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DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

POWER QUALITY ASSESSMENT AT SELECTED INDUSTRIAL PLANTS IN ADDIS ABABA CITY

BY
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Declaration

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

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Date of submission: _________________

This thesis work has been submitted for examination with my approval as a university advisor.

Prof. Wolde-Ghiorgis, Woldemariam ________________________________

Advisor's Name Signature

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Abstract

This thesis presents a general-purpose power quality assessment at selected industries in the city of Addis Ababa. From the point of view of its academia purpose, the assessment investigates all the major transient and steady state electrical phenomena that disturb the power quality of a conventional power system. As such, the seven major categories of power quality phenomena listed by the IEEE Standard 1159-1995 are assessed in this thesis work.

The necessary data are collected from recorded data of the Ethiopian Electric Power Corporation and plants of study, from phenomena record of utility eqiupments, and through direct measurement using harmonic analyzer. The time schedule of data collection and measurements, as to meet the IEEE requirements, varies from a single power-period to 11- years depending on the power quality event to be studied. From the ground of the objective of the assessment, the monitoring locations on the other hand are chosen to be the service entrances of the corresponding industries.

The collected data are analyzed and the results are then compared with the IEEE requirements. In that case, voltage variations reaching 21% and frequency deviations of 1% to 4% are discovered. Current distortions of THD value that reach 33.5% are also discovered at Wubcon plc. Harmonic filters, that have an added feature of power factor correction, are therefore designed for Wubcon plc.

Software simulations are run using SimPowerSystems, Simulink to show the level of mitigation of the proposed solutions for capacitor-switching transients. The designed filters for Wubcon plc are also run on SimPowerSystems.

Key words: Power quality, Power quality phenomena, IEEE standards, Reliability indices, Benchmarking metrics.

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List of Abbreviations

A:	Amperes
ac:	Alternating current
ANSI:	American National Standards Institute
ASD:	Adjustable speed drive
C:	Capacitance
CBEMA:	Computer Business Equipment Manufacturers Association
CT:	Current transformer
DC:	Direct current
DG:	Distributed generation
DPQ:	Distribution Power Quality
EEPCo:	Ethiopian Electric Power Corporation
EMI:	Electromagnetic interference
EPRI:	Electric Power Research Institute
F:	Farad
H:	Henry
Hz:	Hertz; cycles per second
I:	Current
IEC:	International Electro technical Commission
IEEE:	Institute of Electrical and Electronics Engineers
ITIC:	Information Technology Industry Council
k:	Kilo
L:	Inductance
LC:	Inductor-capacitor
ms:	Millisecond
MOV:	Metal-oxide varistor
MW:	Mega watt
MVA:	Mega volt ampere
NEMA:	National Equipment Manufacturers Association
P:	Active power

PCC:	Point of common coupling
PF:	Power factor
PFC:	Power factor corrector
PQ:	Power quality
PT:	Potential transformer
pu:	Per unit
Q:	Reactive power
R:	Resistance
rms:	Root-mean-square (effective value)
SEMI:	Semiconductor Equipment and Materials International
SPD:	Surge-protective device
TDD:	Total demand distortion
THD:	Total harmonic distortion
TVSS:	Transient voltage surge suppressor
V:	Volts
var:	Volt ampere reactive
μ:	Micro, one millionth

CHAPTER ONE

INTRODUCTION

1.1 Background

Starting from the 1980s, electric utilities, academic and research centers, equipment manufacturers, and other end users of electric power are becoming increasingly concerned about the quality of electric power. This is due mainly to high sensitivity of newer-generation load equipment to power quality variations, the increasing application of harmonic-generating devices in power systems, increased awareness of end users about power quality issues, sever consequence of a single fault in interconnected power systems, and high emphasis on maximizing efficiency and system performance.

Whenever the issue of power quality is raised, the utility has the responsibility to produce good quality voltage sine waves; whereas, end-use customers have the responsibility to limit the harmonic currents their electric loads inject into the utility system. The utility 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 the context of Ethiopia, electric power interruption is becoming a day to day phenomenon. Even there are times that electric power interruption occurs several times a day, not only at the low voltage but also at the medium voltage distribution systems.

Even though end-users of electric power are utilizing harmonic-generating devices, there is no that much emphasis on harmonic-filters both at the utility side and the end-user side. However, harmonics are potentially dangerous in negatively affecting both the utility and end-users of electric power that they need a big concern to be given.

The drop of the voltage, especially at the residential loads, is causing early failure of equipments, blackening of light bulbs, and decreased efficiency and performance of high-power appliances. Damage of electronic devices and burning of light bulbs have also occurred due to over voltages.

1.2 Problem Statement and Motivation

When an electric utility supplies its customers with electric power, there should be binding regulations both on the utility side and the customer side. On the utility side, it should supply the customers with a certain minimum quality of power. On the customer side also, an end user of electric power is allowed to draw a certain permissible degree of distorted current. In that case, a lot of countries have developed standards and regulations for the attainment of the desired electric power quality.

In the case of Addis Ababa city and the country at large, electric power interruption is highly frequent that industrial plants, governmental and non-governmental organizations, business centers, commercial centers, residences and other electric power users are facing challenges for the achievement of their goals. And still there are no standards that state the minimum reliability of the electric power.

The next significant problem of the electric power supply is the very high voltage drop, especially at residential usage. It is highly decreasing the performance of electric stoves and heaters that end users of electric power are forced to wait for a long time to make stew, to bake bread, and to boil water. Moreover, the working life of light bulbs, in addition to giving less-bright lights, is getting shortened due to under voltages. This is because in certain equipments, undesirable effects such as carbonization get intense when the equipment operates below its rated voltage.

It is also a lot of times that light bulbs and electronic appliances get burned due to over voltages, which is a symptom of weak voltage regulation of the power system. Negligence of the effects of voltage and current distortions from both the utility side and end-user side is another motivating factor. Even though utilization of harmonic generating devices is increasing from day to day, no emphasis is given to the issue of harmonic distortions.

The loss of electric power at moderate to heavy rain, and following lightning strokes; the increasing number of distribution transformers with high oil leakage; hanging overhead lines and resulting short circuits are also some of the major observations that lead to questionable electric power quality of the utility.

1.3 Objectives

The research work is aimed at exploring the electrical power quality at selected industrial plants in and around Addis Ababa city, with the following general objective and specific objectives.

General Objective:

The general objective of this research work is to assess the quality of the electric power supplied to selected industrial plants, and to investigate the level of power quality disturbance of those industrial loads on the supplying power system.

Specific Objectives:

The specific objectives of this work are:

- to investigate the power quality disturbances that arise from both the customer side and the electric utility side, at selected industrial plants,
- to compare the level of those disturbances with tolerable values set by appropriate standards,
- to find out both the causes and undesirable impacts of the identified problems, and finally
- to propose solutions to the discovered power quality problems.

1.4 Literature Review

Power quality is defined in different ways depending on one's frame of reference— the utility, end user of electric power, or manufacturer of load equipment. A utility may define power quality simply as reliability. A manufacturer of load equipment, on the other hand, defines power quality as those characteristics of the power supply that enable the equipment to work properly. From the end users frame of reference, power quality problem is defined as any deviations in voltage, current, or frequency that results in failure or disoperation of customer equipment. IEEE Standard 1159 defines power quality as the concept of powering and grounding sensitive equipment in a manner that is suitable for the operation of that equipment [1].

A lot of works have been done on the issue of electric power quality in different parts of the world. 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. In the area of academia, the following are some of the works done on the issue of power quality.

Surajit Chattopadhyay et al [2] have presented a paper on area based approach for assessment of power quality parameters using analysis of fundamental and harmonic voltage and current waveforms. They have calculated the active power, reactive power, and total harmonic distortion factors using area-based approach.

M.A. El-Kady et al [7] have published their paper on composite reliability and quality assessment of interconnected power systems. They have presented a practical method for computing contingency based reliability and quality indices in power systems. They have also identified how much the balance among generation systems, transmission capabilities and consumer demands is maintained.

Shady A. El-Kashlan and Hussein El-Desouki Saied [14] published a paper on power quality assessment via coordinated voltage control in distributed power generation. On their paper, they presented the advantages of active approach in distribution network operation. Their study focused on a voltage quality problem and introduced the coordinated voltage control technique to increase the share of distribution generation in distribution networks and to supply the customers with the required power quality.

In the early 1990s, the Electric Power Research Institute (EPRI) initiated a project called the Distribution Power Quality (DPQ) Project, which resulted in power quality monitoring at 277 distribution sites statistically chosen throughout the United States to gain valuable knowledge regarding the frequency and severity of power quality events. C.J. Melhorn, A. Maitra et al [15] have made a distribution system power quality assessment. Their paper presents the findings of a follow-on project, referred to as DPQ II, which was conducted in 2001 and 2002. The project resulted in characterizing power quality in terms of short-duration variations such as voltage sags, voltage swells, and voltage interruptions.

Mário César Giacco Ramos and Carlos Márcio Vieira Tahan [17] have made an assessment of the impacts of electric power quality and electrical installation on medical electrical equipment operations at health care facilities. They have also demonstrated the effect of polluting-equipment current consumptions upon the sensitive equipments of medical centers.

Yao-Hung Chan et al [18] have undertaken a power quality assessment on specially connected transformers. Their paper examines and compares the voltage deviation, voltage unbalance, and harmonic distortion of V-V, Scott, and Le Blanc connected transformers by a novel approach.

Utilities have also entered into contractual agreements with end users with respect to power quality variations. In 1995 Detroit Edison entered into long-term pricing and service quality agreements with Chrysler Corporation (now DaimlerChrysler), Ford

Motor Company, and General Motors Corporation [1]. The terms were specified in an agreement known as the Special Manufacturing Contract (SMC). The service agreement covered voltage interruptions and voltage sags and established service guarantees with compensation.

1.5 Methodology

1.5.1 Data Collection and Measurements

The monitoring period is a direct function of the monitoring objective. Usually the monitoring period should capture a complete power period, an interval in which the power usage pattern begins to repeat itself [3]. An industrial plant, for example, may repeat its power usage pattern each day, or each shift depending on the largeness of the plant and the time-pattern of operation of its machines.

The total task of data collection is accomplished through direct measurement, from recorded data and equipment/ wiring specifications, and by asking the personnel who works on the specific area of concern. As the electrical events characterizing power quality are different, different mechanisms and time-schedules of data collection are utilized for those events.

As a result, to characterize power quality disturbances associated with randomly occurring natural phenomena, data of a long time-period (several months and years) are utilized. However, to characterize events which are associated with operation of industrial equipments, data are taken during a complete power-period of the industry as per the requirement of IEEE Std. 1159-1995. Moreover, measurements are also taken while the specific industry is working at full load, to see the cumulative characteristics of the industrial loads.

For the analysis and characterization of fault occurrences, interruptions and power frequency variations, the necessary data are taken from recorded data of the substation and industrial plants, readings on some equipments and by asking the technician who directly attends and monitors the system of concern.

For the cases of under/over voltages, voltage unbalances, fluctuations and waveform distortion, measurements are taken while all loads of the plant are working, so that the cumulative effects of equipments of the industrial plant can be measured. The measurements are taken from the transformer secondary chosen as the monitoring locations at which the task of power quality evaluation is performed.

As per the general objective of the research, the monitoring locations are chosen to be the service entrance points of each industry. In that case, power quality measurements are taken from the secondary of service transformers of industries. The points of common coupling are the tapping points on the 15 kV feeders to each 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.

1.5.2 Equipments Utilized

Instruments used to monitor electrical and electromagnetic phenomena can be as simple as an analog voltmeter to an instrument as sophisticated as a spectrum analyzer [3]. Selecting and using the correct type of monitor requires the user to understand the capabilities and limitations of the instrument, its responses to power system variations, and the specific objectives of the analysis.

A "MICROVIP3 PLUS" portable energy and harmonics analyzer is utilized for measurement. The device can measure average 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 [13].

The MICROVIP3 PLUS gives a reading of the desired variables in their waveforms or in numbers which is helpful for better characterization, quantization, understanding and visualization of the power quality phenomena.

However, it cannot measure interharmonics, phase angles of harmonic contents, high frequency harmonics (greater than 24th harmonic), and wide band noises. It is also a limitation that, it records and/or gives print out data of 80 ms (4-cycles) duration every three seconds at its best settings. Moreover, the equipment cannot be utilized for measurement at the 15 kV side of the transformer as the maximum measurable voltage limit of the equipment is 600 V. Below is an image of the MICROVIP3 PLUS measuring equipment along with its current transformers.

Figure 1.1 MICROVIP3 PLUS measuring equipment.

Event indicators are the other equipments utilized for data collection on under voltage, power frequency variation, transient and interruption. Event indicators collect power system variation data by comparing the steady-state condition of the power system with one or more threshold parameters [3]. These parameters may be preset or user adjustable. In the event that the threshold(s) are exceeded, a power system variation is detected and recorded. These threshold parameters dictate the types and number of power system variations that are detected by this type of monitor.

For simulation of the major power quality phenomena and to show the level of mitigation of the proposed solutions, the SimPowerSystems, Simulink software is utilized. The software is designed for modeling and analyzing power systems, so that models of power system parameters (elements) are available in its library. It is chosen over other alternative softwares for the purposes of its versatility, simplicity and ease of access.

1.6 Selected Industries

Industries are selected from a limited number of alternatives at which the power quality measurement is achievable while the EEPCo takes its own measurements. In that way from the alternatives, some are selected on the criteria of their power level, and significance of one or more power quality problems. The selected industries of power quality assessment are listed as follows.

1. St. George Brewery: A beer factory of 3.5 MVA capacity located in Western district of Addis Ababa.
2. National Tobacco Enterprise: A tobacco factory of 1.26 MVA capacity located in Western district of Addis Ababa.
3. Wubcon plc: A textile factory of 515 kVA capacity located in Southern district of Addis Ababa.
4. Mohan plc: A plastic factory of 430 kVA capacity located in Southern district of Addis Ababa.
5. Sun Optics plc: A glass factory of 200 kVA capacity located in Southern district of Addis Ababa.
6. Novastar Garment Factory: A garment factory of 315 kVA capacity located in Southern district of Addis Ababa.
7. Alek Terrazzo Factory: A terrazzo factory of 515 kVA capacity located in Southern Addis Ababa district.

1.7 Terms and Definitions

It is a necessary step to compile a list of power quality related terms and definitions to ensure that contributing parties would at least speak the same language and to provide instrument manufacturers with a common base for identifying the intended power quality phenomena [3].

This paper uses the terms and definitions of the Institute of Electrical and Electronics Engineers (IEEE) to describe the electrical phenomena of a power system related to the issue of power quality. In that case, the time specifications that a certain event stays are also taken from IEEE standards. In case other standards are found to be necessary for event characterization, they are explicitly specified. The IEEE definitions of the useful power quality terms are included in appendix-A of this paper.

The IEEE standards and definitions are chosen in this thesis work for their widely usage in academic and research areas, and their high-level of completeness to characterize all the major electrical phenomena comprising power quality.

1.8 Applicability of the Research

The result of this research is applicable to both the Ethiopian Electric Power Corporation (EEPCo) and the selected industrial plants of study.

At the EEPCo side, application of this research work increases reliability of its electric power supply. The high level of voltage drop and power loss on the transmission and distribution system will also be decreased. Moreover, early failure and frequent damage of utility equipments will be mitigated when the research is applied by EEPCo.

For the industrial plants, application of this research primarily aids them to save the extra money they are charged for the reactive power they consume. It also aids them to protect their equipments from transients that arise from capacitor switching, and to increase efficiency, performance and useful lives of their equipments.

1.9 Organization of the Thesis

This report paper is organized into six chapters- Introduction, Power Quality Assessment Procedure, Power Quality Phenomena, Power Quality Measurement and Benchmarking, Solutions and Simulation Results, and finally Conclusion and Recommendation.

The first chapter discusses the introduction part in which the background, motivation, objective, literature review, methodology, selected industries, terms and definitions, and applicability of the research are included.

The power quality assessment procedure comprises the second chapter of this report. In this chapter, the power quality evaluation procedure, including the major steps of the assessment are discussed.

The third chapter discusses the power quality phenomena that are categorized into seven sub-categories as per IEEE standard 1159-1995. The causes and undesirable impacts of the problems are also described.

The fourth chapter outlines the power quality measurement and benchmarking. In this chapter, the measurement results are described along with the benchmarking metrics.

Solutions and simulation results are put in the fifth chapter of this report. Proposed solutions to the major investigated power quality problems and the appropriate software simulations are talked about in the fifth chapter

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

CHAPTER TWO

PROCEDURE OF POWER QUALITY ASSESSMENT

The power quality phenomena encompass a wide range of electrical phenomena having a variety of causes, electrical characteristics, and degrees of negative impacts on the utility system and/or end-user equipments. The objective of the assessment also varies from a simple investigation of a certain power quality phenomenon to an inclusive general-purpose power quality assessment. There can therefore be different procedures of power quality evaluation depending on one's scope of study and objectives of power quality assessment.

From the stand point of a general purpose power quality assessment, all the major potential disturbances associated with a conventional power system are investigated in this research. The investigation emphasizes only on the existing power quality phenomena. On the grounds of the above mentioned objectives and scopes of study, the power quality evaluation procedure followed in this research includes the following major steps.

2.1 Identification of Power Quality Phenomena

Identification of the power quality phenomena is the first and basic step in the task of power quality assessment, since the consequent tasks are scheduled depending on the nature, causes and characteristics of the power quality events in hand. The IEC classifies electromagnetic phenomena into several groups as shown in Table 2.1 below [3]. The IEC standard addresses the conducted electrical parameters shown in Table 2.1. The terms high-frequency and low-frequency are not defined in terms of a specific frequency range, but instead are intended to indicate the relative difference in principal frequency content of the phenomena listed in these categories.

Table 2.1 Principal phenomena causing electromagnetic disturbances as classified by the IEC

Conducted low-frequency phenomena	Harmonics, interharmonics
	Signal systems (power line carrier)
	Voltage fluctuations
	Voltage dips and interruptions
	Voltage imbalance
	Power frequency variations
	Induced low-frequency voltages
	DC in ac networks
Radiated low-frequency phenomena	Magnetic fields
	Electric fields
Conducted high-frequency phenomena	Induced continuous wave voltages or currents
	Unidirectional transients
	Oscillatory transients
Radiated high-frequency phenomena	Magnetic fields
	Electric fields
	Electromagnetic fields
	Continuous waves
	Transients
Electrostatic discharge phenomena	-
Nuclear electromagnetic pulse	-

However, the IEEE Standard 1159-1995, classifies the above electrical phenomena into seven major categories listed as hereunder.

1. Transient
2. Short duration voltage variation
3. Long duration voltage variation
4. Waveform distortion
5. Voltage unbalance

6. Frequency deviation
7. Voltage fluctuation

From the points of view of a conventional power system that needs a power quality study of only the conducted low frequency electrical phenomena, non-availability and/or expensiveness of the measuring equipments, and lesser significance of high frequency radiated electromagnetic phenomena, the power quality categories of the IEEE Standard 1159-1995 are adopted in this research work over the IEC classifications.

2.2 Characterizing the Power Quality Phenomena

At this step, electrical characteristics of the problems are discussed along with the system response at different conditions. The phenomena listed above can be described further by listing appropriate attributes. For steady-state phenomena, the following attributes can be used [3]:

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

For non-steady state phenomena, on the other hand, the following attributes are required for describing the power quality problem.

- Rate of rise,
- Amplitude,
- Duration,
- Spectrum,
- Frequency, and
- Rate of occurrence.

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

2.3 Scheduling Data Collection and Measurements

Schedules of data collection through measurements are also outlined here. Having understood the nature of causes of the power quality problems, from where and when to take measurements are decided at this step.

The monitoring period is a direct function of the monitoring objective. Usually the monitoring period should capture a complete power period, an interval in which the power usage pattern begins to repeat itself [3]. An industrial plant, for example, may repeat its power usage pattern each day, or each shift depending on the largeness of the plant and the time-pattern of operation of its machines.

The total task of data collection is accomplished through direct measurement, from recorded data and equipment/ wiring specifications, and by asking the personnel who works on the specific area of concern. As the electrical events characterizing power quality are different, different mechanisms and time-schedules of data collection are utilized for those events.

As a result, to characterize power quality disturbances associated with random phenomena, data of a long time-period (several months and years) are utilized. However, to characterize events which are associated with operation of industrial equipments, data are taken during a complete power-period of the industry as per the requirement of IEEE Std. 1159-1995. Moreover, measurements are also taken while all the machines of the industry are working, to see the cumulative characteristics of the industrial loads.

For the analysis and characterization of fault occurrences, interruptions and power frequency variations, the necessary data are taken from recorded data of the substation and industrial plants, readings on some equipments and by asking the technician who directly attends and monitors the system of concern.

For the cases of under/over voltages, voltage unbalances, fluctuations and waveform distortion, measurements are taken while all loads of the plant are working, so that the cumulative effects of equipments of the industrial plant can be measured.

For assessment of electric power quality supplied to industrial plants and power quality disturbances of the industries onto the electric power system, the monitoring locations are chosen to be the service entrance points of each industry. The points of common coupling are the tapping points on the 15 kV feeders to each 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 points of common couplings (PCC) are shown below in figure 2.1.

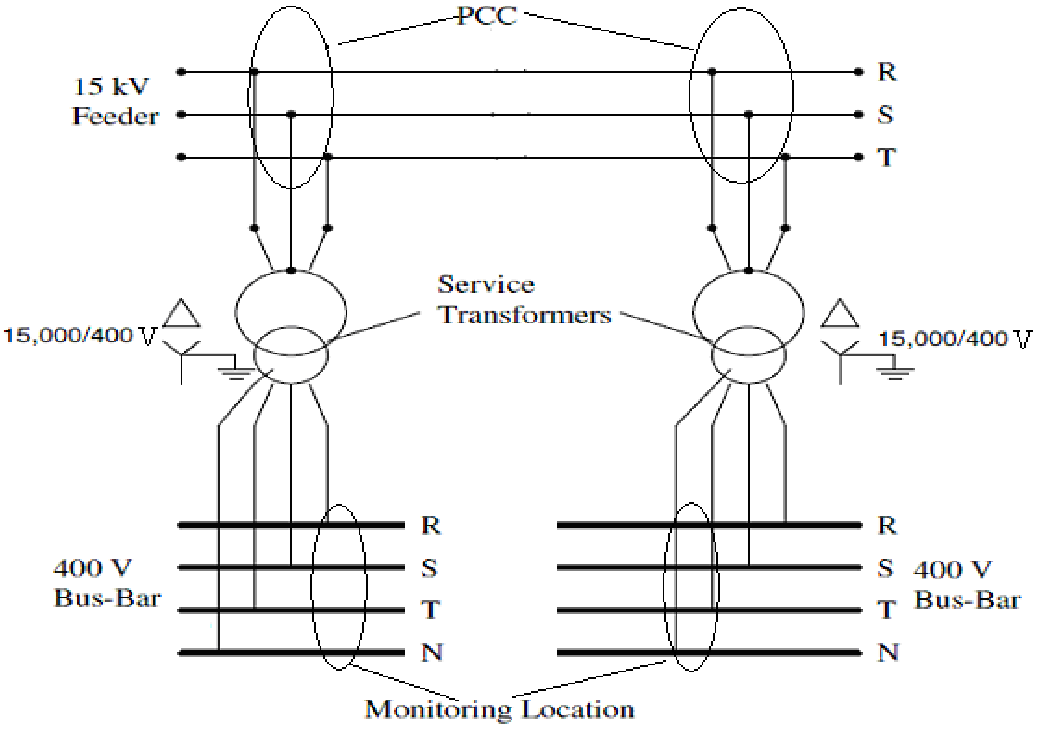

Figure 2.1 Monitoring location and point of common coupling (PCC).

2.4 Analyzing Data and Computing Benchmarking Metrics

Data obtained through measurements, from event indicators and from recorded sources are analyzed at this step. Having made the appropriate analysis, the benchmarking metrics are computed to compare with permissible values set by some standards as IEEE recommended practice for power quality monitoring, IEEE recommended practice for harmonic control, NEMA and ANSI.

As a result the equivalent TDD values are computed from the measured current THD values. This is because the measuring equipment gives the current distortion values in terms of THD values; whereas, the IEEE Std. 519-1992 gives the limits of current distortions in terms of TDD values. For discussing the interruption of electric power, the reliability indices are computed from the interruption records of feeders.

2.5 Power Quality Benchmarking

The computed metrics above are utilized to benchmark the result of the power quality assessment with a standard tolerable value. The benchmarking process is made with the CBEMA/ITIC curves for voltage variation, the harmonic voltage and current limits of IEEE Std. 519-1992, the design target values of electric power system reliability indices, the voltage fluctuation curves, and the derating curve for unbalanced operation.

2.6 Proposing Solutions

Once the cause and electrical characteristics of a certain power quality problem are identified, the solution of a certain power-quality-problem will be discovered to lie in one of the following ranges.

- Utility generation units
- Utility transmission system
- Utility distribution system
- End-use customer system

- Equipment design/ specifications

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. All technically feasible solutions cannot be recommended as solutions of a certain problem, rather the economic impact of the problem is considered as 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.

CHAPTER THREE

THE POWER QUALITY PHENOMENA

Power quality problems encompass a large number of electrical and electromagnetic phenomena. As a result, it is common to see different phenomena listed as elements of power quality problems, in different literatures. From the point of view of the electrical characteristics and durations of the power quality events that a conventional power system encounters, the following power quality phenomena are considered in this thesis, as categorized by IEEE Standard 519-1995.

1 Transient
    - Impulsive transient
    - Oscillatory transient
2 Short duration voltage variation
    - Interruption
    - Sag
    - Swell
3 Long duration voltage variation
    - Sustained interruption
    - Under voltage
    - Over voltage
4 Waveform Distortion
    - DC offset
    - Harmonics
    - Inter harmonics
    - Notching
    - Noise
5 Voltage unbalance
6 Voltage fluctuation
7 Frequency deviation

3.1 Transient

The term transient describes voltage and/or current variation in a power system that is undesirable and momentary in nature. The main sources of transients are lightning strokes, capacitor switching, energizing transformers, power electronic converters and other switching phenomena within end-user systems.

Transients caused by lightning strokes are often dangerous and result in a sever equipment damage unless proper protection systems are installed. However, capacitor switching usually results in non-dangerous transients. Switching of grounded-wye transformer banks may also result in unusual transient voltages in the local grounding system due to the current surge that accompanies the energization [1].

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

Surge arresters and transient voltage surge suppressors (TVSSs) are used to limit the transient over voltage. The elements that make up these devices can be classified by two different modes of operation, crowbar and clamping [1].

Crowbar devices are normally open devices that conduct current during overvoltage transients. Once the device conducts, the line voltage will drop to nearly zero due to the short circuit imposed across the line. On the other hand, clamping devices for ac circuits are commonly nonlinear resistors (varistors) that conduct very low amounts of current until an overvoltage occurs. Then they start to conduct heavily, and their impedance drops rapidly with increasing voltage.

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

I. Impulsive Transient

An impulsive transient is a sudden, unipolar and non-power frequency change in the steady-state condition of voltage and current. It is characterized by its amplitude, rise time and decay time, which can also be revealed by its spectral content. The spectral contents of impulsive transients are of mainly high frequency, due to its non-periodic nature of occurrence.

Because of the high frequency spectral contents, the shape of impulsive transients can be changed quickly by circuit components and may have significantly different characteristics when viewed from different parts of the power system. They are generally not conducted far from the source of where they enter the power system. Impulsive transients can excite the natural frequency of the power system circuits and produce oscillatory transients.

The most common cause of impulsive transients is lightning. An impulsive transient due to lightning strokes can occur because of a direct strike to a power line or from magnetic induction or capacitive coupling from strikes on adjacent lines [3]. The frequency and amplitude of lightning-induced transients vary geographically depending on the rainy nature of the area, vulnerability to lightning strokes and relative height of the system.

II. Oscillatory Transient

An oscillatory transient is a sudden, non-power frequency change in the steady state condition of voltage, current or both that includes both positive and negative polarity values. It is described by the frequency at which the oscillation takes place, the duration of the transient before it dies out, and its magnitude. The commonly occurring oscillatory transients are categorized into subclasses of high frequency, medium frequency and low frequency oscillatory transients. The frequency ranges for these classifications are chosen to coincide with common types of power system oscillatory transient phenomena [3].

a) High Frequency Transients

High frequency transients are oscillatory transients with a primary frequency component greater than 500 kHz and a typical duration measured in microseconds. These are often the result of a local system response to an impulsive transient. Power electronic devices also produce oscillatory voltage transients as a result of commutation and RLC snubber circuits. The transients can be in the high kilohertz range, last a few cycles of their fundamental frequency, and have repetition rates of several times per 50 Hz cycle (depending on the pulse number of the device) and magnitudes of 0.1 pu (less the 50 Hz component) [3].

b) Medium Frequency Transients

These are with a primary frequency component between 5 and 500 kHz with duration measured in tens of microseconds. Back-to-back capacitor energization results in oscillatory transient currents in the tens of kilo hertz. This phenomenon occurs when a capacitor bank is energized in close electrical proximity to a capacitor bank already in service. The energized bank sees the de-energized bank as a low impedance path (limited only by the inductance of the bus to which the banks are connected, typically small) [3]. Cable switching results in oscillatory voltage transients in the same frequency range. Medium frequency transients can also be the result of a system response to an impulsive transient.

c) Low Frequency Transients

Low frequency transients are transients with a primary frequency component less than 5 kHz and duration of from 0.3 to 50 ms. These are frequently encountered on utility sub transmission and distribution systems and are caused by many types of events. Capacitor bank energization results in an oscillatory voltage transient with a primary frequency between 300 and 900 Hz. The peak magnitude can reach 2.0 pu, but is typically 1.3 to 1.5 pu with a duration of between 0.5 and 3 cycles depending on the system damping.

Oscillatory transients with principal frequencies less than 300 Hz can also be found on the distribution system. These are generally associated with ferroresonance and transformer energization.

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.

3.2 Short-Duration Voltage Variation

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

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

I. Voltage Sag

Voltage sag is a decrease in rms voltage or current to between 0.1 and 0.9 pu at the power frequency for durations of 0.5 cycle to 1 minute. Under voltages that last less than one-half cycle cannot be characterized effectively by a change in the rms value of the fundamental frequency value [1]. Therefore, these events are considered transients rather than sags.

Voltage sags are usually associated with system faults. They are also caused by energization of heavy loads, or starting of large motors that draw very large amount of current at startup.

II. Voltage Swell

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

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

III. Interruption

A short duration interruption is said to occur when the supply voltage or load current decreases to less than 0.1 pu for a period of time not exceeding 1 minute.

Interruptions result from power system faults, equipment failures, and control malfunctions. The duration of an interruption due to a fault on the utility system is determined by the operating time of utility protective devices. Instantaneous reclosing generally will limit the interruption caused by a nonpermanent fault to less than 30 cycles. Delayed reclosing of the protective device may cause a momentary or temporary interruption. The duration of an interruption due to equipment malfunctions or loose connections can be irregular.

3.3 Long Duration Voltage Variation

Long duration voltage variations encompass root-mean-square (rms) deviations at power frequencies for longer than 1 minute. ANSI C84.1 specifies the steady state voltage tolerances expected on a power system [3]. A voltage variation is considered to be long duration when the ANSI limits are exceeded for greater than 1 minute.

The voltage variations, which may be either of short duration or long duration, are deviations of the voltage magnitude which last for more than half a cycle. Those deviations can be characterized using graphs of magnitude versus duration.

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

I. Under Voltage

An under voltage is a decrease in the rms ac voltage to less than 90% at the power frequency for a duration of longer than 1 minute. It is the result of switching events and due to overloading.

Utilities generally try to maintain the service voltage supplied to an end user within ±5 percent of nominal. Under emergency conditions, for short periods, ANSI Standard C84.1 permits the utilization voltage to be in the range of 6 to 13 percent of the nominal voltage. Some sensitive loads have more stringent voltage limits for proper operation and, of course, equipment generally operates more efficiently at near nominal voltage.

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 transmission line). Conversely, when the source voltage is boosted to overcome the impedance, there can be an over voltage condition when the load drops too low.

Undesirable effects of under voltage are mainly:

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

II. Over Voltage

An over voltage is an increase in the rms ac voltage greater than 110% at the power frequency for a duration longer than 1 minute. It is generally not a result of system faults, but is caused by load variations on the system and system switching operations, such as switching off a large load, energizing a capacitor bank, and incorrect tap settings on transformers.

Over voltages result because either the system is too weak for the desired voltage regulation or voltage controls are inadequate. The position of the transformer tap-changer can also be a cause of over voltage during light load conditions.

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

The range of solution lies in either of the utility transmission and/or distribution system or end-use customer system. Highly sensitive and expensive equipments of the end user may be provided with an over voltage protective device at the end use customer system. However, it is both economical and inclusive to provide a reliable voltage regulation system at the utility transmission and/or distribution system.

It is also the task of the utility to avoid over voltage conditions beyond some tolerable limits, so that the solution of that condition lies in the utility system.

III. Sustained Interruption

When the supply voltage drops to less than 10% of the nominal value for a period of time in excess of 1 minute, the long-duration variation is considered a sustained interruption. Interruptions can result from control malfunction, faults, or improper breaker tripping.

Interruptions have their own impacts in the economic and social activities of a society and the country at large. Different industries and factories, public institutions and the likes are forced to stop their jobs due to electric power interruptions. The country's attractions for foreign investors are also affected by the electric power reliability and the consequent cost for power usage.

3.4 Waveform Distortion

Waveform distortion is defined as any steady-state deviation of the voltage and/or current waveform from an ideal sine wave of the power frequency. The waveform distortion is principally characterized by its spectral contents which are investigated using a Fourier transform, expressed as [21]:

$$F(t) = F_0 + \sum_{n=1}^{\infty}(F_n \cos(\mathrm{n} * \omega\mathrm{o} + \phi\mathrm{n})) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.1)$$

Where, F(t) is the voltage/current waveform,

Fo is the dc-component,

Fn is the sinusoidal spectral content,

n is the harmonic number

ω_o is the fundamental angular frequency, and

ϕn is the phase shift of the spectral content.

The effect of the harmonic contents on the distortion of the sinusoidal waveform can be observed from the above equation, equation (3.1).

Usually, the voltage waveform has negligible harmonics that it can be assumed to be pure sinusoidal at the fundamental frequency. In that case, if the current drawn by the load has harmonics, the active power of the load is consumed only at the fundamental component of the load current. The remaining harmonics generate a reactive power.

There are five primary forms of waveform distortion of which one or more events occur in a distorted voltage or current waveform.

I. DC Offset

Dc offset is the dc voltage or current component of the spectral contents in an ac voltage or current. This occurs mainly as the result of a geomagnetic disturbance or asymmetry of electronic power converters, such as half-wave rectification. Mathematically, dc offset of a voltage or current waveform F(t) is expressed as follows [21]:

$$\text{DC Offset}= \frac{1}{T}\int_{0}^{T} F(t)dt \quad \text{...} \quad (3.2)$$

Where, T= period of the voltage/current waveform,

F(t)= voltage/current waveform as a function of time, t.

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

II. Harmonics

Harmonics are sinusoidal voltage or current components of the waveform. They have frequencies that are integer multiples of the fundamental frequency. They are mathematically given as follows [21]:

$$H_n = \frac{1}{T}\int_{O}^{T}\{F(t) * \cos(n * \omega_o * t + \phi_n)\}dt \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.3)$$

Where, H_n is the nth harmonic
T is period of the voltage/current waveform,
F(t) is voltage/current waveform as a function of time t,
n is the harmonic number
ω_o is the fundamental angular frequency
ϕn is the phase angle of the nth harmonic

Harmonics originate from the nonlinear characteristics of devices and loads that require currents other than a sinusoid on the power system. The most common of these loads are static power converters, although several other loads are also non-sinusoidal, such as the following [2]:

- Arc furnaces and other arc-discharge devices, such as fluorescent lamps
- Resistance welders (impedance of the joint between dissimilar metals is different for the flow of positive vs. negative current)
- Magnetic cores, such as transformer and rotating machines that require third harmonic current to excite the iron
- Synchronous machines (winding pitch produces fifth and seventh harmonics)
- Adjustable speed drives used in fans, blowers, pumps, and process drives
- Solid-state switches that modulate the current-to-control heating, light intensity, etc.
- Switched-mode power supplies, used in instrumentation, PCs, televisions, etc.
- Static var compensators
- Electronic phase controllers
- High-voltage dc transmission stations (rectifiers of ac to dc, and dc to ac invertors)
- Photovoltaic invertors converting dc to ac

Harmonic distortion levels are described by the complete harmonic spectrum with magnitudes and phase angles of each individual harmonic component. It is also common to use a single quantity, the total harmonic distortion (THD), as a measure of the effective value of harmonic distortion. Mathematically, THD values of voltage and current, THDV and THDI respectively, are given as follows [22].

$$\text{THDV}=\frac{\sqrt{V^2-V_1^{\,2}}}{V_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.4)}$$

Where, V is rms terminal-voltage,

V_1 is rms voltage at the fundamental frequency.

$$\text{THDI}=\frac{\sqrt{I^2-I_1^{\,2}}}{I_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.5)}$$

Where, I is rms load-current,

I_1 is rms current at the fundamental frequency.

Total Demand Distortion (TDD) is another commonly used harmonic index used to quantify current distortion. It is similar to the THD concept except that the distortion is expressed as a percentage of some rated or maximum load current magnitude, rather than as a percentage of the fundamental current. It is expressed as follows [22].

$$\text{TDD}=\frac{\sqrt{I^2-I_1^{\,2}}}{I_L} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.6)}$$

Where, I is rms load-current,

I_1 is rms current at the fundamental frequency,

I_L is the rated load-current.

The degree to which harmonics can be tolerated is determined by the susceptibility of the load or utility equipments to harmonics. The least susceptible type of equipment is that in which the main function is in heating, as in an oven or furnace [6]. In this case, the harmonic energy generally is utilized and hence is quite completely tolerable. The most susceptible type of equipment is that whose design or constitution assumes a (nearly) perfect sinusoidal fundamental input. This equipment is frequently in the categories of communication or data processing equipment. A type of load that normally falls between these two extremes of susceptibility is the motor load.

A major effect of harmonic voltages and currents in rotating machinery (induction and synchronous) is increased heating due to iron and copper losses at the harmonic frequencies [6]. The harmonic components thus affect the machine efficiency, and can also affect the torque developed.

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

On transformers, current harmonics cause an increase in copper losses and stray flux losses, and voltage harmonics cause an increase in iron losses. The overall effect is an increase in the transformer heating. The transformer losses caused by both harmonic voltages and harmonic currents are frequency dependent. The losses increase with increasing frequency and, therefore, higher frequency harmonic components can be more significant than lower frequency components in causing transformer heating. Current harmonics also result in increased audible noise of the transformer.

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

On the load itself, harmonics have the undesirable impact of decreasing the power factor as power factor is composed of two components. The first component is due to the phase shift between the sinusoidal input voltage and current at the power frequency induced by the inductive or capacitive nature of the load and is referred to as the displacement power factor (DPF). The second component is due to non-linear characteristics of the load and is referred to as the distortion factor. The load's power factor is therefore the product of its distortion factor and its displacement power factor given as follows [6].

$$P.F= \frac{1}{\sqrt{1+THD^2}}\cos(\phi) \quad \text{..} \quad (3.7)$$

Where, P.F. is the load's power factor,

Φ is the displacement angle between the fundamental current and voltage,

THD is the total current distortion of load current.

Increased neutral current in 3-phase wye-connected distribution networks is another undesirable effect of harmonics. In a 3-phase wye connected system, the neutral current is dominated by any dc-component and odd triplen harmonics which is expressed as [6]:

$$I_{n(rms)} = \sqrt{I_o^{\,2} + \sum_{k=3,9,12,...} \left(I_k^{\,2} \right)} \quad \text{..} \quad (3.8)$$

Where, $I_{n(rms)}$ is the rms current of the neutral wire,

I_o is the dc-component of the phase current,

I_k is the triplen harmonic.

III. Inter harmonics

These are voltage and/or current components having frequency that are not integer multiples of the fundamental frequency. They can appear as discrete frequencies or as a wideband spectrum.

Interharmonics are generally the result of frequency conversion activities. The main sources of interharmonics are static frequency converters, cycloconverters, induction furnaces, and arcing devices. Power line carrier signals can also be considered as interharmonics.

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

IV. Notching

Notching is a drop in voltage as close to zero as permitted by system impedance caused by a momentary short circuit between two phases, during current commutation in the normal operation of power electronic devices.

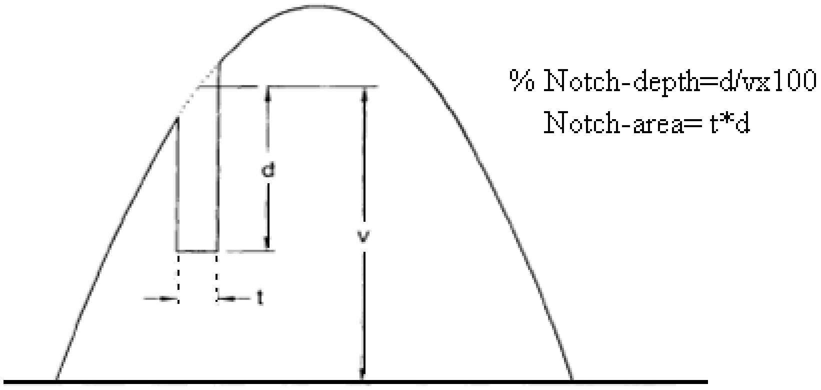

Figure 3.1 Definition of Notch-depth and Notch-area .

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

V. Noise

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

Noise in power systems can be caused by power electronic devices, control circuits, arcing equipment, loads with solid-state rectifiers, and switching power supplies.

Noise problems are often exacerbated by improper grounding that fails to conduct noise away from the power system. Basically, noise consists of any unwanted distortion of the power signal that cannot be classified as harmonic distortion or transients.

Noise disturbs electronic devices such as microcomputer and programmable controllers. The problem can be mitigated by using filters, isolation transformers, and line conditioners.

3.5 Voltage Unbalance

Voltage unbalance, also called voltage imbalance is non-equalization of the three phase voltages. It is defined by the National Electrical Manufacturers Association (NEMA) as 100 times the absolute value of the maximum deviation of the line voltage from the average voltage on a three-phase system, divided by the average voltage [11]. Unbalance is more rigorously defined in some standards using symmetrical components as the ratio of either the negative or zero sequence component to the positive-sequence component. The most recent standards specify that the negative-sequence method be used. It is recommended that the voltage unbalances at the motor terminals not exceed 1%.

Common causes of voltage unbalance include:
- Unevenly distributed single-phase loads on the same power system.
- Unidentified single-phase to ground faults.
- An open circuit on the distribution system primary.

- Unbalanced or unstable utility supply.
- Faulty operation of power factor correction equipment.
- Unbalanced transformer bank supplying a three-phase load that is too large for the bank.

Voltage unbalance degrades the performance and shortens the life of a three-phase motor [11]. Voltage unbalance at the motor stator terminals causes phase current unbalance far out of proportion to the voltage unbalance. Unbalanced currents lead to torque pulsations, increased vibrations and mechanical stresses, increased losses, and motor overheating, which results in a shorter winding insulation life.

Unbalanced voltage inputs decrease the efficiency of a motor that it results in wastage of energy and in turn money. A motor will run hotter when operating on a power supply with voltage unbalance. The additional temperature rise is calculated with the following equation [11]:

$$\text{Percent additional temperature rise} = 2 \times (\%\ \text{voltage unbalance})^2 \quad \text{………….……… (3.9)}$$

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

3.6 Voltage Fluctuation

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

Higher power loads that draw current which bears continuous and rapid variations in its magnitude can cause voltage fluctuations.

The term flicker is derived from the impact of the voltage fluctuation on lamps such that they are perceived by the human eye to flicker. Although voltage fluctuation and flicker are often used interchangeably, strictly speaking, voltage fluctuation is an electromagnetic phenomenon while flicker is an undesirable result of the voltage on the humans' sense of seeing.

One of the most common causes of voltage fluctuations on utility transmission and distribution systems is an arc furnace. On the other hand, during Ferro resonance the voltage magnitude may fluctuate wildly. End users at the secondary circuit may actually see their light bulbs flicker. Some electronic appliances may be very susceptible to such voltage excursions. Prolonged exposure can shorten the expected life of the equipment or may cause immediate failure.

Voltage flicker is measured with respect to the sensitivity of the human eye [1]. Typically, magnitudes as low as 0.5 percent can result in perceptible lamp flicker if the frequencies are in the range of 6 to 8 Hz.

The simplest and generally most effective technique for compensating for existing or potential flicker is to provide a sufficiently stiff source of power so that the effect is negligible at the point where the flicker source is tapped off from the rest of the power distribution system. Compensatory methods are also used to emulate the stiff source. Series capacitors, thyristor switching of inductors with shunt capacitors (static var control), saturating shunt inductors, and thyristor switched shunt capacitors may be used to maintain a relatively steady voltage at the tie point [6].

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

3.7 Power Frequency Variation

Power frequency variations are deviations of the power system fundamental frequency from it specified nominal value.

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

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

On modern interconnected power systems, significant frequency variations are rare. Frequency variations of consequence are much more likely to occur for loads that are supplied by a generator isolated from the utility system. In such cases, governor response to abrupt load changes may not be adequate to regulate within the narrow bandwidth required by frequency-sensitive equipment.

CHAPTER FOUR

POWER QUALITY MEASUREMENT AND BENCHMARKING

4.1 Transient

The main sources of transients are lightning strokes and switching events at utilities and/or end-use customers. Lightning protection systems are installed at Addis Center substation, the 132 kV incoming overhead line, and distribution transformers. At the Substation, 120 kV, 10 kA surge arresters are also installed at each phase of the primary side of the transformers to absorb the transient over voltages which may enter the power line past the lightning protection systems.

Three surges that exceed 120 kV with respect to ground (157.5% of nominal voltage) are recorded to occur at the substation since February 18, 2000 for the last 11 years. This gives the failure rate of the lightning protection system at Addis center substation to be 0.2727 per year. The significance of this figure of failure rate depends on the level of protection desired to save expensive equipments from lightning strokes. There is therefore no single maximum value of failure rate not to be exceeded, set by standards. The installation of surge arresters in addition to the lightning protection system has protected the system well from lightning strokes that no damage has occurred in the substation for the last 11-years.

However, neither harmonic filters nor power factor correctors are installed at Addis Center Substation and all the selected industries of study except St. George Brewery and National Tobacco Enterprise. At St. George Brewery and National Tobacco Enterprise, the power factor correctors are subdivided into 12-smaller units, so that the capacitor switching is less vulnerable to dangerous transients. As a result, significant oscillatory transients are not discovered by the measurements. Figure 4.1 shown below shows the small transient found in St. George Brewery. As can be observed from the voltage waveform in the figure, a transient over voltage has occurred at the 53rd msec of the waveform shown. The occurrence of the transient at a point other than the peak of the voltage waveform helps the equipment breakdown voltage not to be exceeded. Regarding the rms value of the voltage, the short duration of the transient does not significantly change the rms voltage of the system.

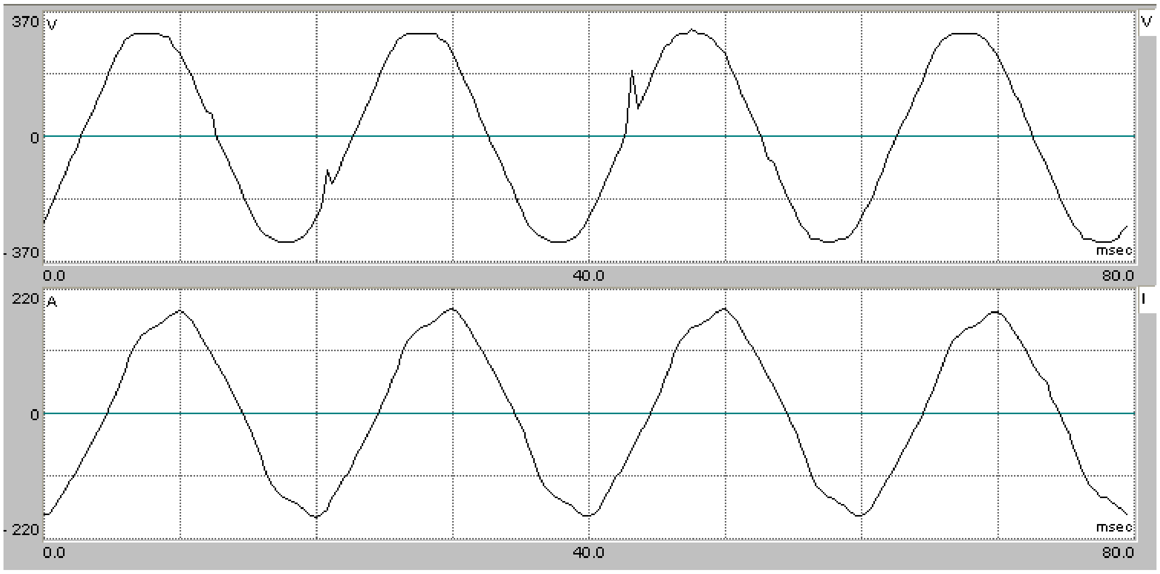

Figure 4.1 Switching transient at St. George Brewery.

4.2 Voltage Variation

The voltage variations, which may be either of short duration or long duration, are deviations of the voltage magnitude which last for more than half a cycle. Those deviations can be benchmarked using graphs of magnitude versus duration such as the CBEMA, ITIC, SEMI and equipment-specific curves. The graphs are suitable as they can benchmark both short duration and long duration voltage variations. In that case, both short duration and long duration variations are discussed here in parallel. The ITIC (CBEMA) curve is shown below in Figure 4. 2.

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

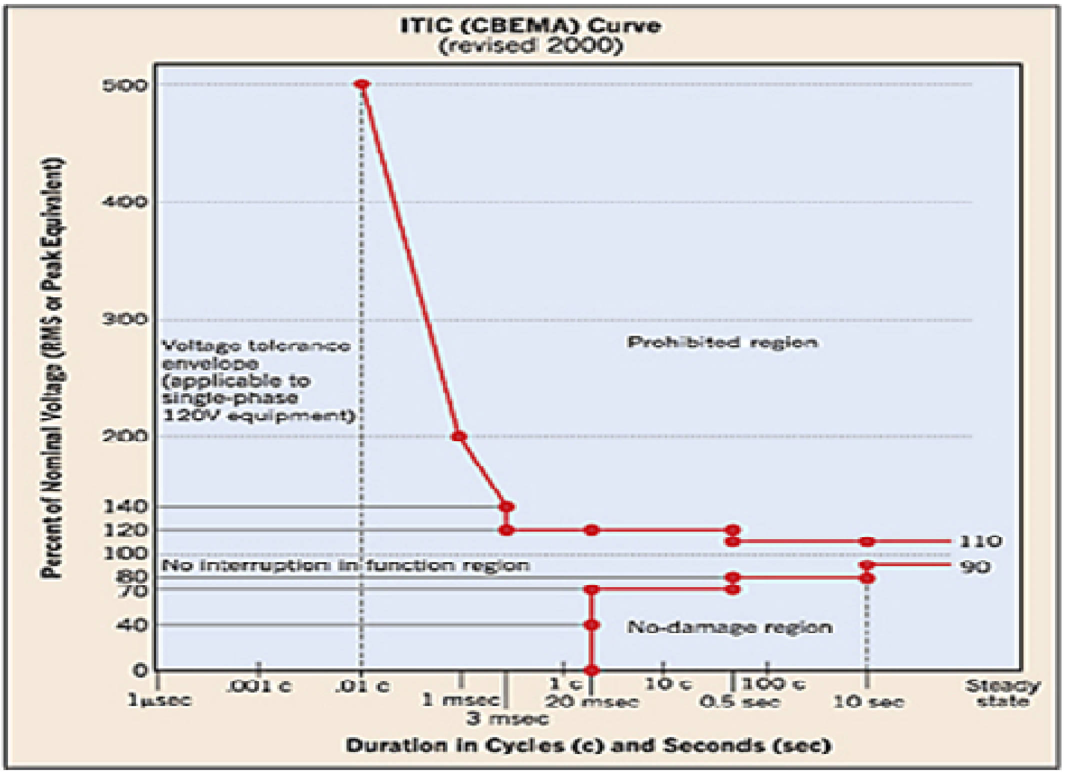

Figure 4.2 The ITIC (CBEMA) curve [6].

At Addis Center Substation, over voltages that reach 150 kV (113.64%) are recorded at the 120kV side of the transformer, on 25th August 2010. As per IEEE C57.12.00-1987 recommended practice, this condition (13.64% over voltage) is much beyond the tolerable value which is 5% at rated load. The breaker was therefore turned off to isolate the system from that faulty condition from 2:24 pm to 4:10 pm. However, at normal operation typical voltage profile of the 132 kV line is as shown below.

Table 4.1 Typical voltage profile of the 132 kV line at Addis Center Substation.

Hour (AM)	1	2	3	4	5	6	7	8	9	10	11	12
P (MW)	22	20	19	18	20	25	30	37	45	50	49	45
Q (MVAR)	10	9	8	8	8	9	10	14	18	22	22	22
System Voltage (kV)	132	133	133	132	132	132	131	130	127	130	130	130

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

Below are the maximum voltage variations, that are both short duration and long duration depending on the speed of fault clearance, recorded at the selected industries of study put in tabular form. The nominal voltage is 400 V for line voltage and 230 V for phase voltage as per the voltage specification of the transformer at each industry.

Table 4.2 Maximum phase-voltage variations at industrial plants of study.

S/N	Industry	Minimum Phase Voltage (V) Recorded .	Maximum deviation in percent of nominal
1	St. George Brewery	200	13.04
2	Wubcon plc	198	14.0
3	Mohan plc	200	13.04
4	Sun optics plc	186	19.13
5	Novastar Factory	180	21.74
6	Alek Terrazzo Factory	194	15.65
7	National Tobacco Enterprise	192	16.52

The results of this research work indicate that voltage variations of mainly under voltages occur at the electric supply to industrial plants. Although the IEEE requirement is a maximum voltage variation of ±10% at steady state, variations that reach 21.74% are recorded. However, these voltage variations occur not in synchronization with load variation which in turn indicate faulty conditions.

The occurrence of voltage variation has forced the St. George Brewery to purchase equipments that shutdown sensitive equipments when the voltage goes out of the range of ±10% of the nominal voltage. Having installed that equipment, the system isolated the protected system 10-times in three weeks. There were times that the protective system operated to isolate sensitive equipments four times a day due only to voltage variations.

4.3 Interruption

The interruption may be either of short duration or sustained interruption. However, the auto-reclosure feature of the breakers at Addis center substation is intentionally disabled that all interruption phenomena are changed into sustained interruptions.

Interruption, which may be either of short duration or sustained, 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 [4]. Mathematically, it is expressed as under in Equation (4.1).

$$\textbf{SAIFI}= \frac{Cn*In}{Ct} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (4.1)$$

where, Cn is number of customers interrupted, In is number of interruptions, and Ct 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 in Equation (4.2) below.

$$\textbf{SAIDI}= \sum. \frac{Cn*Id}{Ct} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.2)$$

where, Id 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 by Equation (4.3).

$$\textbf{CAIFI}= \frac{\sum \boldsymbol{Ci}}{\boldsymbol{Cn}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.3)$$

where, Ci is number of customer interruptions.

IV. CAIDI: Customer average interruption duration index represents the average time required to restore service. Mathematically, this is given by Equation (4.4).

$$\textbf{CAIDI=}\frac{\sum Id}{\sum Ci}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4.4)}$$

V. ASAI: Average system availability index represents the fraction of time (often in percentage) that a customer has received power during the defined reporting period. Mathematically, this is given in Equation (4.5).

$$\textbf{ASAI=}\frac{Hca}{Hcd}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4.5)}$$

where, Hca is customer hours service availability, and Hcd is customer hours service demand.

Since all the industries are supplied directly from 15 kV lines, it is better to study the electric power interruption of the feeders from the substation as follows. This is because there is no isolating mechanism between the substation-breaker and the 15kV feeder tapping points.

As the research work began in Augest-2010, the data are taken starting from June-2010. It is also an advantage to include the summer seasons of the country, because reliability of power systems that have large portions of overhead transmission lines is highly affected by rains and heavy winds. For the purpose of comparison, the month of dry season-December is also included.

The following reliability indices are then computed, from the monthly average interruption data shown in Table 4.3 below utilizing the above mathematical relations.

- SAIFI
- SAIDI
- CAIDI
- ASAI

Table 4.3 Interruption history of feeders (Source: Addis Center Substation).

S/N	Line/ Feeder	Monthly average No. of interruptions	Interruption Duration (Hr)					
			June	July	Aug.	Sept.	Dec.	Average
1	Arbegnoch	18	6.87	10.82	8.22	31.68	13.95	14.308
2	Kaliti	14.6	4.72	5.33	5.6	14.5	11.17	8.2632
3	Mekanisa	15	7.33	4.45	6.15	6.23	6.67	6.166
4	Sabata	24.4	15.03	6.53	15.08	23.28	12.3	14.444
5	Adowa	2.4	0.37	0	2.07	3.4	0.5	1.268
6	Kolfie	14.6	4.65	10.27	7.17	21.7	11.38	11.034
7	Old-Bole	12.4	3.83	2.22	11.35	6.7	3.4	5.5
8	Kera	8.8	4.93	5.75	5.13	13.87	11.6	8.256
9	Churchile	14.4	3.77	4.28	2.48	4.32	1.47	3.264
10	Aboware	4.8	2.78	0.23	2.62	8.33	6.12	4.016
11	New-Bole	11.75	10.01	5.33	6.35	17.67	11.03	10.095

The computed values of the reliability indices, using equations (4.1) to (4.5), are then tabulated as shown in Table 4.4 below.

Table 4.4 Reliability indices of 15 kV feeders at Addis Center Substation.

S/N	Line/ Feeder	Monthly average no. of interruptions	Monthly Average interruption Duration (Hr)	SAIFI	SAIDI (Hr)	CAIDI (Hr)	ASAI
1	Arbegnoch	18.0	14.3	18.0	14.3	0.8	0.98013
2	Kaliti	14.6	8.3	14.6	8.3	0.6	0.98852
3	Mekanisa	15.0	6.2	15.0	6.2	0.4	0.99144
4	Sabata	24.4	14.4	24.4	14.4	0.6	0.97994
5	Adowa	2.4	1.3	2.4	1.3	0.5	0.99824
6	Kolfie	14.6	11.0	14.6	11.0	0.8	0.98468
7	Old-Bole	12.4	5.5	12.4	5.5	0.4	0.99236
8	Kera	8.8	8.3	8.8	8.3	0.9	0.98853
9	Churchile	14.4	3.3	14.4	3.3	0.2	0.99547
10	Aboware	4.8	4.0	4.8	4.0	0.8	0.99442
11	New-Bole	11.8	10.1	11.8	10.1	0.9	0.98598

To see where the reliability of the electric power supply, purely quantitative values may not be sufficient. For benchmarking, typical design-target values are included as reference frames with which simple comparisons can be made.

Table 4.5 Design target values of reliability indices on per-annum basis [1].

Design Target Values	
SAIFI	1
SAIDI	1-1.5 Hr
CAIDI	1-1.5 Hr
ASAI	0.99983

From the tables above, we can observe that the system-average interruption frequency of the feeders is extremely high when compared to the design target value. The target value is 1-interruption per annum, while the monthly-average interruption frequency of the above mentioned feeders reaches 24.4 which is 292.8 times the typical interruption frequency of the design target value. This result shows that, the interruption frequency is extremely high when compared with the above design target value.

Availability of all the feeders, as observed from the ASAI values, is below the typical target value, which is 0.99983. This indicates that the feeder lines get interrupted for a long duration of period out of the time that they are required for customer demand.

From the customer average interruption duration index, on the other hand, we can observe that all the feeders have CAIDI values of less than the minimum value of the design target value, which is 1-hour. This means that, the feeders have small mean times to repair which in turn is an indicative of frequent interruptions that arise from non-permanent disturbances upon the power system. Otherwise, there are several instances that the interruption stays for five and six hours. However, the frequent occurrence of short duration interruptions has decreased the CAIDI values to less than one.

The results of the system average interruption duration indices (SAIDI) indicate monthly average interruption durations that reach 14.444 hours. Changing this figure into yearly basis, we get 173.328 hours of system average interruption duration per annum. This means that, the duration of electric power interruption of the feeders of the substation reaches 115 times the maximum value (1.5 Hr) of the design target value. This shows that electric power is interrupted for a long period of time.

From the above interruption data of Addis Center Substation, we can also observe that the electric power interruption during the rainy seasons is much smaller than that occurred in September. This in turn shows that much of the electric power interruption is associated with other factors than heavy rain and high wind.

4.4 Waveform Distortion

The basic themes of IEEE Standard 1159-1995 are twofold [5]. On one hand, the utility has the responsibility to produce good quality voltage sine waves. On the other hand, end-use customers have the responsibility to limit the harmonic currents their circuits draw from the utility line. The IEEE Standard 519-1992 permissible voltage distortions that a utility can supply and current distortions that an end-user can draw from the utility are tabulated as below.

Table 4.6 IEEE voltage distortion limits [6].

Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
≤ 69 kV	3	5
69.001 kV-161 kV	1.5	2.5
≥ 161.001kV	1	1.5

Table 4.7 IEEE current harmonic distortion limits [6].

I_{sc}/I_L	<11	11≤h<17	17≤h<23	23≤h<35	35≤h	TDD
<20	4	2	1.5	0.6	0.3	5
20<50	7	3.5	2.5	1	0.5	8
50<100	10	4.5	4	1.5	0.7	12
100<1000	12	5.5	5	2	1	15
>1000	15	7	6	2.5	1.4	20

- ♣ Even harmonics are limited to 25% of the odd harmonic limits above.
- ♣ Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

Moreover, the IEEE Std. 519-1992 sets limits on the commutation notches. According to the standard, the notch depth, the total harmonic distortion factor (THD), and the notch area of the line-to-line voltage at PCC should be limited as shown in Table 4.8 below.

Table 4.8 Low-voltage system classification and distortion limits [6].

	Special Applications	General System	Dedicated System
Notch Depth	10%	20%	50%
THD (Voltage)	3%	5%	10%
Notch Area (in V.μs)	16,400	22,800	36,500

In the Table 4.8 above, special applications include hospitals and airports whereas a dedicated system is exclusively dedicated to the converter load [6].

The harmonic current distortion limits, as outlined in Tables 4.9 are only permissible provided that the transformer connecting the user to the utility system will not be subjected to harmonic currents in excess of 5% of the transformers rated current as stated in IEEE C57.12.00-1987 [6]. If the transformer connecting the user will be subjected to harmonic levels in excess of 5%, the installation of a larger unit, capable of withstanding the higher levels of harmonics, should be considered.

The short circuit current and rated current of each 15 kV feeder at the point of common coupling are averaged to be 10 kA and 300 A respectively, which give Isc/I_L ratio in the range of 20<50. As a result, the TDD values of the current harmonics should not exceed 8% at the point of common coupling.

As the electric power supplies of all industries are given from the 15 kV feeders by directly tapping into the service transformer of the corresponding industry, the primary sides of transformers are taken as points of common coupling.

1. Wubcon plc

The maximum voltage and current harmonic contents of the electric power of Wubcon plc, when the industry is working at full load are shown below.

Table 4.9 Maximum voltage and current harmonics at Wubcon plc.

PHASE 1					**PHASE 2**					**PHASE 3**				
H.No.	V	%	I(A)	%	H.No.	V	%	I(A)	%	H.No	V	%	I(A)	%
0	3	1.4	0	0	0	2	0.9	0	0	0	4	1.8	0	0
2	0	0	5	4	2	0	0	6	4.3	2	0	0	7	5.4
3	2	0.9	15	11.9	3	2	0.9	17	12.2	3	0	0	18	13.9
5	4	1.8	35	27.8	5	4	1.8	31	22.3	5	4	1.8	38	29.2
7	2	0.9	8	6.4	7	0	0	4	2.9	7	1	0.5	7	5.4
11	0	0	2	1.6	11	0	0	2	1.4	9	2	0.9	3	2.3
13	2	0.9	3	2.4	13	0	0	3	2.2	13	0	0	3	2.3
15	1	0.5	0	0	15	0	0	2	1.4	15	1	0.5	0	0
17	2	0.9	4	3.2	17	1	0.5	2	1.4	17	2	0.9	4	3.1
21	1	0.5	3	2.4	21	0	0	0	0	21	1	0.5	0	0
23	1	0.5	2	1.6	23	0	0	0	0	23	0	0	0	0
THDV= 2%, THDA= 31.6%					**THDV= 2%, THDA= 26.1%**					**THDV= 2%, THDA= 33.5%**				

The point of common coupling is the primary side of the transformer serving the industry. The transformer is delta-wye connected, so that the triplen harmonics cannot enter to the primary side of the transformer from the load side. As a result, omitting the 3rd and 9th harmonics, we get a maximum current THD value of 30.4% at the point of common coupling.

Computing the equivalent current TDD value at the rated current of 137A using equations (3.5) and (3.6), we get a TDD value of 28.8%. It is therefore a necessity to install harmonic filters, to meet the IEEE requirements at the worst case.

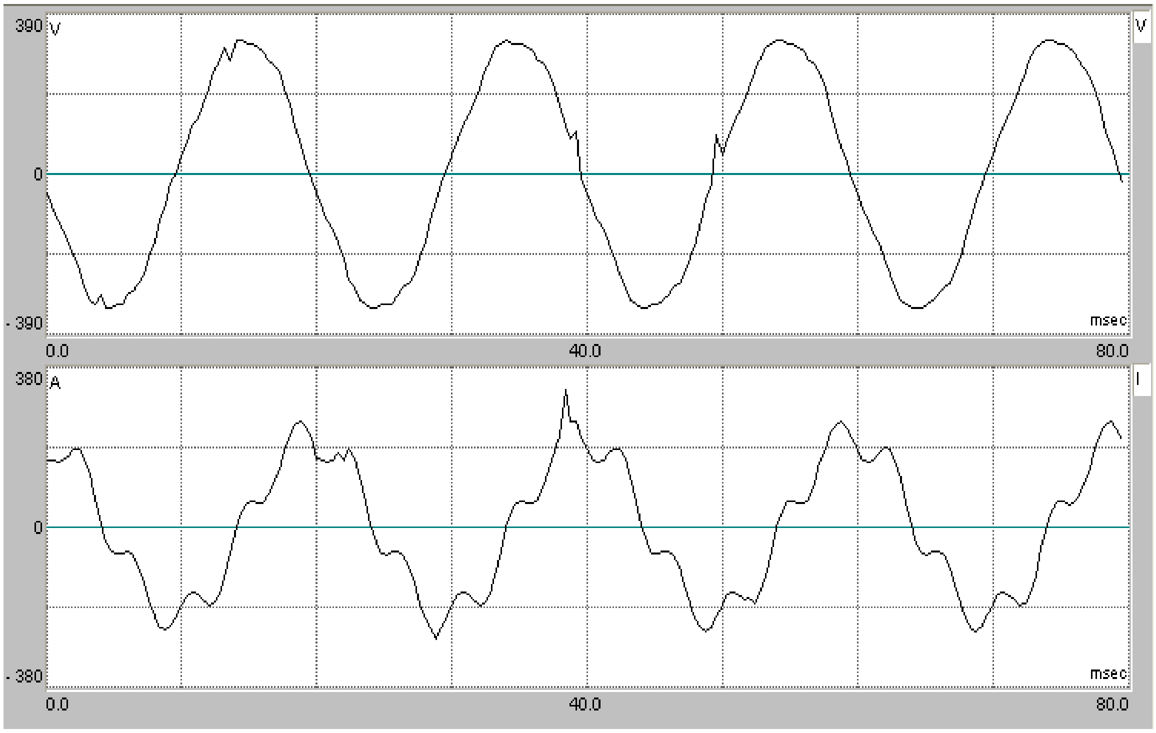

Figure 4.3 Waveforms of maximum voltage and current distortions at Wubcon plc.

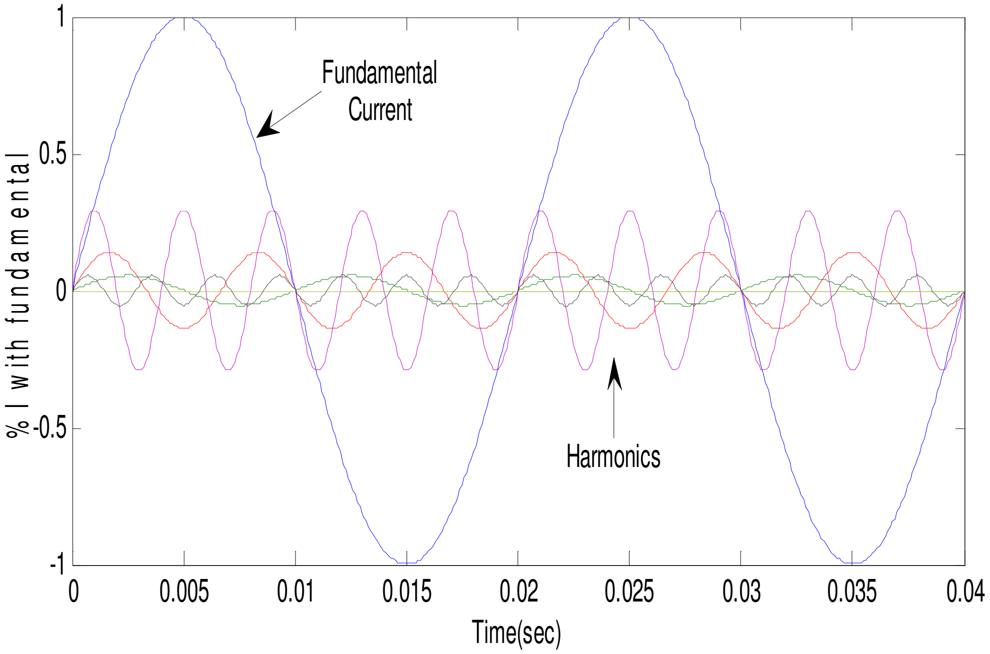

Figure 4.4 Spectral contents of the current at Wubcon plc.

2. Mohan plc

The maximum rated current at Mohan plc is 620A. The current THD values obtained below through direct measurement are then changed into equivalent TDD values for benchmarking with standard values.

Table 4.9 Maximum voltage and current harmonics at Mohan plc.

PHASE 1					**PHASE 2**					**PHASE 3**				
H.N	V	%	I(A)	%	H.N.	V	%	I	%	H.N.	V	%	I	%
0	3	1.3	0	0	0	3	1.3	0	0	0	4	1.7	0	0
2	0	0	2	0.6	3	0	0	2	0.9	3	0	0	5	1.6
5	2	0.9	35	11	5	2	0.9	32	14	5	1	0.4	36	11
7	2	0.9	18	5.5	7	1	0.4	17	7.5	7	2	0.9	17	5.5
11	0	0	5	1.5	11	0	0	6	2.6	11	0	0	5	1.6
13	0	0	3	0.9	13	0	0	2	0.9	13	0	0	2	0.6
17	0	0	3	0.9	17	0	0	3	1.3	17	0	0	3	1
19	0	0	3	0.9	19	0	0	2	0.9	19	0	0	2	0.6
THDV= 2%, THDA= 11.8%					THDV 2%, THDA 16%					THDV2%, THDA13%.				

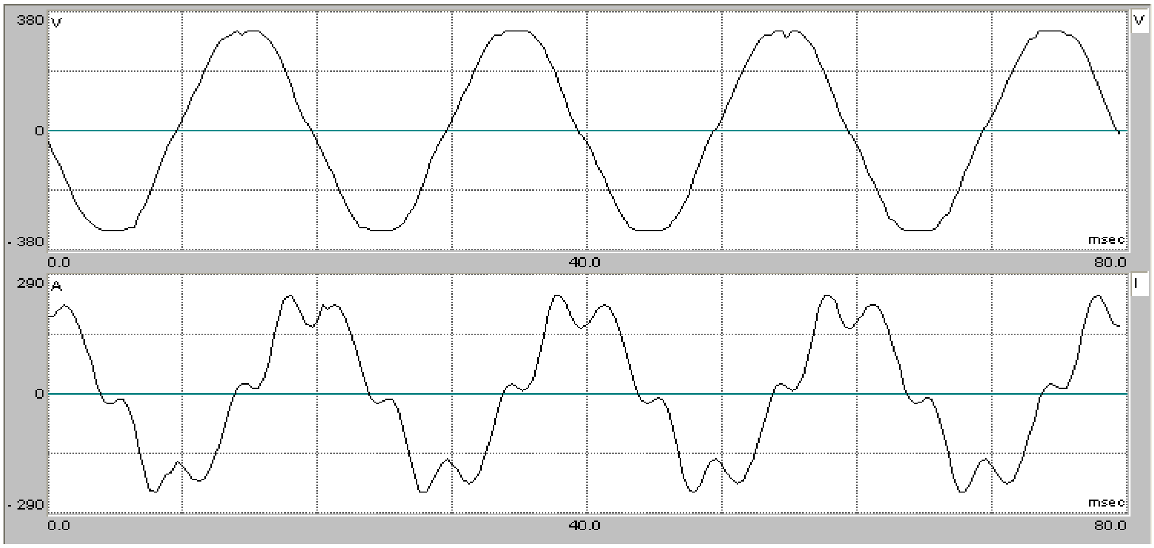

Figure 4.5 Waveforms of maximum voltage and current distortions at Mohan plc.

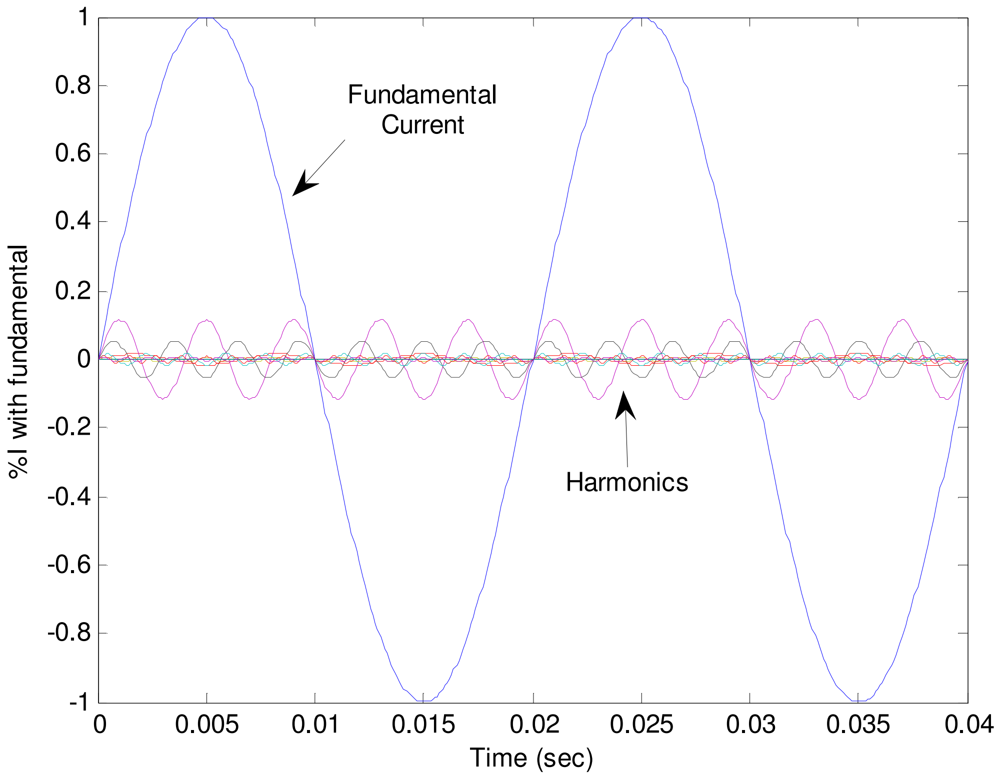

Figure 4.6 Spectral contents of the distorted-current at Mohan plc.

At Mohan plc, the maximum current distortion is 16.2% at the second phase. Subtracting the 3rd harmonic at the point of common coupling, as the service transformer is delta-wye connected, we get a THD value of 16.17%. The corresponding TDD value at PCC is 5.9% which is within permissible range.

3. St. George Brewery

The voltage distortions expressed in terms of THD values, at the St. George Brewery reach a maximum value of 2.9% which is small compared to the permissible value of 5%. The current distortion, on the other hand reaches 16.75% at full load. Because the service transformer is delta-wye connected, omitting triplen harmonics, a maximum current THD value of 16.62% is obtained at the point of common coupling. The corresponding TDD value, at 1800A rated current and computed using equations (3.5) and (3.6), is 7.26% which is within permissible range.

Table 4.10 Maximum voltage and current harmonics at St. George Brewery.

Phase-1					Phase-2				Phase-3			
H.No	V	%	I(A)	%	V	%	I(A)	%	V	%	I(A)	%
3	0	0	15	1.9	1.1	0.5	7.4	0.9	0	0	9.25	1.16
5	4.9	2.2	118	15	5.6	2.5	111	14	4.9	2.2	118	14.9
7	1.8	0.5	37	4.8	3	1.3	39	4.8	1.1	0.5	32.7	4.11
9	1.2	0.5	5.9	0.8	1.6	0.7	5.4	0.7	0	0	5.52	0.69
11	1.2	0.5	38	4.9	2	0.9	29	3.6	0	0	28.5	3.58
13	1.3	0.6	5.6	0.7	1.5	0.6	4.3	0.5	0	0	3.93	0.49
19	0	0	2.1	0.3	1.6	0.7	0	0	1.5	0.7	2.48	0.31
THDV= 2.6, THDA= 16.8%					THDV= 2.8, THDA= 15%				THDV= 2.7, THDA= 16%			

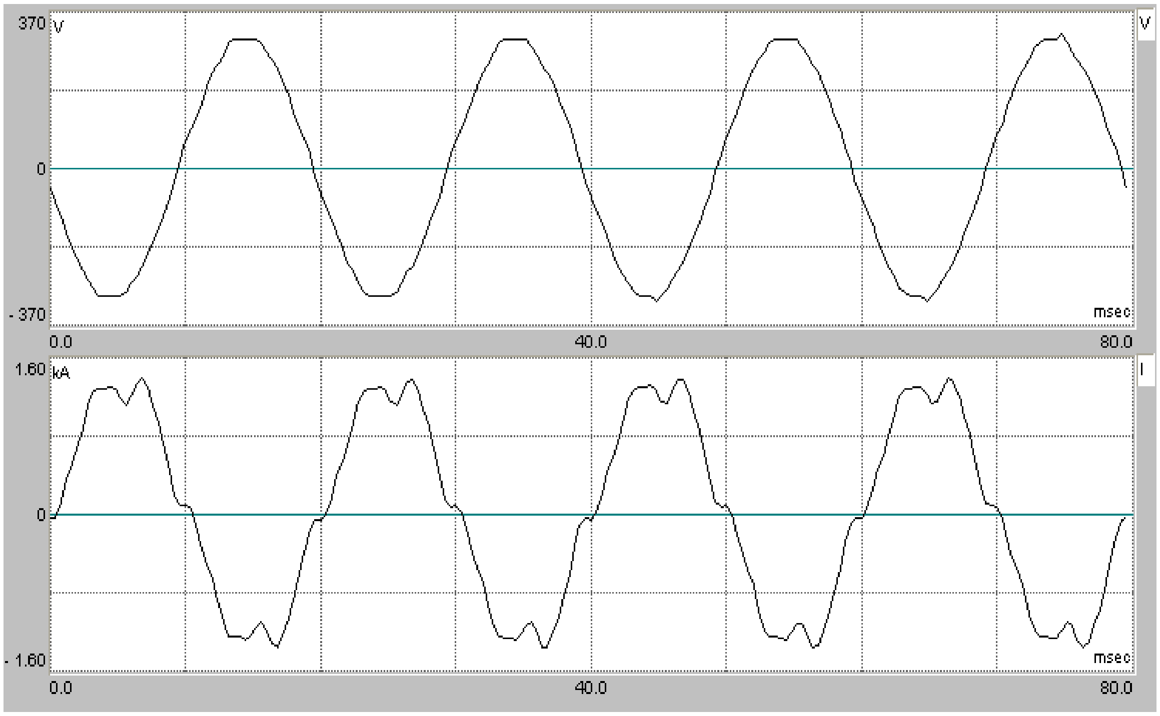

Figure 4.7 Waveforms of maximum voltage & current distortions at St. George Brewery.

4. National Tobacco Enterprise

At National Tobacco Enterprise, harmonic current distortions are small with respect to the permissible values such that both the voltage and current distortions are within tolerable limits. Below are shown the measurement results.

Table 4.11 Maximum voltage and current harmonics at National Tobacco Enterprise.

Phase-1					Phase-2				Phase-3			
H.No	V	%	I(A)	%	V	%	I(A)	%	V	%	I(A)	%
3	0	0	6.8	1.0	0	0	3.2	0.9	0	0	2.5	0.8
5	4.3	2	12	1.8	4.0	1.8	8.6	2.4	4.2	1.9	5.9	1.9
7	1.3	0.6	5.2	0.8	0	0	3.3	0.9	1.2	0.5	2.6	0.8
9	0	0	3	0.4	1.1	0.5	0	0	0	0	0	0
11	0	0	4.0	0.6	0	0	7.3	2.1	1.2	0.6	6.9	2.2
13	1.0	0.5	3.9.	0.6	0	0	3.7	1.0	0	0	3.7	1.2
19	0	0	0	0	0	0	0	0	0	0	0	0
THDV= 2.1, THDA= 2.4%					THDV= 1.8, THDA= 3.6%				THDV= 2.0, THDA= 3.4%			

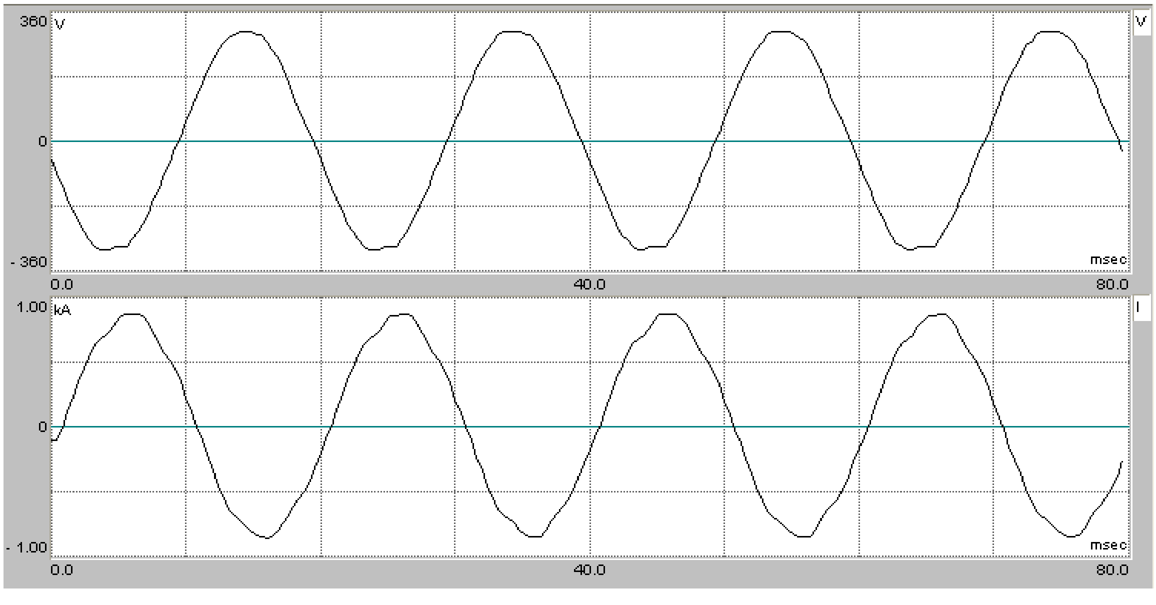

Figure 4. 8 Maximum voltage & current distortions at National Tobacco Enterprise.

5. Novastar Garment Factory

At Novastar Garment Factory, both the current and voltage distortions are small compared to the IEEE distortion limits. Measurement results of voltage and current harmonics are shown as follows.

Table 4.12 Voltage and current harmonics at Novastar Garment Factory.

PHASE 1					**PHASE 2**					**PHASE 3**				
H.No.	Volt	%	I(A)	%	H.No.	V	%	I(A)	%	H.No.	Volt	%	I(A)	%
0	3	1.4	0	0	0	3	1.5	0	0	0	3	1.5	0	0
3	2	1	6	5.4	2	1	0.5	0	0	3	2	1	3	2.7
5	2	1	3	2.7	5	2	1	2	1.7	5	1	0.5	0	0
7	0	0	3	2.7	7	1	0.5	3	2.5	7	0	0	2	1.8
9	1	0.5	0	0	9	1	0.5	0	0	9	1	0.5	0	0
THDV= 2%, THDA= 6.9%					THDV= 1.8, THDA= 2.6%.					THDV= 1.6, THDA= 2.8%				

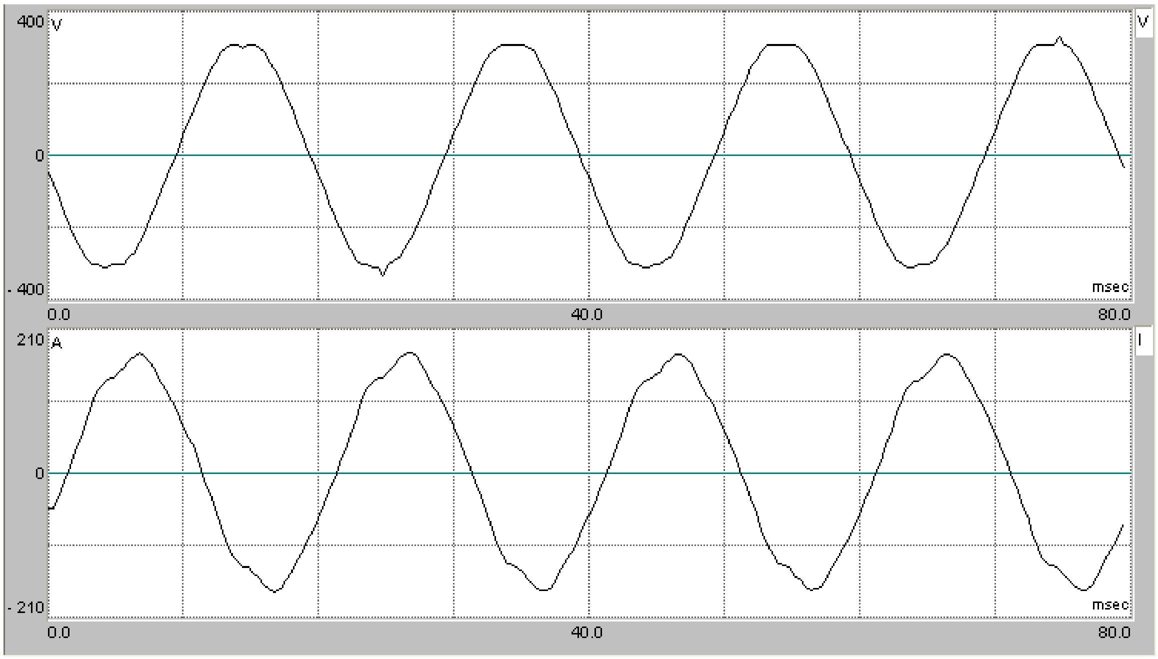

Figure 4.9 Waveforms of voltage and current distortions at Novastar Garment Factory.

6. Sun Optics plc, Alek Terrazzo Factory

The voltage and current waveforms at Sun optics plc and Alek Terrazzo Factory have less significant distortions that the typical current THD value is 3% and the voltage THD value is 1.6%. Consequently, both the voltage and current distortions at these industries are tolerable. The typical measurement result of the voltage and current waveforms are shown below.

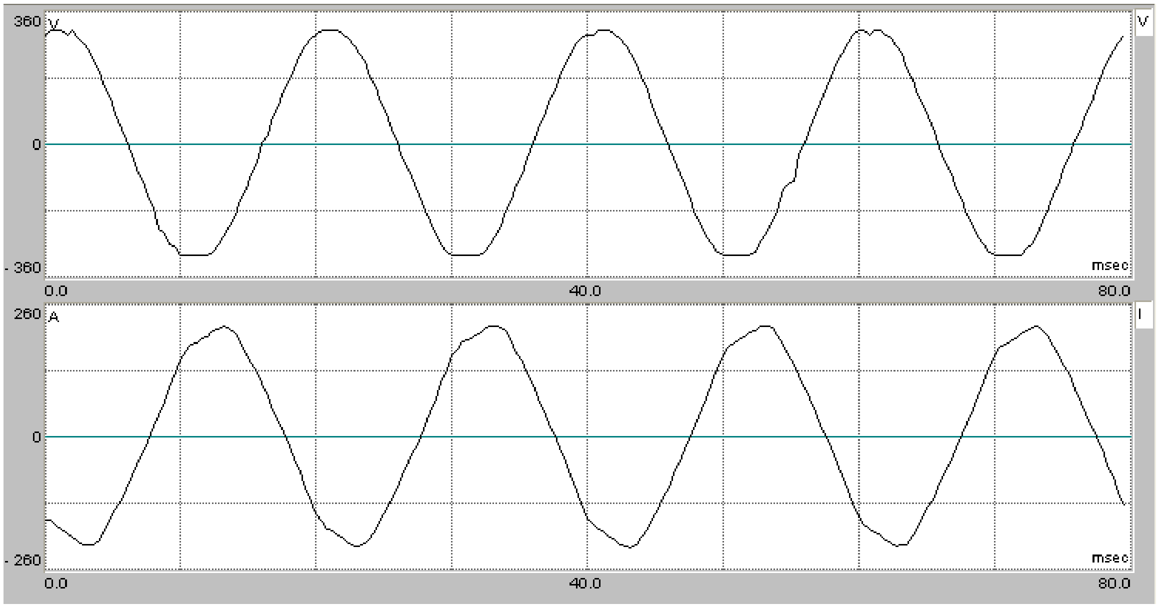

Figure 4.10 Waveforms of voltage & current distortions at Sun optics plc and Alek Terrazzo Factory.

4.5 Voltage Unbalance

While measurements were being taken, some faulty and unwise methods of powering were discovered. At National Tobacco Enterprise one of the two powering cables on one of the three phases was loaded to only 5% of its share. At Novastar Garment Factory on the other hand, the service transformer of the plant was placed outside their compound.

The maximum values of voltage unbalances discovered through measurements are tabulated as follows.

Table 4.13 Measurement result of maximum voltage unbalances at industrial plants.

S/N	Industrial plant	Voltage (V)				Unbalance (%)
		Phase-I	Phase-II	Phase-III	Average	
1	St. George Brewery	222	223	225	223.3	0.75
2	Wubcon plc	220	218	221	219.7	0.61
3	Mohan plc	228	231	229	229.3	0.73
4	Sun Optics plc	220	218	216	218.0	0.92
5	Alek Terrazzo Factory	229	231	230	230.0	0.43
6	National Tobacco	214	217	219	217.0	1.80
7	Novastar Garment	212	206	208	208.7	1.60

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

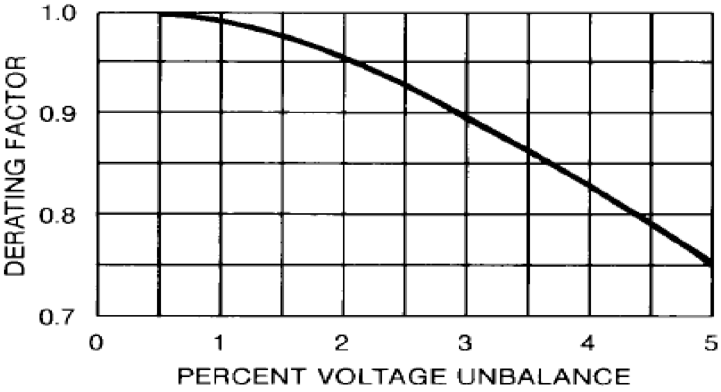

Figure 4.11 Curve for motor derating factor operating on unbalanced voltage [6].

From Table 4.13 and the derating curve on figure 4.11 above, we can see that the level of voltage unbalance is insignificant to cause the undesirable effects of motor pulsations and vibrations. The effects of voltage unbalance on overheating and drop of efficiency are functions of the level and duration of the unbalance. However, the steady state voltage unbalance is even smaller than the above indicated values in Table 4.13.

The current powering of the Novastar Garment Factory is therefore vulnerable to voltage unbalance due to its long distance (150 m) electric power lines at low voltage. It is therefore recommended to place the transformer near to the load center than to utilize motor derating to avoid the problems of both under voltage and voltage-unbalance.

At National Tobacco Enterprise, two cables run for each phase from the transformer secondary to the bus bar. However, on one of the three phases only one cable carries more than 95% of the load on that phase. As a result, voltage unbalance comes in to being due to non-equalized impedance. Therefore, it is recommended to maintain the faulty cable, but not to derate motors.

4.6 Voltage Fluctuation

Selected industries of study consume power that does not have 1-7% fluctuation at low frequency. As a result, voltage fluctuations that reach 1-10% and of frequency around 5 Hz are not discovered at any of the seven selected plants. Below is a sample pattern of voltage along with variation of power consumption at St. George Brewery.

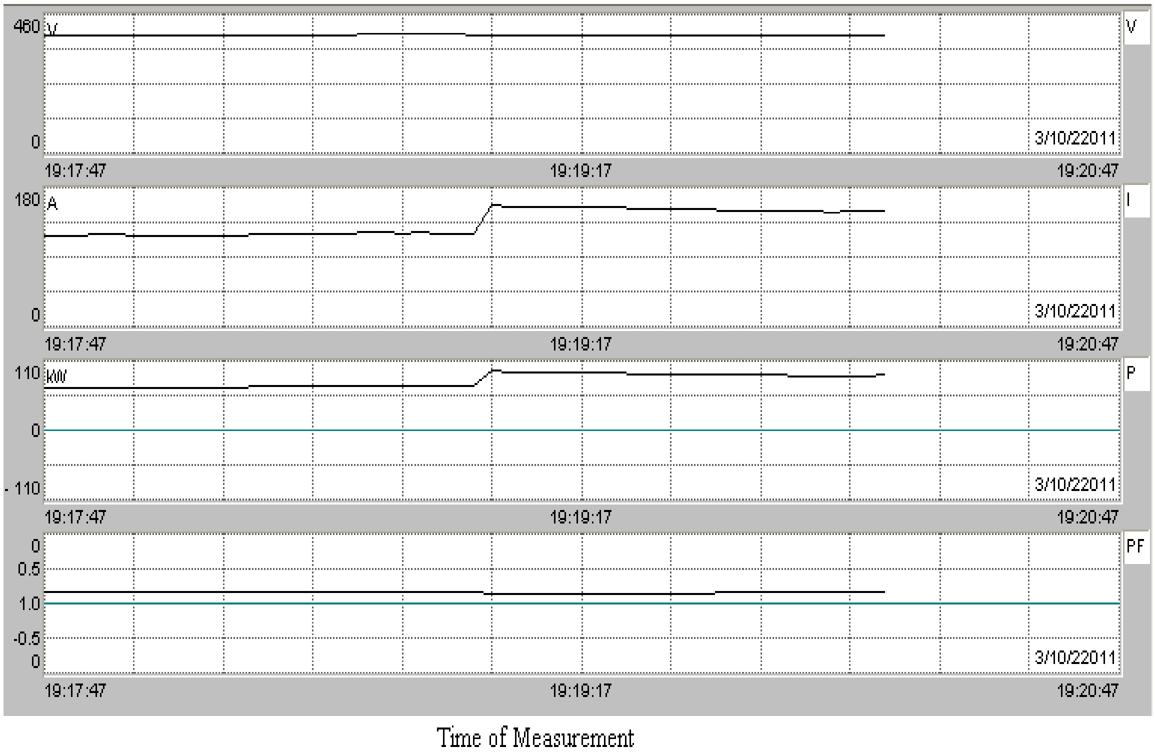

Figure 4.12 Typical trend of voltage fluctuation at St. George Brewery.

Figure below is offered as a benchmark of voltage fluctuations and flickers. The curve is derived from empirical studies made by several sources [6].

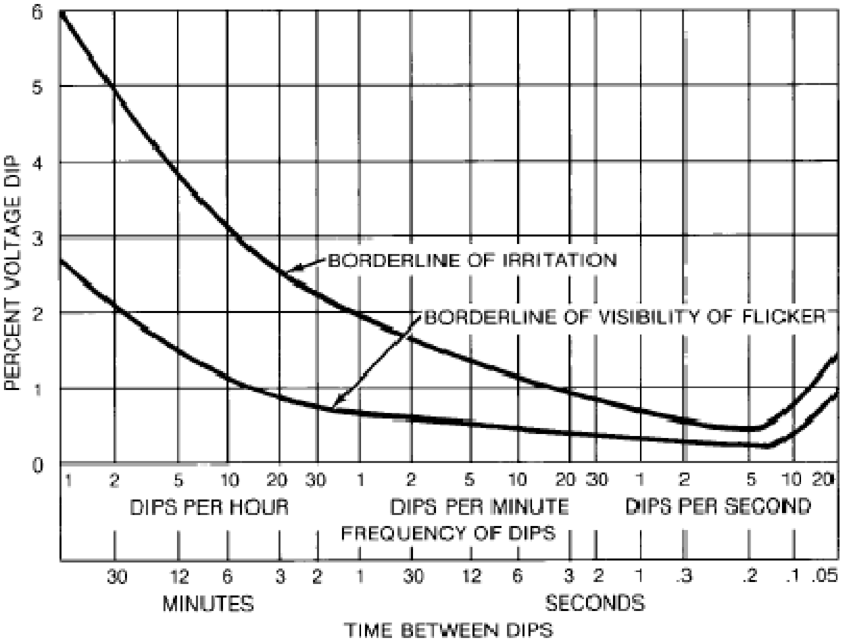

Figure 4.13 IEEE Standard 141-1993 curve for voltage fluctuation limits [6].

Even though, voltage fluctuations of 1 to 7% at low frequency are not discovered during the measurement, the power line impedance is not a guarantee to voltage fluctuation. This can easily be deduced from the high voltage drop at moderate amount of loading as observed in Novastar Garment Factory. It is due to absence of high power loads drawing a fluctuating current that flicker is not observed.

4.7 Power Frequency Variation

Since frequency is the same all over the interconnected power system, frequency measurements can be made anywhere in the power system. In that case, the places of frequency measurements are not paid that much attention for the discussion in hand. Below is the result of power frequency measurement taken at Gafat Armament Industry.

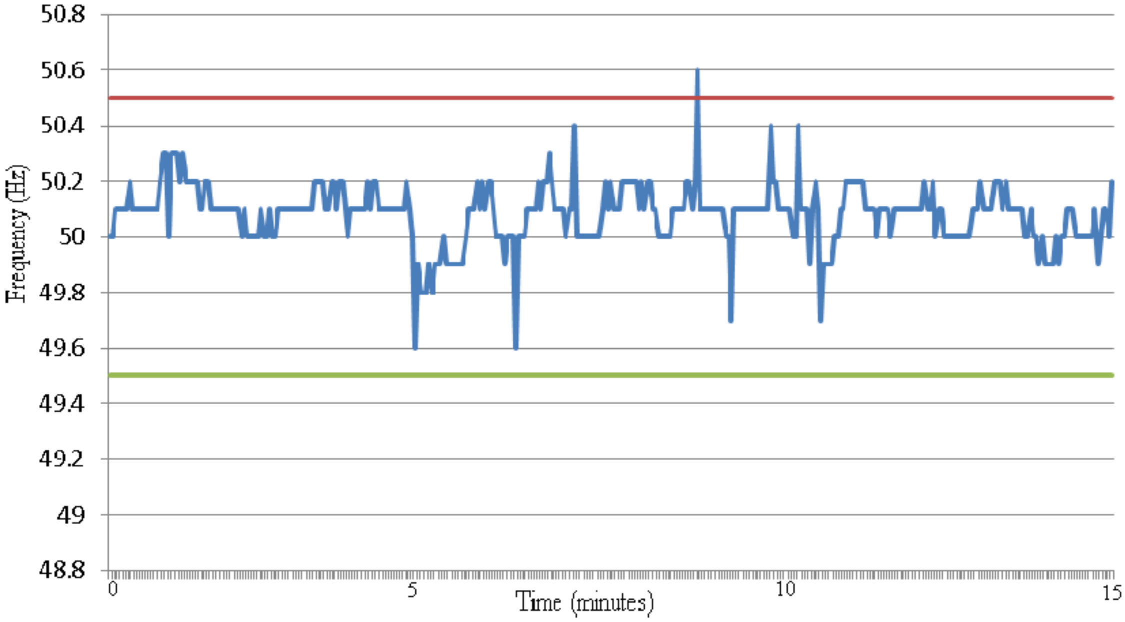

Figure 4.14 Typical power frequency variation.

At normal operation, the measurement result above shows that the power frequency constantly varies from 49.4 Hz to 50.6 Hz. The result shows that the permissible values of the IEEE, variations of ±1% (49.5 Hz to 50.5 Hz at 50 Hz nominal frequency), are exceeded. Moreover, the frequency reaches the maximum limits several times, and varies constantly within the permissible range.

At Addis Center Substation, under frequencies that reach 48 Hz (4%) are recorded and resulted in breaker operations to protect the system from high level of frequency variation. The under frequency phenomena that fall to less than or equal to 48.6 Hz are recorded at Addis Center Substation as follows in Table 4.14.

Table 4.14 Under frequency records at Addis Center Substation

S/N	Month	No. of breaker operations due to under frequency (≤ 48.6 Hz)
1	June, 2010	5
2	July, 2010	8
3	August, 2010	10
4	Sept., 2010	6
5	Dec., 2010	1

The Ethiopian Electric power system is an interconnected-into-grid system in which significant power frequency variations are not expected to occur. Although, most of the time the frequency variation is limited to within the permissible range, it is several times that very large frequency variations occur in the power system. This is due to the frequent outage and reconnection of a huge load including one or more distribution substations.

Consequently, the result shows that the Ethiopian grid system including the power generating units is highly ineffective in resisting power frequency variations.

CHAPTER FIVE

SOLUTIONS AND SIMULATION RESULTS

5.1 Transients

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

The alternative solutions for transients associated with capacitor switching are discussed below along with their electrical modeling and simulation using SimPowerSystems software. The simulations show the effect of capacitor switching and the effectiveness of the techniques used to mitigate the transients associated with capacitor switching.

The simulation model is made for a typical of the selected industries with an inductive load of 1pu (at 400 V base-voltage and 1 MVA base apparent power) at power factor of 0.50. The power factor corrector of reactive power 0.4023 pu is then installed to increase the power factor to 0.9. It is calculated as follows:

$$Q = (1pu)x(\sin(\cos^{-1} 0.5) - \sin(\cos^{-1} 0.9)) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.... (5.1)$$

The utility side is variable both in its terminal voltage and impedance as seen from the industry of study due to the constantly changing loads on the power system. The voltage variation can be ignored whereas the impedance is modeled by some typical values of a conventional power system.

Switching of the above power factor compensator, during the peak of load voltage, results in a transient of 1.9 pu which is high enough to damage some electronic equipments. The simulation result is shown as under.

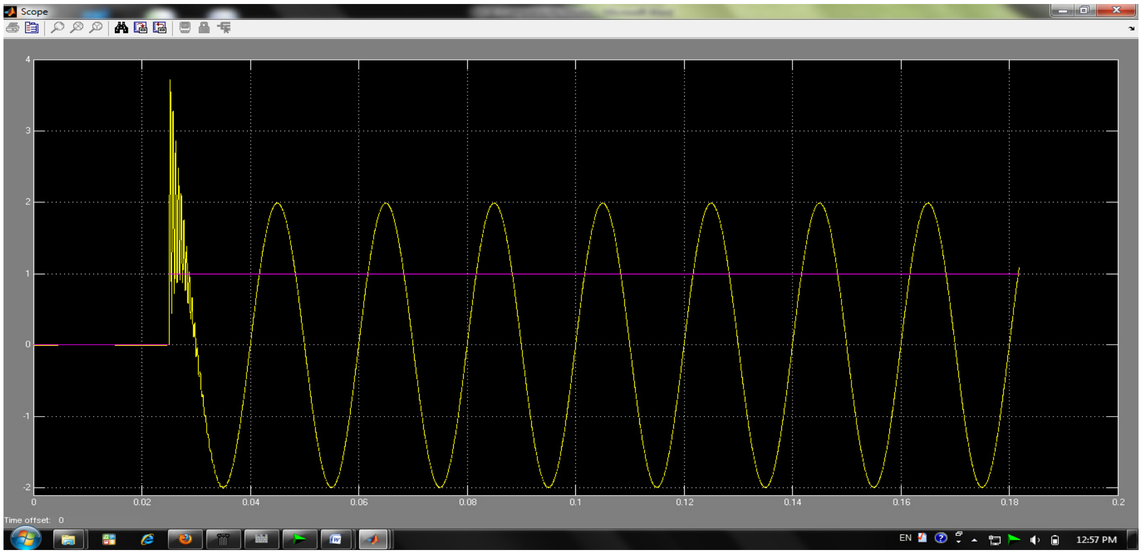

Figure 5.1 Simulation result of the transient associated with capacitor bank energization.

To circumvent the above problems different mechanisms can be utilized. The first one and which also helps to utilize stepwise power factor correction is to use smaller-unit compensators assembled to yield the desired reactive power injection through automatic switching of each unit at a time. The simulation results to show the effect of transient reduction by using sub-divided units are discussed below.

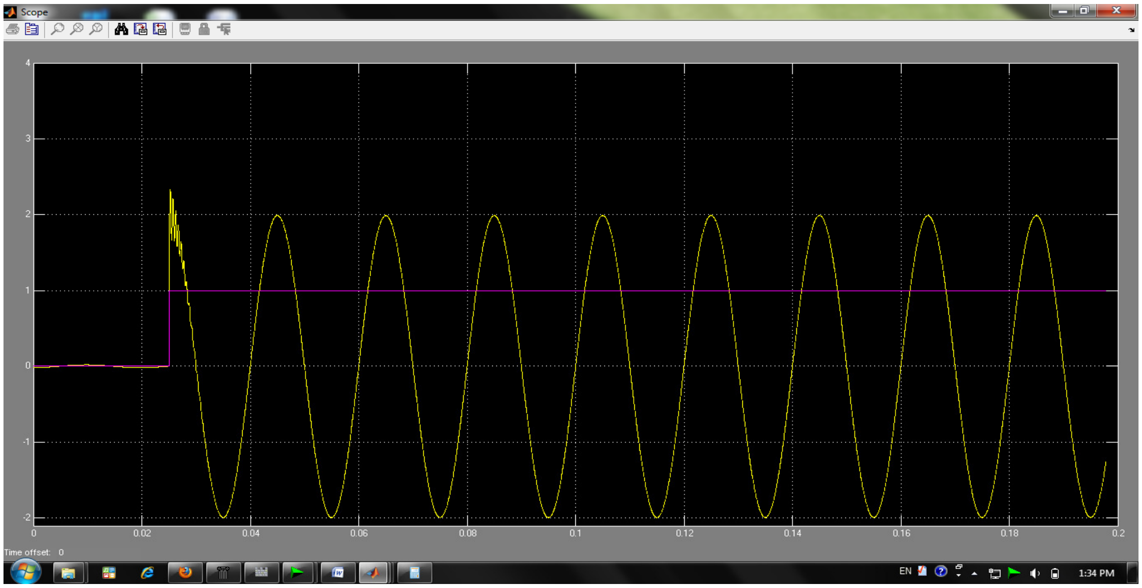

Figure 5.2 Simulation result of transient reduction using 5-unit compensator.

Subdividing the above required power factor corrector (of reactive power capacity 0.40 pu) into five smaller units each having 0.08 pu capacity, the resulting transient can be reduced to 1.2 pu. Figure 5.2 shown above, illustrates the simulation result to show reduction of transient over voltage by using five-units of power factor correctors.

Utilizing further smaller units of power factor correctors can reduce the transient over voltage even more. The ten-subunits assembled into the total capacity of corrector decreases the transient over voltage to 1.08 pu. The simulation result that shows transient reduction by using ten-units is shown in figure 5.3 below.

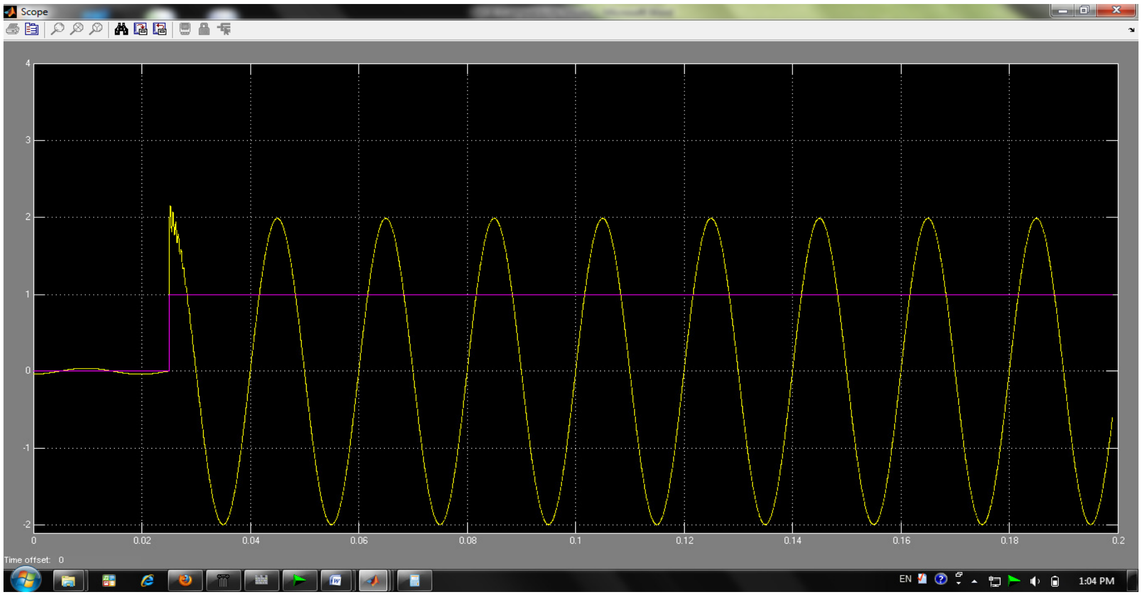

Figure 5.3 Simulation result of transient reduction using 10-unit compensator.

Moreover, using synchronous closing breakers or switches can significantly reduce the overshoot. Synchronous closing prevents transients by timing the contact closure such that the system voltage closely matches the capacitor voltage at the instant the contacts mate [1]. This avoids the step change in voltage that normally occurs when capacitors are switched, causing the circuit to oscillate.

The other alternative solution is to add a feature of harmonic filter to the corrector, simply by adding a reactor in serious with the capacitor. As the current through a reactor does not change instantly, the resulting over voltage is also decreased.

The above simulation results, that show the effect of capacitor switching and the levels of mitigation of the alternative solutions, are summarized in tabular form as follows.

Table 5.1 Levels of mitigation of proposed solutions of switching transients.

	Switching time			QTY of capacitor units		
Parameter	Crossing at zero voltage (ideal)	Crossing at half of peak voltage	Crossing at peak voltage	1	5	10
Transient in (pu)	1	1.38	1.9	1.9	1.2	1.08

As observed from the simulation results, oscillatory transients that arise from capacitor switching are functions of the switching time, and utilization of multiple units that add up to the desired capacity. Although switching the capacitors at the zero crossing of the capacitor voltage decreases significantly the consequent transient, it is ideal and difficult to find the capacitor totally discharged to zero. Therefore, it is better option to use sequential switching which are also switched at their near-to-zero crossings one at a time, for decreasing transient over voltages associated with capacitor switching.

5.2 Voltage Variations

The above mentioned phenomena of voltage variations do not occur periodically with the power period of the industry. The voltage deviations are not significant during the load variation of the industry. Moreover, all the industries of study have their own transformers with five alternative tap-positions to be set by the industry as appropriate to their plants. We can therefore deduce that, voltage variations at industrial plants arise mainly from faults on the distribution system and the poor voltage regulation at the level of the national grid.

Protective systems of short circuit and earth faults must also be appropriately installed to prevent voltage variations that arise from faults. The other solution lies at the grid level that effective voltage regulation systems should be used to avoid both under voltages and over voltages.

5.3 Interruption

From the benchmarking results discussed in chapter four, the ASAI, SAIDI, SAIFI show that, the electric power is poor in its reliability. The major factors degrading the reliability of the electric power supply are discovered to be as listed below.

- Poor protection scheme at the distribution systems,
- Poor voltage and frequency regulation mechanisms,
- Lack of regular inspections and maintenances,
- High exposure to environmental disturbances, such as tree branches, animals, and car accidents,
- Intentional outage for operational purposes and
- Little emphasis on reliability.

As a result the EEPCO should work hard on the power system to upgrade the reliability of the electric power supply. The proposed solutions are listed below.

- Replacing the radial distribution system with ring or doubly-fed systems,
- Utilizing effective protection schemes as to isolate the minimum possible number of customers,
- Using underground transmission and distribution systems in areas that are highly exposed to environmental disturbances,
- Making regular inspections and maintenances and
- Upgrading the voltage and frequency control mechanisms.

5.4 Waveform Distortion

Current distortions result from non-linear loads utilized at the industrial plants. The proposed solution for current harmonic-distortion is to filter the harmonics; but avoiding those equipments cannot be a solution. Therefore, filters are designed for the distortions that exceed harmonic limits set by the IEEE Standard 519-1992. In that case, the current distortions at Wubcon plc only exceed the limits.

Filter Design for Wubcon plc

Although the 3rd harmonic current doesn't appear at the point of common coupling, it is more than 5% of the rated current that it should also be filtered as per IEEE C57.12.00-1987. Therefore, filtering the 2nd, 3rd, and 5th harmonic contents, a TDD value of 7.02% is attained which satisfies the IEEE requirements.

There are three main techniques used to reduce or, more accurately, to control the flow of harmonic currents from nonlinear loads in industrial and commercial plants into utility power systems [2]. They are:

- Use of shunt filters
- Use of multi pulse static power converters or phase-shifting transformers
- Harmonic current injection.

The first one, use of shunt filters, is the best economical, technically simple and most common in industrial loads. Therefore, shunt filters are designed for 2nd, 3rd and 5th harmonics of this plant. The filters are inaddition desired to correct the power factor to 0.95. They are arranged in star connection, so that 220 V is impressed across each filter. The measurement result shows the system to be 92 kVA at 0.6 power factor. Adding a 25% extra capacity for our design, the requirement is to design for a 120 kVA system.

Each phase is 1/3rd of the total capacity which is 40 kVA at 0.6 power factor. Each phase, therefore, draws a reactive power of:

$$Q1= 40\text{kvar}*\sin(\cos^{-1}(0.6)) = 32 \text{ kvar} \quad \text{(5.2.a)}$$

When the power factor is corrected to 0.95, a reactive power given in equation (5.2.b) only is drawn from the electric utility.

$$Q2= 24 \text{ kW}*\tan(\cos^{-1}(0.95))= 8 \text{ kvar} \quad \text{(5.2.b)}$$

The remaining 24 kvar of reactive power is then to be injected by the filters of the three harmonics on each phase. Again dividing the 24 kvar of reactive power equally to be supplied by each harmonic filter, they should supply 8 kvar each.

To filter nth harmonic:

$$X_{Cn}= X_{Ln} \rightarrow \frac{1}{2\omega_o C_n} = 2\omega_o L_n \quad \text{(5.3)}$$

To inject 8 kvar reactive power at the fundamental frequncy, neglecting other harmonics:

$$(X_{Cn}-X_{Ln}) = \frac{kV^2}{M\text{ var}} = \frac{0.22^2}{0.008} = 6.05\,\Omega \quad \text{(5.4)}$$

where n is 2, 3 or 5.

Second Harmonic Filter:

To filter 2nd harmonic, and to inject 8 kvar reactive power at the fundamental frequncy, C_2= 0.3948 mF and L_2= 6.4225 mH using equations (5.3) and (5.4).

Then, to calculate the the rms current through the reactor (I_{L2rms}) and peak voltage (V_{C2P}) across the capacitor:

$$I_{L2rms}= I_{1rms}+I_{2rms} \quad \text{(5.5)}$$

$$I_{1rms}= \frac{220V}{6.05\Omega} = 36.36 \text{ A} \quad \text{(5.6)}$$

$$I_{L2rms}= \sqrt{36.36^2 + 7^2} \text{ A} = 37.03 \text{ A} \quad \text{(5.7)}$$

$$V_{C2P} = \sqrt{2} * 36.36A * \frac{1}{314 * 0.3948mF} + \sqrt{2} * 7A * \frac{1}{2 * 314 * 0.3948mF} \quad \text{........ (5.8)}$$

From equation (5.8) above, we get V_{C2P} = 454.72V.

Third Harmonic Filter:

To filter 3rd harmonic, and to inject 8 kvar reactive power at the fundamental frequncy, C_3= 0.4679 mF and L_3= 2.4084 mH, using equations (5.3) and (5.4).

rms current through the reactor (I_{L3rms}) and peak voltage (V_{C3P}) across the capacitor:

I_{L3rms}= $\sqrt{36.36^2 + 18^2}$ A = 40.57 A ……………………………………..……... (5.9)

$$V_{C3P} = \sqrt{2} * 36.36A * \frac{1}{314 * 0.3948mF} + \sqrt{2} * 18A * \frac{1}{3 * 314 * 0.4679mF} \quad \text{........... (5.10)}$$

From equation (5.10) above, we get V_{C3P} = 472.55V.

Fifth Harmonic Filter:

To filter 5th harmonic, and to inject 8 kvar reactive power at the fundamental frequncy, C_5= 0.5053 mF and L_5= 0.8028 mH, using equations (5.3) and (5.4).

rms current through the reactor (I_{L5rms}) and peak voltage (V_{C5P}) across the capacitor:

I_{L5rms}= $\sqrt{36.36^2 + 38^2}$ A = 52.59 A ………..……………………….…………..…. (5.11)

$$V_{C5P} = \sqrt{2} * 36.36A * \frac{1}{314 * 0.3948mF} + \sqrt{2} * 38A * \frac{1}{5 * 314 * 0.5053mF} \quad \text{........... (5.12)}$$

From equation (5.12) above, we get V_{C5P} = 482.53V.

The current THD value after it is filtered is reduced to 7.02% which is less than 8%. The simulation result that shows mitigation of the current waveform using the above designed harmonic filters is shown below in figure 5.4.

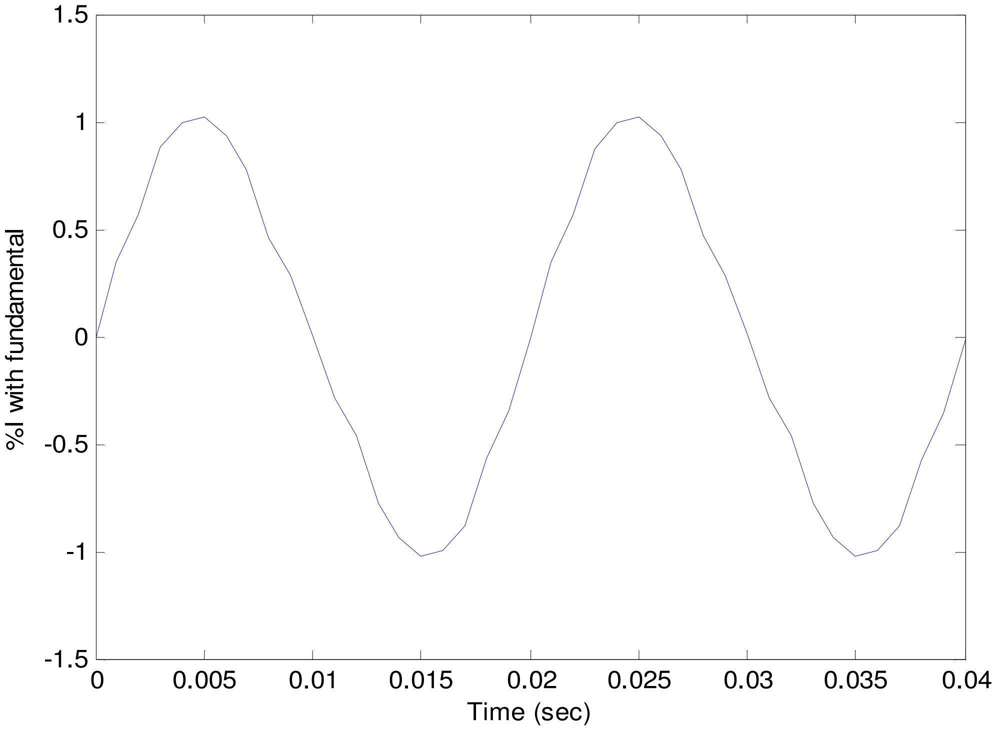

Figure 5.4 Current waveform at Wubcon plc after 2nd, 3rd and 5th harmonics are filtered.

5.5 Power Frequency Variation

As a solution to the problem of a constantly changing power frequency, each generating unit of the country should utilize effective governor control mechanisms to maintain the power frequency within the permissible range. On the other hand, increasing the reliability of the power system can be one solution to the frequently occurring frequency variations which are very large (more than 4%). This is because, interruption of bulk power system from transmission or distribution substation causes a large level of unbalance between power generation and consumption which is in turn a cause of high level of frequency variation.

CHAPTER SIX

CONCLUSIONS, RECOMMENDATION AND SUGGESTIONS FOR FUTURE WORK

Based on the results of the power quality assessment carried out at selected industries of Addis Ababa city, the following major conclusions are drawn. Moreover, useful recommendations are forwarded and the main areas of future work are suggested.

6.1 Conclusions

Industries included in the research work, are facing frequent electric power interruptions that they are forced to invest extra money for purchase of alternative power sources. They are also forced to stop and start their processes following frequent interruptions which also expose them for wastage of semi processed products. Early failure of machines due to wear and tear is the other major problem caused by unexpected power interruptions.

The voltage variations, both undervoltage and overvoltage, are causing equipment malfunctions and ultimately equipment damage to industries under study. Industries are then forced to purchase protective devices against voltage variations. The extreme drop of voltage at industrial plants and the high level of over voltage at the high voltage lines shows that the voltage regulation and protective systems are weak. Flickers are not discovered in this assessment, which shows that the power distribution is stiff enough to withstand the existing power fluctuations.

The power frequency violates the permissible maximum deviations several times every 15-minutes. It varies constantly within the permissible range reaching the maximum limits. Power frequency variations that reach 4% of the nominal values occur on the power system and tripping of protective systems occurred due only to frequency variations. We can therefore conclude that the frequency control of the Ethiopian power system is poor.

Significant problems of voltage unbalances are discovered at none of the selected industries of study. This is mainly because the major loads of the industries are three-phase that are distributed on the three phases equally. There is therefore less chance of unbalance problem at industrial loads. However, unbalances caused by faults on the transmission and distribution lines have been encountered.

Wubcon plc draws a highly distorted current of up to 33.5% THD at its full load. The St. George Brewery, Mohan plc and National Tobacco Enterprise also inject harmonics that reach 18% THD. Computing the equivalent TDD values, it is only at the Wubcon plc that the IEEE current distortion limits are exceeded. Form the utility side, on the other hand, the maximum voltage THD discovered from all industries of study is 4% which is tolerable as per IEEE voltage distortion limits.

6.2 Recommendations

The Ethiopian Electric Power Corporation should work a lot on the whole power system, from generation to distribution, to mitigate the reliability, voltage variation and frequency variation of its electric power supply. It should also work to avoid voltage unbalances caused by faulty conditions.

All the selected industries of study except St. George Brewery and National Tobacco Enterprise, have no capacitor banks for power factor correction. The Ethiopian Electric Power Corporation asks payment for the reactive power consumption at less than 0.85 power factor as a regulatory mechanism of power factor correction. As a result, industries are paying a large amount of money for their consumption of reactive power due to absence of power factor correction. This mechanism, however, can neither enhance the attainable capacities of the transmission and distribution system nor eliminate the power loss on the transmission and distribution systems. It is therefore recommended to install power factor correctors at industrial plants as it is better solution for both the industrial plants and the Ethiopian Electric Power Corporation.

Wubcon plc is recommended to install harmonic filters to limit its harmonic current injections to within tolerable values. Supply voltages of industries that draw harmonic currents of up to 33.5% THD value have a maximum voltage THD value of 2.8% which shows that the electric power system has no burden of waveform distortion.

6.3 Suggestions for Future Work

The major areas of study listed here under are suggested for future work.

1. Annual economic losses due to electric power interruptions in Ethiopia,
2. The trend of harmonic and EMI disturbances of the Ethiopian electric power system, and
3. Effectiveness of the Ethiopian national grid to supply a quality electric power.

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

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

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

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

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

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

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

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

Failure mode: The effect by which failure is observed.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Appendix B: Electrical Models for Simulation

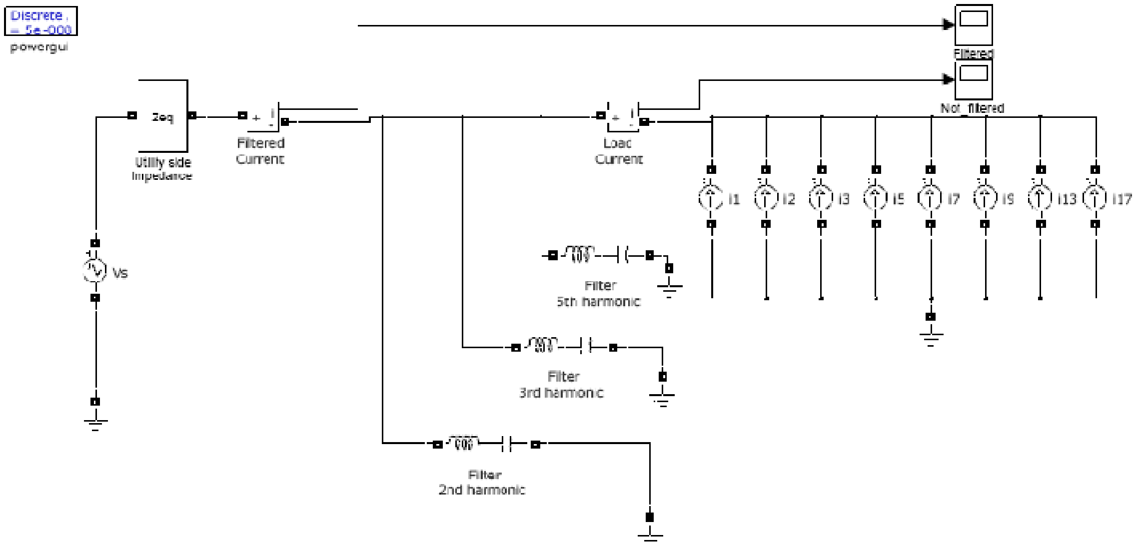

Figure B-1 Simulation Model for Filtering Harmonic Currents.

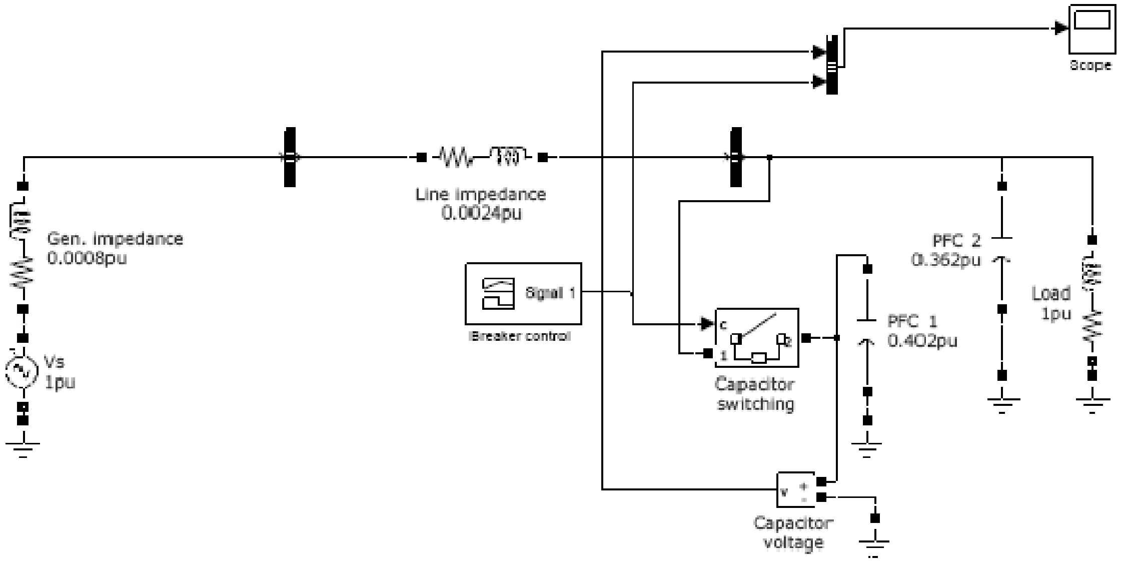

Figure B-2 Simulation Model for Capacitor Bank Switching