduction of equipment efficiency. The study may also be used as a reference and may provide foundation for further research on similar areas of study by other researchers.

## 1.5.Methodology

The research methodologies and the flow of the research are presented as follows:

- **a. Literature review:** a number of published ideas about power quality problems assessment and mitigation techniques in books, papers, articles, journals, lecture notes, materials have been reviewed.
- **b. Walk-through tour:** to become familiar with the electrical system of the industry and examine the power quality problems.
- **c. Interview:** with electrical personnel to obtain detailed information about power quality problems
- **d. Data collection:** the power quality measurement is taken from the secondary of service transformers of the industry using Fluke 434/435 three phase Power Quality Analyzer.

  A "Fluke 434/435 three phase Power Quality Analyzer" is a portable device utilized for measurement. The device can measure three-phase and phase-to-neutral true rms voltage on all three phases, equivalent three phase current and true rms current per phase, total three phase power and power per phase, total three phase power factor and power factor per phase, reactive and apparent three phase system power, frequency, active and reactive energy consumption/export, voltage and current total harmonic distortion per phase.
- **e. Data analysis:** the aforementioned collected data have been analyzed and compared to the IEEE Standard 1159-1995.
- **f. Propose solution:** appropriate solutions for power quality problems exceeding limits.
- **g. Modeling and Simulation:** using MATLAB/SIMULINK software modeling and simulation of power quality problems have been carried out for the modeled networks.
- **h. Analysis of the result:** analyze the results of the simulation obtained from the simulating software.
- **i. Conclusion and recommendations:** significant for the industry have been made.

## 1.6.Description of the Study Area

In this research the selected site for case study is National Tobacco Enterprise which is located in ADDIS ABABA LIDETA sub-city. National Tobacco Enterprise (Ethiopia) Share Company (NTE) was established as per the Tobacco Regie Act No.30, 2nd year Negarit Gazetta, No.2/1935 as “Imperial Ethiopian Tobacco Monopoly” with paid up capital of 50,000 ‘Mariatereza’. It started its work with a single cigarette machine and a single brand, Nigusu. The production capacity of the machine was 300 pieces per hour.

In 1981 the Enterprise was re-structured by proclamation No.1971/1981 and has become the “National Tobacco and Match Corporation” with the capital outlay of 80 million Ethiopian Birr. Later, the Enterprise has again been re-organized as “National Tobacco Enterprise” in accordance with proclamation No. 37/1992. In article 4 of this proclamation the enterprise has been given an exclusive right to produce, process, manufacture, distribute, import and export tobacco and tobacco products in Ethiopia.

Currently the Company is among the top public enterprises in terms of annual turnover, profitability, and its contribution to the economy as a whole. Annual turnover has continually increased, on average by Birr 190 million, during the previous five years period. Similarly, its contribution to the economy in terms of taxes paid, dividend to the share holders and job creation to the citizen as a whole is persistently increasing. Annual tax related contribution to the economy (VAT, Excise tax, Income tax, dividend tax etc) has currently reached more than Birr 700 million. In addition to this, the Enterprise with one cigarette factory at Addis Ababa and four tobacco development farms at ShewaRobit, Awassa, Bilatie and Wolaita has employed more than 934 permanent employees and 3,305 temporary and casual workers.

The enterprise is supplied through a 15 kV feeder emanating from the near substation. The factory contains two, 630 KVA transformers that supply power to the different processes like steam drier machines, thresher line, blending box, tobacco conditioner, conveyors, and lighting. Due to the huge investment and the expensive equipments found in the factory problems associated with power quality should be studied before any major equipment failure or production loss occurs.

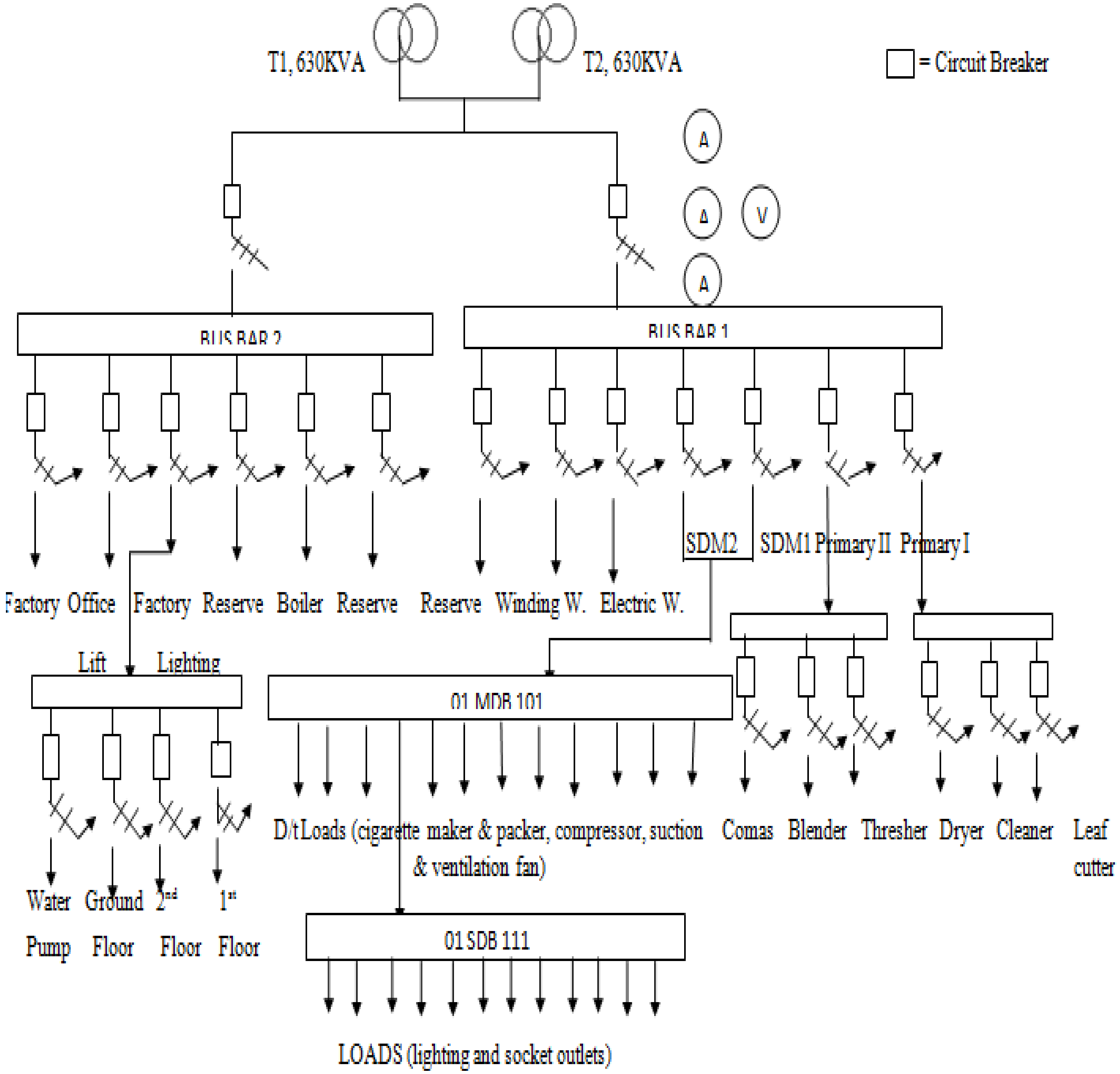


Figure1.1 Single Line Diagram of National Tobacco Enterprise

## 1.7.Outline of the Thesis

The thesis is organized into 6 chapters namely Introduction, Fundamentals of Power Quality Problems, Power Quality Field Measurement Values, 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 part in which the background, problem statement, literature review, objective, significance of the study, methodology and description of the study area are included.

Chapter 2 presents about the 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 outlines the power quality measurement and benchmarking and the measurement results are described along with the standard values.

Chapter 4 discusses the existing power quality problems and mitigation techniques. Proposed solutions and mitigation techniques are discussed and designed in detail to alleviate the problems.

Chapter 5 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.

Chapter 6 is the last chapter, 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 2

# POWER QUALITY PROBLEMS ASSESSMENT

In an electrical power system, 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. To study the PQ problems a general purpose power quality evaluation (assessment) procedure is followed [2]:

## 2.1.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 research. The investigation emphasizes only on the existing power quality problems. The power quality evaluation procedure followed in this research includes the following general steps [3].

### 2.1.1. Identify Power Quality Problems

It 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 [3].

However, the IEEE Standard 1159-1995, classifies the power quality problem into seven major categories described as follows:

#### 2.1.1.1.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. Some of them are: Arcing between the contacts of the switches, sudden switching of loads, poor or loose connections, and lightning strokes. These transients are categorized into impulsive and oscillatory transients [4].

### a. Impulsive Transient

An impulsive transient is “a sudden, non-power frequency change in the steady state condition of voltage, current, or both, that is unidirectional in polarity”. Impulsive transients are normally characterized by their rise and decay times, which can also be revealed by their spectral content. Impulsive transients are generally caused by lightning strikes. 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 [5].

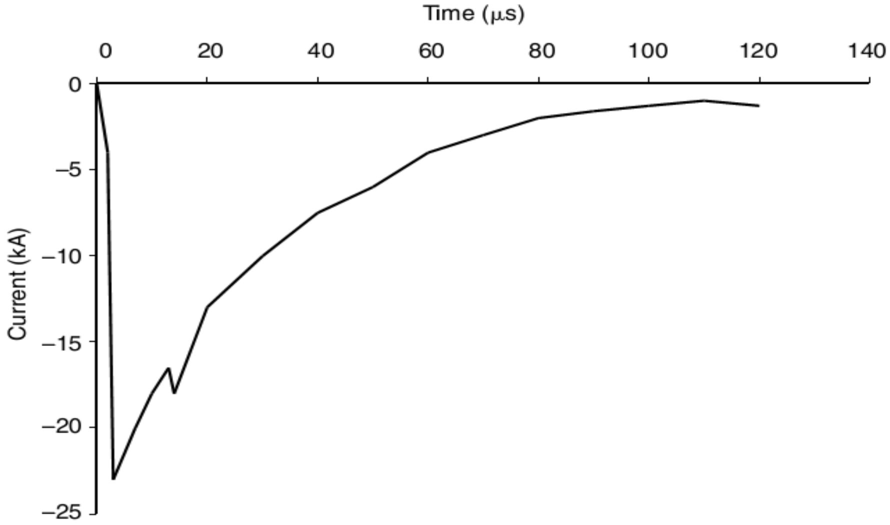


Figure 2.1 Lightning stroke current impulsive transient.

### b. 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. An oscillatory transient consists of a voltage or current whose instantaneous value changes polarity rapidly. It is described by its spectral content, duration, and magnitude.

They are characterized by fluctuations in the measured quantity at very high frequencies. These can be further classified according to their frequency as high frequency transients (transients with a primary frequency component greater than 500 kHz and a typical duration measured in microseconds), medium frequency transients (transients with a primary frequency component between 5 and 500 kHz with duration measured in tens of microseconds.) or low frequency transients (transients with a primary frequency component less than 5 kHz and duration of from 0.3 to 50 ms), with the cause of the fault dependent upon the frequency. 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 equipments due to the over voltage condition. Utility switching and capacitor energization are just two causes of oscillatory transient faults [6].

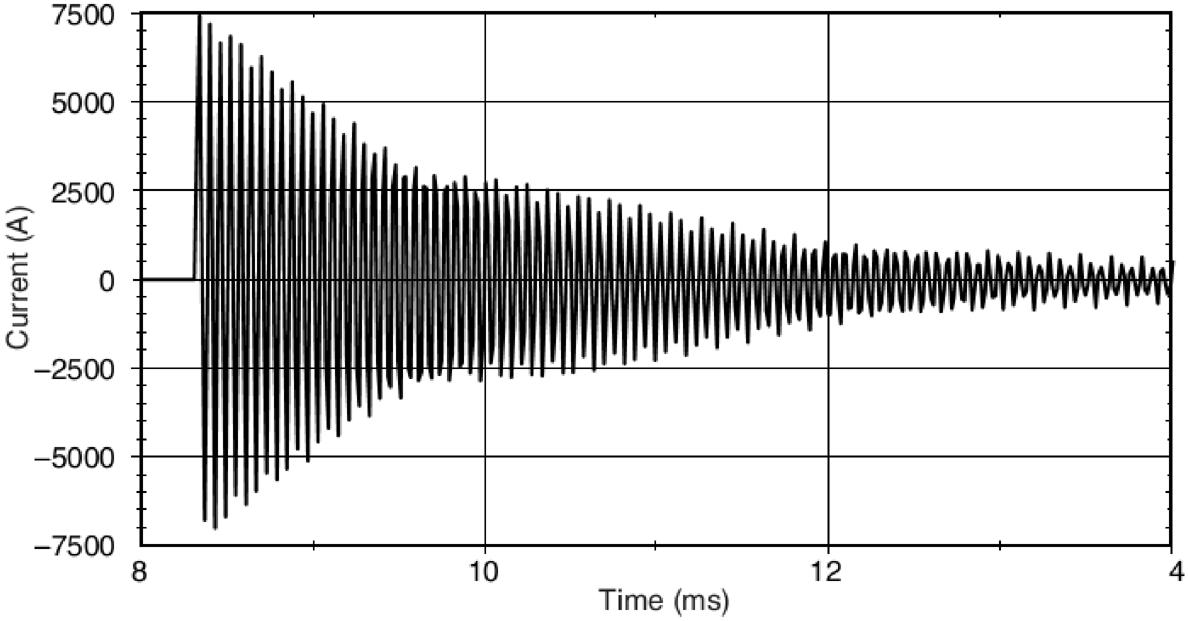


Figure 2.2 Oscillatory transient

### 2.1.1.2.Short-Duration Voltage Variation

These types of disturbance include root mean square (rms) voltage variations at power frequencies for a period of less than one minute. They are caused by faulty conditions, energization of large loads which require high starting currents, or intermittent loose connections in the power wiring. Based on the type of fault, the short duration voltage variation may be classified into voltage sag (dip), voltage rise (swell), or interruption [3].

#### a. 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 [6].

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.

#### b. Voltage Swell

A swell (also known as momentary overvoltage) is an increase in rms voltage or current at the power frequency to between 1.1 and 1.8 PU for durations from 0.5 cycles to 1 min. Swells are commonly caused by system fault conditions, switching off a large load or energizing a large capacitor bank [6].

#### c. 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 [6].

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.

### 2.1.1.3.Long Duration Voltage Variation

Long duration voltage variations encompass root-mean-square (rms) deviations at power frequencies for longer than 1 minute. They are usually not caused by system faults but system switching operations and load variations on the system. The long duration voltage variation may be either of an under voltage, over voltage or sustained interruption as discussed below [3].

#### a. Overvoltage

An overvoltage is defined as an increase in the rms ac voltage greater than 110% at the power frequency for duration of longer than 1 min. Overvoltages can be the result of switching off a large load, energizing a capacitor bank or incorrect tap settings on transformers. These occur mainly because either the voltage controls are inadequate or the system is too weak for voltage regulation. Possible effect could be hardware failure in the equipment due to overheating and insulation flashover of utility equipments [6].

### b. Undervoltage

An undervoltage is a decrease in the rms ac voltage to less than 90% at the power frequency for a period of time greater than 1 minute. Undervoltage 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. Therefore, the terminal voltage drops too low under heavy load due to the weak power system (high voltage drop on the 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. Possible effects include system shutdown, malfunctioning of certain equipments, and equipment operation at reduced efficiency [6].

### c. Sustained Interruption

When the supply voltage has been zero or drops to less than 10% of the nominal value for a period of time greater than 1 minute. Voltage interruptions longer than 1 min are sometimes permanent and require human intervention to repair the system for restoration. Interruptions can result from control malfunction, faults, or improper breaker tripping [6].

### 2.1.1.4.Voltage Unbalance

Voltage unbalance (or imbalance) is non-equalization of the three phase voltages. It is a condition in which 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. The primary source of voltage unbalances of less than 2 percent is single-phase loads on a three-phase circuit. Voltage unbalance can also be the result of blown fuses in one phase of a three-phase capacitor bank. Severe voltage unbalance (greater than 5 percent) can result from single-phasing conditions. In addition to these causes unidentified single-phase to ground faults, an open circuit on the distribution system primary, unbalanced or unstable utility supply, unequal line impedances are also some of the causes of voltage unbalance [7].

Voltage unbalance degrades the performance and shortens the life of a three-phase motor. Voltage unbalance at the motor stator terminals cause phase current unbalance far out of proportion to the voltage unbalance. Unbalanced currents lead to increased vibrations and mechanical stresses, increased losses, and motor overheating, which results in a shorter winding insulation life [7].

#### 2.1.1.5.Waveform Distortion

Waveform distortion is a condition whereby a steady-state deviations of the voltage and/or current waveform from an ideal sine wave of power frequency.  There are generally five types of waveform distortion, namely, dc offset, harmonics, interharmonics, notching and noise.

#### a. DC Offset

DC offset is the presence of a dc current or voltage in an ac power system. This can occur due to the effect of half-wave rectification. Direct current found in alternating current networks can have a harmful effect. This can cause additional heating and destroy the transformer [3].

#### b. Harmonics

Harmonics is a growing problem for both electricity suppliers and users. A 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. Distorted waveforms can be decomposed into a sum of the fundamental frequency and the harmonics. Harmonic distortion originates in the nonlinear characteristics of devices and loads on the power system [6].

Harmonics refers to both current and voltage harmonics. Harmonic voltages occur as a result of current harmonics, which are created by non linear electronic loads. These nonlinear loads will draw a distorted current waveform from the supply system.  Loads like electric arc furnaces, discharge lighting (such as fluorescent lamps), magnetic cores, such as transformer and rotating machines that require third harmonic current to excite the iron, adjustable speed drives used in fans, blowers, pumps, and process drives can cause harmonic distortion. The effect of harmonics in the power system includes the corruption and loss of data, overheating or damage to sensitive equipment and overloading of capacitor banks. The high frequency harmonics may also cause interference to nearby telecommunication system.

Using the Fourier series expansion, we can represent a distorted periodic wave shape by its fundamental and harmonics [1].

$$u(t) = U_{dc} + \sum_{n=1}^{\infty} \left(U_{(n)s} \sin(n\omega t) + U_{(n)c} \cos(n\omega t)\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .. (2.1)$$

The coefficients are obtained as follows:

$$U_{(n)s} = \frac{1}{\pi} \int_0^{2\pi} u(t) \sin(n\omega t)\, d\omega t \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.2)$$

$$U_{(n)c} = \frac{1}{\pi} \int_0^{2\pi} u(t) \cos(n\omega t)\, d\omega t \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.3)$$

Where n is an integer and $\omega = \frac{2\pi}{T}$ .T is the fundamental period time.

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, $THD_U$ and $THD_I$, respectively, are given as follows:

$$THD_U = \frac{\sqrt{\sum_{n=2}^{\infty} U_{(n)}^2}}{U_{(1)}} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . \ldots\ldots\ldots\ldots\ldots\ldots . (2.4)$$

$$THD_I = \frac{\sqrt{\sum_{n=2}^{\infty} I_{(n)}^2}}{I_{(1)}} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . (2.5)$$

Effective value $$U_{RMS} = \sqrt{\frac{1}{T}\int_0^T u(t)^2 dt} = U_{(1)}\sqrt{1 + THD_U^2} \ldots\ldots\ldots\ldots\ldots\ldots (2.6)$$

$$I_{RMS} = \sqrt{\frac{1}{T}\int_0^T i(t)^2 dt} = I_{(1)}\sqrt{1 + THD_I^2} \ldots\ldots\ldots\ldots\ldots\ldots .. (2.7)$$

For characterizing harmonic currents in a consistent fashion, IEEE Standard 519-1992 defines another term, the total demand distortion (TDD). This term is the same as the total harmonic distortion except that the distortion is expressed as a percent of some rated load current rather than as a percent of the fundamental current magnitude at the instant of measurement [3].

$$\mathrm{TDD} = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_L} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(2.8)$$

Where, $I_h$ is the harmonic currents,

$I_L$ is the rated load-current.

The development of current distortion limits is to:

1. Reduce the harmonic injection from each single consumer so that they will not cause unacceptable voltage distortion levels for normal system characteristics.
2. Restrict the overall harmonic distortion of the system voltage supplied by the utility.

### c. Interharmonics

Interharmonics are defined as voltages or currents having frequency components that are not integer multiples of the frequency at which the supply system is designed to operate. Interharmonics can be found in networks of all voltage classes. The main sources of interharmonic are cycloconverters, static frequency converters and arcing devices. It is generally the result of frequency conversion activities and is often not constant; it varies with load. Such interharmonic currents can excite quite severe resonances on the power system as the varying interharmonic frequency becomes coincident with natural frequencies of the system [7].

### d. 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 [6].

### f. 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.

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. The problem can be mitigated by using filters, isolation transformers, and line conditioners [6].

#### 2.1.1.6.Voltage Fluctuation

Voltage fluctuation is defined as the random variations of the voltage envelope where the magnitude does not exceed the voltage ranges of 0.9 to 1.1 PU. Higher power loads that draw current which bears continuous and rapid variations in its magnitude can cause voltage fluctuations [6].

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. The flicker signal is measured by its rms magnitude expressed as a percent of the fundamental whereas voltage flicker is measured with respect to the sensitivity of human eye. It is possible for lamp to flicker if the magnitudes are as low as 0.5% and the frequencies are in the range of 6 to 8 Hz. One common cause of voltage fluctuations on utility transmission and distribution system is the arc furnace [7].

#### 2.1.1.7.Power Frequency Variations

Any deviation of the power system fundamental frequency from its nominal value (usually 50 or 60 Hz) is defined as power frequency variations. The power system frequency is associated with 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 [6].

Frequency variations can be the cause of faults on power transmission system, large load being disconnected or a large source of generation going off-line. Frequency variations usually occur for loads that are supplied by a generator isolated from the utility system. The response to sudden load changes may not be sufficient to adjust within the narrow bandwidth required by frequency sensitive equipment. Possible effect could result in data loss, system crashes and equipment damage [8].

### 2.1.2. 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: amplitude, frequency, and spectrum. On the other hand, for non-steady state phenomena, the following characteristics are required for describing the power quality problem, rate of rise, duration, and rate of occurrence [3].

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.

### 2.1.3. 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 [3].

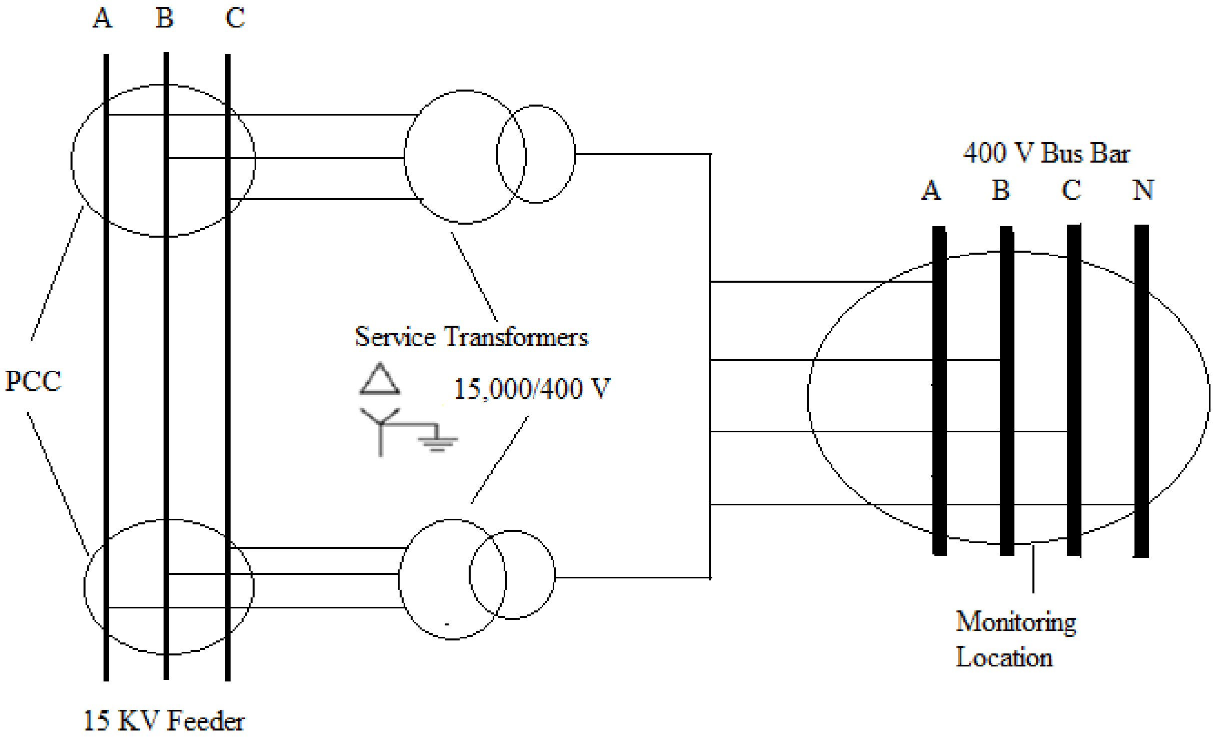


Figure 2.3 Monitoring location and point of common coupling.

### 2.1.4. 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) [8].

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. 519-1992, the voltage fluctuation curves, and the derating curve for unbalanced operation [8].

### 2.1.5. 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.

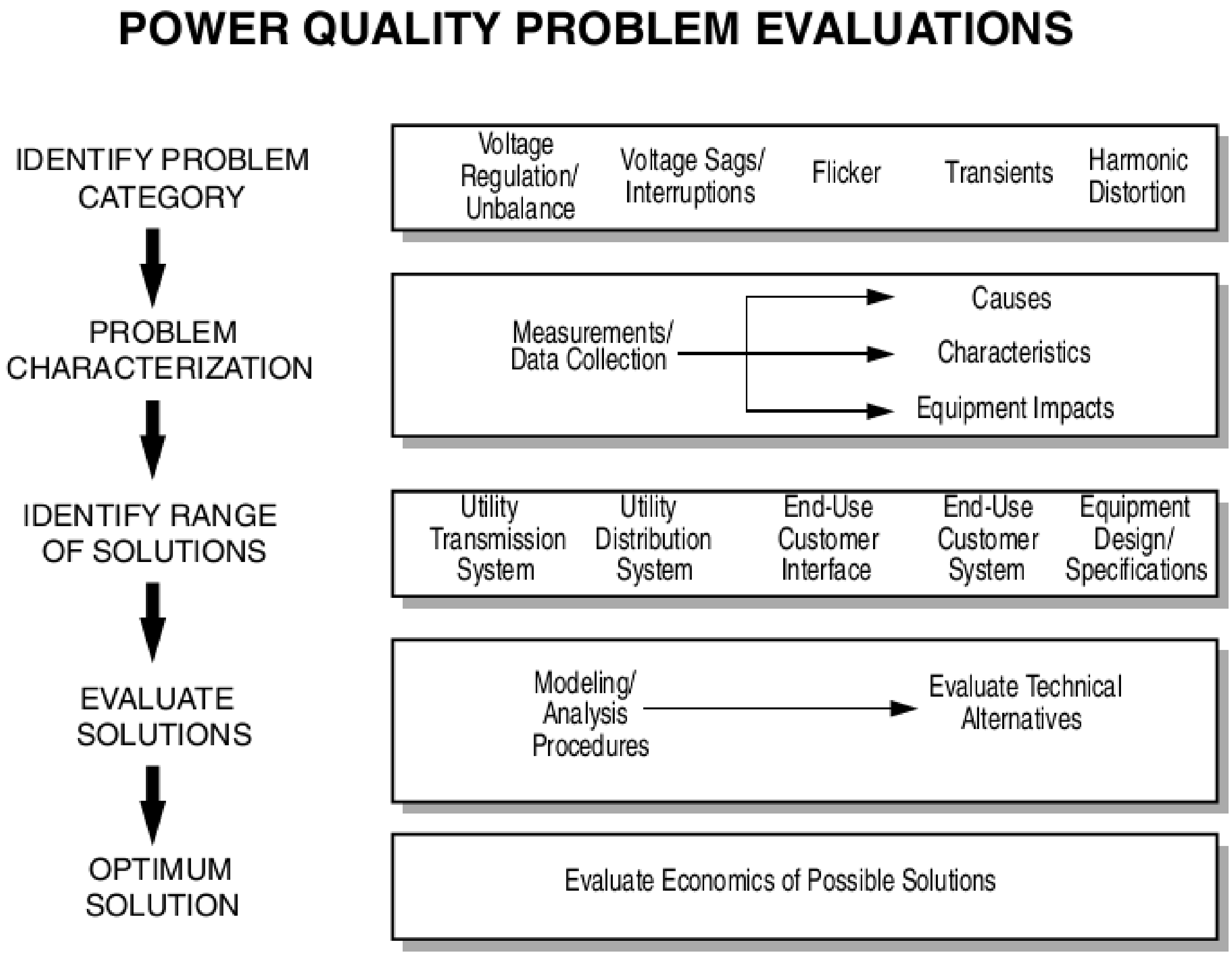


Figure 2.4 Basic steps involved in a power quality evaluation [3].

## 2.2 Literature 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 [3].

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 [8].

Case 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. The issue of power quality has reached up to making national regulations in some countries. The following are some of the works done before on power quality problems and mitigation techniques.

**Harjit Singh Birdi**, (2006) [9], describes a technique to automate the classification and analysis of the power quality events using relay recorded data. The technique uses voltage duration and magnitude (as specified in the IEEE Std. 1159 - 1995, IEEE Recommended Practice for Monitoring Electric Power Quality) of three phases to detect and classify the events. The classified results are then presented in a user-friendly graphical form. Fast Fourier

Transformation (FFT) is used to estimate the fundamental frequency and harmonic components in power systems.

**Hussein Mohamed El-Eissawi Fathi**, (2012) [10], investigates and mitigate the power quality problems in nuclear installations. Normally electrical power is supplied to the installations via two sources and each source is designed to carry the full load. The assessment of power quality was performed at the nuclear installations for both sources at different operating conditions. In both sources there were several disturbances, which exceeded the thresholds of the power quality standards defined by IEEE Std. 1159 - 1995. Effective and economic mitigation techniques were suggested to the power quality problems occurred.

**Jeff McGuire**, (1999) [11], presents three case studies on power quality. The first case study was conducted at the Caltex Oil Refinery in the Brisbane suburb of Lytton for duration of 17 days, followed by a study in the Chemistry building at the University of Queensland for 11days, before the final study in the laser laboratory within the Physics building also at the University of Queensland is presented. A thorough description of the equipment used in the surveys is also presented, as well as a description of the California Instruments AC Power Source- another piece of equipment useful for studying power quality.

**Alexandre Nassif**, (2009) [12], presents an evaluation of the relative severity of the harmonic currents from power electronic-based home appliances and the impact of the discrepancy of the harmonic current phase angles. An investigation is carried out on the common filter topologies, and the most cost-effective topologies for mitigating harmonics are identified. As many of the larger harmonic loads also generate interharmonics, interharmonics have become prevalent in today’s medium-voltage distribution system. Mitigation cannot be carried out until the interharmonic source location is known. A method for interharmonic source determination is proposed and then verified through simulation and field measurement studies.

**Muhammad Yasir,** (2011) [13], proposes generic evaluation approach for estimating the financial impact of voltage sag events on customer operations. The proposed technique is based on the event tree method. Using this approach, it is possible to consider the impacts of operational failure of various sensitive equipments involved in the customer operations on the financial losses expected from voltage sag events. A methodology, based on the developed approach, is also proposed for analyzing the effectiveness and practical viability of various voltage sag mitigation solutions. A quantitative case study is conducted in the thesis to illustrate the applicability of the purposed approach. Moreover, a comparative assessment was made to find out the applicability of various mitigation options. The method can be applied by customers to select the most economical mitigation option for their operations.

**Nexant SARI,** (2003), [14], found that the main economic impact of power interruptions, both planned and unplanned, is the loss of output in the industrial sector. These losses can be as high as US$ 81 million annually (0.65%of GDP) under a typical scenario (300 hours of planned outages) of imposing power interruptions such as those experienced during 2001. Also the impact due to unplanned outages can be as high as US$ 47 million (0.38%of GDP) in a typical year having 100 hours of unplanned outages. This is a significant economic loss especially in comparison to the 4.5 %to 5%average GDP growth that has taken place in Sri Lanka during the last few years. The economic losses due to planned and unplanned power interruptions can also be expressed in other forms. One commonly used measure is the economic loss (in US$) per unit of supply (kWh); identified as the cost of unserved energy. These findings emphasize the importance of reducing both planned and unplanned interruptions.

**M.K.Pradhan, Kamlesh Keharia, Rajesh Darapu, B. Mariappan,** (2008) [15], presents a case study of application of solid-state harmonic filter to improve electric power quality and reduce energy consumption in textile industries. Detailed studies were carried out in various textile firms in India and the effects of poor power quality especially harmonics were analyzed on the productivity and energy consumption. Harmonic current generated by nonlinear loads like motors driven by Variable Frequency Drives (VFD) cause power system heating and add to user power bills. The harmonic related losses are present in the power cables, bus bars linking the loads with source, the power transformer itself. A more serious effect of harmonic loads served by transformer is due to an increase in winding eddy current losses. The heat generated due to harmonics must be removed in order to save electrical energy, thus leading to savings in the utility bill. The paper is a case study where a 1.5 MVA transformer used for powering the spinning section of a textile mill. The current harmonics is recorded with & without using the harmonic filter. The power parameters are recorded on both the primary & secondary side of transformer to demonstrate how the harmonic filter can reduce the effects of harmonics and save energy.

**Franz Alois Hemetsberger**, (2003) [16], identify power quality problems in the isolated Porgera Mine System located in the Highlands of Papua New Guinea. For the problems identified, recommendations are suggested to improve the power quality. The voltage sag caused by the starting of large motors is investigated with measured data from the mine and simulated using a power-system-computer-aided-design-software (PSCAD/EMTDC) to observe the extent of the sag throughout the system. The extent of sags from faults is also simulated including some mention of harmonics propagation. Results of the project include the total harmonic voltage distortion being within IEEE standards, characterization of the measured voltage sags, the severity of the sag throughout the system, identification that some sags fall below tolerance curves for sensitive equipment according to the CBEMA curve and correct mitigation techniques available for the problems identified. It was found that line conditioning practices at the mine are adequate but advised that for further expansion a further voltage study be carried out.

# CHAPTER 3

# POWER QUALITY MEASUREMENT AND BENCHMARKING

The equipment used for power quality measurement is Fluke 434/435 three phase Power Quality Analyzer, the detail of the instrument is described in Appendix A. The equipment measures the following power quality problems:

## 3.1.Transients

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 [9]. During the period of monitoring, impulsive transients are not seen because lightning protection systems are installed at NTE and the 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.

But there is frequent oscillatory transient for a period of 15.5 msec detected by the measurements due to capacitor energization in the industry and it reaches up to 510 V which is twice as much the standard voltage. The measured value for oscillatory transient is shown in figure 3.1.

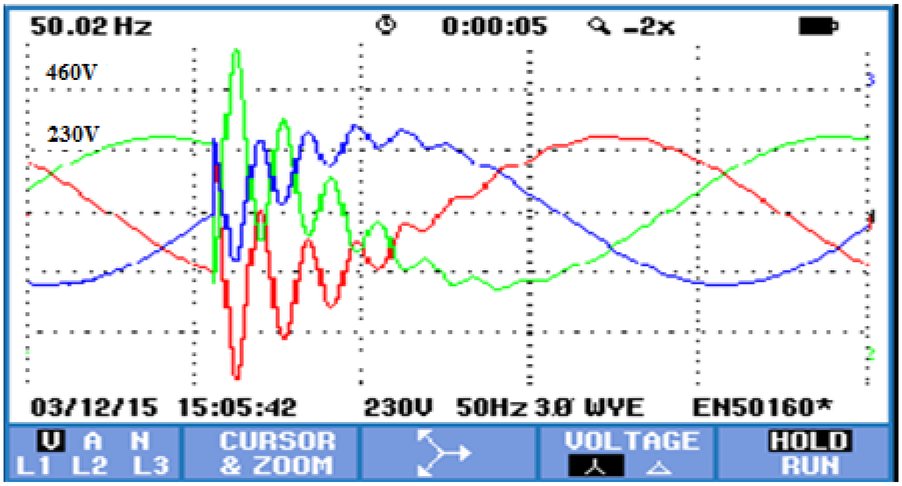


Figure 3.1 Measured value of voltage waveform for oscillatory transient

### 3.1.1. Effect Oscillatory Transient Overvoltage due to Capacitor Switching

Transient overvoltages can cause damage to equipments if they are not adequately protected. Transients can also reduce insulation life without causing immediate insulation failure. Oscillatory transient overvoltage is a concern to the industries but most of the time not of concern to the utility; since peak magnitudes are usually just below the level at which utility overvoltage protection devices such as surge arresters begin to operate (about 180% of normal peak operating voltage or above).

Transient overvoltages can cause the following in the connected load equipment: - Malfunction: behavior other than expected but no immediate damage; Damage: equipment will no longer function as designed. In NTE oscillatory transient overvoltages due to capacitor switching have the following effects:

a. Sensitive electronic or power electronic equipment (e.g. programmable logic controllers (PLC) and variable speed drives (VSD)), are particularly susceptible to such transient effects and become malfunction or be damaged;
b. Nuisance tripping of variable speed drives;
c. High line-line overvoltages may result on a transformer due to the magnification effects of power factor correction capacitors;
d. Computer network problems, e.g. data corruption.

Capacitor banks are used in the industries to improve the power factor. However, capacitor switching gives rise to a transient overvoltage at the instant of switching. It is caused by the inrush of current into the capacitor bank at the instant of switching.

Transient overvoltages due to capacitor switching can cause a wide range of problems, such as tripping of variable speed drives (VSD's) [11], and tripping of power supplies [17]. In order to reduce the magnitude of this overvoltage, different methods should be applied.

## 3.2.Short Duration Voltage Variations

Short-duration voltage variations encompass root-mean-square (rms) deviations at power frequencies for less than 1 minute. In order to obtain good measuring data of short duration voltage variations the measurements are taken at the secondary of the service transformer for the duration of one week. The voltage variations under this category are the following:

### a. Voltage Sag

During the measuring process in one week duration from dips & swells events table the voltage sag is detected on phase 1, 2 and 3 and the voltage decreases to 202.86 V, 201.25 V, 200.33 V for duration of 200 msec, respectively and occurred on the 3rd day at (15:12:40). The problem is caused by three phase short circuit fault at the electrical system of the industry 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.

### 3.2.1 Effect of Voltage Sag on the Industry

Voltage sags are the most costly of all power quality disturbances. While perhaps not as costly as interruptions, voltage sags are much more prevalent and in some cases may have the same impact as a supply interruption. Relatively shallow voltage sags can lead to the disruption of manufacturing processes due to equipment being unable to operate correctly at the reduced voltage levels. Industrial equipment such as variable speed drives and some control systems are particularly sensitive to voltage sags. In many manufacturing processes, loss of only a few vital pieces of equipment may lead to a full shut down of production; leading to significant financial losses as well as the time taken to clean up and restart the process must also be considered.

At NTE, during the measuring process for voltage variation the problem of voltage sag was occurred for a duration of 200 msec. caused by three phase short circuit fault resulting in tripping of protective device. Based on this recorded data when we discuss with the electrical department head of the industry about the problem he told me that short circuit faults are frequently occurred in the industry due to insulation failure of windings, mechanical damage of wires and improper wiring by technicians resulting in reduction of voltage profile, the problem of voltage sag measured is an indicator for this.

Electronic process controls, sensors, computer controls, PLC's and variable speed drives, even conventional electrical relays are all to some degree susceptible to voltage sags. In many cases one or more of these devices may trip if there is a voltage sag to less than 90% of nominal voltage even if the duration is only for one or two cycles i.e. less than 100 milliseconds. The time to restart production after such an unplanned stoppage can typically be measured in minutes, hours or even days. Costs per event can be many tens of thousands of Dollars or Birr. The resulting effect of voltage sag in the industry is failure of the breaker to trip in case of a fault detected by the protective relays due to prolonged exposure of short circuit currents, failure of sensors which check the quantity and proper packaging of cigarette, the tripping of controls to the dc drives, and programmable logic controllers (PLCs) system is found in the industry which is very sensitive to voltage sags and the remote I/O units, for instance, have been found to trip which leads to a partly shut down of production for hours or even days leading to significant financial losses. It also reduces efficiency and life span of electrical equipment, particularly motors. In the industry these events occurred 40 to 45 times per year. As a result, the plant loses huge amount of money, which is up to 1.6 million Birr/year ($80,000/year) (this includes production loss, maintenance cost and workers salary payment without work).

### b. Voltage Swell

It is an increase in rms voltage or current at the power frequency to between 1.1 and 1.8 PU for durations from 0.5 cycles to 1 min. During the measurement event the problem of voltage swell haven't been detected in any of the three phases.

### c. Interruptions

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. In NTE, throughout the whole survey, there has not been short-period interruption detected which lasted for a time duration of less than one minute. Therefore, in the industry the occurrence of temporary interruption is rare; as a result no need to install equipments for mitigation of temporary interruptions.

### 3.3.Long Duration Voltage Variations

#### a. Overvoltage

During the monitoring period, there is capacitor bank switching on and switching off of large loads but this doesn’t cause a significant overvoltage in the system. As a result, no need to install equipments for the mitigation of overvoltages.

#### b. Undervoltage

Throughout the measurement process noticeable result on undervoltage is not shown even if there is switching off capacitor bank and switching on of large loads.

#### c. Sustained Interruptions

During the monitoring period frequent interruptions has occurred which lasted for longer than 1 minute. The interruptions occurred on the 2nd, 4th, and 7th day at (09:46:02, 14:30:45, and 11:18:54 respectively). The cause of the interruption in the industry comes from the utility system problems. Therefore, in order to protect sensitive and power electronic loads from damage and loss of production, it is required to find a solution to this serious problem.

Table 3.1 Events Table for short and long duration voltage variations

| Events ( 16/03/2015 - 22/03/2015) | | | | | | |
|---|---|---|---|---|---|---|
| Date | Time | Type | Voltage Levels | | | Duration |
| | | | L1 | L2 | L3 | |
| 16/03/2015 | All day | Normal | Normal | Normal | Normal | All Day |
| 17/03/2015 | 09:46:02 | Sustained interruption | 0 V | 0 V | 0 V | 38 min. |
| 18/03/2015 | 15:12:40 | Voltage Dip | 202.86 V | 201.25 V | 200.33 V | 200 msec |
| 19/03/2015 | 14:30:45 | Sustained interruption | 0 V | 0 V | 0 V | 108 min. |
| 20/03/2015 | All day | Normal | Normal | Normal | Normal | All Day |
| 21/03/2015 | All day | Normal | Normal | Normal | Normal | All Day |
| 22/03/2015 | 11:18:54 | Sustained interruption | 0 V | 0 V | 0 V | 43 min |

## 3.4.Voltage Unbalance

The measured values of maximum voltage unbalances at the industry to compute the percentage of voltage unbalance at NTE are the following:

Table 3.2 Measurement results of maximum voltage unbalances at the industry.

| Voltages | | Measured values in (V) |
|---|---|---|
| Phase to neutral voltage | $V_1$ | 217.96 |
| | $V_2$ | 227.42 |
| | $V_3$ | 219.46 |
| Phase to phase voltage | $V_{12}$ | 377.51 |
| | $V_{23}$ | 393.92 |
| | $V_{31}$ | 380.12 |

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.

$$\%\,\text{Voltage unbalance} = \frac{\text{maximum deviation from mean of } (V_{12},\ V_{23}\,, V_{31})}{\text{mean of } (V_{12},\ V_{23}\,, V_{31})} \times 100 \ldots\ldots(3.1)$$

Therefore,

$$\text{mean of } (V_{12},\ V_{23}\,, V_{31}) = 383.85\ \text{V}$$

$$\%\,\text{Voltage unbalance} = \frac{393.92 - 383.85}{383.85} \times 100\%$$

$$\%\,\text{Voltage unbalance} = 2.62\ \%$$

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

### 3.4.1 Causes and Effects of Voltage Unbalance in the Industry

The underlying causes of voltage unbalance are numerous, and may include [18]:

a. The power supplied by the utility can be the source of unbalanced voltages. This can be due to malfunctioning equipment including blown capacitor fuses, open-delta regulators, and open-delta transformers.
b. Voltage unbalance can also be caused by uneven single-phase load distribution among the three phases.
c. Faulty operation of power factor correction equipment.
d. Unidentified single-phase to ground faults.

The voltage unbalance in the industry under study is caused by uneven single-phase load distribution among the three phases, this is identified that the load current on phase 2 and 3 reaches up to 1179 A and 1250 A, respectively while phase 1 load current is 913 A as shown in Appendix B (Table B.2). As a result, many of the single phase loads are on phase 2 and 3.

The main effects of voltage unbalance are decreased motor efficiency and performance resulting in motor damage from excessive heat which affects the company's profitability. Voltage unbalance can create a current unbalance 6 to 10 times the magnitude of voltage unbalance. Consequently, voltage unbalance will increase the $I^2R$ losses in the rotor and stator, meaning more of the supplied power will be converted to heat in the motor windings therefore the motor will run hotter and it breaks down winding insulation, consequently, the motor becomes less efficient and damaged permanently. The percent of winding heat increase, expressed in degree Celsius, due to a voltage unbalance is exponential, and approximately increases by twice the square of the percent of voltage unbalance. Mathematically, the relationship is given as [18];

$$\%\text{ of temperature rise } = 2 \times (\%\text{ Voltage Unbalance})^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.2)$$

The percentage of voltage unbalance obtained in the industry using the measured data is 2.62%.

Therefore, the percentage of temperature rise will be

$$\%\text{ of temperature rise } = 2 \times (2.62)^2 = 13.7288\ ℃$$

The result of the voltage unbalance of 2.62% is a motor winding running 13.7288 ℃ hotter than normal temperature.

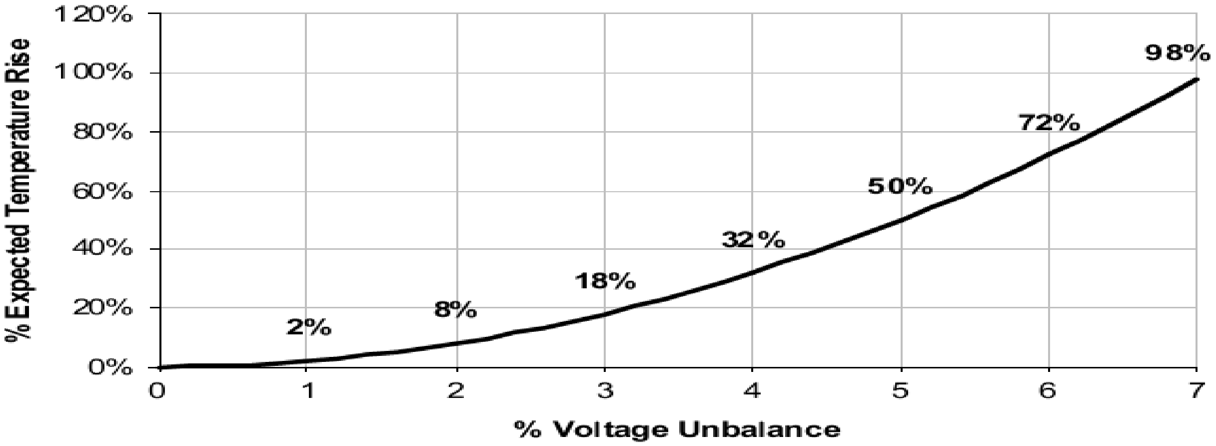


Figure 3.2 Percent Temperature Rise Due to Voltage Unbalance

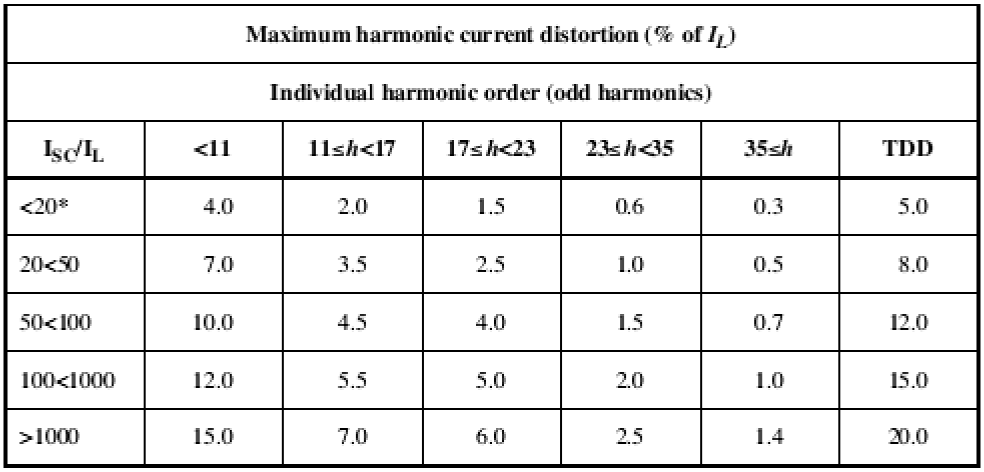
Resistive loads are relatively unaffected by voltage unbalance, but it causes additional heating/losses with three-phase motors. Variable speed drives (VSD) trip off due to an increase in AC line currents caused by a compensation for the voltage unbalance.

### 3.5.Harmonics

The main industry standard used for harmonics in power systems is IEEE Std 519-1992. This standard has been developed through the IEEE Industry Applications Society and the IEEE Power Engineering Society. Through the joint effort of these two societies, IEEE Std 519-1992 suggests limits on the harmonic currents that a user can induce back into the utility power system and also specifies the quality of the voltage that the utility should supply the user.

The table below lists the harmonic current limits based on the size of the load with respect to the size of the power system to which the load is connected. The ratio $\frac{I_{sc}}{I_L}$ is the ratio of the short-circuit current available at the PCC to the maximum fundamental load current. The standard suggests that the amount of current taken by a facility would have a bearing on the amount of harmonics it could interject into the utility's distribution system. The requirement of the utility to furnish a good quality of voltage is listed in table 3.3.

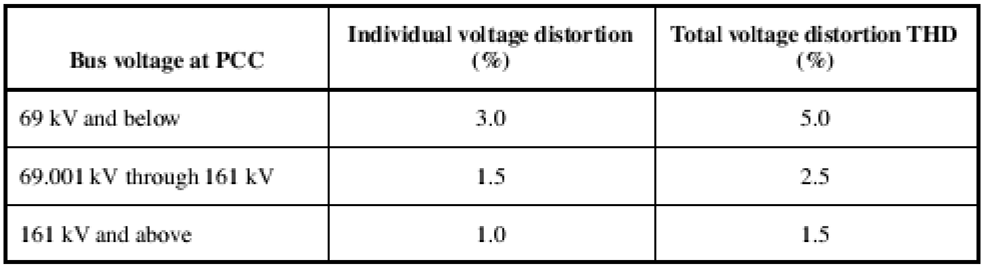
Table 3.3 Current distortion limits for general distribution systems (120 V to 69 000 V) [3]



| Maximum harmonic current distortion (% of $I_L$) | | | | | | |
|---|---|---|---|---|---|---|
| Individual harmonic order (odd harmonics) | | | | | | |
| $I_{SC}/I_L$ | <11 | $11 \le h < 17$ | $17 \le h < 23$ | $23 \le h < 35$ | $35 \le h$ | TDD |
| <20* | 4.0 | 2.0 | 1.5 | 0.6 | 0.3 | 5.0 |
| 20<50 | 7.0 | 3.5 | 2.5 | 1.0 | 0.5 | 8.0 |
| 50<100 | 10.0 | 4.5 | 4.0 | 1.5 | 0.7 | 12.0 |
| 100<1000 | 12.0 | 5.5 | 5.0 | 2.0 | 1.0 | 15.0 |
| >1000 | 15.0 | 7.0 | 6.0 | 2.5 | 1.4 | 20.0 |

The short circuit current and rated current of 15 kV feeder at the point of common coupling are averaged to be 10 kA and 1000 A respectively, which give $\frac{I_{sc}}{I_L}$ ratio in the range of <20. As a result, the TDD values of the current harmonics should not exceed 5% at the point of common coupling.

Table 3.4 Voltage distortion limits [3]



| Bus voltage at PCC | Individual voltage distortion (%) | Total voltage distortion THD (%) |
|---|---|---|
| 69 kV and below | 3.0 | 5.0 |
| 69.001 kV through 161 kV | 1.5 | 2.5 |
| 161 kV and above | 1.0 | 1.5 |

The maximum voltage and current harmonic contents of the electric power of NTE, when the industry is working at full load are shown in table 3.5.

The voltage THD values obtained in the three phases are within the permissible range of the IEEE voltage distortion limits, but for current distortion it is beyond the limit. The PCC is taken as the primary side of the transformers serving the industry loads. The transformer is connected in delta-wye, so that the triplen harmonics (the harmonics which are multiple of three) cannot enter to the primary side of the transformer which comes from the load side. As a result, omitting those triplen harmonics, we get a maximum current THD value of 18.10% at the PCC.

Table 3.5 Maximum voltage and current harmonics level at NTE.

| H.N | PHASE 1 | | | | PHASE 2 | | | | PHASE 3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | %V | V | %I | I(A) | %V | V | %I | I(A) | %V | V | %I | I(A) |
| 1 | 100 | 217.96 | 100 | 1064 | 100 | 227.42 | 100 | 1179 | 100 | 219.46 | 100 | 1250 |
| 3 | 0.2 | 0.44 | 3.2 | 34.05 | 0.2 | 0.455 | 3.9 | 45.98 | 0.2 | 0.438 | 3.2 | 40 |
| 5 | 0.3 | 0.65 | 14.3 | 152.15 | 0.4 | 0.909 | 14.6 | 172.13 | 0.4 | 0.878 | 14.5 | 181.25 |
| 7 | 1.0 | 2.18 | 10.6 | 112.78 | 0.3 | 0.682 | 10.2 | 120.26 | 0.4 | 0.878 | 10.8 | 135 |
| 9 | 0.3 | 0.65 | 1.4 | 14.89 | 0.2 | 0.455 | 1.5 | 17.69 | 0.1 | 0.219 | 1.4 | 17.5 |
| 11 | 0.2 | 0.44 | 0.8 | 8.51 | 0.1 | 0.227 | 0.7 | 8.253 | 0.1 | 0.219 | 0.7 | 8.75 |
| 13 | 0.2 | 0.44 | 0.5 | 5.32 | 0.2 | 0.455 | 0.6 | 7.074 | 0.2 | 0.438 | 0.5 | 6.25 |
| 15 | 0.1 | 0.218 | 0.2 | 2.128 | 0.1 | 0.227 | 0.2 | 2.358 | 0.1 | 0.219 | 0.2 | 2.5 |
| 17 | 0.1 | 0.218 | 0.1 | 1.064 | 0.1 | 0.227 | 0.1 | 1.179 | 0.0 | 0.00 | 0.1 | 1.25 |
| | **$THD_V$ = 1.15 %** | | **$THD_A$ =18.17%** | | **$THD_V$ = 0.632 %** | | **$THD_A$ = 18.32 %** | | **$THD_V$ = 0.655 %** | | **$THD_A$ = 18.44 %** | |

TDD value can be computed using the equations given below for the rated current of 1250 A.

$$\mathrm{TDD} = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_L} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (3.3)$$

$$\sqrt{\sum_{h=2}^{\infty} I_h^2} = 230.447$$

$$\mathrm{TDD} = \frac{230.447}{1250} \times 100$$

$$= 18.43\ \%$$

So the result of TDD is 18.43%. It is therefore necessary to install harmonic filters for filtering out the harmonics to meet the IEEE standards.

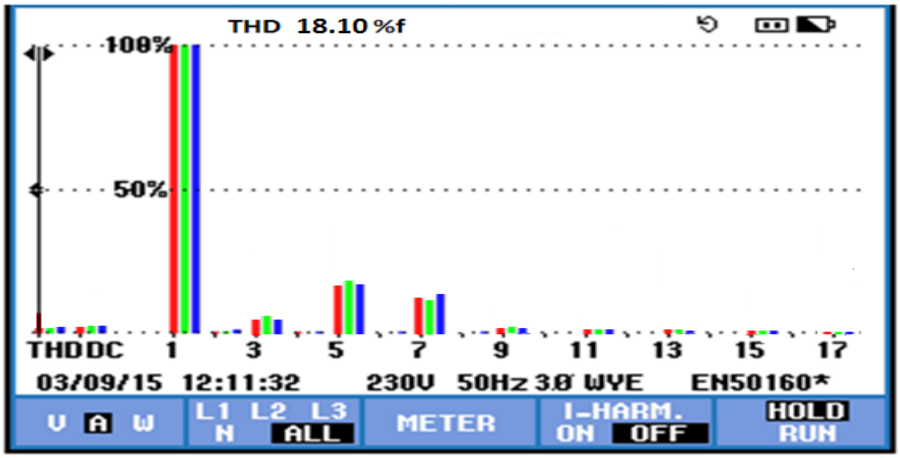


Figure 3.3 Harmonics spectrum

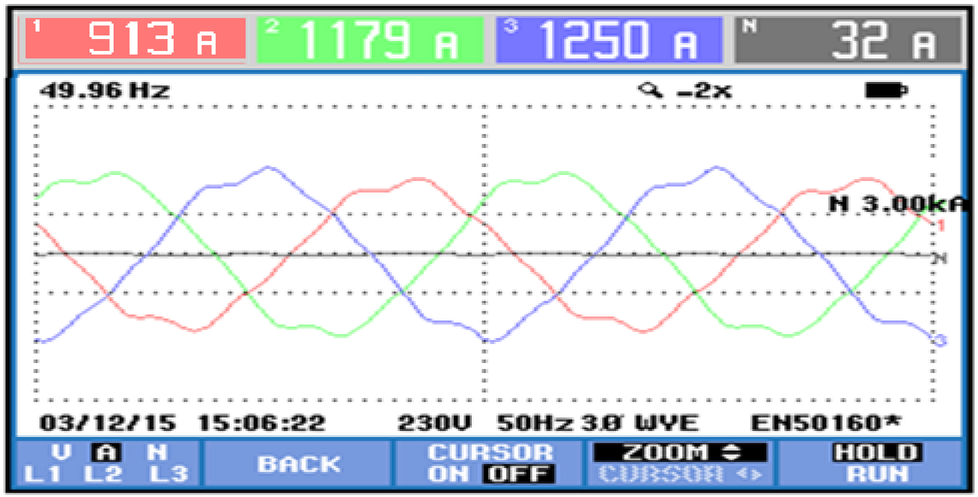


Figure 3.4 Current waveform

### 3.5.1 Sources and Effect of Harmonic Currents in the Industry

Harmonic current emissions originate from all types of non-linear loads. Non-linear loads are loads which draw non-sinusoidal current even when the supply voltage is perfectly sinusoidal. Non-linear loads include saturated magnetic circuits, such as those in power system transformers and rotating machines, arc furnaces, fluorescent lighting and of course power electronic loads. Power electronic loads by far are the most significant harmonic contributors relative to the amount of energy they draw [19].

Specifically, fifth and seventh harmonics are caused by static power converters used in adjustable speed drives for motor control, switched mode power supplies and six-pulse static drives. Fifth and seventh harmonics creates a negative and positive torque, respectively on motors running from three phase supply.

Current distortions results from non-linear loads have significant adverse effects on both power system components and customer devices. These effects may result into permanent damage of the devices. The effects of harmonics in the industry range from false or spurious operations and trips of fuses and circuit breakers, overheating of transformers due to increased copper and core losses. The harmful effects of harmonics on transformers often unnoticed until an actual failure occurs and increased heating in motors due to additional copper losses and iron losses in the stator winding, rotor circuit and rotor laminations.

### 3.6.Flicker

Voltage fluctuations can cause light intensity fluctuations that can be perceived by our brains. This effect, popularly known as flicker, can cause significant physiological discomfort. More precisely, flicker is the impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution properly fluctuates with time [20].

From the instantaneous flicker values, the following indices characterizing the intensity of flicker annoyance are obtained: the short- term flicker severity and the long-term flicker severity. The short-term flicker severity ($P_{st}$) is measured over a period of ten minutes. The long-term flicker severity ($P_{lt}$) is calculated from a sequence of 12 $P_{st}$ values over a two-hour interval, according to the following relationship:

$$P_{lt} = \sqrt[3]{\frac{\sum_{i=1}^{12} P_{sti}^{3}}{12}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (3.4)$$

In IEC 61000-3-7–1996, specifies the limit for the short- term flicker and the long-term flicker as a result the limits are $P_{st} = 1.0$ and $P_{lt} = 0.8$ [20]. $P_{sti}$ is a short- term flicker severity which is measured over the interval of 10 minutes.

The measured values on flickering in the industry for the three phases are tabulated below. Each values of the short-term flicker severity ($P_{st}$) are measured over a period of ten minutes and the long-term flicker severity ($P_{lt}$) values are calculated from 12 consecutive values of $P_{st}$ by using the above equation.

Table 3.6 Measured values of $P_{st}$ and $P_{lt}$

| | | Measured over 10 minutes interval | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Phases | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | **$P_{lt}$** |
| $P_{sti}$ | $L_1$ | 0.15 | 0.5 | 0.13 | 0.25 | 0.42 | 0.56 | 0.62 | 0.7 | 0.78 | 0.6 | 0.55 | 0.5 | **0.546** |
| | $L_2$ | 0.1 | 0.25 | 0.12 | 0.14 | 0.21 | 0.45 | 0.51 | 0.43 | 0.72 | 0.4 | 0.45 | 0.44 | **0.428** |
| | $L_3$ | 0.10 | 0.29 | 0.1 | 0.16 | 0.18 | 0.45 | 0.55 | 0.45 | 0.71 | 0.47 | 0.5 | 0.47 | **0.448** |

Having these measured values and compared with the IEC 61000-3-7 standard limits the short-term flicker ($P_{st}$) and the long-term flicker ($P_{lt}$) values are within the acceptable limits. And also in the industry there are no luminance fluctuations in the range of 6–8 Hz. Therefore, the problem of flickering is not a concern and this is due to the absence of high power loads drawing a fluctuating current.

## 3.7.Power Frequency Variation

The electric power network is designed to operate at a specified value of frequency (i.e., 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 indicates that the power frequency doesn’t vary much from the permissible limits.

Table 3.7 Frequency variation measurements

| S.No | Time (24 Hr. format) | Frequency (Hz) | Frequency variation |
|---|---|---|---|
| 1 | 10:02:55 | 50.06 | +0.06 |
| 2 | 10:07:05 | 50.00 | 0 |
| 3 | 10:12:09 | 49.99 | -0.01 |
| 4 | 10:17:11 | 49.96 | -0.04 |
| 5 | 10:23:19 | 50.03 | +0.03 |
| 6 | 15:04:46 | 49.92 | -0.08 |
| 7 | 15:09:49 | 50.00 | 0 |
| 8 | 15:14:21 | 49.96 | -0.04 |
| 9 | 15:19:30 | 50.01 | +0.01 |
| 10 | 15:24:20 | 49.99 | -0.01 |

# CHAPTER 4

# THE EXISTING POWER QUALITY PROBLEMS AND MITIGATION TECHNIQUES

Among the power quality problems those which are existing in NTE are oscillatory transient overvoltage, voltage sag, sustained interruption, voltage unbalance and harmonic pollution. These PQ problems have significant adverse effects on the power system and equipments of the industry. Therefore, various mitigation techniques should be proposed and applied to alleviate the problems.

## 4.1.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 [11]. The simulink model with pre insertion resistor is shown in Appendix E (Figure E.2).

### 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 quite high as well. 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 [11]. 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.

## 4.2.Voltage Sag Mitigation using Dynamic Voltage Restorer

Voltage sag is one of the power quality problems which exist in NTE. 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, a capacitor bank 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 means of 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 [21].

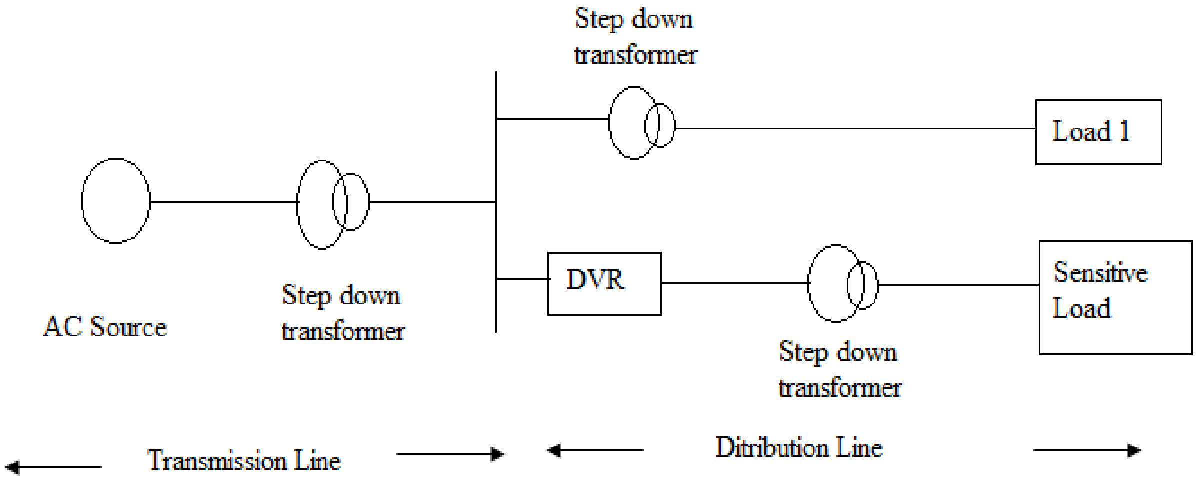


Figure 4.1 Location of DVR

### 4.2.1 Basic Configuration of DVR [21]

The general configuration of the DVR consists of:

#### I. Injection/ Booster Transformer

An Injection / Booster transformer is a specially designed transformer that connects the DVR to the distribution network via the HV-windings and transforms and couples the injected compensating voltages generated by the voltage source converters to the incoming supply voltage. It also serves the purpose of isolating the load from the system (voltage source converter (VSC) and control mechanism).

#### II. Harmonic Filter

The main task of harmonic filter is to keep the harmonic voltage content generated by the VSC to the permissible level.

#### III. Voltage Source Converter

A VSC is a power electronic system consists of a storage device and switching devices, which can generate a sinusoidal voltage at any required frequency, magnitude, and phase angle.
In the DVR application, the VSC is used to temporarily replace the supply voltage or to generate the part of the supply voltage which is missing.

There are four main types of switching devices which are used in VSC these are: Metal Oxide Semiconductor Field Effect Transistors (MOSFET), Gate Turn-Off thyristors (GTO), Insulated Gate Bipolar Transistors (IGBT), and Integrated Gate Commutated Thyristors (IGCT). For this case IGBT is used as a switching device for compensation of voltage sags due to its high switching frequency (low switching times) and low ON state power loss.

#### IV. Storage Devices

The purpose of storage devices is to supply the necessary energy to the VSC via a dc link for the generation of injected voltage. The different kinds of energy storage devices are superconductive magnetic energy storage, batteries and capacitance.

### V. Control and Protection

The control mechanism of the general configuration typically consists of hardware with programmable logic. Differential current protection of the transformer, or short circuit current on the customer load side are two examples of many protection functions.

The basic functions of a controller in a DVR are the following:

a. Detection of voltage sag/swell events in the system.
b. Computation of the correcting voltage.
c. Generating of trigger pulses to the sinusoidal PWM based DC-AC inverter.
d. Correction of any anomalous (abnormality) in the series voltage injection.
e. Termination of the trigger pulses when the system has passed.

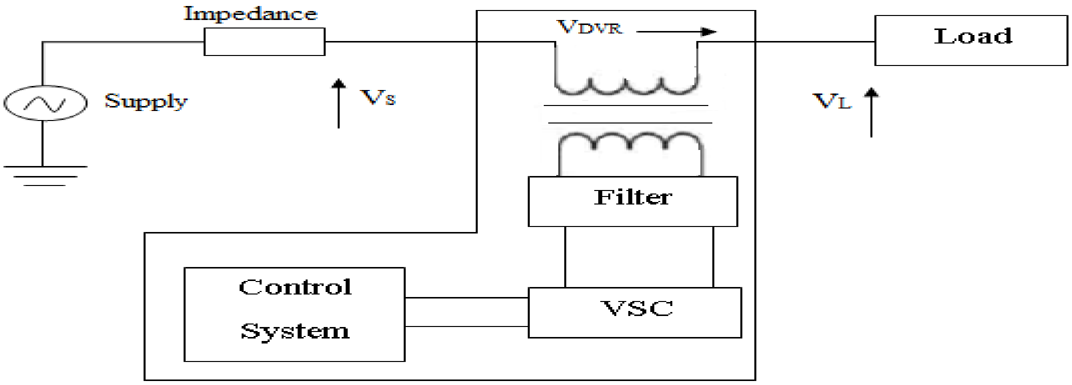


Figure 4.2 Schematic diagram of DVR [21]

### 4.2.2 DVR Capacity and Specification [22]

Referring to the electrical system of National Tobacco Enterprise:

$V_{pcc}$ = 15 KV
S = 1260 KVA, PF = 0.82
Response time = 5 msec.
Max three phase voltage sag = 70 %
Duration of sag to protect = 400 msec.
KVA capacity of DVR =?
Required Energy for DVR (kJ) =?

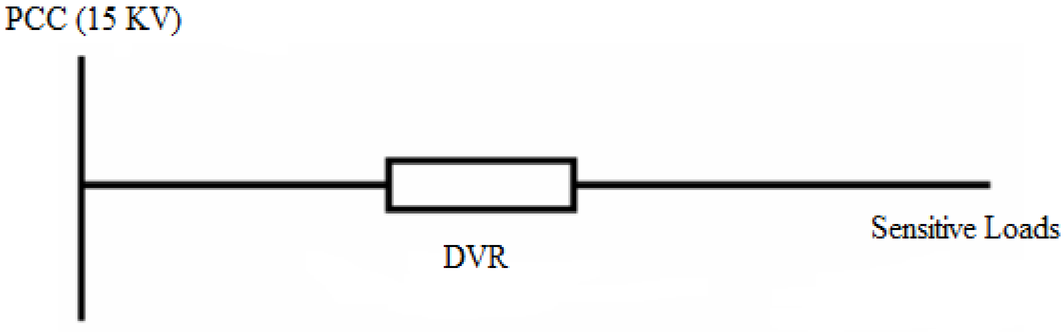


Figure 4.3 Insertion of DVR for voltage sag mitigation

It is recommended to adopt DVR technology to compensate the bus voltage sag and restore to 100 % of the rated value. When the sag depth is lower than 70 %, therefore, the compensating voltage of DVR should be 75 % or 0.75 PU.

By taking into consideration of peak load 1260 KVA with power factor of 0.82

$$\text{The compensating power} = 0.75 \times 1260\ \text{kVA} = 945\ \text{kVA}$$

$$\text{Energy} = \text{power} \times \text{time} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(4.1)$$

The duration of sag to protect is 400 msec. so,

$$\text{The required energy} = (\text{kVA} \times \text{PF}) \times \text{time}$$

$$\text{E} = (945 \times 0.82) \times 400 \times 10^{-3}$$

$$\text{E} = 309.96\ \text{kJ}.$$

For more reliability and availability DVR with (1000 KVA, 500 kJ) is selected. And it should be installed in the 15 kV side of the system.

### 4.2.3 Cost and Payback Period of DVR [23]

This section describes the cost and benefit analysis of installing DVR to mitigate voltage sag.

Assume Cost of DVR = $C_{DVR}$

Cost of single voltage sag = $C_{VS}$

Number of sags per year = $N_{VS}$

Payback period = T, (year)

Then,

$$C_{DVR} = C_{VS} \times N_{VS} \times T \ldots\ldots\ldots\ldots\ldots\ldots..\ldots\ldots\ldots\ldots\ldots\ldots.(4.2)$$

$$\text{Cost of DVR } = \frac{\$300}{\text{KVA}} + 5\% \left(\frac{\$300}{\text{KVA}}\right) \text{ [maintenance and running cost]}$$

$$C_{DVR} = 1000 \text{ kVA } \times (300 \times 1.05)/\text{KVA} = \$ \, 315{,}000$$

The cost of voltage sag, $C_{VS}$ at NTE is (\$1,778/year), and by taking the upper limit of the number of voltage sag occurrence, $N_{VS}$ is 45/year.

Then, the payback period will be,

$$T = \frac{C_{DVR}}{C_{VS} \times N_{VS}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (4.3)$$

$$T = \frac{\$ \, 315{,}000}{\$ \, 1{,}778 \, \times 45/\text{year}}$$

$$T = 3.937 \text{ year } \approx 4 \text{ years}$$

Since the average life time of the DVR is about 15 years, so the solution is very economical and feasible.

## 4.3. Mitigation of Voltage Unbalance

Because voltage unbalance can be very harmful, 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. 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.

## 4.4. 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 are relatively inexpensive compared with other means 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 [19].

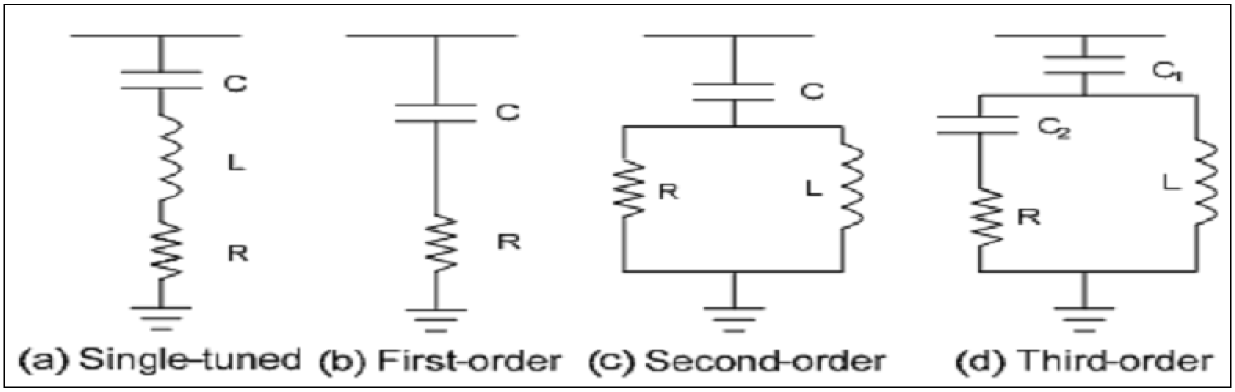


Figure 4.4 Common passive filter configurations.

The most common type of passive filter is single-tuned notch filter, shown in figure (4.4a), 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 [19]. The first order high-pass filter, in the above figure, 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 $C_2$. Moreover, the rating of $C_2$ is very small compared with $C_1$.

### b. Active Filters

Active filters are relatively new types of devices for eliminating harmonics. They are based on sophisticated power electronics and are 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 [19].

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 research 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 and their Design

This section illustrates a procedure for designing harmonic filters for industrial applications. Passive filters always provide reactive compensation to a degree dictated by the volt-ampere size and voltage of the capacitor bank used, they can in fact be 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 [24].

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 means multiple single-tuned filters are designed to eliminate multiple harmonics, as illustrated in figure 4.8 [24].

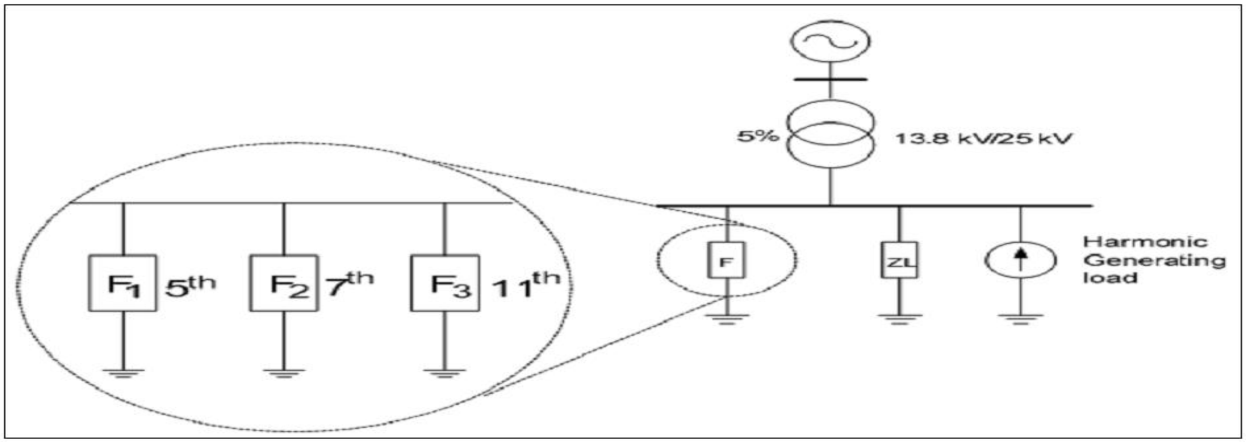


Figure 4.5 Three-branch filters

This section presents design procedures and equations of single-tuned filters. The main components of a harmonic filter are the capacitors, reactor, and a damping resistance if necessary. The series-connected resistance decides the sharpness of the filtering action. But it is usually ignored because the value of R usually results in a significant increase in losses within the filter. Therefore, practically the value of R consists only of the internal resistance of the inductor.

The recommended procedure for the design and validation of single-tuned harmonic filters is summarized as follows:

1. Select capacitor bank needed to improve the power factor from the present level typically to around 0.96 or higher

The capacitive reactance needed to compensate the needed VAR to improve the power factor from $PF_1$ (associated with $\theta_1$) to $PF_2$ (associated with $\theta_2$) is given by

$$\mathrm{Q_{com}} = \mathrm{P}(\tan\theta_2 - \tan\theta_1) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . (4.4)$$

Where P is the active power & $\mathrm{Q_{com}}$ is the reactive power needed for compensation.

The capacitance for a single filter can be set to [25]

$$\mathrm{Q_f} = \mathrm{Q_{com}} \ldots\ldots\ldots\ldots\ldots\ldots . . \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . \ldots (4.5)$$

For a multiple parallel single-tuned filter system, the capacitance corresponding to the h<sup>th</sup> harmonics can be distributed by [25]

$$\mathrm{Q_{fh}} = \mathrm{Q_{com}} \times \frac{\mathrm{I_h}}{\mathrm{I_2} + \mathrm{I_3} + \cdots}, \mathrm{h} = 2,3, \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . (4.6)$$

Where $I_h$ is the h<sup>th</sup> harmonic current and $Q_{fh}$ is the capacity of the hth harmonic filter. Also, the filter capacity $Q_{fh}$ contains the capacity of capacitance ($Q_C$) and capacity of inductor ($Q_L$),

$$Q_c = \frac{h^2}{h^2 - 1} \times Q_{fh} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.(4.7)$$

$$Q_L = Q_c - Q_{fh} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.(4.8)$$

$$Q_L = \frac{1}{h^2} \times Q_c \dots\dots\dots\dots\dots\dots\dots.\dots\dots\dots\dots\dots\dots\dots\dots\dots(4.9)$$

2. Choose reactor that, in series with capacitor, tunes filter to desired harmonic frequency. The use of an inductor in series with a capacitor results in a voltage rise at the capacitor terminals given by:

$$V_c = \left(\frac{h^2}{h^2 - 1}\right) V_{sys} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(4.10)$$

Where h = tuned impedance harmonic order of the frequency

$V_{sys}$ = system line-to-line voltage, KV

$V_C$ = capacitor line-to-line voltage, KV

The capacitive reactance required is obtained with the following relation

$$X_{c1} = \frac{V_c^2}{Q_c} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.\dots\dots.(4.11)$$

At harmonic frequency h, this reactance is:

$$X_{ch} = \frac{X_{c1}}{h} \dots\dots\dots\dots\dots\dots\dots.\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(4.12)$$

And the inductive reactance at frequency of order h is given by

$$X_{Lh} = hX_{L1} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(4.13)$$

At the resonant frequency the capacitive and reactive impedances are equal. Then $X_L$ and $X_C$ are related by the following equation

$$X_L = \frac{X_c}{h^2} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..(4.14)$$

3. Determine whether capacitor-operating parameters fall within IEEE-182 maximum recommended limits. This may require a number of iterations until desired reduction of harmonic level is achieved.
   a. Capacitor Voltage: The rms and peak voltage of the capacitor must not exceed 110 and 120%, respectively, of the rated voltage. They can be determined as follows:

$$V_{cpeak} = \sqrt{2}(V_{c1} + V_{ch}) \dots\dots\dots\dots\dots\dots.\dots\dots\dots\dots\dots\dots.(4.15)$$

$$V_{crms} = \sqrt{{V_{c1}}^2 + {V_{ch}}^2} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (4.16)$$

Where voltage through the capacitor at fundamental frequency is given by:

$$V_{c1} = X_{c1} I_{c1} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (4.17)$$

$V_{ch}$ is found in terms of $I_{ch}$, which must be determined from measurements or from a typical harmonic spectrum of the corresponding non-linear load.

$$V_{ch} = X_{ch} I_{ch} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (4.18)$$

$I_{C1}$ is the current through the capacitor and it is calculated in terms of the maximum phase -to-neutral voltage, which in turn is specified 5% above the rated value, to account for voltage regulation practices:

$$I_{c1} = 1.05 \times \left[ \frac{\frac{V_{L-L}}{\sqrt{3}}}{X_{c1} - X_{L1}} \right] \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (4.19)$$

b. Current through the capacitor bank: The RMS current through the capacitor bank must be within 135% of the rated capacitor current, to comply with IEEE-18. Its value is determined from the fundamental current and from the harmonic currents under consideration:

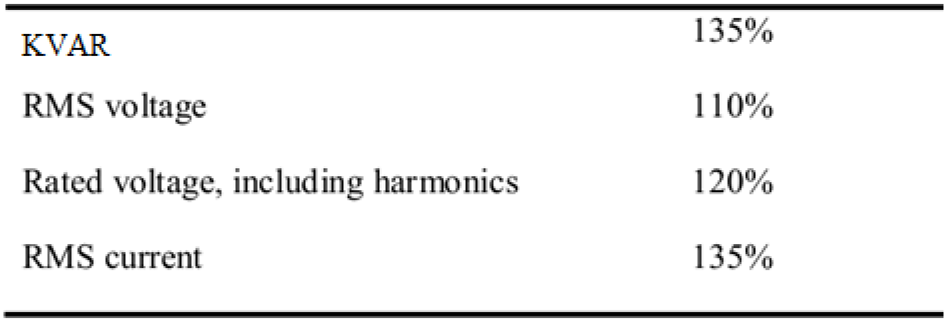
$$I_{crms} = \sqrt{{I_{c1}}^2 + {I_{ch}}^2} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (4.20)$$

c. Determine the capacitor bank duty and verify that it is within recommended IEEE-18 limits.

$$\mathrm{KVAR} = \frac{V_{crms} I_{crms}}{1000} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (4.21)$$

Where $V_{Crms}$ is the voltage through the capacitor $I_{Crms}$ is the current through the capacitor. This value must be within 135%. The maximum recommended values are summarized in table 4.3.

Table 4.1 Maximum Recommended Limits for Continuous Operation of Shunt Capacitors under Contingency Conditions [19]



| | |
|---|---|
| KVAR | 135% |
| RMS voltage | 110% |
| Rated voltage, including harmonics | 120% |
| RMS current | 135% |

If IEEE-18 is not met, the process may require more than one iteration to resize the capacitor bank. For designing appropriate tuned filter, the IEEE filter design practice for limiting harmonic and improving reactive compensation, depicted in Appendix C (Figure C.1), is going to be used for this research.

### 4.4.1 Design of Multi-Branch Single-Tuned Filter

The filter will be designed for 5th and 7th harmonics because these are the dominant harmonic frequencies in the plant. Therefore, multiple-branch single tuned harmonic filter is going to be designed. The harmonic filter design will be done according to the equations given above. The recorded data of the power and power factor are given in table 4.2.

Table 4.2 Recorded data of the power and power factor

| Measured Data | |
|---|---|
| S, KVA | 718.1 |
| P, KW | 588.842 |
| Q, KVAR | 411.014 |
| P.F | 0.82 |

As can be seen from the above table, the current power factor obtained is 0.82 and it is required to improve this value to 0.96. The total active power for this condition is 588.842 KW. The harmonic level of 5th and 7th are high and should be eliminated.

Step 1: The first step is to determine the reactive power to be provided by the filer capacitor banks and to calculate the value of the capacitor reactance from it.

$$\mathrm{Q_{com}} = \mathrm{P} \times (\tan(\arccos\emptyset_0) - \tan(\arccos\emptyset_1))$$

$$= 588.842\big(\tan\big(\cos^{-1}(0.82)\big) - \tan\big(\cos^{-1}(0.96)\big)\big)$$

$$\mathrm{Q_{com}} = 239.069 \text{ KVAR}$$

Where $Q_{com}$ = reactive power to be compensated.

For a multiple parallel single-tuned filter system, the capacitances corresponding to the $h^{th}$ harmonics are obtained using the equations given above. The reactive power is distributed among $5^{th}$ and $7^{th}$ harmonic filters as follows:

$$\mathrm{Q_{f5}} = \mathrm{Q_{com}} \times \frac{\mathrm{I_5}}{\mathrm{I_5} + \mathrm{I_7}}$$

$$= 239.069 \times \frac{168.51}{168.51 + 122.68}$$

$$\mathrm{Q_{f5}} = 138.348 \text{ KVAR}$$

$$\mathrm{Q_{f7}} = \mathrm{Q_{com}} \times \frac{\mathrm{I_7}}{\mathrm{I_5} + \mathrm{I_7}}$$

$$= 239.069 \times \frac{122.68}{168.51 + 122.68}$$

$$\mathrm{Q_{f7}} = 100.721 \text{ KVAR}$$

Where $Q_{f5}$, and $Q_{f7}$ are reactive power share of $5^{th}$ and $7^{th}$ harmonic filters respectively.

## For 5th Harmonic Filter

The voltage across the capacitor is determined as,

$$\mathrm{V_c} = (\frac{\mathrm{h}^2}{\mathrm{h}^2 - 1})\mathrm{V_{sys}}$$

Where $V_{sys} = 400$ V

$$\mathrm{V_c} = \left(\frac{5^2}{5^2 - 1}\right) \times 0.4 \text{ KV}$$

$$= 0.417 \text{ KV}$$

The standard voltage available near this value is 480 V. The reactive power to be supplied by the capacitor is,

$$\mathrm{Q_c} = \frac{5^2}{5^2 - 1} \times \mathrm{Q_{f5}}$$

$$= \frac{25}{24} \times 138.348$$

$$\mathrm{Q_c} = 144.113\ \text{kvar}$$

Near to this standard value is 145 KVAR. Then $X_C$ is,

$$\mathrm{X_c} = \frac{\mathrm{V_c^2}}{\mathrm{Q_c}} \times 1000$$

$$= \frac{0.48^2}{145} \times 1000$$

$$\mathrm{X_c} = 1.589\ \Omega$$

**For 7th Harmonic Filter**

Using similar procedure voltage across the capacitor is

$$\mathrm{V_c} = (\frac{\mathrm{h}^2}{\mathrm{h}^2 - 1})\mathrm{V_{sys}}$$

Where $\mathrm{V_{sys}} = 400\ \mathrm{V}$

$$\mathrm{V_c} = \left(\frac{7^2}{7^2 - 1}\right) \times 0.4\ \mathrm{KV}$$

$$\mathrm{V_c} = 0.408\ \mathrm{KV}$$

The standard voltage available near this value is 480 V. Similarly the reactive power to be supplied by the capacitor is calculated as follows

$$\mathrm{Q_c} = \frac{7^2}{7^2 - 1} \times \mathrm{Q_{f7}}$$

$$= \frac{49}{48} \times 100.721$$

$$\mathrm{Q_c} = 102.819\ \mathrm{KVAR}$$

Near to this standard value is 105 KVAR. Then $X_C$ is determined as

$$\mathrm{X_c} = \frac{\mathrm{V_c^2}}{\mathrm{Q_c}} \times 1000$$

$$= \frac{0.48^2}{105} \times 1000$$

$$\mathrm{X_c} = 2.194\ \Omega$$

Step 2: The second step is to calculate the reactor size providing the resonance, $X_L = \frac{X_c}{h^2}$ for the filters.

**For 5th Harmonics** $$X_L = \frac{X_{c1}}{5^2}$$

$$X_L = \frac{1.589}{5^2} = 0.064\ \Omega$$

**For 7th Harmonics** $$X_L = \frac{X_{c1}}{7^2}$$

$$X_L = \frac{2.194}{7^2} = 0.045\ \Omega$$

Step 3**:** The third step is to determine whether capacitor-operating parameters, RMS current through the filter, VAR limit, RMS & peak voltage values fall within IEEE 18 recommended limits. First the designed values for 5th harmonic filter are compared with the standard values.

**For the 5th Harmonics**

The designed values for the VAR limit, RMS current through the filter, RMS & peak voltage values are calculated as follows

Let $X_c = X_{c1} = 1.589\ \Omega$ and $X_L = X_{L1} = 0.064\ \Omega$ then,

$$X_{c5} = \frac{X_{c1}}{h}$$

$$X_{c5} = \frac{1.589}{5} = 0.3178\ \Omega$$

$$X_{L5} = hX_{L1}$$

$$X_{L5} = 5 \times 0.064 = 0.32\ \Omega$$

$$V_{cpeak} = \sqrt{2}(V_{c1} + V_{ch})$$

$$V_{c1} = X_{c1}I_{c1}$$

$$I_{c1} = 1.05 \times [\frac{\frac{V_{L-L}}{\sqrt{3}}}{X_{c1} - X_{L1}}]$$

$$I_{c1} = 1.05 \times \left[\frac{400/\sqrt{3}}{1.589 - 0.064}\right] = 159.008\ \text{A}$$

$$V_{c1} = 1.589 \times 159.008$$

$$V_{c1} = 252.664\ \text{V}$$

$$V_{ch} = X_{ch} I_{ch}$$

$$= X_{c5} I_{c5}$$

$$= 0.3178 \times 168.51$$

$$V_{c5} = 53.552 \text{ V}$$

$$V_{cpeak} = \sqrt{2}(252.664 + 53.552) = 433.055 \text{ V}$$

$$V_{crms} = \sqrt{{V_{c1}}^2 + {V_{ch}}^2}$$

$$V_{crms} = \sqrt{252.664^2 + 53.552^2} = 258.277 \text{ V}$$

$$I_{crms} = \sqrt{{I_{c1}}^2 + {I_{ch}}^2}$$

$$I_{crms} = \sqrt{159.008^2 + 168.51^2} = 231.688 \text{ A}$$

$$\text{kvar}_{\text{Cap (wye),total}} = \sqrt{3} \times I_{\text{rms,total}} \times \text{kV}_{\text{L−L,Cap (rms,total)}}$$

$$= \sqrt{3} \times 231.688 \times \sqrt{3} \times 0.258277$$

$$= 179.519 \text{ kvar}$$

And $\text{KVAR}_{\text{cap, rated}}$ can be given as

$$\text{KVAR}_{\text{Cap ,rated}} = \sqrt{3} \times I_{\text{cap,rated}} \times \text{kV}_{\text{L−L,cap(rated)}}$$

From this $I_{\text{cap,rated}}$ can be calculated as

$$I_{\text{Cap ,rated}} = \frac{145}{\sqrt{3} \times 0.48} = 174.408 \text{ A}$$

Now compare the designed values for 5th harmonic filter with the standard values.

Table 4.3 Comparison Table comparing filter duty limit of 5th harmonic filter

| Duty | Definition | Limit (%) | Actual Values | Actual Values (%) |
|---|---|---|---|---|
| KVAR | $\frac{kvar_{Cap\ (wye),total}}{kvar_{Cap\ ,rated}}$ | 135 | 1.24 | 124 |
| RMS Voltage | $\frac{V_{L-G,Cap\ (rms,total)}}{V_{rated}}$ | 110 | 0.93 | 93 |
| Peak Voltage | $\frac{V_{L-G,Cap\ (max,peak)}}{V_{rated,peak}}$ | 120 | 1.1 | 110 |
| RMS Current | $\frac{I_{rms,total}}{I_{cap,rated}}$ | 135 | 1.33 | 133 |

All the designed values are within the IEEE 18 recommended limits for the 5th harmonics.

Now calculate the capacitance and inductance values for the fifth harmonics

As calculated above, $X_c = 1.589\ \Omega$ and$X_L = 0.064\ \Omega$ then the capacitance will be

$$C = \frac{1}{2\pi f X_c} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (4.22)$$

$$C = \frac{1}{2\pi \times 50 \times 1.589} = 0.002\ F$$

and the inductance will be

$$L = \frac{X_L}{2\pi f} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (4.23)$$

$$L = \frac{0.064}{2\pi \times 50} = 0.204\ mH$$

Therefore, the 5th harmonic filter configuration looks as shown below

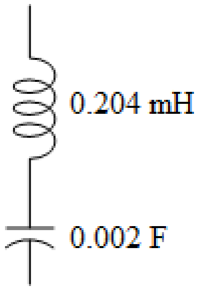


Figure 4.6 5th Harmonic filter branch with designed values

### For the 7th Harmonics

The designed values for the VAR limit, RMS current through the filter, RMS & peak voltage values can be calculated as follows

Let $X_c = X_{c1} = 2.194\ \Omega$ and $X_L = X_{L1} = 0.045\ \Omega$ then,

$$X_{c7} = \frac{X_{c1}}{h}$$

$$X_{c7} = \frac{2.194}{7} = 0.313\ \Omega$$

$$X_{L7} = hX_{L1}$$

$$X_{L7} = 7 \times 0.045 = 0.315\ \Omega$$

$$V_{cpeak} = \sqrt{2}(V_{c1} + V_{ch})$$

$$V_{c1} = X_{c1} I_{c1}$$

$$I_{c1} = 1.05 \times [\frac{\frac{V_{L-L}}{\sqrt{3}}}{X_{c1} - X_{L1}}]$$

$$I_{c1} = 1.05 \times \left[\frac{400/\sqrt{3}}{2.194 - 0.045}\right] = 112.837\ \mathrm{A}$$

$$V_{c1} = 2.194 \times 112.837$$

$$V_{c1} = 247.564\ \mathrm{V}$$

$$V_{ch} = X_{ch} I_{ch}$$

$$= X_{c7} I_{c7}$$

$$= 0.313 \times 122.68$$

$$V_{c7} = 38.399\ \mathrm{V}$$

$$V_{cpeak} = \sqrt{2}(247.564 + 38.399) = 404.413\ \mathrm{V}$$

$$V_{crms} = \sqrt{{V_{c1}}^2 + {V_{ch}}^2}$$

$$V_{crms} = \sqrt{247.564^2 + 38.399^2} = 250.524\ \mathrm{V}$$

$$I_{crms} = \sqrt{{I_{c1}}^2 + {I_{ch}}^2}$$

$$I_{crms} = \sqrt{112.837^2 + 122.68^2} = 166.681\ \mathrm{A}$$

$$\mathrm{kvar}_{\mathrm{Cap\ (wye),total}} = \sqrt{3} \times I_{\mathrm{rms,total}} \times \mathrm{kV}_{\mathrm{L-L,Cap\ (rms,total)}}$$

$$= \sqrt{3} \times 166.681 \times \sqrt{3} \times 0.250524$$

$$\mathrm{kvar}_{\mathrm{Cap\ (wye),total}} = 125.273\ \mathrm{kvar}$$

And $\mathrm{KVAR}_{\mathrm{cap,\ rated}}$ can be given as

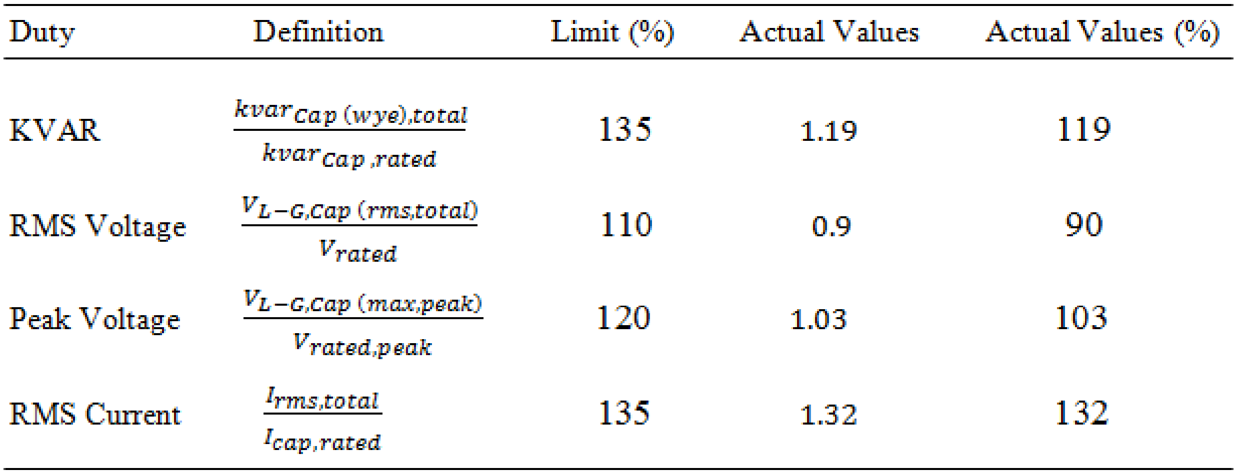
$$\mathrm{KVAR}_{\mathrm{Cap\ ,rated}} = \sqrt{3} \times I_{\mathrm{cap,rated}} \times \mathrm{kV}_{\mathrm{L-L,cap(rated)}}$$

From this $I_{\mathrm{cap,rated}}$ can be calculated as

$$I_{\mathrm{Cap\ ,rated}} = \frac{105}{\sqrt{3} \times 0.48} = 126.295\ \mathrm{A}$$

Now compare the designed values for 7th harmonic filter with the standard values.

Table 4.4 Comparison Table comparing filter duty Limit of 7th harmonic filter



| Duty | Definition | Limit (%) | Actual Values | Actual Values (%) |
|---|---|---|---|---|
| KVAR | $\frac{kvar_{Cap\ (wye),total}}{kvar_{Cap\ ,rated}}$ | 135 | 1.19 | 119 |
| RMS Voltage | $\frac{V_{L-G,Cap\ (rms,total)}}{V_{rated}}$ | 110 | 0.9 | 90 |
| Peak Voltage | $\frac{V_{L-G,Cap\ (max,peak)}}{V_{rated,peak}}$ | 120 | 1.03 | 103 |
| RMS Current | $\frac{I_{rms,total}}{I_{cap,rated}}$ | 135 | 1.32 | 132 |

All the designed values are within the IEEE 18 recommended limits for the 7th harmonics.

Now calculate the capacitance and inductance values for the 7th harmonics

As calculated above, $X_c = 2.194\ \Omega$ and$X_L = 0.045\ \Omega$ then the capacitance will be

$$C = \frac{1}{2\pi f X_c}$$

$$C = \frac{1}{2\pi \times 50 \times 2.194} = 0.0015\ F$$

and the inductance will be

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

$$L = \frac{0.045}{2\pi \times 50} = 0.143\ mH$$

Therefore, the 7th harmonic filter configuration looks as shown below

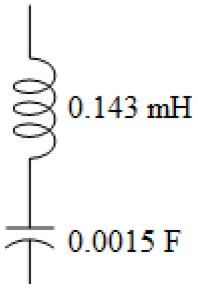


Figure 4.7 7th Harmonic filter branch with designed values

The design parameters for the 5th and 7th harmonics are summarized as follows:

Table 4.5 Design parameters of multi-branch harmonic filter

| Branch | $Q_c$, KVAR | $V_c$, V | $X_c$, Ω | C, F | $X_L$, Ω | L, mH |
|---|---|---|---|---|---|---|
| 5th | 145 | 480 | 1.589 | 0.002 | 0.064 | 0.204 |
| 7th | 105 | 480 | 2.194 | 0.0015 | 0.045 | 0.143 |

### 4.4.2 Cost of Filter

The cost of fully automatic system is $ 20 / KVAR [26]

For the case study the ratings for 5th and 7th harmonic filters are 145 and 105 KVAR, respectively, and then the cost of filter can be calculated as:

$$\text{Cost of filter} = (145 + 105)\text{kVAR} \times \frac{\$20}{\text{kVAR}} = \$\ 5{,}000 \text{ Or } 107{,}100 \text{ Birr}$$

Since the effect of harmonics on the industry cause false operations and trips of fuses and circuit breakers which leads to the damage of equipments and stops production process and also overheating of transformers and motors resulting in decreased efficiency and failure of winding insulation causing short circuit and damage the machines permanently. Therefore, the solution is very economical as compared to the effect of harmonics on electrical equipments and it improves the productivity of the industry.

### 4.5.Solution to Sustained Interruptions

Sustained interruption is characterized and quantified by the following major reliability indices that are computed as follows:

i. SAIFI: System average interruption frequency index indicates how often the average customer experiences a sustained interruption over a predefined period of time. Mathematically, it is expressed as

$$\text{SAIFI} = \frac{C_n \times I_n}{C_t} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.24)$$

Where, $C_n$ is number of customers interrupted, $I_n$ is number of interruptions, and $C_t$ is total number of customers.

ii. SAIDI: System average interruption duration index shows the total duration of interruption for the average customer during a predefined period of time. It is commonly measured in customer minutes or customer hours of interruption. Mathematically, this is given as

$$\mathrm{SAIFI} = \sum \frac{\mathrm{C_n} \times \mathrm{I_d}}{\mathrm{C_t}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . (4.25)$$

Where, $I_d$ is interruption duration.

iii. CAIFI: Customer average interruption frequency index gives the average frequency of sustained interruptions for those customers experiencing sustained interruptions. The customer is counted once regardless of the number of times interrupted for this calculation. Mathematically, this is given as

$$\mathrm{CAIFI} = \frac{\sum \mathrm{C_i}}{\mathrm{C_n}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . . (4.26)$$

Where, $C_i$ is number of customer interruptions.

iv. CAIDI: Customer average interruption duration index represents the average time required to restore service. Mathematically, this is given as

$$\mathrm{CAIDI} = \frac{\sum \mathrm{I_d}}{\sum \mathrm{C_i}} \ldots\ldots\ldots . \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.27)$$

The interviews with the electrical section head of the industry have clearly confirmed that frequent sustained interruptions are major challenges to the industry. During this study, three sustained power interruptions at different days in one week duration which lasts for 38, 108 and 43 minutes respectively have been recorded. As per the information from the section head, the power interruption lasts for 5 up to 6 hours in a week and the interruptions come from the utility. The industry is not equipped with automatic stand-by switching system and is provided only with a manually operated generator whose power rating is 810 KVA that is used when the power is interrupted and it requires at least 20 minutes for the starting production because all the machines stop working and the production process of the industry is interrupted resulting in substantial losses. The generator is used as a backup power option but its running cost is very high, i.e., it consumes 172 liters of fuel per hour and the cost of fuel (naphtha) per liter is 19.56 birr as a result this costs the industry huge amount of money annually as discussed below.

So, the annual fuel cost of the industry due to interruption will be

$$\text{Annual fuel cost} = 6\ \text{hrs/wk} \times 52\ \text{wks/yr} \times 19.56\ \text{Birr/lt} \times 172\ \text{lt/hr}$$

$$= 6 \times 52 \times 19.56 \times 172$$

$$\text{Annual fuel cost} = 1{,}067{,}976\ \text{Birr/yr}$$

The daily production of the industry when all the machines are working is 1600 carton, one carton contains 50 steaka and the selling value of on steaka is 88 Birr. Therefore, selling value of one carton is 4400 Birr and for 1600 carton it is 7,040,000 Birr/day in the daily production. So, if this amount of money is obtained in 24 hrs production. Since we have 168 hrs/week and there is production stoppage which lasts for at least 2 hours/week until the machines start to work by using the generator when there is power interruption, in 24 hrs the revenue gained is 7,040,000 Birr, and in 2 hrs it will be

$$= \frac{2\ \text{hrs} \times 7{,}040{,}000\ \text{Birr/day}}{24\ \text{hrs/day}}$$

$$= 586{,}667\ \text{Birr/week}$$

Hence, the industry faced a loss of 586,667 Birr/week and annually the loss will be 30,506,667 Birr/year or $ 1,525,334/year due to power interruption.

Therefore, another alternative power supply system should be designed which supplies the whole system automatically when there is power interruption. In this thesis solar photovoltaic (PV) system with Automatic Transfer Switch is identified to supply power due to its availability and reliability in that area and it can suit a wide range of applications such as residential, commercial, industry, etc.

Solar photovoltaic system or solar power system is one of renewable energy system which uses PV modules to convert sunlight into electricity. The electricity generated can be stored or used directly, fed back into the grid line or combined with one or more other electricity generators.

### 4.5.1 Major Components of PV System

Solar PV system includes different components that should be selected according to system type and applications. The major components for solar PV system are solar panels, solar charge controller, inverter, battery bank and loads (appliances).

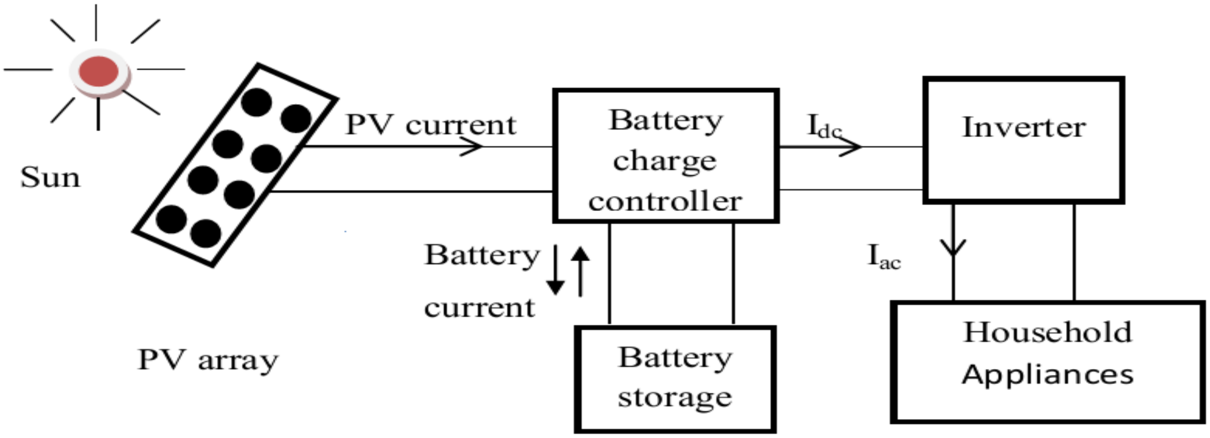


Figure 4.8 PV system block diagram.

### 4.5.1.1 Solar PV Array

A solar cell also called photovoltaic cell or photoelectric cell is a solid state electrical device that converts the energy of sunlight directly into electricity by using the photoelectric effect. Assemblies of cells are used to make solar modules which are also known as solar panels. The energy generated from these solar modules is referred to as solar power or solar energy.

Solar cells are also usually connected in series, creating an additive voltage. Connecting cells in parallel will yield a higher current. Modules are then interconnected, in series or parallel, or both, to create an array with the desired peak direct voltage and current [27].

The most prevalent bulk material for solar cells is crystalline silicon and categorized into [27].

1. Monocrystalline - silicon (c-Si): Single-crystal wafer cells tend to be expensive, and do not completely cover a square solar cell module without a substantial waste of refined silicon. Its efficiency reaches up to 15 per cent to 18 per cent.
2. Poly or multi crystalline silicon (poly-Si or mc-Si): Poly-Si cells are less expensive to produce than single crystal silicon cells, but they are less efficient. Its efficiency is 13 percent to 16 per cent. Ribbon silicon is a type of multi crystalline silicon.
3. Amorphous or thin-film Silicon: Amorphous (formless) silicon does not form a regular crystal structure, but an irregular network. Its efficiency is 5 per cent to 7 per cent module efficiency (stabilized condition).

One of the most important factors to consider when designing a photovoltaic system is the location of placement. By understanding the parameters associated with the module's tilt, one could optimize the effectiveness of the system to alleviate sizing and costs. More specifically, the location of placement describes the amount of irradiance the solar panel will be exposed to. Irradiance is normally used to describe the intensity of sunlight at a surface [27].

### a. Peak Sun Hours

Solar irradiation or Insolation is a measure of solar radiation energy received on a given surface area and recorded during a given time. In regards to irradiance, irradiation is normally expressed in terms of peak sun hours - the amount of solar radiation energy expressed in hours of full sunlight per square meter. Peak sun hours represent the average amount of sun light available per day throughout the year and correspond to the length of time in hours at an irradiance level of 1KW/m$^2$ needed to produce the daily irradiation [27].

$$\text{Peak Sun Hour} = \frac{\text{average irradiance per day}}{\text{irradiance level}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.28)$$

Table 4.6 Addis Ababa, Ethiopia - Solar energy and surface meteorology [28]

| | I | II | III | IV | V | VI | VII | VIII | IX | X | XI | XII |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Insolation, kWh/m²/day | 5.57 | 5.95 | 5.97 | 5.94 | 6.07 | 5.38 | 4.78 | 4.84 | 5.44 | 6.01 | 5.95 | 5.67 |
| Temperature, °C | 18.54 | 20.30 | 22.21 | 22.36 | 22.84 | 20.63 | 19.06 | 18.97 | 19.57 | 19.67 | 18.84 | 18.09 |
| Wind speed, m/s | 4.32 | 4.21 | 3.94 | 3.64 | 3.60 | 3.93 | 3.76 | 3.41 | 3.10 | 3.39 | 3.74 | 3.98 |

From the above table average irradiance per day for Addis Ababa is, $G_{av}$ = 5.63 KWhr/m$^2$/day, therefore,

$$\text{Peak Sun Hour} = \frac{5.63\ \text{KWhr/m}^2\text{/day}}{1\text{KW/m}^2\text{/day}} = 5.63\ \text{hr}$$

### b. Tilt Angle

The tilt angle represents the solar panel's angular displacement, from the horizontal axis, to achieve the most irradiance throughout the day. Most solar panels are tilted at an angle equal to the location's latitude. As Addis Ababa is situated +9.03 (9°01'48"N) north latitude and +38.74 (38°44'24"E) east longitude, the panel inclination should be 9.03 degree facing south [27].

### 4.5.1.2 Rechargeable Batteries

Energy storage is required in most stand-alone systems, as energy generation and consumption do not generally coincide. Most stand-alone solar systems have batteries. The most common type of battery found in stand-alone solar systems comprises rechargeable lead-acid-batteries. These are the most cost-effective and can handle large and small charging currents with high efficiency. They can also operate reliably for at least eight years [29].

### 4.5.1.3 Charge Controllers

In stand-alone systems, the system voltage of the PV array should be matched to that of the batteries; the usual system voltages are 12V, 24V and 48V. The charge controller voltage must be higher than the battery voltage. For example, with a 12V battery, it can be up to 14. 4 V. Crystalline standard modules with 36 to 40 solar cells supply a nominal voltage of 15V to 18V. The nominal voltage must be higher than the batteries' charge voltage. The charge controller therefore measures the battery voltage and protects the battery against overcharging [30].

### 4.5.1.4 Inverter

Storage batteries use and store Direct Current and have an output usually in the range of 12 - 24 volts. Virtually all modern appliances operate on Alternating Current. An inverter is a device that takes the power from DC battery source and converts it to AC electricity [31].

### 4.5.2 Photovoltaic System Design

The first step in designing a solar PV system is to find out the total power and energy consumption of all loads that need to be supplied by the solar PV system. The total installed power of NTE is 1,082,368 W. Therefore in NTE the power and energy consumption of all the loads are described in Appendix D.

#### 4.5.2.1 PV Array Sizing

From Appendix D, the total watt-hours per day, $E_o = 14{,}460{,}872 \text{ Whrs/day}$
Average solar radiation for Addis Ababa is, $G_{av} = 5.63 \text{ kwhr/m}^2\text{/day}$.
The following parameters are used for sizing:

1. Battery efficiency = 90%
2. Average cell temperature is 60°c @ Temperature Correction Factor (TCF) = 0.8
3. DC bus voltage, $V_{DC}$ = 48V
4. Inverter AC voltage = 400V
5. Inverter efficiency = 85 %.

Siemens Solar M-320 Module Specification is selected

Module Type S/M 320W
Maximum Power, $P_m = 320W_p$
Maximum Power Voltage, $V_m = 36V$
Maximum Power Current, $I_m = 8.88A$
Open Circuit Voltage, $V_{oc} = 34.9V$
Short Circuit Current, $I_{sc} = 9.16A$
Module Efficiency (%), $\eta_{pv} = 17.2\%$

The output efficiency will be,

$$\eta_{out} = \eta_{bat} \times \eta_{inv} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (4.29)$$

$$\eta_{out} = 0.9 \times 0.85 = 0.765$$

Therefore, the PV array area can be calculated as follows [23]:

$$PV_{area} = \frac{E_o}{G_{av} \times TCF \times \eta_{out}} \dots\dots\dots\dots\dots\dots (4.30)$$

$$= \frac{14{,}460{,}872\text{Whrs/day}}{5.63 \times 1000 \text{ whr/m}^2\text{/day} \times 0.8 \times 0.765}$$

$$PV_{area} = 4{,}196.958 \text{ m}^2$$

Now we can calculate PV peak power by using the following equation [32],

$$\mathrm{PV_{peakpower}} = \mathrm{PV_{area}} \times 1000\,\frac{\mathrm{w}}{\mathrm{m^2}} \times \eta_{\mathrm{pv}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.31)$$

$$= 4{,}196.958 \times 1000 \times 0.172$$

$$\mathrm{PV_{peakpower}} = 721{,}876.776\ \mathrm{W_p}$$

From the typical module power and PV peak power the total number of modules ($N_t$) required can be determined as follows,

$$\mathrm{N_t} = \frac{\mathrm{P_{peakpower}}}{\mathrm{P_{modulepower}}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..\ldots\ldots..(4.32)$$

$$= \frac{721{,}876.776\ \mathrm{W_p}}{320\ \mathrm{W_p}}$$

$$\mathrm{N_t} = 2{,}255.9$$

Actual requirement, $\mathrm{N_t} = 2{,}256$

For DC bus voltage (system nominal voltage) of 48 V, the number of modules to be connected in series, $N_s$ will be

$$\mathrm{N_s} = \frac{\text{System Nominal Voltage } (\mathrm{V_{DC}})}{\text{Operating Voltage of a single module}(\mathrm{V_m})} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.33)$$

$$\mathrm{N_s} = \frac{48}{36} = 1.33$$

Approximately, $N_s$=2 modules should be connected in series.

Then the number of solar modules connected in parallel which are called strings ($N_p$) can be calculated by dividing the total number of modules required to the number of series modules

$$\mathrm{N_p} = \frac{\mathrm{N_t}}{\mathrm{N_s}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.34)$$

$$\mathrm{N_p} = \frac{2{,}256}{2} = 1{,}128$$

Therefore, 1,128 strings will be connected in parallel.

The PV modules can be put on the roof of the buildings and near to the industry there is a huge area (around 3500$m^2$) occupied by the industry for expansion and at this time used as a store.

#### 4.5.2.2 Sizing of the Battery

Solar panels should be used in conjunction with deep cycle batteries. These batteries are designed to be charged and discharged over a long period of time. Deep cycle batteries are rated in Ampere Hours [Ah]. This rating specifies the amount of current in Amps that the battery can supply over a period specified in hours.

DOA – Days of Autonomy (largest number of continuous cloudy days of the site) = Two to five days is recommended. But for this paper, two days are chosen; this is because Addis Ababa has adequate irradiance level.

DOD – Depth of Discharge = 0.8

The storage capacity of the battery can be calculated according to the following formula [32],

$$\mathrm{Storage_{capacity}} = \frac{\mathrm{DOA} \times \mathrm{E_o}}{\mathrm{DOD} \times \eta_{\mathrm{out}}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (4.35)$$

$$= \frac{2 \text{ days} \times 14{,}460{,}872\mathrm{Whrs/day}}{0.8 \times 0.765}$$

$$\mathrm{Storage_{capacity}} = 47{,}257{,}751.63 \text{ Whrs}$$

The required battery size in AH becomes,

$$\mathrm{AH_{capacity}} = \frac{\mathrm{Storage_{capacity}}}{\mathrm{V_{DC}}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.. (4.36)$$

$$= \frac{47{,}257{,}751.63 \text{ Whrs}}{48 \text{ V}}$$

$$\mathrm{AH_{capacity}} = 984{,}536.49 \text{ AH}$$

Once the required battery capacity in Amp-Hours has been determined, battery cell can be therefore be selected by using manufacturers' catalogue. From the Exide battery manufacturers' specification a 6E95-11's with a 12 volt and 673 amp-hours battery capacity is selected.

Now we can determine the number of batteries, $N_b$ required,

$$\mathrm{N_b} = \frac{\mathrm{AH_{capacity}}}{\text{Nominal AH capacity}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.. (4.37)$$

$$\mathrm{N_b} = \frac{984{,}536.49 \text{ AH}}{673 \text{ AH}} = 1{,}462.9$$

So, the required numbers of batteries, $N_b$ = 1,463. Then the next step is determining the number of series connected batteries $N_{bs}$.

$$\mathrm{N_{bs}} = \frac{\text{System bus voltage}}{\text{Nominal battery voltage}} \dots\dots\dots\dots\dots\dots\dots\dots\dots.. (4.38)$$

$$\mathrm{N_{bs}} = \frac{48 \text{ V}}{12} = 4$$

Four batteries are connected in series arrangement.

Number of parallel batteries, $N_{bp}$

$$N_{bp} = \frac{N_b}{N_{bs}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots . (4.39)$$

$$N_{bp} = \frac{1{,}463}{4} = 365.75$$

So, $N_{bp}$= 366 batteries are connected in parallel arrangement.

### 4.5.2.3 Solar Charge Controller Sizing

To give the battery longer lifetime it should be charged safely and the charge controller protects the battery from over charging and under charging. It has to be capable of carrying the short circuit current of the PV array. The size of the controller can be determined as follows [32],

$$\text{charge controller rating} = N_P \times I_{SC} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (4.40)$$

$$= 1{,}128 \times 9.16 \text{ A}$$

$$\text{charge controller rating} = 10{,}333 \text{ A}$$

### 4.5.2.4 Inverter Design

Its size is depending on the demand and its efficiency. The proper design of an inverter enables to carry the maximum expected power of the AC loads [32].

Total power of the loads, $P_t = 1{,}082{,}368 \text{ W}$. For reliable operation, the inverter capacity is increased by 20 – 25 %

$$\text{Inverter}_{\text{power rating}} = (0.2 \times P_t) + P_t \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots .... (4.41)$$

$$= (0.2 \times 1{,}082{,}368) + 1{,}082{,}368$$

$$\text{Inverter}_{\text{power rating}} = 1{,}298{,}841.6 \text{ W}$$

To obtain the current rating of the stand-alone inverter divide the inverter’s power output rating by its lowest DC operating voltage, and then multiply by the inverter’s efficiency [33].

$$\text{Inverter}_{\text{current rating}} = \frac{\text{Inverter}_{\text{power rating}}}{V_{DC}} \times \eta_{inv} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots .. (4.42)$$

$$= \frac{1{,}298{,}841.6 \text{ W}}{48 \text{ V}} \times 0.85 = 23{,}000 \text{ A}$$

Therefore, the inverter should have a power rating value of 1,298,841.6 W or greater with 400 V AC, frequency 50Hz and 48V DC and current rating (short circuit capacity) of 23,000A.

### 4.5.3 Automatic Transfer Switch

The industry loses huge amount of money because the generator needs manual start up to supply the loads. So, an Automatic Transfer Switch (ATS) is required with the solar PV system in order to avoid this loss of production during power interruption to change the power supply from utility system to the stand alone PV system. An automatic transfer switch (ATS) is an electrical/electronic switch that senses when the mains or utility supply is interrupted and automatically starts up a solar PV system if the utility remains unavailable. It eliminates the element of manpower interaction in starting a generator and changing power supply from one source to another [34].

Relay switching: This block consists of the combination of the voltage monitoring relay(VMR) and the finder relays (11-pin relays) which serve as sensor used to determine the availability or non availability of voltage supply from either power sources before triggering the control sections of the ATS. The VMR is used for measuring and comparing the voltage level of the utility supply with a set voltage tolerance range (365-430V A.C).

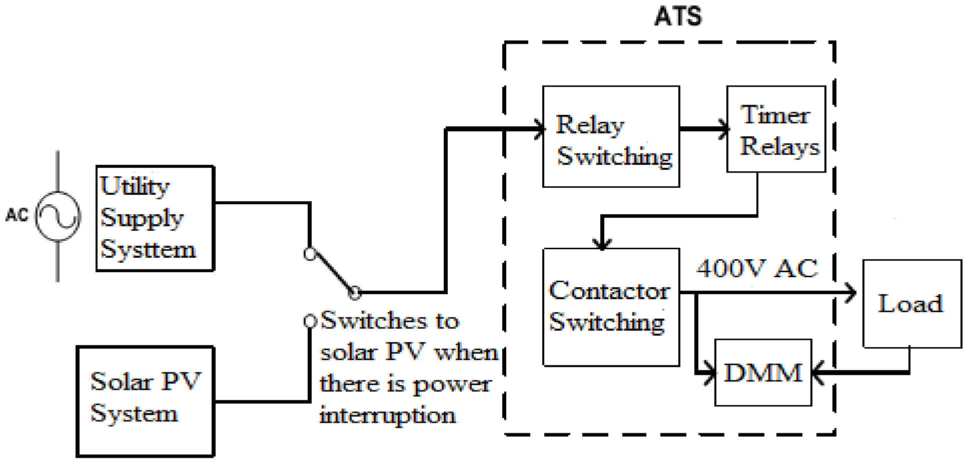


Figure 4.9 Block diagram showing the working principle of ATS [29]

Timer relay: The Timer relay helps to delay the supply of electric power, thus preventing the occurrence of equipment damage due to fluctuations in voltage supply. The delay time for the timer relay is 5-6 seconds.

The contactor switching: This block is made up of contactors on each side of the ATS. The function of the contactor is to switch the current to the connected loads. This is because they are made to handle large amount of current flow in electrical installations.

### Contactor Selection

With the input voltage supply from either power sources, V = 400Va.c supply

Measured load power, P = 588.842 KW

The power factor, Cos Ø = 0.82

Rated contactor set current in Ampere is,

$$I = \frac{P}{\sqrt{3} \times V \times \cos\emptyset} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (4.43)$$

$$= \frac{588.842 \times 1000}{\sqrt{3} \times 400 \times 0.82}$$

$$I = 1036.5\ A$$

Therefore, the contactor selected for the ATS is a 1200A rated contactor.

The Digital Multimeter (DMM): The digital multimeter in the ATS is an electronic device used for measuring the output voltage, load current and frequency of the supply voltage to the connected load.

### 4.5.4 Cost Analysis for PV System and ATS

The costs of a stand-alone PV system in the industry include initial costs, operating costs, maintenance costs, replacement costs, transportation costs and installation costs. The initial cost for the system is summarized in the table below [32].

The unit costs for PV module, battery, charge controller, and inverter are obtained from Siemens solar panels, Exide battery, Xantrex manufacturer's(for both charge controller and inverter), respectively.

Table 4.7 Cost summary of the PV system

| Items(components) | Rating | Cost/rating | Total cost ($) |
|---|---|---|---|
| PV module | 721,876.776 W | $0.6/W | 433,126.066 |
| Battery | 984,536.49 AH | $1.2/AH | 1,181,443.788 |
| Charge controller | 10,333 A | $5.2/A | 53,731.6 |
| Inverter | 1,298,841.6 W | 0.7 $/W | 909,189.12 |
| Total | | | 2,577,490.57 |

There is almost no operating and maintenance cost (no fuel costs). Replacement costs are mainly for batteries and its lifetime is considered to be 8 years so at least there should be a battery replacement two times. Thus, the batteries have to be purchased, after 8 years and 16 years, assuming inflation rate i of 5 % and a discount or interest rate d of 8 %. Therefore, the present worth of the 1st group of batteries (purchased after N = 8 years), $C_{B1PW}$, can be calculated as,

$$C_{B1PW} = C_B\left(\frac{1+i}{1+d}\right)^N \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (4.44)$$

Where, $C_B$ = Initial cost of batteries

i = inflation rate

d = discount or interest rate

N = number of years

$$C_{B1PW} = \$\ 1{,}181{,}443.788 \times \left(\frac{1+0.05}{1+0.08}\right)^8$$

$$C_{B1PW} = \$\ 943{,}055.846$$

The present worth of the 2nd group of batteries (purchased after N = 16 years), $C_{B2PW}$, can be obtained as,

$$C_{B2PW} = \$\ 1{,}181{,}443.788 \times \left(\frac{1+0.05}{1+0.08}\right)^{16}$$

$$C_{B2PW} = \$\ 752{,}769.059$$

$$C_{B1PW} + C_{B2PW} = \$\ 1{,}695{,}824.906$$

The transportation cost is considered to be 5% of the total cost

$$\text{Transportation cost, } \mathrm{C_{Trans}} = 0.05 \times 2{,}577{,}490.57$$

$$\mathrm{C_{Trans}} = \$\ 128{,}874.529$$

The Installation cost is considered to be 10% of the PV module cost so

$$\text{Installation cost, } \mathrm{C_{Inst}} = 0.1 \times 433{,}126.066$$

$$\mathrm{C_{Inst}} = \$\ 43{,}312.607$$

Therefore, the total cost required for the solar PV system in NTE which is expected to work for 25 years is,

$$\mathbf{C_{PV}} = \$(2{,}577{,}490.57 + 1{,}695{,}824.906 + 128{,}874.529 + 43{,}312.607)$$

$$\mathbf{C_{PV}} = \$\ 4{,}445{,}502.612$$

The cost of 3-phase, 1200A Thomson TS870SE-TCP Automatic Transfer Switch is $16,899.00

The total cost of solar PV system and ATS is, $\mathrm{C_{PV\&ATS}} = \$\ 4{,}445{,}502.612 + \$\ 16{,}899.00$

$$\mathrm{C_{PV\&ATS}} = \$\ 4{,}462{,}401.612$$

**Payback Period for the PV System**

Total Cost of solar PV system and ATS, $\mathrm{C_{PV\,\&\,ATS}} = \$\ 4{,}462{,}401.612$

Cost of power interruption per year, $\mathrm{C_{int}} = \$\ 1{,}525{,}334/\mathrm{yr}$

Payback period = T, year

$$\mathrm{T} = \frac{\mathrm{C_{PV\,\&\,ATS}}}{\mathrm{C_{int}}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (4.45)$$

$$\mathrm{T} = \frac{\$\ 4{,}462{,}401.612}{\$\ 1{,}525{,}334/\mathrm{yr}}$$

$$\mathrm{T} = 2.9 \text{ year} \approx 3 \text{ years}$$

Since the average serving life time of the solar PV system is about 25 years, so the solution is very economical and the industry save the money lost due to power interruption for almost 22 years. Currently the company is among the top public enterprises in terms of annual revenue and profitability. Annual turnover has continually increased, on average by Birr 190 million, during the previous five years period.

It is also possible to use the solar PV system as a standalone main supply for the industry by neglecting the utility supply system, the use of solar PV has these benefits environmental friendly and renewable energy in addition, the problem of power interruption will not be a concern anymore, no production stoppage and there is no loss of money due to power interruption. Based on the previous PV cost estimations, the following calculation, which takes into account the industry expansion for the future, will be done in order to know the total cost and payback period of the PV system which will be used as a standalone supply system.

By considering the industry works for 24 hours and approximately the installed power of the industry is 1100 KW and taking diversity factor of 0.85 (meaning 85 % of the machines are working at the same time), the annual energy production from the PV system will be,

$$\mathrm{E} = 1100\ \mathrm{KW} \times 24\ \mathrm{hrs/day} \times 365\mathrm{days/yr} \times 0.85$$

$$\mathrm{E} = 8{,}190{,}600\,\frac{\mathrm{KWhrs}}{\mathrm{yr}}$$

Since the energy produced annually from the PV system which considers the operating time of each machine (equipment) and the system is used as a backup power option for the industry during power interruption is,

$$\mathrm{E_0} = \left(\frac{365\mathrm{days}}{\mathrm{yr}} \times \frac{14{,}460{,}872\mathrm{Whrs}}{\mathrm{day}}\right)$$

$$\mathrm{E_0} = 5{,}278{,}218.28\,\frac{\mathrm{KWhrs}}{\mathrm{yr}}$$

And the total installation cost of the system needed to produce this much amount of energy is,$ $4{,}462{,}401.612$. Then, taking direct relationship of energy production and the cost of installation for the system, the cost for installing the PV system which generates $8{,}190{,}600\,\frac{\mathrm{KWhrs}}{\mathrm{yr}}$ of energy will be, $\mathrm{C_{PV}} = \$\ 6{,}924{,}638$.

The industry expansion should be taken into account to estimate the total cost for the PV system and considering 25 % of the investment cost $C_{PV}$ for producing energy which is used to supply the loads which will be added by industry expansion and it becomes, $ $1{,}731{,}160$. Therefore, the total cost needed to install the standalone solar PV system will be,

$$\mathrm{C_{PV}} = \$\ (6{,}924{,}638 + 1{,}731{,}160)$$

$$\mathrm{C_{PV}} = \$\ 8{,}655{,}798$$

Since the power interruption in NTE reaches up to 6 hrs/week and the expected daily production of the industry in terms of money is $7{,}040{,}000\ \mathrm{Birr/day}$, as result the loss of money due to power interruption will be,

$$= \frac{5\ \text{hrs/wk} \times 7{,}040{,}000\ \text{Birr/day} \times 7\ \text{days/wk}}{168\ \text{hrs/wk}}$$

$$= 1{,}466{,}667\ \text{Birr/wk}$$

Annually, it will be

$$= 1{,}466{,}667\ \text{Birr/wk} \times 52\ \text{wks/yr}$$

$$\text{Annual loss} = 76{,}266{,}667\ \text{Birr/year}$$

The electric bill shows that the industry pays to EEU up to $1{,}200{,}000$ Birr annually for electric power usage but if the industry uses the standalone solar PV system it saves the money paid to EEU. Therefore, the cost of the industry is $\mathrm{C_{total}} = 77{,}466{,}667\ \text{Birr/yr}$ or $\$\ 3{,}296{,}454/\text{yr}$ and the industry will save this much amount of money if solar PV system is installed.

Then, the payback period will be

$$\mathrm{T} = \frac{\mathrm{C_{PV}}}{\mathrm{C_{total}}}$$

$$\mathrm{T} = \frac{\$\ 8{,}655{,}798}{\$\ 3{,}296{,}454/\text{yr}}$$

$$\mathrm{T} = 2.68\ \text{years} \approx 3\ \text{years}$$

From this analysis it is clear that, the industry can use the energy obtained from the standalone solar PV system at least for 20 years without any payment or cost. So, if the industry is determined to install the system it will be very economical and feasible.

# CHAPTER 5

## SIMULATION STUDIES AND DISCUSSION OF RESULTS

### 5.1.Mitigation of Oscillatory Transients

Among the causes of oscillatory transient, capacitor energization is the one which occurs in the industry and has various effects on sensitive industrial equipments. Therefore, proper mitigation technique should be applied. Since the size of the capacitor bank installed in the industry is 450 KVAR and the study has been performed using this capacitor bank. The solutions for transients associated with capacitor switching have been simulated using MATLAB/SIMULINK/ 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.

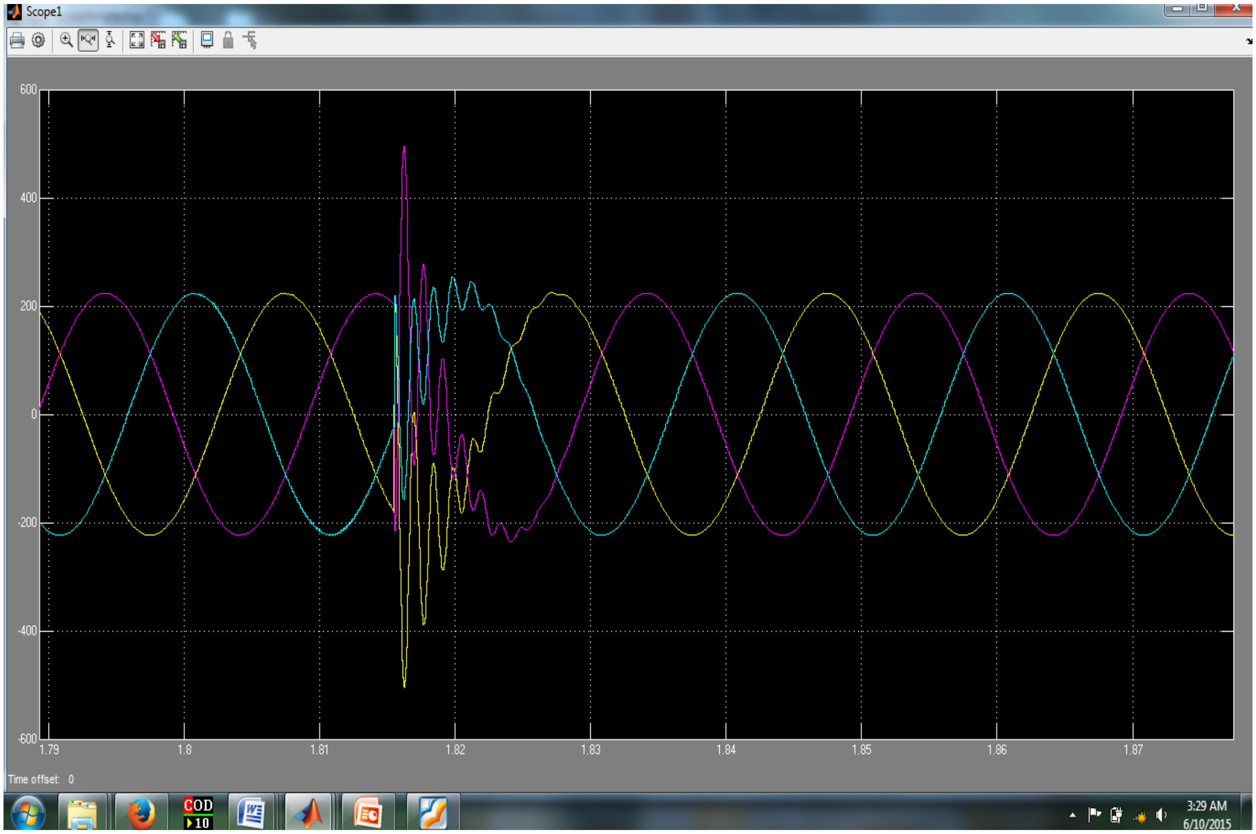


Figure 5.1 Oscillatory transient voltage waveform without pre-insertion resistor

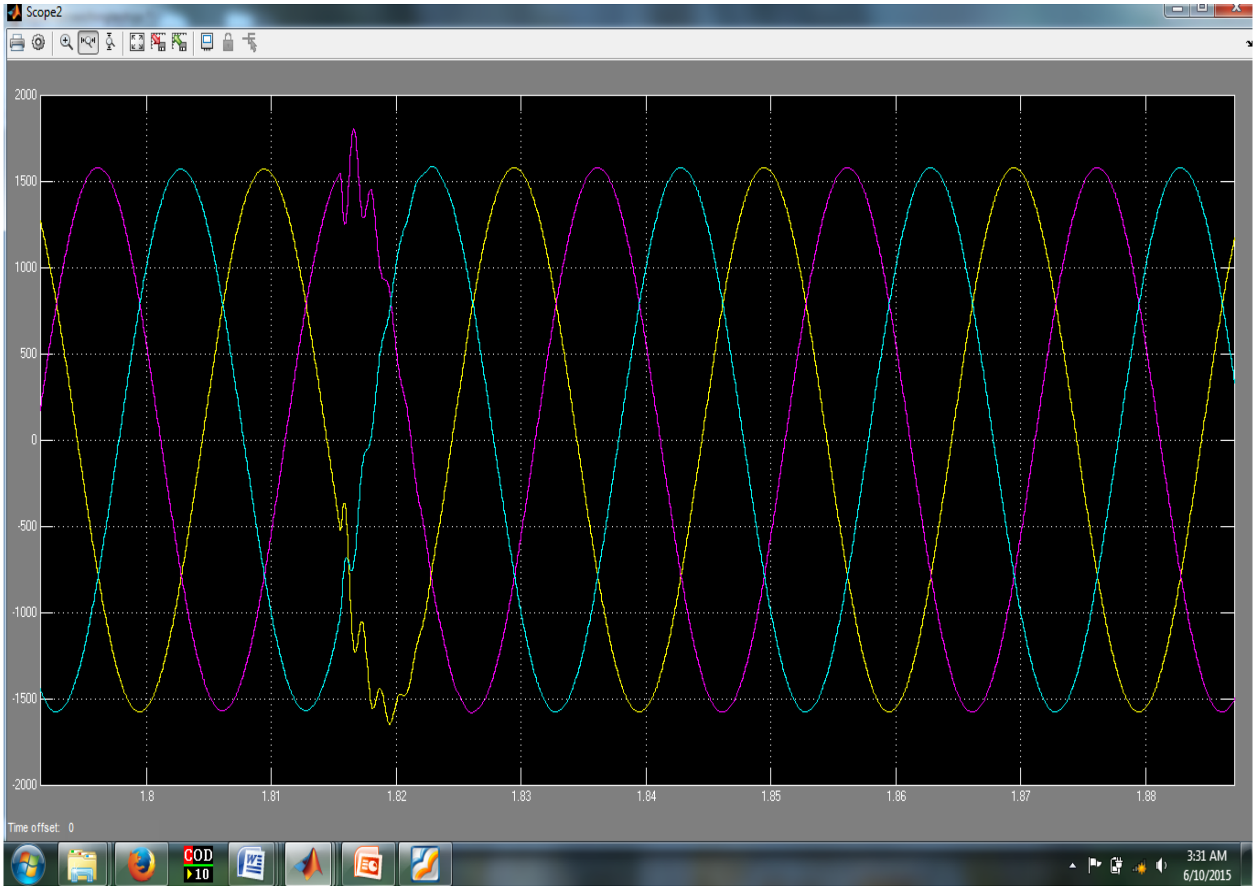


Figure 5.2 Oscillatory transient current waveform without pre-insertion resistor

To circumvent the problem of oscillatory transient overvoltage which lasts for a period of 15.5 msec due to capacitor energization in the industry that reaches up to 510 V, which is twice as much the standard operating voltage level shown in figure 5.1 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 with the value of 5 Ω is used as mitigation equipment; thus, the overshoot is significantly reduced to the required standard voltage level, i.e. 230 V.  The simulation results that show the effect of transient reduction by using pre-insertion resistor are shown in figure 5.3.

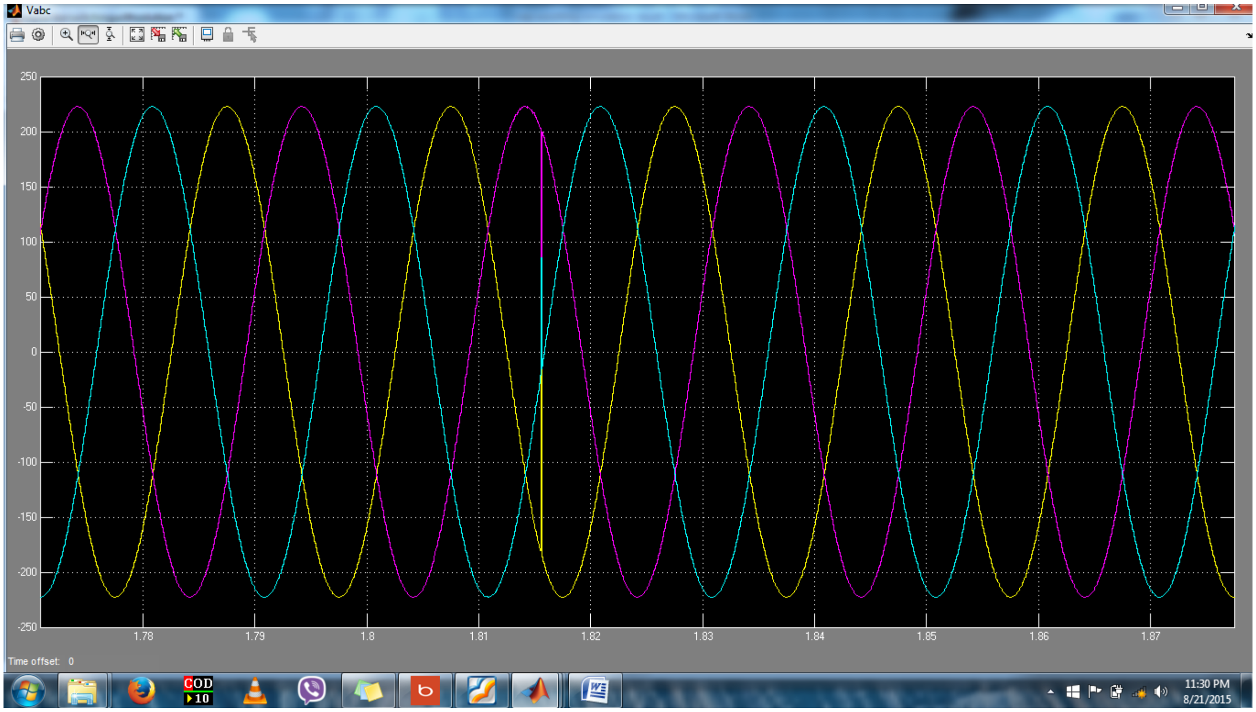


Figure 5.3 Oscillatory transient voltage waveform with pre-insertion resistor.

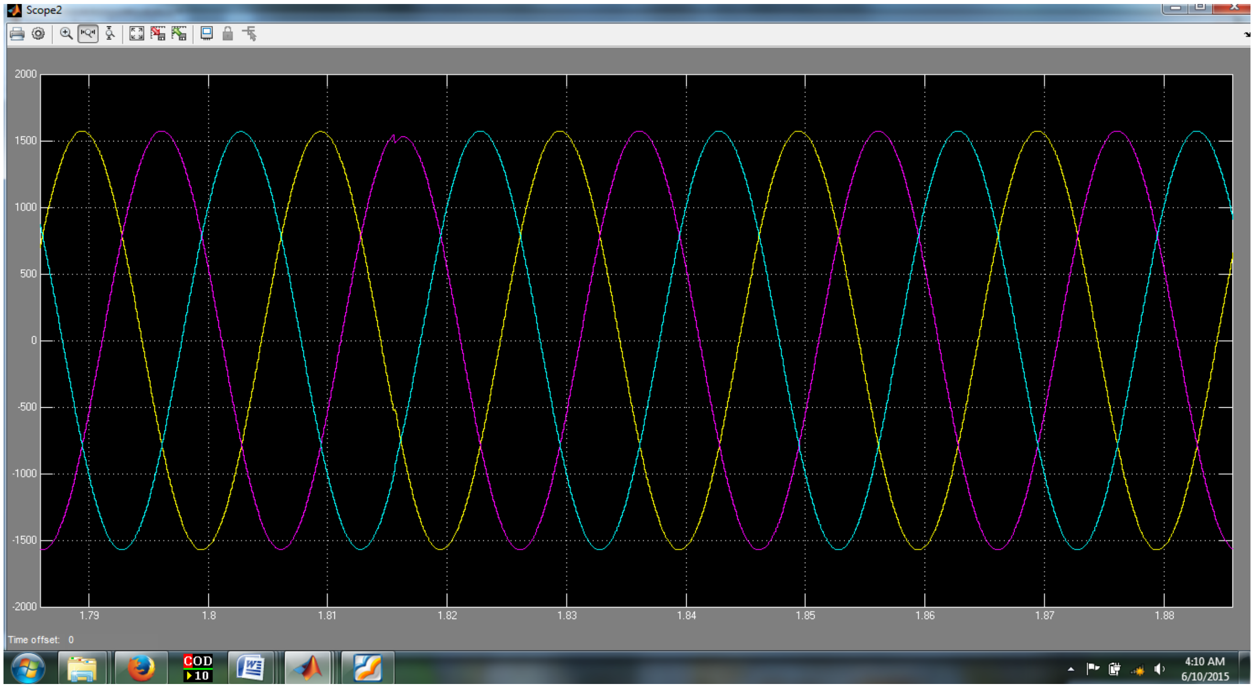


Figure 5.4 Oscillatory transient current waveform with pre-insertion resistor.

## 5.2.Mitigation of Voltage Sag Problem

The solution for voltage sag problem is modeled and simulated using MATLAB/SIMULINK/ software. The first simulation shows voltage sag problem without DVR when there is a three phase short circuit fault in the system at a point with fault resistance of 2 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.

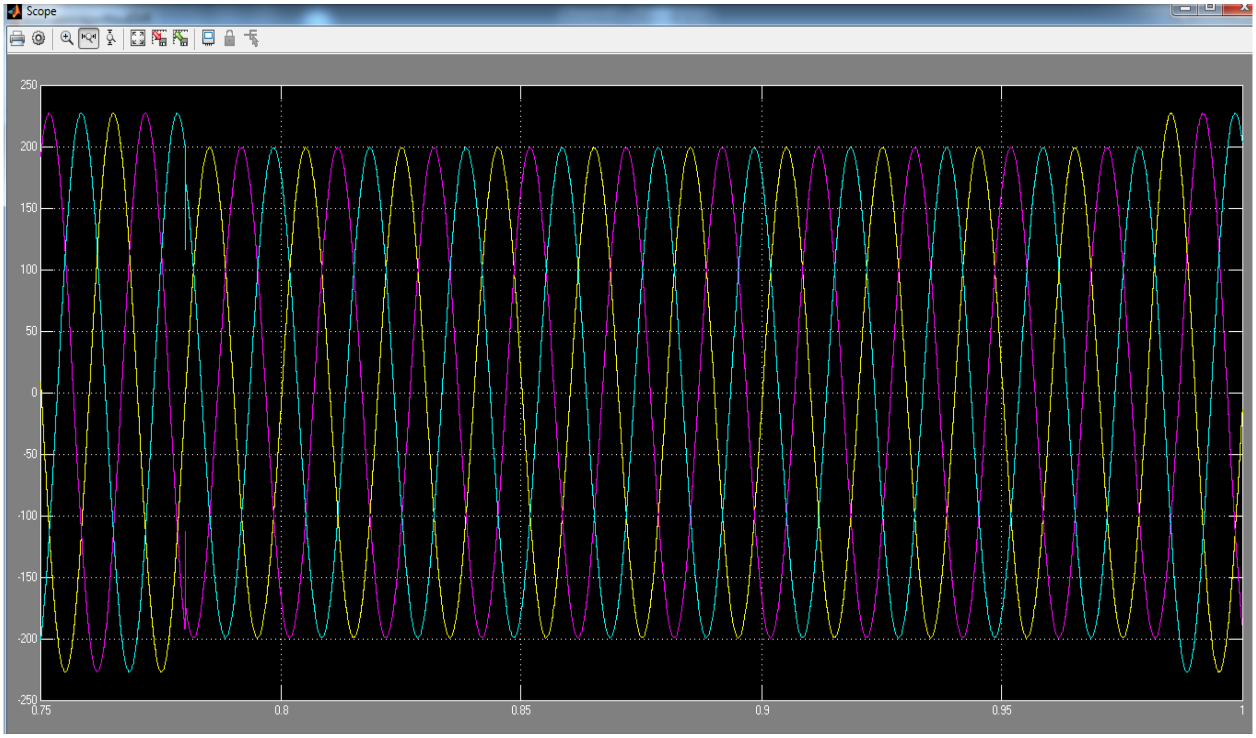


Figure 5.5 Voltage sag problem without DVR

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 short circuit fault. The proposed dynamic voltage restorer responds to this sag and injects the appropriate amount of missing voltage that reaches 25 V 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 the voltage waveform that is obtained after connection of DVR the voltage restores for the three phases from 202.86 V, 201.25 V, and 200.33 V, respectively to 230 V.  This shows that the installed DVR is working efficiently.

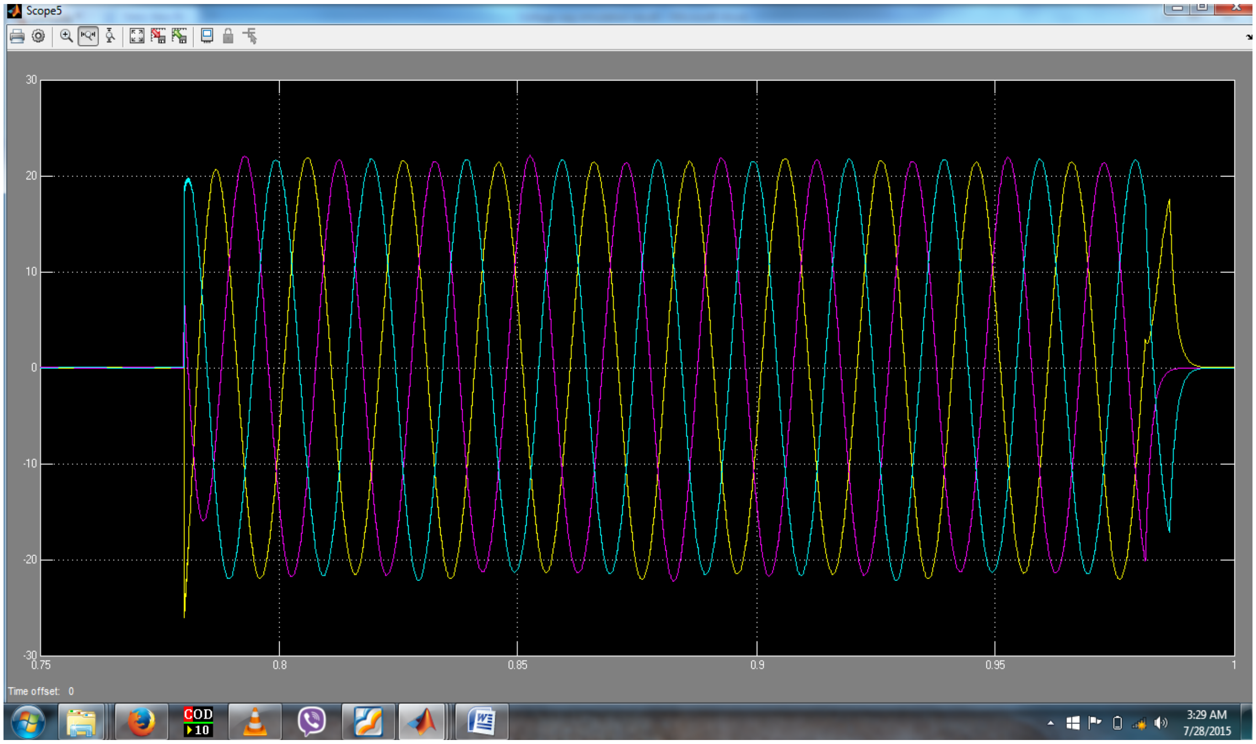


Figure 5.6 Injected voltage by DVR

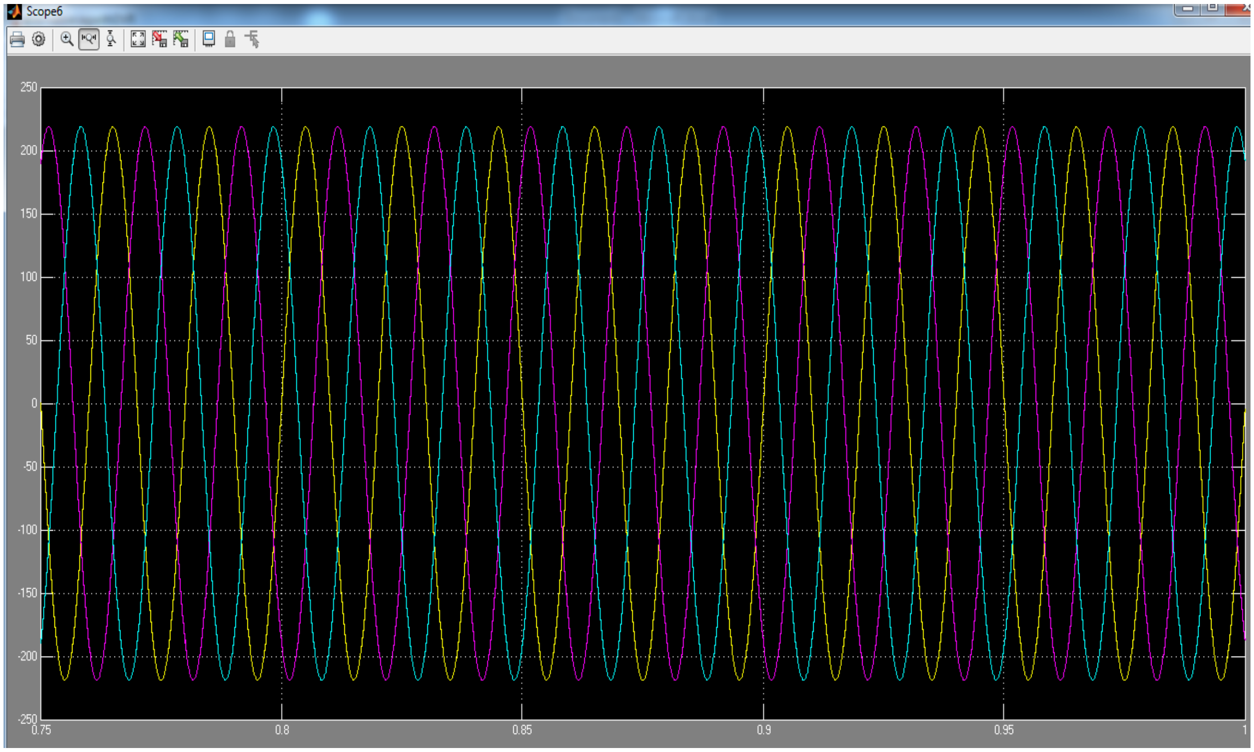


Figure 5.7 Voltage sag with DVR

## 5.3. Mitigation of Harmonic Pollution

The solutions for harmonic pollutions have been simulated using MATLAB/SIMULINK/ software. The designed multi-branch harmonic filters (5th and 7th harmonic filters) are simulated to see if they can effectively reduce the distortion levels to acceptable values. The current waveforms before and after filtering are presented for comparison.

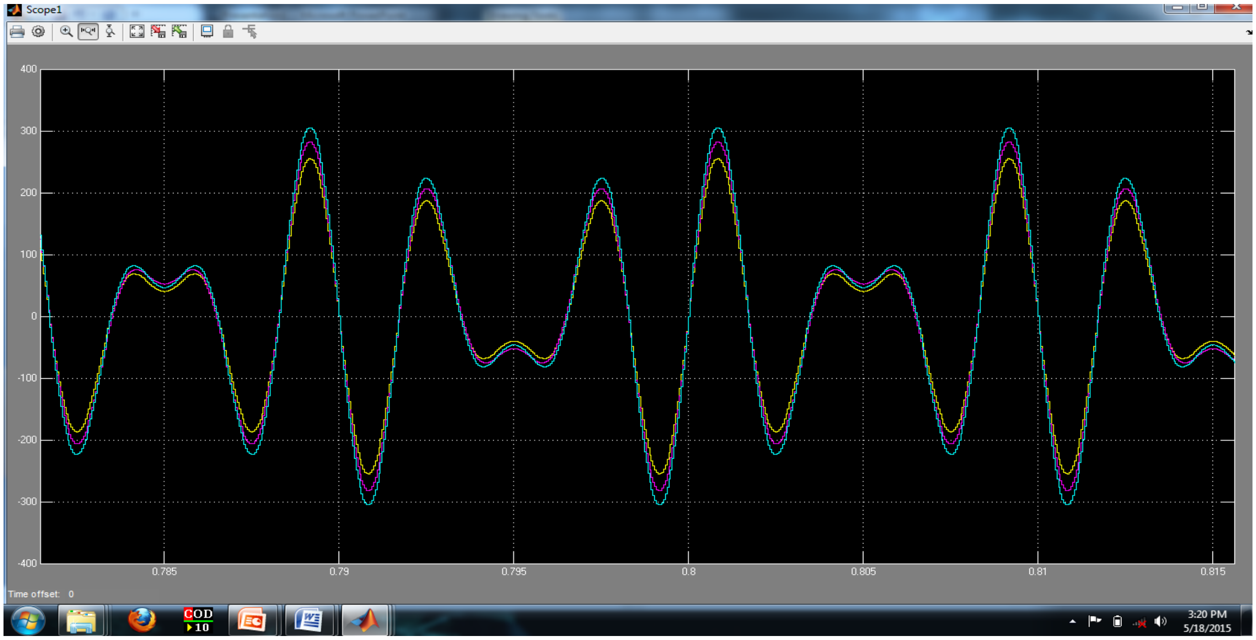


Figure 5.8 Harmonic currents injected by non-linear loads

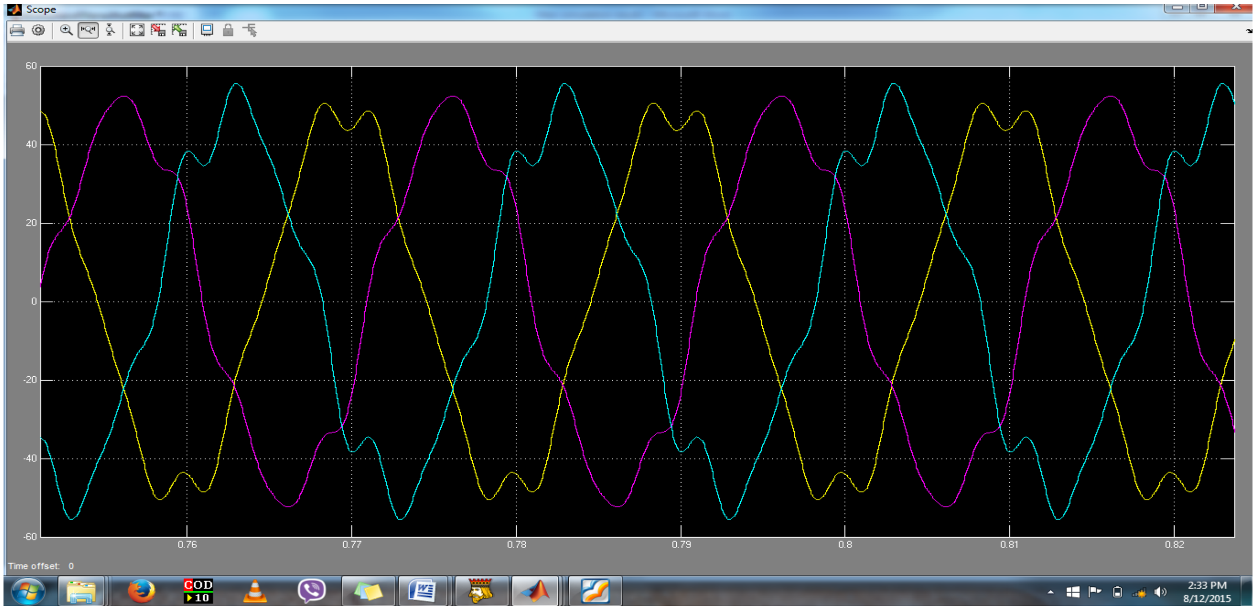
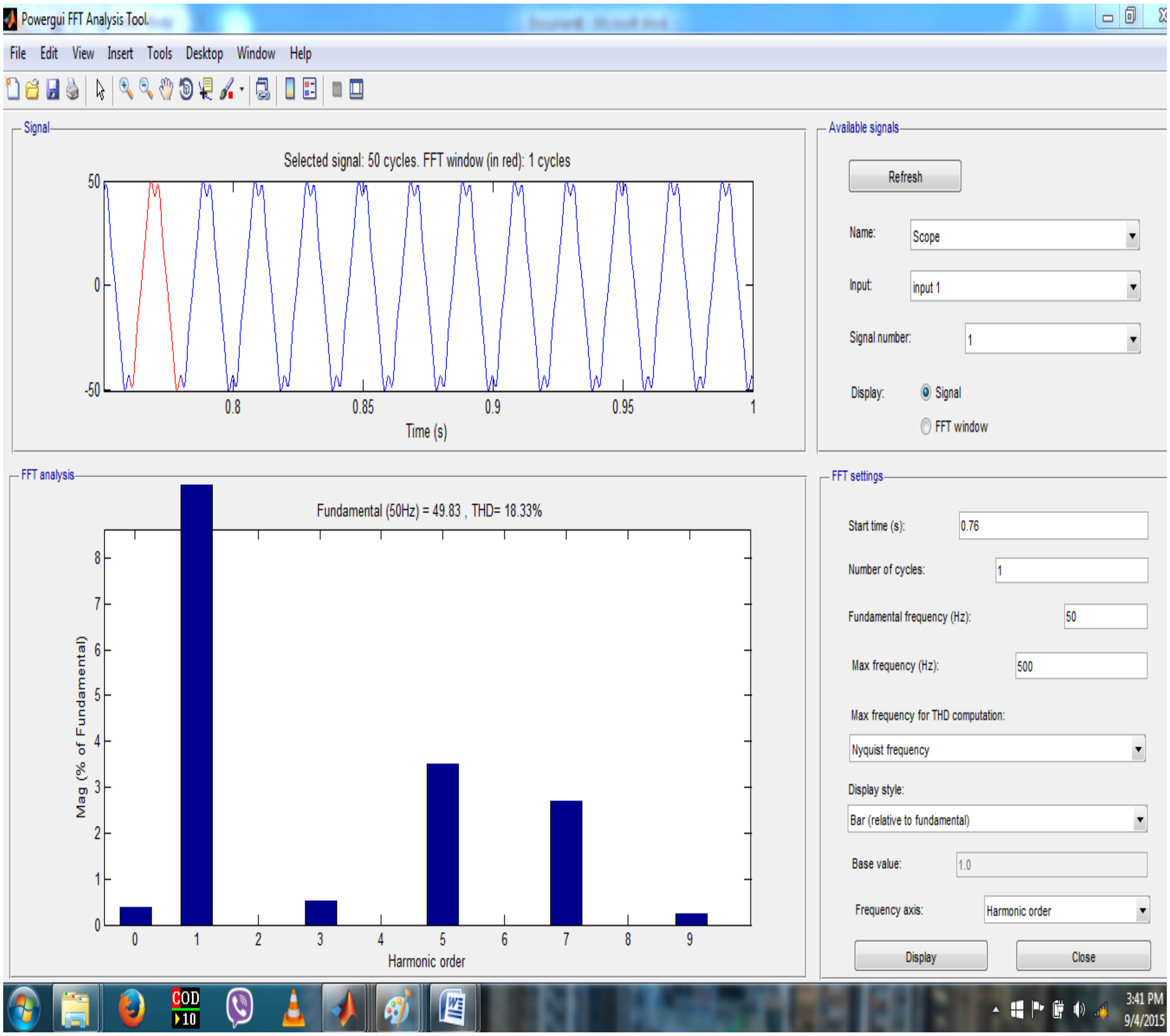


Figure 5.9 Current waveform without filter



Name: Scope

Input: input 1

Signal number: 1

Display: ● Signal ○ FFT window

Start time (s): 0.76

Number of cycles: 1

Fundamental frequency (Hz): 50

Max frequency (Hz): 500

Max frequency for THD computation: Nyquist frequency

Display style: Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Harmonic order

Figure 5.10 FFT analysis of the harmonic currents before filtering

As we can seen from figure 5.9 the problem of harmonics produces a distorted waveform and in figure 5.10 from the Fast Fourier Transform (FFT) analysis the THD value is 18.33 which 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.

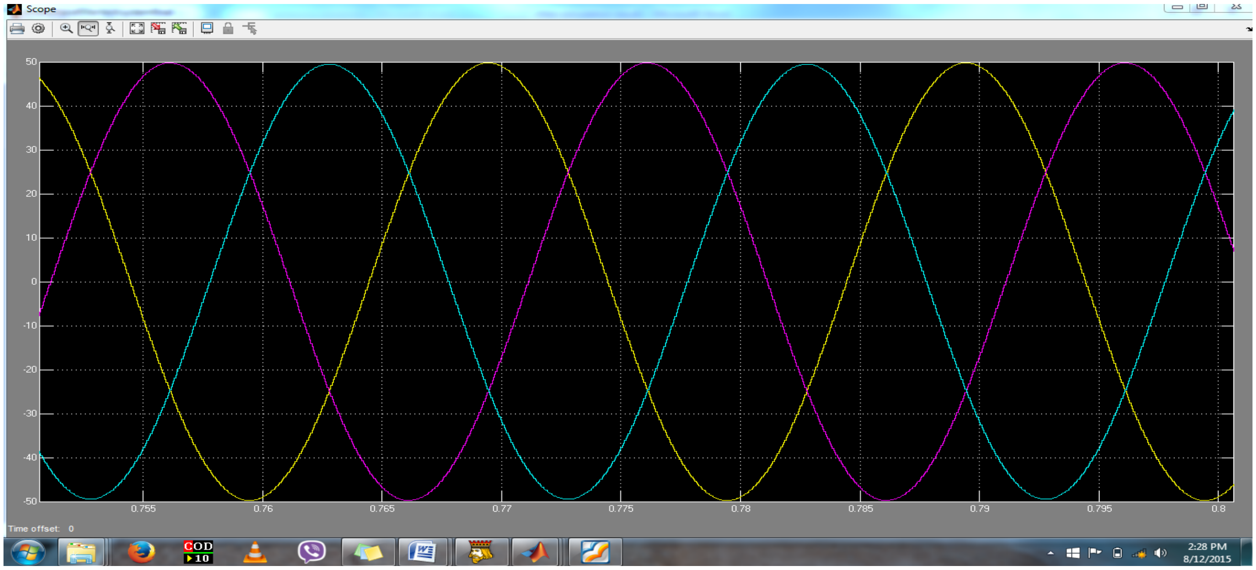
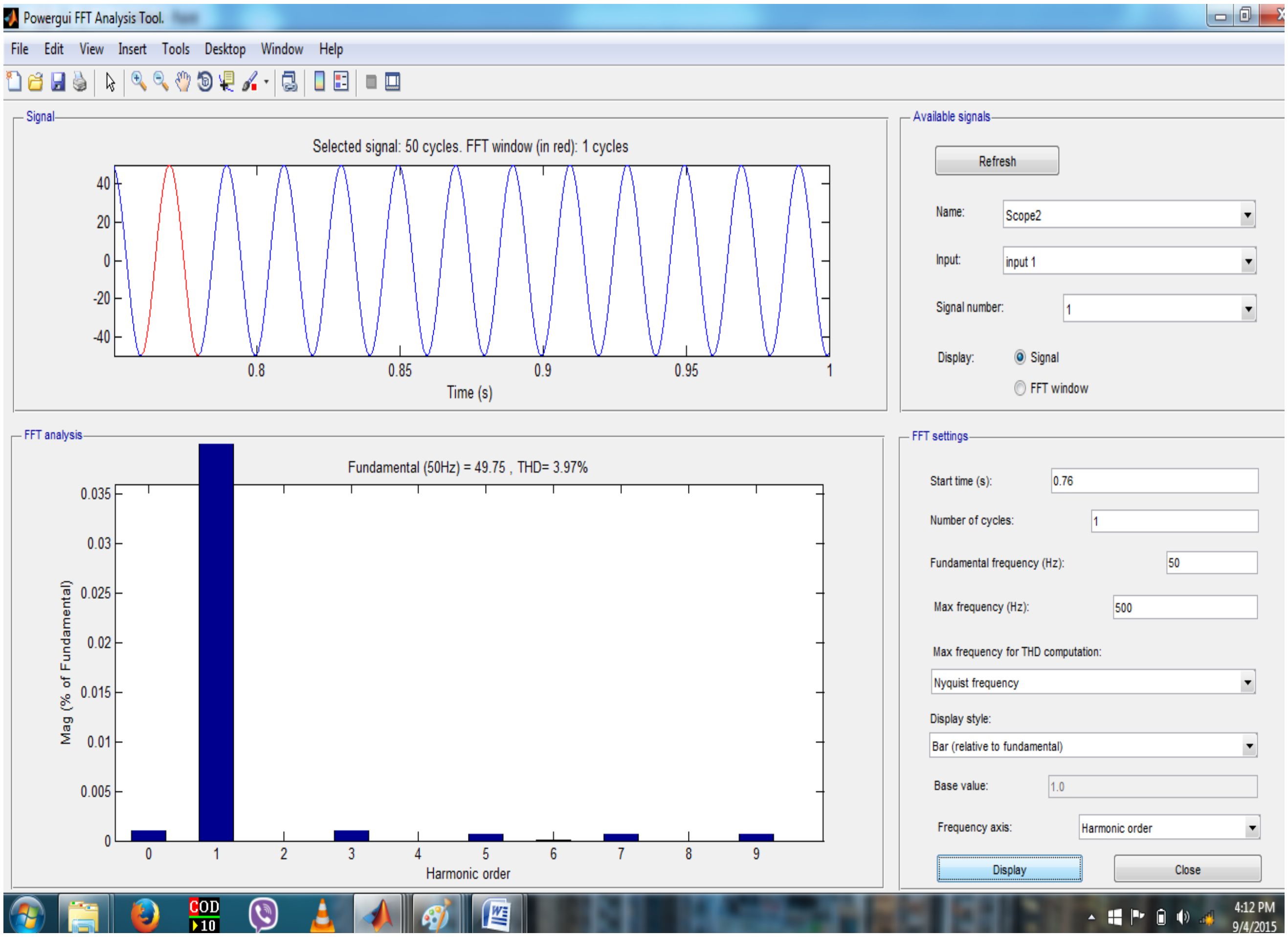


Figure 5.11 Current waveform with filter



Selected signal: 50 cycles. FFT window (in red): 1 cycles

Name: Scope2

Input: input 1

Signal number: 1

Display: ● Signal ○ FFT window

Fundamental (50Hz) = 49.75 , THD= 3.97%

Start time (s): 0.76

Number of cycles: 1

Fundamental frequency (Hz): 50

Max frequency (Hz): 500

Max frequency for THD computation: Nyquist frequency

Display style: Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Harmonic order

Figure 5.12 FFT analysis of the harmonic currents after filtering

The results obtained in figure 5.11 show the multi-branch single tuned filter has significantly reduced the harmonic currents that appear at the secondary terminal of the transformer. The current THD level is reduced from 18.33 % to 3.97 %, due to the compensation provided by the multi-branch harmonic filter. It is clear that the filters effectively reduce the distortion level to the acceptable magnitude, i.e. less than 5 %.

# CHAPTER 6

# CONCLUSIONS, RECOMMENDATIONS AND SUGGESTIONS FOR FUTURE WORK

## 6.1.Conclusions

The aim of this research was to investigate and examine the power quality problems in the National Tobacco Enterprise distribution system, compare with standard values, and design mitigation equipments if the level exceeds the standard level. Based on the results of the power quality assessment carried out at NTE, the following major conclusions are drawn.

Transients are disturbances that occur for a very short duration. It is of two types, i.e. impulsive transient and oscillatory transient but the later one is occurred in the industry. The energization of three phase industry capacitor bank which is used to improve the power factor, gives rise to oscillatory transient overvoltage which is as much the value $2U_{max}$ for duration of about 15.5 ms. 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 are used to mitigate the effect of the problem and were observed to reduce the oscillatory transient overvoltage from 510 V to 230 V.

The short duration voltage variation, voltage sag, was occurred on the three phases and the percentage voltage reduction are 11.8% and the voltage decreases to 202.86 V, 12.5% and the voltage decreases to 201.25 V, 12.9% and the voltage decreases to 200.33 V for duration of 200 msec. caused by three phase short circuit fault resulting in tripping of protective device and failure of sensors which check the quantity and proper packaging of cigarette. 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 a distribution system between the supply and the critical load feeder at the PCC, to restore the voltage to the normal standard voltage level, i.e. 230 V.

The industry is facing frequent sustained electric power interruptions that enforced them to invest extra money for the purchase of fuel for the manual diesel generator which is used as a backup power option for the industry during power interruption. It affects the production process, causing downtimes of several machines, resulting in substantial losses. Early failure of machines due to wear and tear is the other major problem caused by unexpected power interruptions. In order to avoid the losses due to sustained power interruptions an alternative power supply system, which is solar PV system (renewable and environment friendly), was designed by considering its initial investment cost and payback period of the system to be installed.

The problem of voltage unbalance is discovered at the industry. The voltage unbalance is caused by uneven single-phase load distribution among the three phases, most of the single phase loads are connected to phase 2 and 3, this is identified by measuring the currents in the three phases and the values are 913 A, 1179 A and 1250 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 the company's profitability. So the problem should be mitigated by redistributing the loads equally to the three phases.

The industry draws a distorted current of up to 18.33% THD at its full load and TDD value of 18.43% 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, fifth and seventh 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, multi-branch single-tuned filters were designed for the 5th and 7th harmonic current mitigation and the distortion levels were reduced from 18.33 % to 3.97 %. 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.

## 6.2.Recommendations

The solutions given for the mitigation of power quality problems discovered throughout the study should be implemented and installed by the industry, National Tobacco Enterprise, so as to avoid the loss of money, improve productivity, profitability and early failure of equipments. And on a certain interval of time a complete assessment of power quality problems should be done for the industry and compare with IEEE standards because there can be load changes in the industry which causes power quality problems.

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, we recommend for the industry to keep the power quality problems measuring instrument, Fluke 434/435 three phase Power Quality Analyzer, properly because this device provides great help for studying problems associated to power quality issues smoothly and easily.

### 6.3 Suggestions for Future Work

As we know harmonic have effects on different equipments, therefore, the impact of harmonics on the age of a transformer must be studied in detail in the future.

Tuned filters can cause undesirable system resonance and its effectiveness also change when loads change, other options like active filters, phase-shifting transformers and series reactors must be considered in future research.

# References

[1]. Sandeep Kumarn, Power Quality Issues and its Mitigation Techniques, 2011.

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

[3]. Dugan, Roger C., Mark McGranaghan, Surya Santoso, and H. Wayne Beaty, Electrical

Power Systems Quality, McGraw-Hill Inc., 2003.

[4]. SANDEEP KUMAR N, Power Quality Issues and its Mitigation Techniques, 2012.

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

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

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

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

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

[10]. Hussein Mohamed El-Eissawi Fathi, Power Quality Assessment, Journal of Al-Azhar University Cairo, Egypt , 2012.

[11]. Jeff McGuire, Monitoring of Distribution System Power Quality, October 1999.

[12]. Alexandre Nassif, Modeling, Measurement and Mitigation of Power System Harmonics, University of Alberta, Edmonton, Alberta, Fall 2009.

[13]. Muhammad Yasir, A Novel Approach for Assessing the Impact of Voltage Sag Events on Customer Operations, 2011.

[14]. Nexant SARI, Economic Impact of Poor Power Quality on Industry, Sri Lanka, 2003, Prepared for United States Agency for International Development (USAID) Under South Asia Regional Initiative for Energy (SARI/E).

[15]. M.K.Pradhan, Kamlesh Keharia, Rajesh Darapu, B. Mariappan, A case study of Power quality improvement and energy saving in textile industry using solid state harmonic filter, Fifteenth National Power Systems Conference (NPSC), IIT Bombay, December 2008.

[16]. Franz Alois Hemetsberger, An Investigation of Power Quality Problems in a Remote Mine Site, October 2003.

[17]. R.A. Adams, S.W. Middlekauff, E.H. Camm and J.A. McGee, "Solving Customer Power Quality Problems Due to Voltage Magnification", IEEE Transactions on Power Delivery, Vol. 13, No. 4, October 1998.

[18]. Pacific Gas and Electric Company, Voltage Unbalance and Motors, October 2009.

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

[20]. Pierluigi Caramia, Guido Carpinelli, Paola Verde, Power Quality Indices in Liberalized Markets, John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex,PO19 8SQ, United Kingdom, 2009.

[21]. 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.

[22]. P. Daehler and R. Affolter, "Requirements and Solutions for Dynamic Voltage Restorer, A Case Study", power engineering society winter meeting, IEEE, 2000.

[23]. M.M. Abdel Aziz, G. A. Abdel Salam and S. M. Kozman, "Cost and Mitigation of Voltage sag for Industrial Plants", electrical, electronic and computer engineering international conference. ICEEC 2004. IEEE, 2004.

[24]. Alexandre Nassif, “Modeling, Measurement and Mitigation of Power System Harmonics,” Ph.D. dissertation, University of Alberta, Fall 2009.

[25]. Kun-Ping Lin, Ming-Hoon Lin, and Tung-Ping Lin, “An Advanced Computer Code for Single-Tuned Harmonic Filter Design,” IEEE Transactions on Industrial Applications, vol. 34, no. 4, July/August 1998.

[26]. Mark McGranaghan and Bill Roettger, “Economic Evaluation of Power Quality”, IEEE power engineering review, Feb. 2002.

[27]. Messenger, R. A., & Ventre, J., Photovoltaic Systems Engineering, 3rdedition, Boca Raton, Florida, USA: CRC Press, 2010.

[28]. NASA Surface meteorology and Solar Energy – Available Tables, http://eosweb.larc.nasa.gov/cgi-bin/sse/grid.cgi

[29]. Baldsing, et. al., "Lead-Acid Batteries for Energy Storage", CSIRO Australia, January 1991.

[30]. Dunlop, Bower and Harrington, "Performance of Batter Charge Controllers: First Year Test Report", Proceedings of the 22ndIEEE Photovoltaic Specialists Conference, Las Vegas, Nevada, October 7-11, 1991.

[31]. Wade Byrd, Solar Electric System Basics, Performance Building Consulting, August 21, 2007.

[32]. Abd El-Shafy A. Nafeh, Design and Economic Analysis of a Stand-Alone PV System to Electrify a Remote Area in Egypt, The Open Renewable Energy Journal, 2009.

[33]. Ryan Mayfield, PV Circuit Sizing and Current Calculations, February/March 2012.

[34]. Agbetuyi A. F., Adewale A. A., Ogunluyi J. O., Ogunleyed D. S., Design and Construction of Automatic Transfer Switch, Covenant University, Ota, Nigeria,2011

# APPENDIX A

## EQUIPMENT OVERVIEW OF FLUKE 434/435 THREE PHASE POWER QUALITY ANALYZER

Figure A.1 Fluke 434/435 three phase Power Quality Analyzer.

Fluke 434/435 three phase Power Quality Analyzer detects power line abnormalities and analyzes power quality. The main features of the analyzer are the following

1. **Continuous Long-term monitoring and recording**: Power line anomalities often occur intermittently, so the y must be captured when an anomaly occurs, along with its type and intensity.
2. **Simultaneous measurement of multiple elements of power supply quality**: Multiple power supply quality parameters can be selected as desired for simultaneous measurement.
    - **a. high speed voltage quality parameter:** Transients (impulsive and oscillatory);
    - **b. RMS voltage quality parameters:** voltage swell (surge), voltage dip (sag), voltage interruption ;
    - **c. power quality parameters:** frequency, voltage, current, active power, apparent power, reactive power, power factor (displacement power facto r);

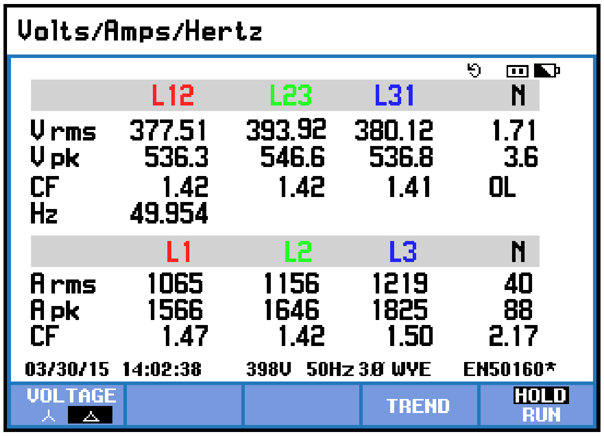
  d. **harmonic quality parameters:** harmonic voltage, current and power, harmonic current and voltage phase angle, total harmonic voltage and current distortion factors (THD-F, THD-R),
  e. **Other parameters:** K factor, flicker

3. **Data is presented in the formats Events Table, Trend Display, and Bar Graph Screen.**
   A. **Events Table:** The events table shows the events that occurred during the measurement with date/time of start, phase, and duration.
   B. **Trend Display**: The Trend screen shows the changes over time of measuring values.
   C. **Bar Graph Screen**: Bar Graphs showing the percentage of time each phase spent within limits for harmonics and Total Harmonic Distortion (THD).
4. **Four functional section Settings:** used to accesses menus to view and change Analyzer settings.
   I. **General Settings**: Date, Time, GPS time synchronization, wiring Configuration, nominal Voltage, nominal Frequency, current and voltage probe type, information language, survey and installation of options.
   II. **FUNCTION PREFERENCES**: adjustment of Offset and Span of Trend and Waveform displays, contents of harmonics Meter screen and harmonics settings, power settings, flicker D-parameter settings, Inrush defaults, and Transient settings.
   III. **USER PREFERENCES**: adjustment of Phase Identification and Colors, Printer and RS-232 settings, Auto shut-off, definition of User name, and display contrast. Many menus have a function key for reset to factory default settings.
   IV. **Limits Settings**: for save, recall, and definition of the limits for power quality monitoring.
5. **Save screens and data:** into the Analyzer’s memory and show how to view, rename and delete them and also explains how to setup the Analyzer for communication with a PC, laptop, and printer.
6. **Up to one month continuous measurement:** Data is saved to internal memory during the measurement period. Use of a PC card enables continuous measurement for one month at maximum.

# APPENDIX B

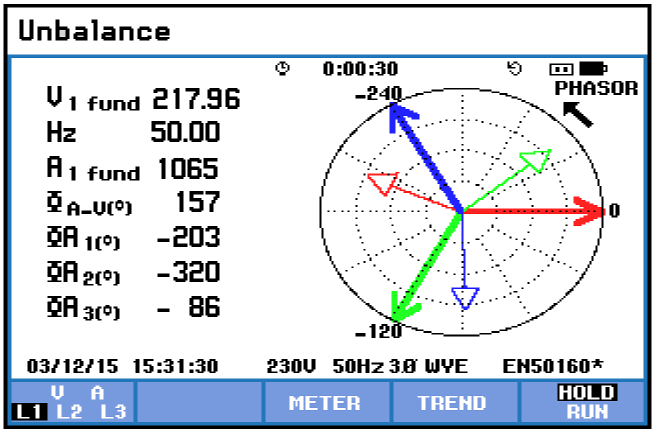
# SAMPLE FIELD MEASUREMENT DATA IN THE INDUSTRY

## Table B.1 Sample Measurement of Voltage Unbalance


Volts/Amps/Hertz

|  | L12 | L23 | L31 | N |
|---|---|---|---|---|
| Vrms | 377.51 | 393.92 | 380.12 | 1.71 |
| Vpk | 536.3 | 546.6 | 536.8 | 3.6 |
| CF | 1.42 | 1.42 | 1.41 | OL |
| Hz | 49.954 |  |  |  |
|  | L1 | L2 | L3 | N |
| Arms | 1065 | 1156 | 1219 | 40 |
| Apk | 1566 | 1646 | 1825 | 88 |
| CF | 1.47 | 1.42 | 1.50 | 2.17 |

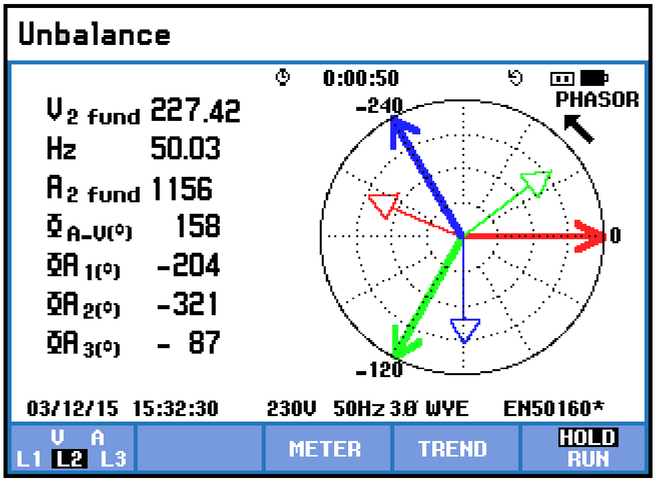
03/30/15 14:02:38 398V 50Hz 3Ø WYE EN50160*


Unbalance

0:00:30

$V_{1}$ fund 217.96
Hz 50.00
$A_{1}$ fund 1065
$\Phi_{A-V}$(°) 157
$\Phi A_{1}$(°) -203
$\Phi A_{2}$(°) -320
$\Phi A_{3}$(°) - 86

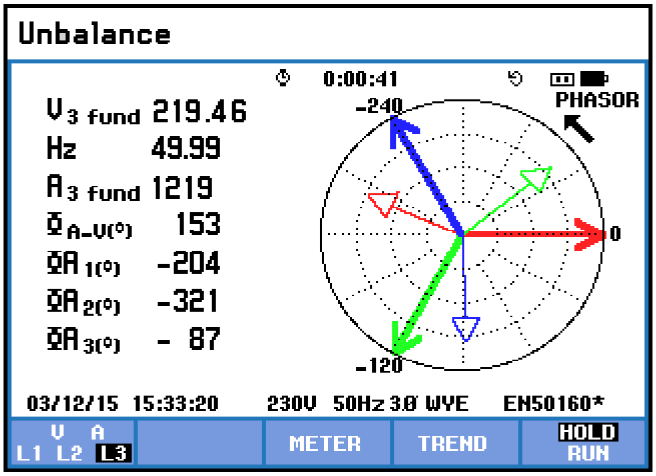
03/12/15 15:31:30 230V 50Hz 3Ø WYE EN50160*


Unbalance

0:00:50

$V_{2}$ fund 227.42
Hz 50.03
$A_{2}$ fund 1156
$\Phi_{A-V}$(°) 158
$\Phi A_{1}$(°) -204
$\Phi A_{2}$(°) -321
$\Phi A_{3}$(°) - 87

03/12/15 15:32:30 230V 50Hz 3Ø WYE EN50160*

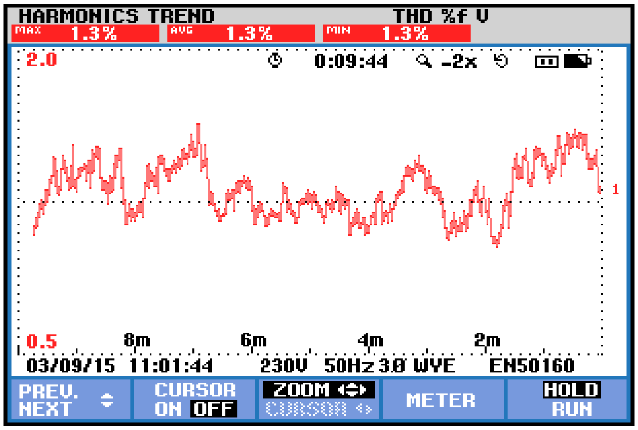

Unbalance

0:00:41

$V_{3}$ fund 219.46
Hz 49.99
$A_{3}$ fund 1219
$\Phi_{A-V}$(°) 153
$\Phi A_{1}$(°) -204
$\Phi A_{2}$(°) -321
$\Phi A_{3}$(°) - 87

03/12/15 15:33:20 230V 50Hz 3Ø WYE EN50160*

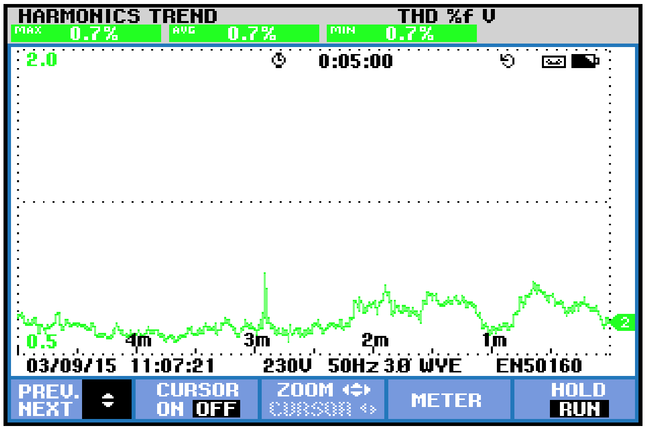
## Table B.2 Sample Measurement of Harmonics Trend and Current Measurement


HARMONICS TREND THD %f V

MAX 1.3% AVG 1.3% MIN 1.3%

0:09:44 -2x

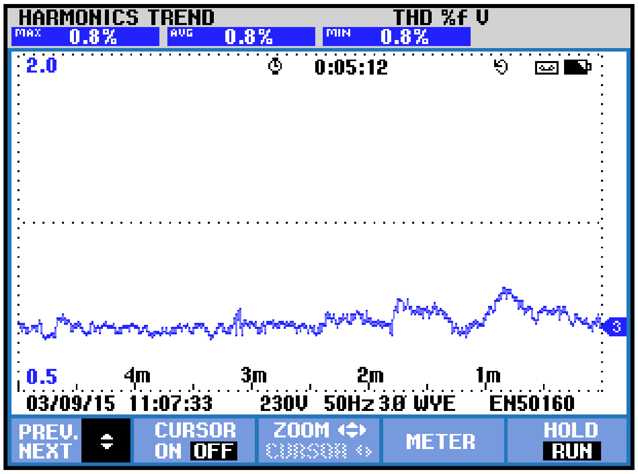
03/09/15 11:01:44 230V 50Hz 3Ø WYE EN50160

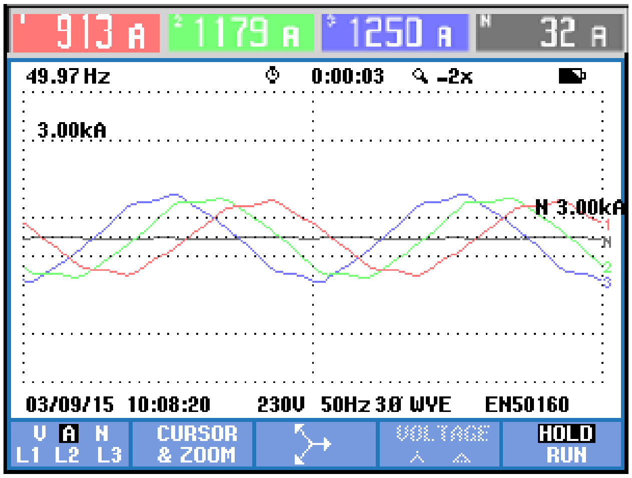

HARMONICS TREND THD %f V

MAX 0.7% AVG 0.7% MIN 0.7%

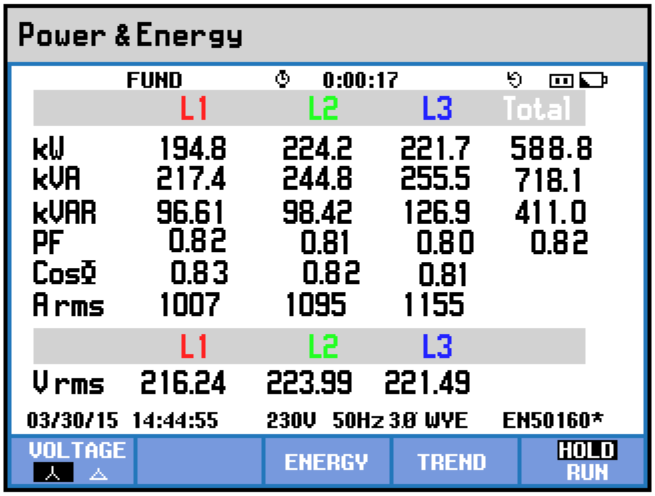
0:05:00

03/09/15 11:07:21 230V 50Hz 3Ø WYE EN50160





### Table B.3 Sample Measurement of Power and Power Factor

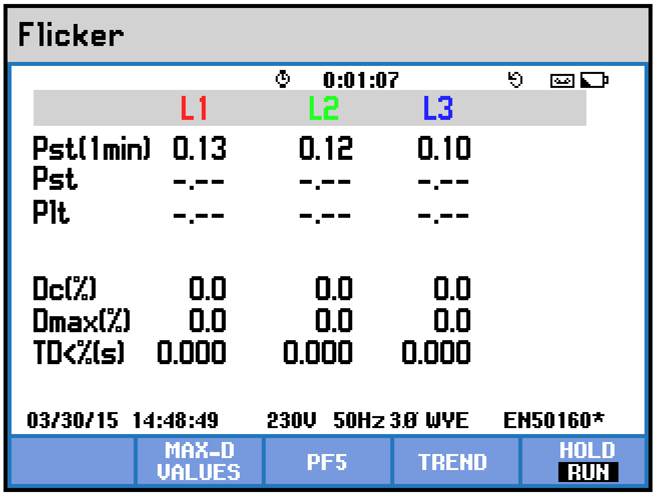


| | L1 | L2 | L3 | Total |
|---|---|---|---|---|
| kW | 194.8 | 224.2 | 221.7 | 588.8 |
| kVA | 217.4 | 244.8 | 255.5 | 718.1 |
| kVAR | 96.61 | 98.42 | 126.9 | 411.0 |
| PF | 0.82 | 0.81 | 0.80 | 0.82 |
| CosΦ | 0.83 | 0.82 | 0.81 | |
| A rms | 1007 | 1095 | 1155 | |

| | L1 | L2 | L3 |
|---|---|---|---|
| V rms | 216.24 | 223.99 | 221.49 |

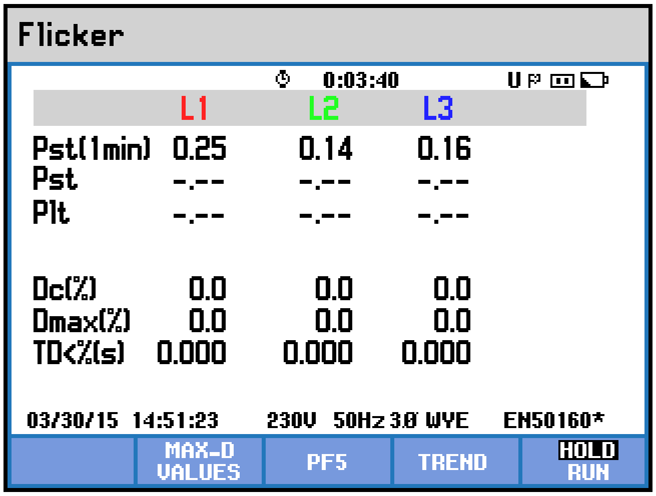
03/30/15 14:44:55 230V 50Hz 3Ø WYE EN50160*

### Table B.4 Sample Measurement of Flicker



| | L1 | L2 | L3 |
|---|---|---|---|
| Pst(1min) | 0.13 | 0.12 | 0.10 |
| Pst | -.-- | -.-- | -.-- |
| Plt | -.-- | -.-- | -.-- |
| Dc(%) | 0.0 | 0.0 | 0.0 |
| Dmax(%) | 0.0 | 0.0 | 0.0 |
| TD<%(s) | 0.000 | 0.000 | 0.000 |

03/30/15 14:48:49 230V 50Hz 3Ø WYE EN50160*



| | L1 | L2 | L3 |
|---|---|---|---|
| Pst(1min) | 0.25 | 0.14 | 0.16 |
| Pst | -.-- | -.-- | -.-- |
| Plt | -.-- | -.-- | -.-- |
| Dc(%) | 0.0 | 0.0 | 0.0 |
| Dmax(%) | 0.0 | 0.0 | 0.0 |
| TD<%(s) | 0.000 | 0.000 | 0.000 |

03/30/15 14:51:23 230V 50Hz 3Ø WYE EN50160*

# APPENDIX C

# DESIGN PROCEDURE FOR SINGLE-TUNED FILTER DESIGN

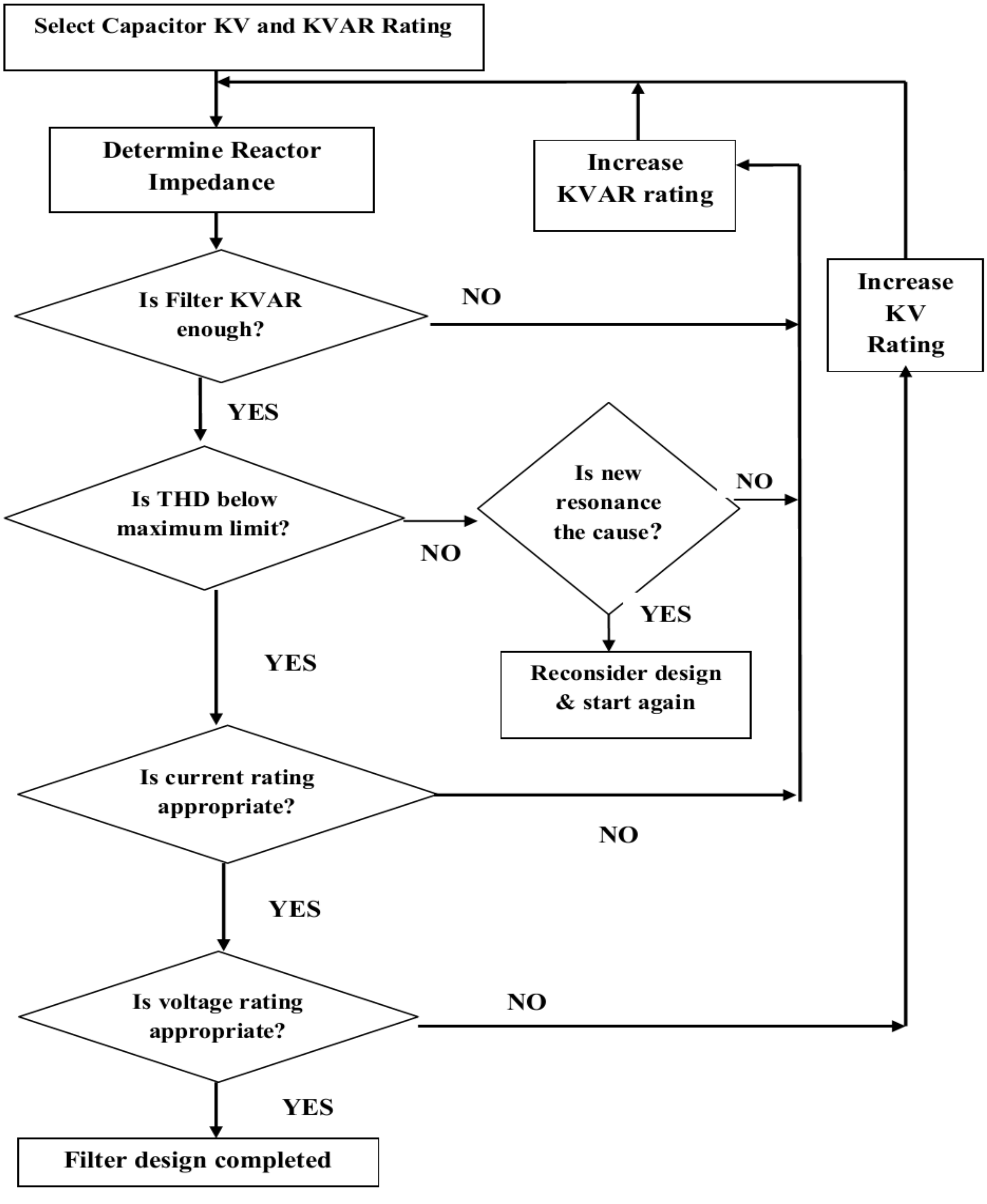


Figure C.1 Decision flow chart for single-tuned filter design [33]

## APPENDIX D

## LOAD TYPES AND SIZES DATA

Table D.1 Existing Load Data of NTE

| Loads | Watts/item | Hrs of operation/day | Energy Consumption Whrs/day |
|---|---|---|---|
| **1. Primary Room**<br>**A. Ground Floor** | | | |
| i. 18.798E machine | 140,130 | 8 | 1,121,040 |
| ii. COMAS machine | 7,400 | 16 | 118,400 |
| iii. Dickinson machine | 26,400 | 16 | 422,400 |
| iv. Schiff & Stern machine | 13,500 | 8 | 108,000 |
| v. Finttener machine | 19,100 | 8 | 152,800 |
| vi. Steam cutter machine | 22,000 | 8 | 176,000 |
| vii. Compressor | 17,400 | 24 | 417,600 |
| viii. Lighting | 4,160 | 24 | 99,840 |
| ix. Machines for steam line | 21,170 | 16 | 338,720 |
| x. Lifters (2) | 2,200 | 8 | 17,600 |
| xi. Steam moisturing machine | 9,600 | 16 | 153,600 |
| **Sub Total** | **283.060 W** | | **3,126,000Whrs/day** |
| **A. First Floor** | | | |
| I. Unicutter machine | 34,000 | 8 | 272,000 |
| II. 18.799 & 18.800 machine | 50,400 | 8 | 403,200 |
| III. KTF cutter machine | 15,500 | 8 | 124,000 |
| IV. Lighting | 2,400 | 24 | 57,600 |
| V. Compressor (2) | 15,000 | 24 | 360,000 |
| VI. TOFI separator | 3,500 | 8 | 28,000 |
| VII. Candle machine & Lighting | 19,610 | 12 | 235,320 |
| **Sub Total** | **140,410 W** | | **1,480,120Whrs/day** |
| **2. Secondary Room** | | | |
| i. Maker machine (2) | 136,000 | 16 | 2,176,000 |
| ii. Packer machine (2) | 36,000 | 12 | 432,000 |

| | | | |
|---|---|---|---|
| iii. Filter Machine | 52,250 | 16 | 836,000 |
| iv. Hard packer machine | 27,500 | 12 | 330,000 |
| v. Lighting | 20,068 | 24 | 481,632 |
| vi. Compressors (5) | 75,000 | 24 | 1,800,000 |
| vii. Suction machine | 79,200 | 16 | 1,267,200 |
| iii. COMAS machine | 4,900 | 16 | 78,400 |
| ix. GODIOLI & BELLANTTI | 5,680 | 8 | 45,440 |
| x. GISSILA machine & Lighting | 63,440 | 16 | 1,015,040 |
| **Sub Total** | **500,038 W** | | **8,461,712Whrs/day** |
| **3. Offices, Cafeteria, & Clinic** | **29,300 W** | 8 | **234,400 Whrs/day** |
| **4. Stores** | **5,000 W** | 8 | **40,000 Whrs/day** |
| **5. Garage including lighting** | **9,000 W** | 8 | **72,000 Whrs/day** |
| **6. Workshops including lighting** | **12,000 W** | 8 | **96,000 Whrs/day** |
| **7. Lifts** | **45,020 W** | 8 | **360,160 Whrs/day** |
| **8. Laboratory** | **8,000 W** | 8 | **64,000 Whrs/day** |
| **9. Boiler with lighting** | **30,540 W** | 12 | **366,480 Whrs/day** |
| **10. Total power for the remaining** | **20,000 W** | 8 | **160,000 Whrs/day** |
| **Total** | **1,082,368 W** | | **14,460,872Whrs/day** |

# APPENDIX E

# ELECTRICAL SIMUINK MODELSFOR SIMULATION

## E.1 Electrical Models for Oscillatory Transient

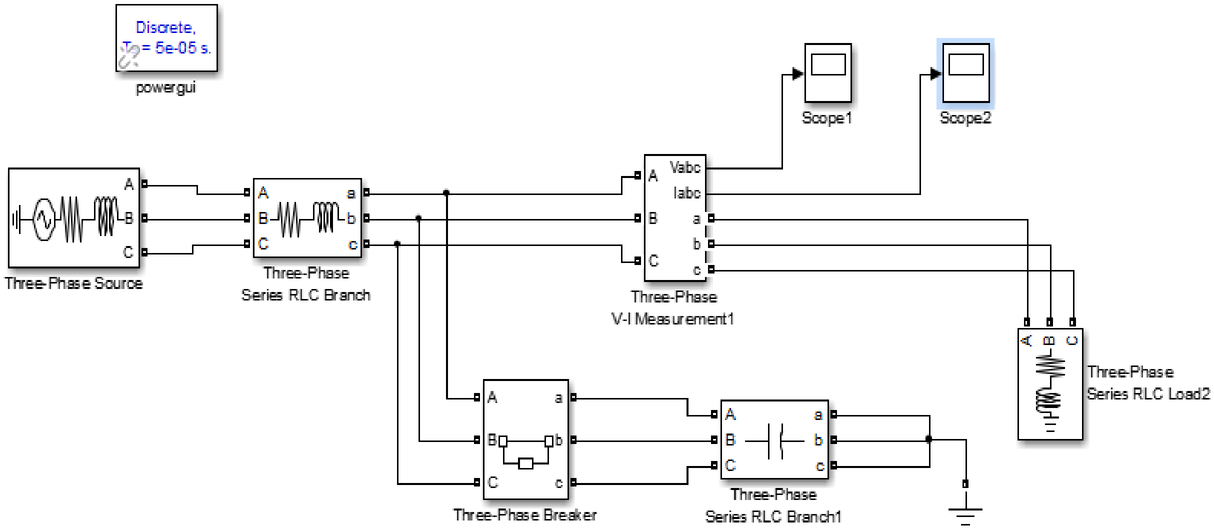


Figure E.1 Simulink model for oscillatory transient

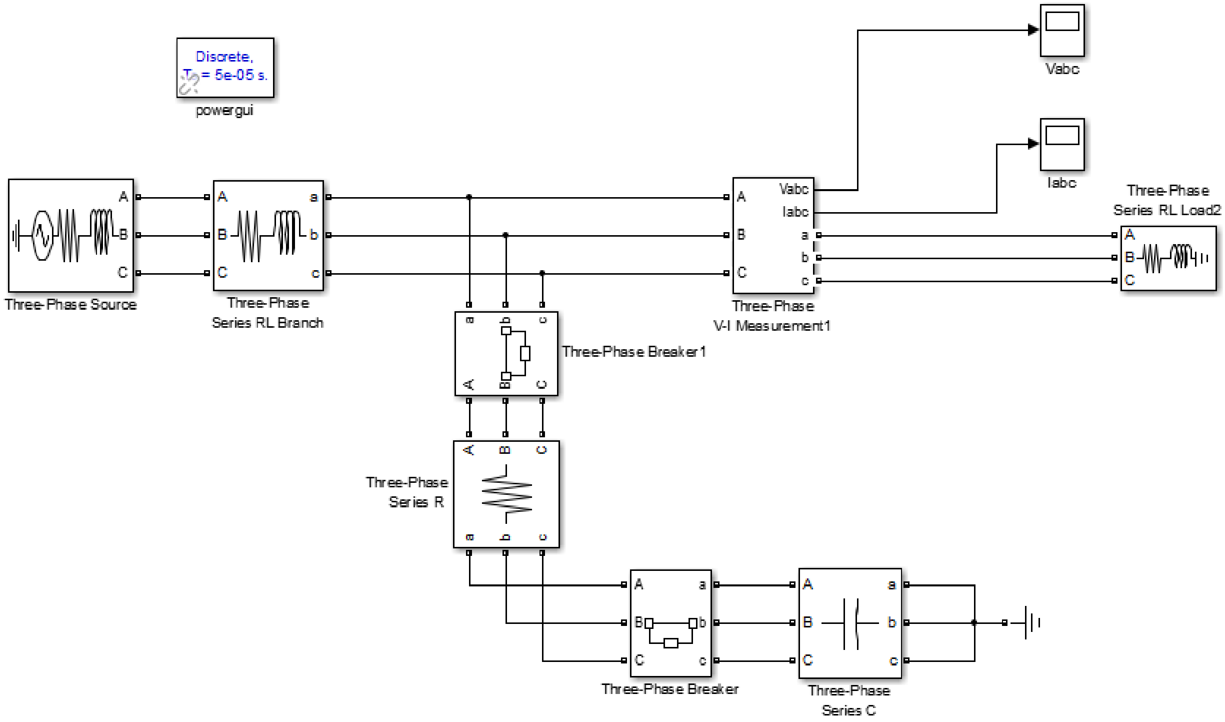


Figure E.2 Simulink model for oscillatory transient with pre-insertion resistor

## E.2 Electrical Models for Voltage Sag

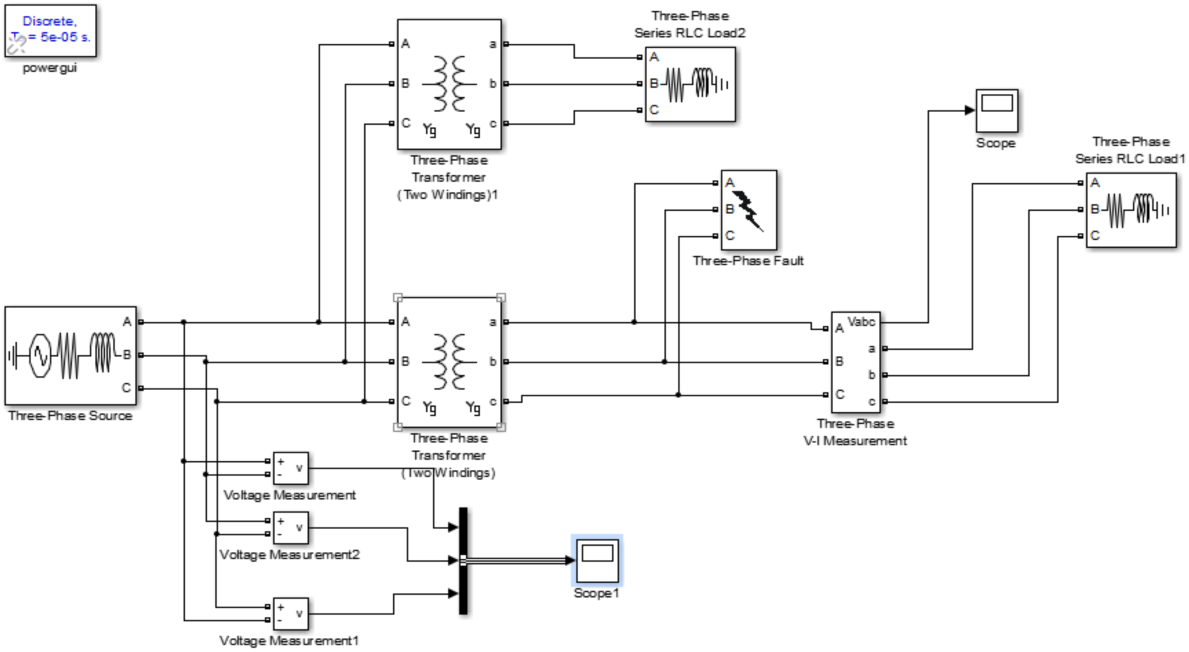


Figure E.3 Simulink model of voltage sag without DVR

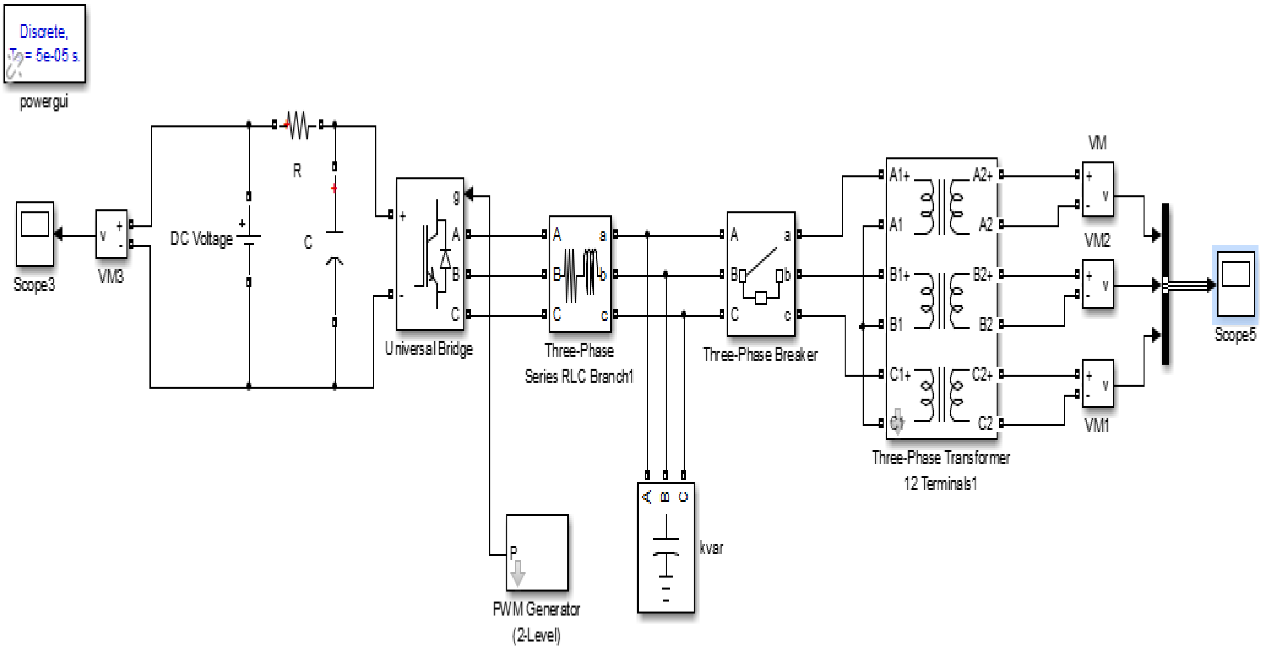


Figure E.4 Simulink model of DVR

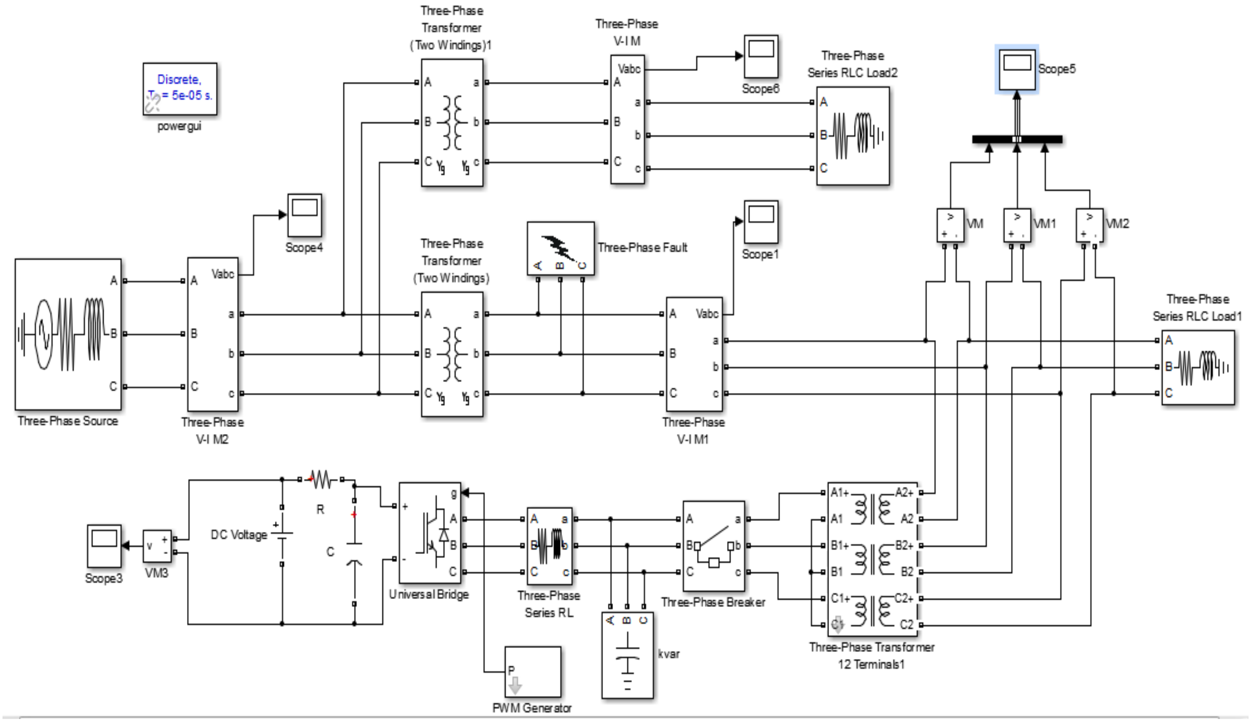


Figure E.5 Simulink model of voltage sag with DVR

## E.3 Electrical Models for Harmonic Distortion

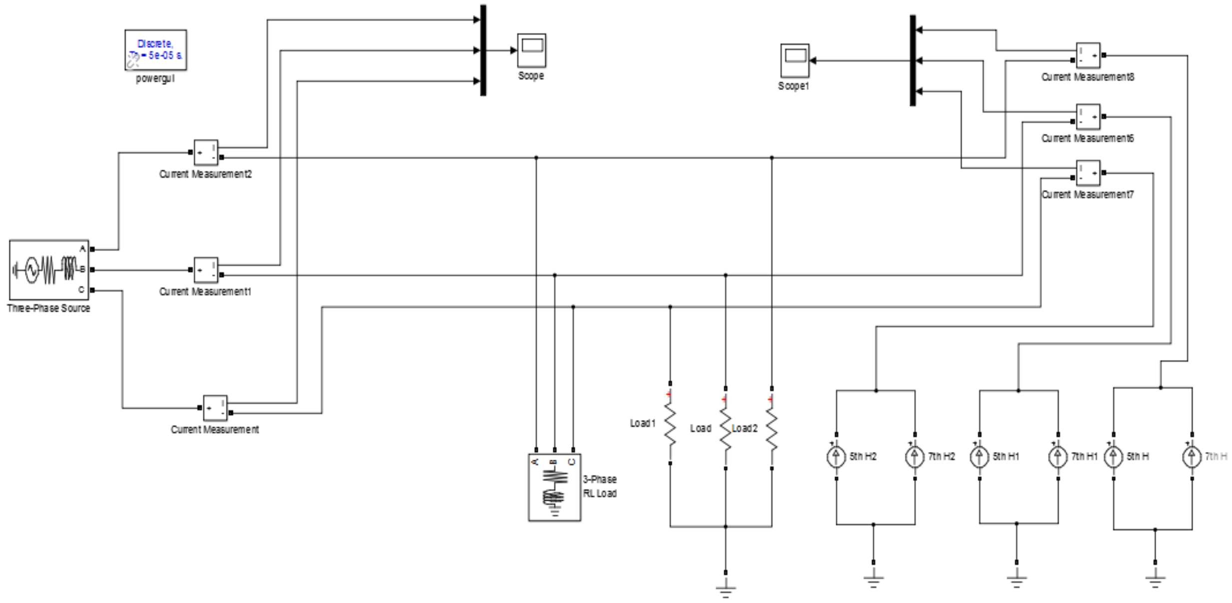


Figure E.6 Simulink model without filter

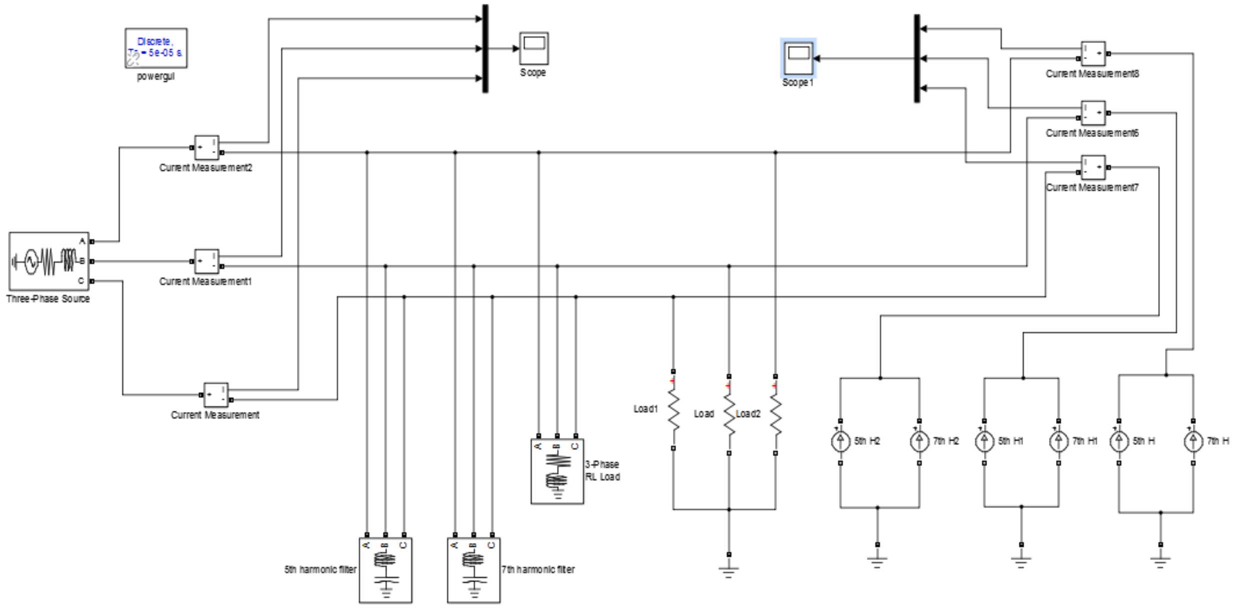


Figure E.7 Simulink model with filter