Investigation and Mitigation of Power Quality Problems

(Case Study: ETUR Textile Factory)

By: Mohammed Mustefa

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A Thesis Summited to

The Department of Electrical Power and Control Engineering

School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Electrical Power Engineering

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Adama, Ethiopia

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Approval Sheet

We, the undersigned, member of the Board of Examiners of the final open defense by Mohammed Mustefa Usme have read and evaluated his thesis entitled "Investigation and Mitigation of Power Quality Problems: A case study at ETUR Textile PLC" and examined the candidates. This is therefore to certify that the thesis has been accepted in partial fulfillment of the degree of Master of Science in Electrical Power Engineering.

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Internal Examiner	Signature	Date

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Declaration

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

Name: Mohammed Mustefa Signature: ____________

Place: Adama, Ethiopia

Date of submission: July 2020

This thesis has been submitted for examination with my approval as a University Advisor.

Dr. Molla Biweta Signature: ____________

Advisor's name

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Mohammed Mustefa

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Acronyms

AC	Alternating Current
ANSI	American National Standard Institute
ASD	Adjustable Speed Drive
AV	Average
CFL	Compact Fluorescent Lamps
DC	Direct Current
DF	Distortion Factor
DPF	Displacement Power Factor
D-STATCOM	Distribution Static Compensator
DVR	Dynamic Voltage Restorer
ETUR	Ethio Turkey Textile
GUI	Graphic User Interface
HVDC	High Voltage Direct Current
HVAC	Heating Ventilation and Air-Conditioning
I_s	Short Circuit Current
IEC	International Electro-technical Commission
IEEE	Institute of Electrical and Electronics Engineers
KHz	Kilo hertz
KVA	Kilo Volt Ampere
ms	Millisecond
MVA	Mega Volt Ampere

NEMA	National Electrical Manufacturers Association
UPS	Uninterruptable Power Supply
PLC	Programmable Logic Controller
PQ	Power Quality
PSCAD	Power System Computer Aided Design software
PQ	Power Quality
PCC	Point of Common Coupling
PC	Personal Computer
PF	Power Factor
PFC	Power Factor Correction
PU	Per Unit
PPF	Passive Power Filter
RMS	Root Mean Square
SMPS	Switched mode power supplies
TDD	Total Demand Distortion
THD	Total Harmonic Distortion
THD_I	Current Total Harmonic Distortion
THD_v	Voltage Total Harmonic Distortion
TCRs	Thyristor Controlled Reactors)
VSCF	Variable Speed Constant Frequency
VFD	Variable Frequency Drives

Abstract

This thesis presents assessment of power quality problems of ETUR Textile factory which is located in Ethiopia, Oromia Regional State at Adama town about 6km from the town towards south on the road to Wonji city. The assessment investigates the major electrical phenomena that disturb the power quality of this particular factory. Because textile industries have high technology machines including electronic control cards and driver controlled motors, poor power quality may damage the system and cause production failure. Many studies showed that the losses caused by electric quality problem in textile industries took at least 2hr to restore at full capacity operation due to these the company loss hug money. In this occasion some of power quality problems have been discussed based on the behavior of the company; it has dedicated line directly from Wonji substation which is around 3km. So the thesis mainly focuses on harmonics and power factor correction rather than other power quality problem. The necessary data are collected from the factory through direct measurement using harmonic analyzer The collected data are analyzed and the results are then compared with the IEEE standards to identify the type and level of the power quality problems The analysis of the harmonic distortion has indicated that the worst individual harmonic distortion of 34.4 % 5^{th}&7^{th} harmonic components have been existing in the power distribution system of the factory. Again, it has been observed that the factory has been working with poor power factor which is 0.814. Consequently, shunt harmonic filters that have an added feature of power factor correction are designed to reduce the amount of current harmonics and for upgrading power factor. With the designed shunt harmonic filters the dominant current harmonic components 5^{th}&7^{th} are reduced to 0.15% and average power factor has been upgraded to 0.96. The modeled systems with and without shunt harmonic filter have been simulated using MatLab /Simulink software to verify the improvements achieved in terms of power quality. The result showed significant improvements. It is concluded that the problems like harmonic distortion; poor power factor has been discussed.

Key words: power quality, Matlab, IEEE, Harmonic, passive power filter.

CHAPTER ONE

Introduction

1.1. Background

Electrical energy is the most efficient and popular form of energy and the modern society is heavily dependent on the electric supply. Today it is difficult to imagine life without supply of electricity. In recent times, electric utilities, academic and research centers, equipment manufacturers, industries and other end users of electric power are becoming increasingly concerned about the quality of electric power because it is very important for the efficient functioning of the end user equipment. Thus maintaining power quality is very essential [7] [8]. Power quality is an issue that is becoming increasingly important to both utilities and electricity consumers at all levels of usage. The term power quality has been widely used by many industrial and commercial electricity end-users. The quality of power is affected if there is any deviation in the voltage, current or frequency values at which the power is being supplied [10].

This affects the performance and life time of the end user equipment. So to maintain the continuity of the power being supplied, the faults should be cleared at a faster rate and for this the power system switching equipment should be designed to operate without any time lag. Whenever the issue of power quality is raised, the utility has the responsibility to produce sine wave voltage; whereas, end-use customers have the responsibility to limit the harmonic currents their electric loads inject into the utility system. The utility is therefore required to supply its customers with a certain minimum quality of electric power, while end users should on their parts limit the power quality disturbances they inject into the power system. In our country, most of the electric power quality problems occur in the industries. Typical power quality phenomena include harmonics, transients, short-duration voltage variations, long duration voltage variations, voltage imbalance, voltage fluctuations, and power frequency variations. [9]

This thesis work is mainly concerned on power quality problems existing in ETUR Textile Factory. These power quality problems have significant adverse effects on the power system and equipment of the industry.

1.2. Statement of the Problem

The motivating factor to work on this thesis work is initiated by effect of power quality problem at ETUR textile factory even if they have their own line(dedicated line) ; causing downtimes of several machines, failure of sensitive machine, increase maintenance cost and left labors without work as a result this affects the industry profit annually. Thus, the thesis focused on finding solutions and appropriate mitigation techniques to the existing power quality problems and improving the profitability of the industry.

1.3. Significance of the Study

The output of this thesis work addresses the existing power quality problems and to increases the efficiency, performance of their equipment and saves the money they lost due to poor power quality which causes production loss, damage to sensitive electronic devices.

1.4. General and Specific Objectives

1.4.1. General Objective

The main objective of this thesis work is to assess and investigate the power quality problems in ETUR Textile Factory and based on the assessment to mitigate the problem.

1.4.2. Specific objective

The specific objectives of this thesis are:

- Identify and examine the power quality problems that arise in ETUR Textile Factory.
- Compare the level of those disturbances with acceptable values set by IEEE standards
- Identify the causes and adverse impacts of the identified PQ problems,
- Study and design appropriate mitigation techniques to the existing PQ problems.

1.5. Scope of the study

This thesis works covers the power quality problems exceeding the IEEE standard and their mitigation techniques for ETUR textile PLC. They have dedicated 15KV line from Wonji substation which is around 3KM far from the substation. Due to this their most PQ problems are most likely from their nonlinear loads. Since the factories have their own dedicated line this thesis works mostly focus on harmonics and power factor correction. Problems other than harmonic and power factor can be manageable by both customer and utility.

1.6. Outline of the Thesis

The Thesis is organized in to six chapters which are briefly discussed below.

Chapter two covers theoretical background and literature of the study topics focused on power quality problems in general.

Chapter three shows methodology and approach of the study have been also explained.

Chapter four presents a detailed description of existing study area.

Chapter five briefly discussed on propose and design of appropriate mitigation techniques for power quality problems occurred in the factory us per their severity.

Finally, Conclusion and Recommendation have been made in Chapter Six.

CHAPTER TWO

Theoretical Background and Review of Literature

2.1. Theoretical Background

The IEEE Standard Dictionary of Electrical and Electronics defines power quality as "the concept of powering and grounding sensitive electronic equipment in a manner that is suitable to the operation of that equipment." Power quality may also define as "the measure, analysis, and improvement of bus voltage, usually a load bus voltage to maintain that voltage to be a sinusoidal at rated voltage and frequency". Another definition of power quality reported in the literature [24] is as follows:

Power quality is "the provision of voltage and system design so that the user of electric power can utilize electric energy from the distribution system successfully without interference or interruption." A broad definition of power quality borders on system reliability, dielectric selection on equipment and conductors, long term outages, voltage unbalance in three-phase systems, power electronics and their interface with the electric power supply and many other areas. In an electrical power system, there are various kinds of power quality disturbances. They are classified into different categories and their descriptions are important in order to classify measurement results and to describe electromagnetic phenomena, which can cause power quality problems. The term electric power quality (PQ) is generally used to assess and to maintain the good quality of power at the level of generation, transmission, distribution, and utilization of AC electrical power. Since the pollution of electric power supply systems is much severe at the utilization level, it is important to study at the terminals of end users in distribution systems. There are a number of reasons for the pollution of the AC supply systems, including natural ones such as lightening, flashover, equipment failure, and faults (around 60%) and forced ones such as voltage distortions and notches (about 40%)[1] [5]. A number of customer's equipment also pollute the supply system as they draw no sinusoidal current and behave as nonlinear loads. Therefore, power quality is quantified in terms of voltage, current, or frequency deviation of the supply system, which may result in failure or mal-operation of customer's equipment. Typically, some power quality problems related to the voltage at the point of common coupling (PCC) where various loads are connected are the presence of voltage harmonics, surge, spikes, notches, sag/dip, swell, unbalance, fluctuations, glitches, flickers, outages, and so on. These problems are present in the supply system due to various disturbances in the system or due to the presence of various nonlinear loads such as furnaces, uninterruptible power supplies (UPSs), and adjustable speed drives (ASDs [1]. However, some power quality problems related to the current drawn from the AC mains are poor power factor, reactive power burden, harmonic currents, unbalanced currents, and an excessive neutral current in poly phase systems due to unbalancing and harmonic currents generated by some nonlinear loads. These power quality problems cause failure of capacitor banks, increased losses in the distribution system and electric machines, noise, vibrations, overvoltage and excessive current due to resonance, negative sequence currents in generators and motors, especially rotor heating, de-rating of cables, dielectric breakdown, interference with communication systems, signal interference and relay and breaker malfunctions, false metering, interferences to the motor controllers and digital controllers, and so on.

These power quality problems have become much more serious with the use of solid-state controllers, which cannot be dispensed due to benefits of the cost and size reduction, energy conservation, ease of control, low wear and tear, and other reduced maintenance requirements in the modern electric equipment. Unfortunately, the electronically controlled energy-efficient industrial and commercial electrical loads are most sensitive to power quality problems and they themselves generate power quality problems due to the use of solid-state controllers in them. Because of these problems, power quality has become an important area of study in electrical engineering, especially in electric distribution and utilization systems. It has created a great challenge to both the electric utilities and the manufacturers. Utilities must supply consumers with good quality power for operating their equipment satisfactorily, and manufacturers must develop their electric equipment either to be immune to such disturbances or to override them.

A number of techniques have evolved for the mitigation of these problems either in existing systems or in equipment to be developed in the near future. It has resulted in a new direction of research and development (R&D) activities for the design and development engineers working in the fields of power electronics, power systems, electric drives, digital signal processing, and sensors. It has changed the scenario of power electronics as most of the equipment using power converters at the front end need modifications in view of these newly visualized requirements. Moreover, some of the well-developed converters are becoming obsolete and better substitutes are required. It has created the need for evolving a large number of circuit configurations of front-end converters for very specific and particular applications. Apart from these issues, a number of standards and benchmarks are developed by various organizations such as IEEE (Institute of Electrical and Electronics Engineers) and IEC (International Electro technical Commission), which are enforced on the customers, utilities, and manufacturers to minimize or to eliminate the power quality problems. The techniques employed for power quality improvements in exiting systems facing power quality problems are classified in a different manner from those used in newly designed and developed equipment. These mitigation techniques are further sub classified for the electrical loads and supply systems, since both of them have somewhat different kinds of power quality problems [8] [11] [19].

In existing nonlinear loads, having the power quality problems of poor power factor, harmonic currents, unbalanced currents, and an excessive neutral current, a series of power filters of various types such as passive, active, and hybrid in shunt, series, or a combination of both configurations are used externally depending upon the nature of loads such as voltage-fed loads, current-fed loads, or a combination of both to mitigate these problems. However, in many situations, the power quality problems may be other than those of harmonics such as in distribution systems, and the custom power devices such as distribution static compensators (DSTATCOMs), dynamic voltage restorers (DVRs), and unified power quality conditioners (UPQCs) are used for mitigating the current, voltage, or both types of power quality problems. Power quality improvement techniques used in newly designed and developed systems are based on the modification of the input stage of these systems with power factor corrected (PFC) converters, also known as improved power quality AC–DC converters (IPQCs), multi pulse AC - DC converters, matrix converters for AC–DC or AC–AC conversion, and so on, which inherently mitigate some of the power quality problems in them and in the supply system by drawing clean power from the utility. This thesis is aimed at providing an awareness of the power quality problems, their causes and adverse effects, an exhaustive exposure of the mitigation techniques to the customers, designers, manufacturers, application engineers, and researchers dealing with the power quality problems [1].

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

2.2 Identify Power Quality Problems

It is the first and basic step in the task of power quality assessment. The specific power quality problems that need to be evaluated will be different from customer to customer. A review of the types of equipment used by the customer, process requirements and economic impacts of problems will lead to a list of problems that need to be studied. They can include possible problems with both the utility distribution system and the customer facilities [7] [13].

The power quality problems have been present since the inception of electric power. There have been several conventional techniques for mitigating the power quality problems and in many cases even the equipment are designed and developed to operate satisfactorily under some of the power quality problems. However, recently the awareness of the customers toward the power quality problems has increased tremendously because of the following reasons: The customer's equipment have become much more sensitive to power quality problems than these have been earlier due to the use of digital control and power electronic converters, which are highly sensitive to the supply and other disturbances. The increased use of solid-state controllers in a number of equipment with other benefits such as decreasing the losses, increasing overall efficiency, and reducing the cost of production has resulted in the increased harmonic levels, distortion, notches, and other power quality problems. It is achieved, of course, with much more sophisticated control and increased sensitivity of the equipment toward power quality problems. Typical examples are ASDs and energy-saving electronic ballasts, which have substantial energy savings and some other benefits; however, they are the sources of waveform distortion and much more sensitive to the number of power quality disturbances [1].

The awareness of power quality problems has increased in the customers due to direct and indirect penalties enforced on them, which are caused by interruptions, loss of production, equipment failure, standards, and so on. The disturbances to other important appliances such as telecommunication network, TVs, computers, metering, and protection systems have forced the end users to either reduce or eliminate power quality problems or dispense the use of power polluting devices and equipment. The deregulation of the power systems has increased the importance of power quality as consumers are using power quality as performance indicators and it has become difficult to maintain good power quality in the world of liberalization and privatization due to heavy competition at the financial level. Distributed generation using renewable energy and other local energy sources has increased power quality problems as it needs, in many situations, solid-state conversion and variations in input power add new problems of voltage quality such as in solar PV generation and wind energy conversion systems. Similar to other kinds of pollution such as air, the pollution of power networks with power quality problems has become an environmental issue with other consequences in addition to financial issues. Several standards and guidelines are developed and enforced on the customers, manufacturers, and utilities as the law and discipline of the land [1] [14].

The quality of power has often been characterized as “clean” or “dirty.” Clean power refers to power that has sinusoidal voltage and current without any distortion and operates at the designed magnitude and frequency. Dirty power describes power that has a distorted sinusoidal voltage and current or operates outside the design limits of voltage, current, and/or frequency. Natural and man-made events in the power system provide sources or initiating events that cause clean power to become dirty. Categories of dirty power quality sources include power system events, nonlinear loads, and poor wiring and grounding.

Examples of dirty power quality sources include lightning, adjustable speed drives, and loose connections. The source of a power quality problem often causes a disturbance or power quality variation. The disturbance can then affect the operation of end-user equipment. This may seem confusing. To make sense of the confusing causes and effects of power quality problems, the power quality engineer breaks down a power quality problem into three parts: sources (initiating events), causes, and effects of power quality. The ability to define and understand the various types of power quality problems provides the necessary background needed to prevent and solve those problems. The power quality signature, or characteristic, of the disturbance identifies the type of power quality problem. The nature of the variation in the basic components of the sine wave, i.e., voltage, current, and frequency, identifies the type of power quality problem. Voltage sags are the most common type of power quality problems [28].

However, the IEEE Standard 1159-1995, classifies the power quality problem into seven major categories described as follows [15] [17] [18]:

a. Voltage Transient

- Impulsive transient
- Oscillatory transient

b. Short duration voltage variation

- Interruption
- Sag
- Swell

c. Long duration voltage variation

- Under voltage
- Over voltage
- Sustained interruption

d. Waveform distortions

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

e. Voltage unbalance

f. Voltage Fluctuation

g. Frequency deviation

(a) Transients

Transients are undesirable momentary changes in voltage and/or current signals in the power system. There are many causes due to which transients are produced in the power system. Some of them are: Arcing between the contacts of the switches, sudden switching of loads, poor or loose connections, and lightning strokes. These transients are categorized into impulsive and oscillatory transients.

- Impulsive Transient

An impulsive transient is "a sudden, non-power frequency change in the steady state condition of voltage, current, or both, that is unidirectional in polarity". Impulsive transients are normally characterized by their rise and decay times, which can also be revealed by their spectral content. Impulsive transients are generally caused by lightning strikes. An impulsive transient due to lightning strokes can occur because of a direct strike to a power line or from magnetic induction or capacitive coupling from strikes on adjacent lines.

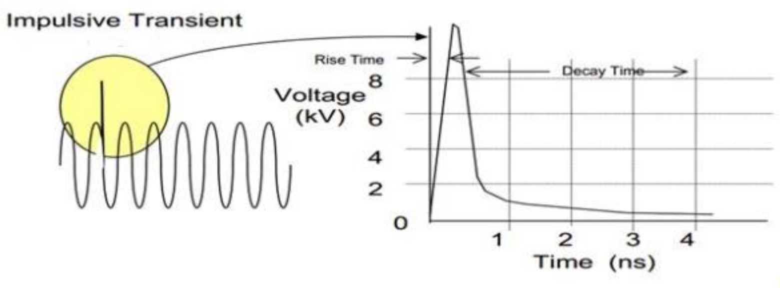

Figure 2.1 Impulsive Transient [28]

- Oscillatory Transient

An oscillatory transient is a sudden, non-power frequency change in the steady state condition of voltage, current or both that includes both positive and negative polarity values. An oscillatory transient consists of a voltage or current whose instantaneous value changes polarity rapidly. It is described by its spectral content, duration, and magnitude. They are characterized by fluctuations in the measured quantity at very high frequencies. These can be further classified according to their frequency as high frequency transients (transients with a primary frequency component greater than 500 kHz and a typical duration measured in microseconds), medium frequency transients (transients with a primary frequency component between 5 and 500 kHz with duration measured in tens of microseconds.) or low frequency transients (transients with a primary frequency component less than 5 kHz and duration of from 0.3 to 50 ms), with the cause of the fault dependent upon the frequency. Due to the high frequency spectral contents of the oscillatory transients, they have undesirable effects of electromagnetic interference. High magnitude oscillatory transients can also damage electrical and electronic equipment due to the over voltage condition. Utility switching and capacitor energization are just two causes of oscillatory transient faults.

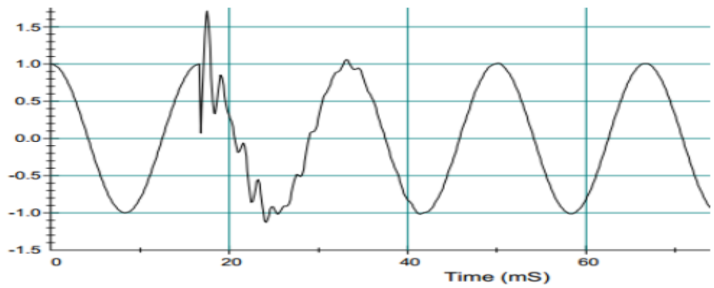

Figure 2.2 Oscillatory Transient [15]

(b). Short-Duration Voltage Variation

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

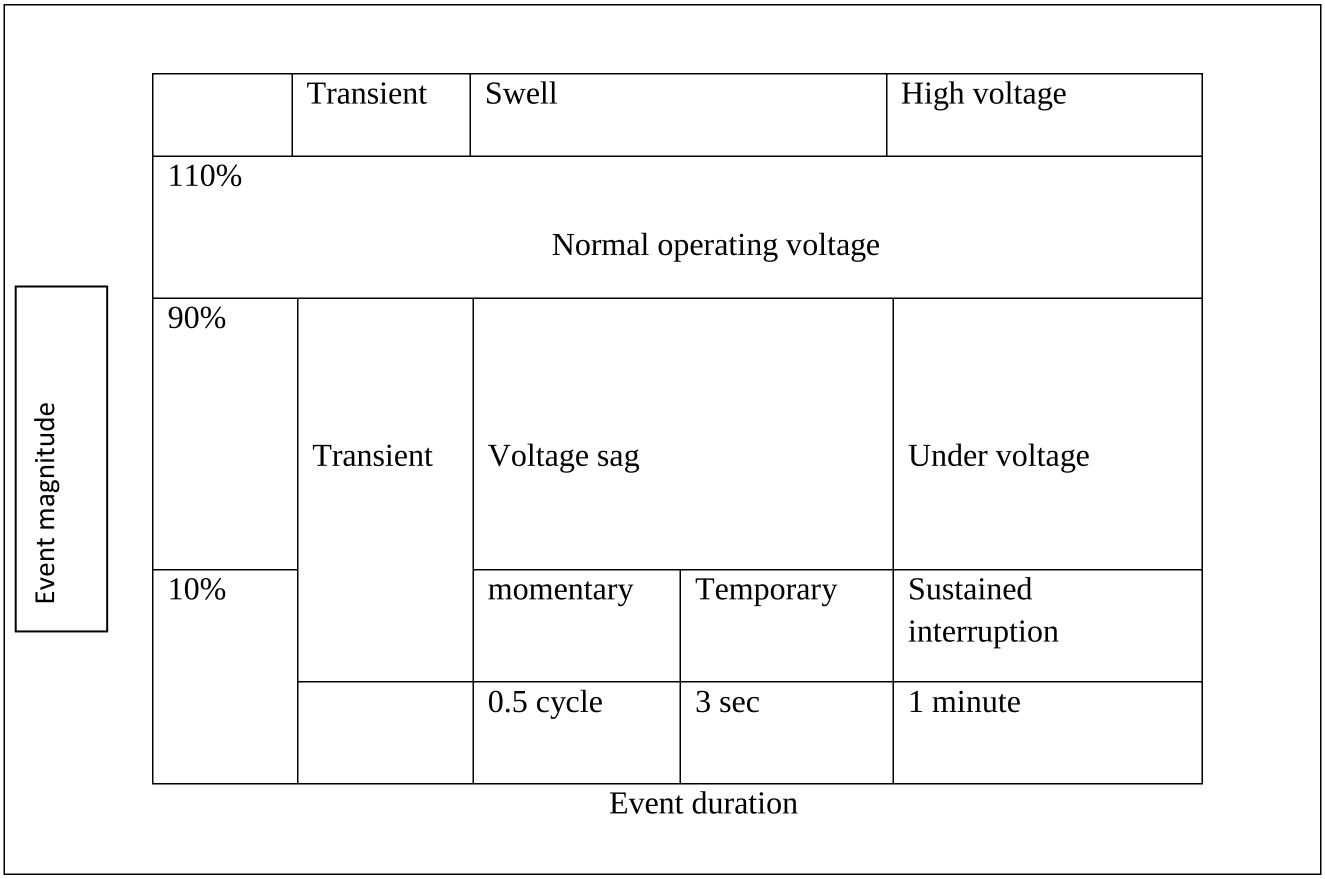

Figure 2.3 Voltage Variations [15]

- Voltage Sag

Voltage sags are referred to as voltage dips in Europe. IEEE defines voltage sags as a reduction in voltage for a short time. The duration of voltage sag is less than 1 minute but more than 8 milliseconds (0.5 cycles). The magnitude of the reduction is between 10 percent and 90 percent of the normal root mean square (rms) voltage at 60 Hz. The rms, or effective, value of a sine wave is the square root of the average of the squares of all the instantaneous values of a cycle and is equal to 0.707 ($1/\sqrt{2}$) times the peak value of the sine wave, as shown in Figure 2.4. A more detailed discussion of rms follows in the section on harmonics. Voltage sags differ from other voltage reduction, other voltage reduction disturbances often occur intermittently, like voltage flicker, while voltage sags occur once, for a short time. Figure 2.4 shows the voltage returning to normal after 0.12- second voltage sag. Utilities and end users can cause voltage sags on transmission and distribution systems. For example, a transformer failure can be the initiating event that causes a fault on the utility power system that result in voltage sag. These faults draw energy from the power system. Voltage sag occurs while the fault is on the utility's power system. As soon as a breaker or re-closer clears the fault, the voltage returns to normal. Transmission faults caused voltage sags that last about 6 cycles, or 0.10 second. Distribution faults last longer than transmission faults, while large motor loads can cause voltage sag on utility's and end user's power systems. Compared to other power quality problems affecting industrial and commercial end users, voltage sags occur most frequently. They reduce the energy being delivered to the end user and cause computers to fail, adjustable-speed drives to shut down, and motors to stall and overheat. Solutions to voltage sag problems include equipment that protects loads that are sensitive to voltage sags. Examples of these types of equipment include ferroresonnant, i.e., constant voltage transformers; dynamic voltage restorers (DVRs); superconducting energy storage devices; flywheels; written pole motor generator sets; and uninterruptible power supplies (UPS).[28]

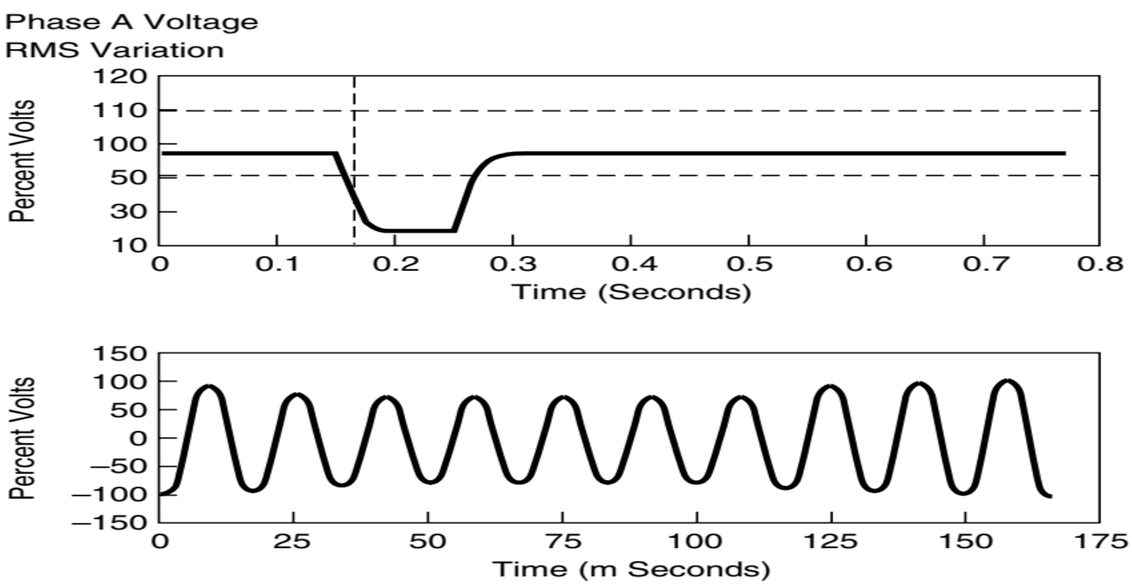

Figure 2.4 Voltage sag [28]

- Voltage Swell

Voltage swells, or momentary overvoltage's, are rms voltage variations that exceed 110 percent of the nominal voltage and last for less than 1 minute. Voltage swells occur less frequently than voltage sags. Single line to ground faults caused voltage swells. Examples of single-line to ground faults include lightning or a tree striking a live conductor. The increased energy from a voltage swell often overheats equipment and reduces its life. Figure 2.5 illustrates a typical voltage swell caused by a single-line to ground fault occurring in an adjacent phase. [28]

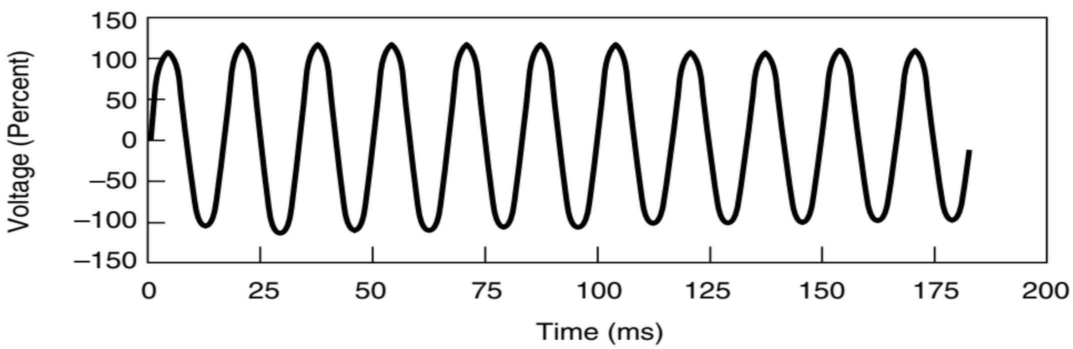

Figure 2.5 Voltage swell [28]

- Interruption

Interruptions are a complete loss of voltage (a drop to less than 10 percent of nominal voltage) in one or more phases. IEEE Recommended Practice for Monitoring Electric Power Quality defines three types of interruptions. They are categorized by the time period that the interruptions occur: momentary, temporary, and long-duration interruptions. Momentary interruptions are the complete loss of voltage on one or more phase conductors for a time period between 0.5 cycles, or 8 milliseconds, and 3 seconds. A temporary, or short-duration, interruption is a drop of voltage below 10 percent of the nominal voltage for a time period between 3 seconds and 1 minute. Long-duration, or sustained, interruptions last longer than 1 minute. Figure 2.6 shows a momentary interruption. Loss of production in a business costs money. Any kind of interruption can result in loss of production in an office, retail market, or industrial factory. Not only does the loss of electrical service cause lost production, but the time required to restore electrical service also causes lost production. Some types of processes cannot "ride through" even short interruptions. "Ride through" is the capability of equipment to continue to operate during a power disturbance. For example, in a plastic injection molding plant, for a short interruption of 0.5 second it takes 6 hours to restore production. The common methods of reducing the impact of costly interruptions include on-site and off-site alternative sources of electrical supply. An end user may install on-site sources, such as battery-operated uninterruptible power supplies (UPS) or motor-generator sets, while a utility may provide an off-site source that includes two feeders with a high-speed switch that switches to the alternate feeder when one feeder fails. [28]

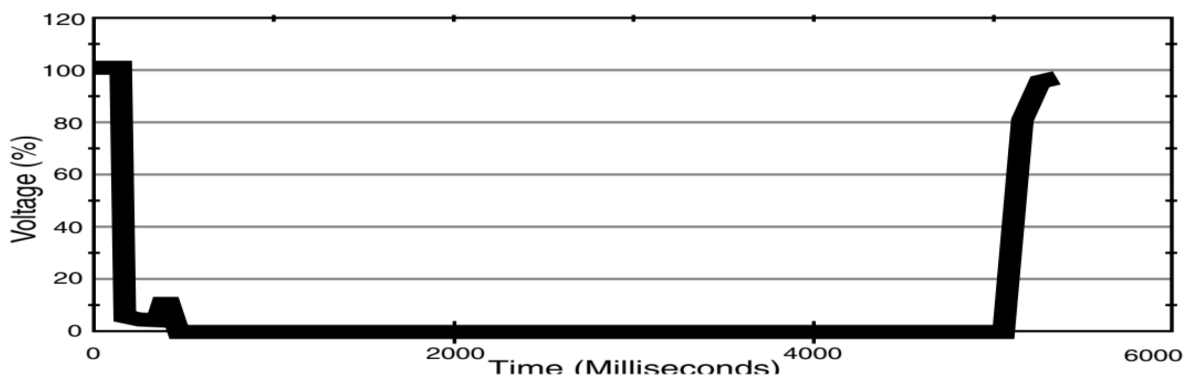

Figure 2.6 Momentary, temporary, and long-duration interruption plots [28]

(c). Long Duration Voltage Variation

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

- Overvoltage

Overvoltages are close cousins to voltage swells, except they last longer. Like voltage swells, they are rms voltage variations that exceed 110 percent of the nominal voltage. Unlike swells, they last longer than a minute. Several types of initiating events cause overvoltage. The major cause of overvoltage is capacitor switching. This is because a capacitor is a charging device. When a capacitor is switched on, it adds voltage to the utility's system. Another cause of overvoltage is the dropping of load. Light load conditions in the evening also cause overvoltage on high voltage systems. Another common cause of overvoltage is the missetting of voltage taps on transformers. Extended overvoltage shortens the life of lighting filaments and motors. Solutions to overvoltage include using inductors during light load conditions and correctly setting transformer taps. Figure 2.7 shows a plot of overvoltage versus time [28].

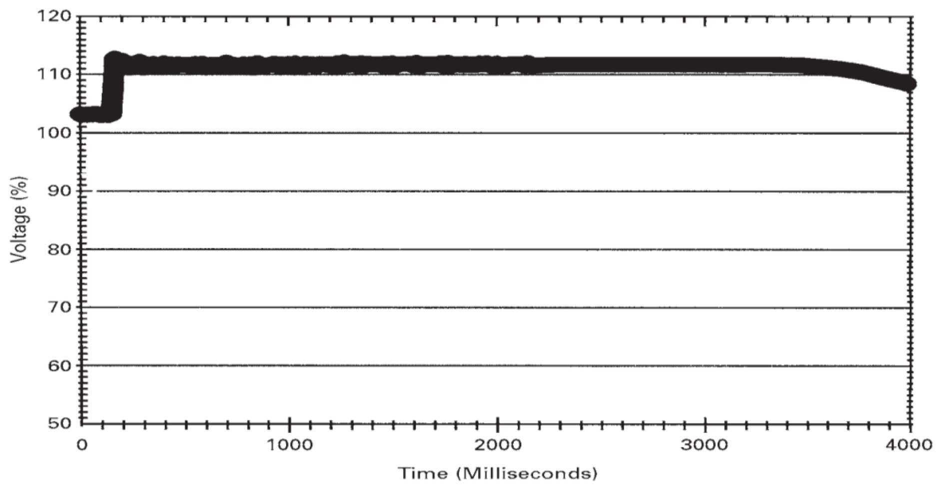

Figure 2.7 over voltage [28]

- Undervoltage

Undervoltage occurs when the voltage drops below 90 percent of the nominal voltage for more than 1 minute. They are sometimes referred to as "brownouts," although this is an imprecise nontechnical term that should be avoided. They are recognized by end users when their lights dim and their motors slow down. Too much load on the utility's system, during very cold or hot weather, for example, or the loss of a major transmission line serving a region can cause under voltages. Overloading inside an end user's own distribution system can cause under voltages. Sometimes utilities deliberately cause under voltages to reduce the load during heavy load conditions. Reducing the voltage reduces the overall load, since load is voltage times current (kW = $V I$). Under voltages can cause sensitive computer equipment to read data incorrectly and motors to stall and operate inefficiently. Utilities can prevent under voltages by building more generation and transmission lines. Figure 2.8 shows a typical plot of under voltage versus time.

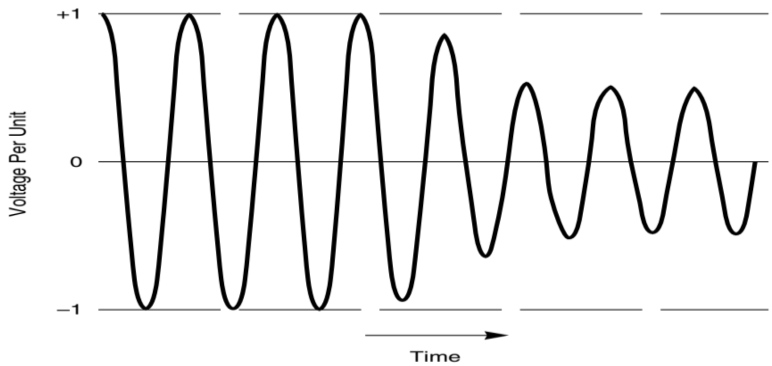

Figure 2.8 Undervoltage plots [28]

(d). Voltage Unbalance

Voltage unbalance or imbalance is the deviation of each phase from the average voltage of all three phases. Most equipment, especially motors, can tolerate a voltage unbalance of 2 percent. A voltage unbalance greater than 2 percent will cause motors and transformers to overheat. This is because a current unbalance in an induction device, like a motor or transformer, varies as the cube of the voltage unbalance applied to the terminals. Potential causes of voltage unbalance include capacitor banks not operating properly, single phasing of equipment, and connecting more single-phase loads on one phase than another. Installing monitors to measure the voltage unbalance provides the necessary data to analyze and eliminate the cause of the unbalance. Winding insulation life is reduced by one-half for each 10°C increase in operating temperature

(e). Voltage Fluctuation

Voltage fluctuations are rapid changes in voltage within the allowable limits of voltage magnitude of 0.95 to 1.05 of nominal voltage. Devices like electric arc furnaces and welders that have continuous, rapid changes in load current cause voltage fluctuations. Voltage fluctuations can cause incandescent and fluorescent lights to blink rapidly. This blinking of lights is often referred to as “flicker.” This change in light intensity occurs at frequencies of 6 to 8 Hz and is visible to the human eye. It can cause people to have headaches and become stressed and irritable. It can also cause sensitive equipment to malfunction. The solution to voltage fluctuations is a change in the frequency of the fluctuation. In the case of an arc furnace, this usually involves the use of costly but effective static VAR controllers (SVCs) that control the voltage fluctuation frequency by controlling the amount of reactive power being supplied to the arc furnace. Figure 2.9 shows voltage fluctuations that produce flicker [28].

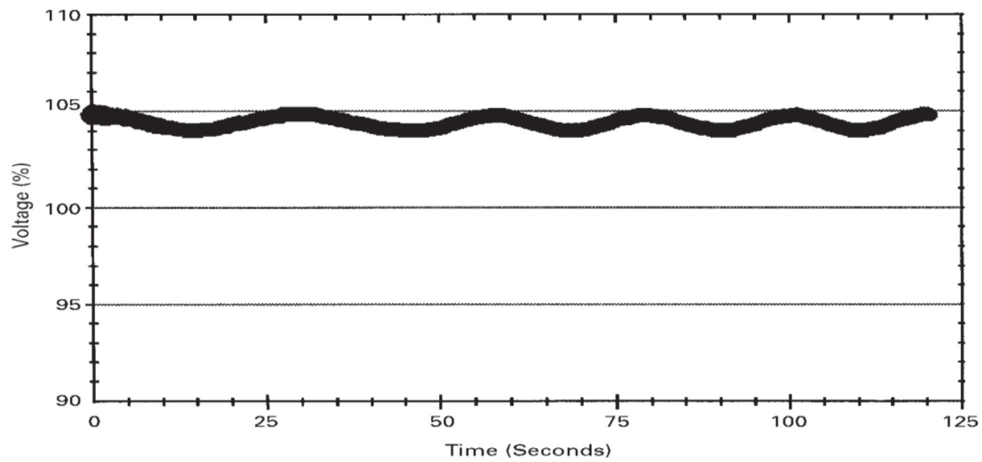

Figure 2.9 Voltage fluctuation (flicker) plot [28]

(f). Waveform Distortion

Waveform distortion is defined as any steady-state deviation of voltage or/and 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 Fourier transform [1].

The effect of the harmonic contents on the distortion of the sinusoidal waveform can be observed usually, the voltage waveform has negligible harmonics that it can be assumed to be pure sinusoidal at the fundamental frequency. In this 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.

- 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. 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.

- Harmonics

Harmonics is a growing problem for both electricity suppliers and users. A harmonics is defined as a sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency usually 50Hz or 60Hz. Distorted waveforms can be decomposed into a sum of the fundamental frequency and the harmonics. Harmonic distortion originates in the nonlinear characteristics of devices and loads on the power system [6].

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

High levels of harmonic distortion can cause such effects as increased transformer, capacitor, motor or generator heating, miss-operation of electronic equipment (which relies on voltage zero crossing detection or is sensitive to wave shape), incorrect readings on meters and miss-operation of protective relays. The likelihood of such ill effects occurring is greatly increased if a resonant condition occurs. Resonance occurs when a harmonic frequency produced by a non-linear load closely coincides with a power system natural frequency [14] [23].The high frequency harmonics may also cause interference to nearby telecommunication system.

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 [1] [7]:

- 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

Using the Fourier series expansion, we can represent a distorted periodic wave shape by its fundamental and harmonics [1] [6] [10]. It is also common to use a single quantity, the total harmonic distortion (THD), as a measure of the effective value of harmonic distortion. For characterizing harmonic currents in a consistent fashion, IEEE Standard 519-1992 defines another term, the total demand distortion (TDD). This term is the same as the total harmonic distortion except that the distortion is expressed as a percent of some rated load current rather than as a percent of the fundamental current magnitude at the instant of measurement [3].

The development of current distortion limits is to:

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

- 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. Inter harmonics are generally the result of frequency conversion activities. The main sources of inter harmonics are static frequency converters, cyclic- converters, induction furnaces, and arcing devices. Power line carrier signals can also be considered as inter harmonics. Inter harmonic currents can excite resonances on the power system as the varying inter harmonic frequency becomes coincident with natural frequencies of the system. The higher frequency inters harmonic signals affect the power-line-carrier signaling. They can also induce visual flicker in fluorescent lamps and other arc lighting as well as in computer display devices [7].

- Notching

Notching is a periodic transient occurring within each cycle as a result of the phase-to-phase short circuit caused by the commutation process in AC–DC converters (Figure 2.10). Being periodic, this disturbance is characterized by the presence of the harmonic spectrum of the voltage waveform; in particular, notching mainly results in high-order harmonics. Most problems caused by notches are confined to a customer's own installation. In fact, the high frequency content of notches not under a utility's control is 'filtered' by the power transformer at the service entrance. Voltage notches are characterized by their depth and duration in combination with the point on the sine wave at which the notching starts. [11]

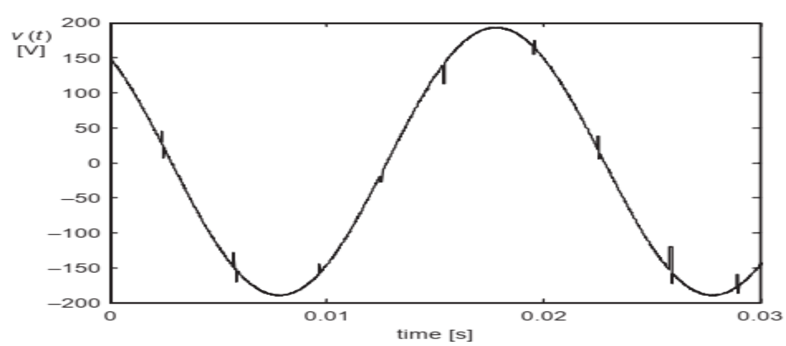

Figure 2.10 Notching [11]

- Noise

When you think of electrical noise, you may think of the audible crackling noise that emanates from high-voltage power lines, or you may imagine the low throbbing hum of an energized transformer. This type of noise can affect your life quality as much as your power quality. In fact, one man complained that the corona noise from a nearby 500-kV power line drowned out the babbling of a brook in his backyard. When power quality experts talk about electrical noise, they do not mean these audible noises. They mean the electrical noise that is caused by a low-voltage, high-frequency (but lower than 200-Hz) signal superimposed on the 60-Hz fundamental waveform. This type of electrical noise may be transmitted through the air or wires. High-voltage lines, arcing from operating disconnect switches, startup of large motors, radio and TV stations, switched mode power supplies; loads with solid-state rectifiers, fluorescent lights, and power electronic devices can all cause this type of noise. Electrical noise adds “hash” onto the fundamental sine wave, as shown in Figure 2.11. Electrical noise can degrade telecommunication equipment, radio, and TV reception, and damage electronic equipment as well. There are two ways of solving the electrical noise problem. One solution is to eliminate the source of the electrical noise. Another way is to either stop or reduce the electrical noise from being transmitted. For example, the use of multiple conductors or installation of corona rings can reduce electrical noise from high-voltage lines. Grounding equipment and the service panel to a common point can eliminate electrical noise from ground loops. This prevents the ground wires from acting as a loop antenna and transmitting a “humming” type noise that interferes with communication signals. The electromagnetic interference (EMI) type of noise is reduced by shielding the sensitive equipment from the source of the electrical noise. Another way of protecting sensitive equipment from EMI is to simply move the source of the EMI far enough away so that the EMI becomes too weak to affect the sensitive equipment. [11]

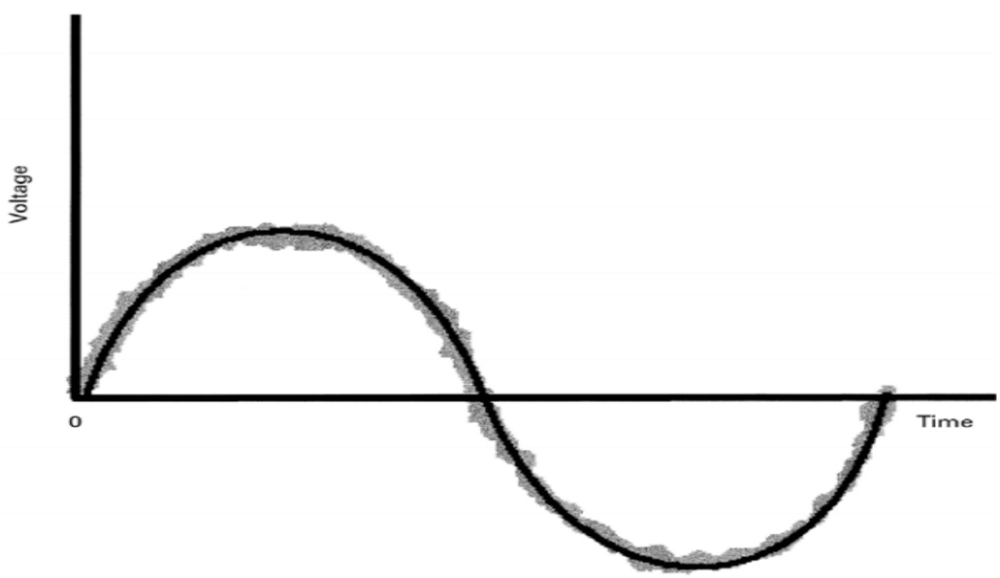

Figure 2.11 Noise [11]

(g). Voltage Fluctuation

A series of voltage changes or a continuous variation in the RMS voltage are denoted voltage fluctuations (Figure 2.12). If fluctuations occur within proper frequency ranges, they cause changes in the luminance of lamps, which can create the visual phenomenon called 'flicker.' Above a certain threshold, the flicker becomes annoying, and annoyance grows very rapidly with the amplitude of the fluctuation. At certain repetition rates, even very small amplitudes can be annoying. The main sources of severe voltage fluctuations are industrial loads, which are particularly troublesome in the steelmaking industry, where there is significant use of arc furnaces, rolling mills and multiple-welder loads. In some cases, large fluctuating motor loads, such as mine winders, can also cause voltage fluctuation problems. Domestic loads with repeated switching, such as cooker hobs, electric showers, heat pumps and air conditioning, have the potential to cause local flicker, but the problem is contained by imposing statutory product design constraints in terms of the size and frequency of load switching. It should be noted that voltage fluctuations and inter-harmonics have an inherent relationship. In fact, the magnitude of a voltage waveform can fluctuate if it contains inter-harmonics, and conversely, the voltage fluctuation can cause the presence of inter-harmonics. Experience has shown that even a small amount of inter-harmonics can result in perceptible light flicker in incandescent and fluorescent lamps. In addition to flicker, an effect produced by voltage fluctuations is the braking or acceleration of motors connected directly to the system [12].

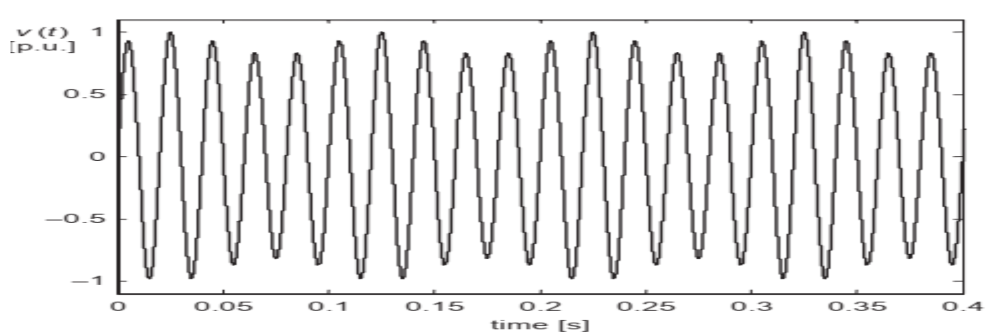

Figure 2.12 voltage fluctuations

(h). Power Frequency Variations

A power frequency variation is a deviation of the frequency from the nominal value (equal to 50 or 60 Hz and denoted the power supply frequency, power system frequency or power frequency). A power frequency variation is linked directly to the variation in rotation speed of the generators supplying the electrical power system. There are slight variations in frequency due to imbalances between load and generation. Slight deviations in frequency can cause severe damage to generators and turbine shafts due to the large torque developed. In addition, cascading system separations can result with even slight deviations in frequency, since electric systems are closely connected and depend on synchronous operation. Actually, significant frequency variations are rare in modern interconnected power systems [12].

2.3 Causes of Power Quality Problems.

There are a number of power quality problems in the present-day fast-changing electrical systems. The main causes of these power quality problems can be classified into natural and man-made in terms of current, voltage, frequency, and so on. The natural causes of poor power quality are mainly faults, lightning, weather conditions such as storms, equipment failure, and so on. However, the man-made causes are mainly related to loads or system operations. The causes related to the loads are nonlinear loads such as saturating transformers and other electrical machines, or loads with solid-state controllers such as vapor lamp-based lighting systems, ASDs, UPSs, arc furnaces, computer power supplies, and TVs. The causes of power quality problems related to system operations are switching of transformers, capacitors, feeders, and heavy loads. The natural causes result in power quality problems that are generally transient in nature, such as voltage sag (dip), voltage distortion, swell, and impulsive and oscillatory transients. However, the manmade causes result in both transient and steady-state types of power quality problems. Table 2.1 lists some of the power quality problems and their causes. However, one of the important power quality problems is the presence of harmonics, which may be because of several loads that behave in a nonlinear manner, ranging from classical ones such as transformers, electrical machines, and furnaces to new ones such as power converters in vapor lamps, switched-mode power supplies (SMPS), ASDs using AC–DC converters, cyclo-converters, AC voltage controllers, HVDC transmission, static VAR compensators, and so on [1].

Table 2.1 lists of the power quality problems and their causes

Problems	Category	Categorization	Causes	Effects
Transients	Impulsive	Peak rise time and duration	Lightning strikes, transformer energization, capacitor switching	Power system resonance
	Oscillatory	Peak magnitude and frequency components	Line, capacitor, or load switching	System resonance
Short-duration voltage variation	Sag	Magnitude, duration	Motor starting, single line to ground faults.	Protection malfunction, loss of production
	Swell	Magnitude, duration	Capacitor switching, large load switching, faults	Protection malfunction stress on computers and home appliances
	Interruption	Duration	Temporary faults	Loss of production, malfunction of fire alarms
Long-duration voltage variation	Sustained interruption	Duration	Faults	Loss of production
	Undervoltage	Magnitude, duration	Switching on loads, capacitor de-energization	Increments losses, heating
	Overvoltage	Magnitude, duration	Switching off loads, capacitor energization	Damage to house hold appliances
Voltage imbalance		Symmetrical components	Single-phase load, single-phase	Heating of motors
Waveform distortion	DC offset	Volts, amperes	Geomagnetic disturbance rectification	Saturation in transformer
	Harmonics	THD, harmonics spectrum	ASDs, nonlinear loads	Increased losses, poor power factor
	Interharmonics	THD, harmonics spectrum	ASDs, nonlinear loads	Acoustic noise in power equipment
	Notching	THD, harmonics spectrum	Power electronic converters	Damage to capacitive components
	Noise	THD, harmonics spectrum	Arc furnace , arc lamps, power converters	Capacitor overloading, disturbance to

			appliance
Voltage flicker	Frequency of occurrence, modulating frequency.	Arc furnace , arc lamps	Human health, irritation, headache, migraine
Voltage fluctuations	Intermittent	Load change	Protection malfunction, light intensity changes
Power frequency variation		Faults, disturbance in isolated customer-owned system and islanding operation	Damage to generator and turbine shafts

2.4. Loads That Cause Power Quality Problems

In true sense, most of the electrical loads have nonlinear behavior at the AC mains. As they draw harmonic currents of various types such as characteristic harmonics, non-characteristic harmonics, inter harmonics, sub harmonics, reactive power component of current, fluctuating current, unbalanced currents from the AC mains, these loads are known as nonlinear loads. Majority of rotating electric machines and magnetic devices such as transformers, reactors, chokes, magnetic ballasts, and so on behave as nonlinear loads due to saturation in their magnetic circuits, geometry such as presence of teeth and slots, winding distribution, air gap asymmetry, and so on. Many fluctuating loads such as furnaces, electric hammers, and frequently switching devices exhibit highly nonlinear behavior as electrical loads. Even non saturating electrical loads such as power capacitors behave as nonlinear loads at the AC mains and they create a number of power quality problems due to switching and resonance with magnetic components in the system and are overloaded due to harmonic currents caused by the presence of harmonic voltages in the supply system. Moreover, the solid-state control of AC power using diodes, thyristors, and other semiconductor switches is widely used to feed controlled power to electrical loads such as lighting devices with electronic ballasts, controlled heating elements, magnet power supplies, battery chargers, fans, computers, copiers, TVs, switched mode power supplies (SMPS) in computers and other equipments, furnaces, electroplating, electrochemical processes, adjustable speed drives (ASDs) in electric traction, air-conditioning systems, pumps, wastewater treatment plants, elevators, conveyers, cranes, and so on. These AC loads consisting of solid-state converters draw non-sinusoidal currents from the AC mains and behave in a nonlinear manner and therefore they are also known as nonlinear loads. These nonlinear loads consisting of solid state converters draw harmonic currents and reactive power component of current from the AC mains. In three-phase systems, they could also cause unbalance and sometimes draw excessive neutral current, especially the distributed single-phase nonlinear loads on three-phase four-wire supply system. These solid-state converters may be AC–DC converters, AC voltage controllers, cyclo-converters, and so on. The injected harmonic currents, reactive power burden, unbalanced currents, and excessive neutral current caused by these nonlinear loads result in low system efficiency, poor power factor (PF), mal-operation of protection systems, AC capacitors overloading and nuisance tripping, noise and vibration in electrical machines, heating of the rotor bars due to negative sequence currents, de-rating of components of distribution system, user equipment, and so on. They also cause distortion in the supply voltage, disturbance to protective devices and other consumers, and interference in nearby communication networks and digital and analog control systems [1] [10]. These nonlinear loads exhibit different behavior thereby causing different power quality problems, and they are therefore often classified according to their performance. Accordingly, the power quality improvement techniques for mitigating the power quality problems caused by nonlinear loads are also different to reduce the rating and cost of devices used for these purposes. One of the major and broad classifications of these nonlinear loads is based on their behavior either as current fed type or as voltage fed type or a combination of both. The current fed type of nonlinear loads with AC–DC converters having constant DC current used for field winding excitation, magnet power supplies, thyristor converter feeding DC motor drives, converter feeding current source inverter-fed AC motor drives, magnetic devices with saturation, and so on draw the pre-specified kind of current pattern. Normally devices used for power quality improvements of such current fed type nonlinear loads are connected in shunt with the loads to supply locally all their current components other than the fundamental active power component of load current. On the contrary, the voltage fed type of nonlinear loads having AC–DC converters feeding almost constant DC voltage loads such as battery chargers, AC–DC converters with large DC filter capacitor as front-end converters in SMPS, AC–DC converters in voltage source inverter feeding AC motor drives, and so on draw highly nonlinear and unpredictable current waveform rich in harmonics with high crest factor (CF) [1].

In general, devices used for power quality improvements of such voltage fed type nonlinear loads are connected in series with these loads to block all their harmonic currents with much reduced rating and they do not have reactive power requirement. The mixed nonlinear loads consist of either several current fed type and voltage type of nonlinear loads or typically AC–DC converters with LC DC bus filter. The devices used for power quality improvements of such mixed nonlinear loads are connected in shunt with these loads or consist of hybrid of shunt and reduced rating series devices. Despite causing power quality problems, the use of nonlinear loads, especially those employing solid-state controllers, is increasing day by day owing to benefits of the low cost and small size, remarkable energy conservation, and simplicity in control, reduced wear and tear, and low maintenance requirements in the new and automated electric appliances leading to high productivity. Although these electronically automated energy efficient electrical loads are most sensitive to power quality problems, they themselves cause additional power quality problems to the supply system. Hence, it is very important to classify and analyze their behavior to identify the proper power quality improvement devices for mitigating the power quality problems or to modify their structure for reducing or eliminating the power quality pollution at the AC mains. Since the inception of AC power, majority of electrical equipment are developed based on the principle of energy storage, which are used in the process of energy conversion and especially in the magnetic energy storage system. They behave as inductive loads causing burden on the AC mains of the lagging reactive power and thereby poor power factor in the AC network that results in increased losses and poor utilization of components of distribution system such as transformers, feeders, and switchgear due to increased current for a given active power. AC power capacitors and synchronous condensers have been used to supply the reactive power locally and to reduce the burden of reactive power on the AC mains. In addition, because of a number of single-phase loads in the distribution system, especially domestic, residential, and commercial in small power ratings and traction, transportation, rural distribution systems, and so on in medium power ratings, there have been additional problems of load unbalancing and excessive neutral current causing increased losses, voltage imbalance, and de-rating of the distribution system. Moreover, switching in many electrical loads causes switching transients and inrush currents resulting in various voltage-based power quality problems such as surges, spikes, sags, voltage fluctuations, voltage imbalance, and so on. These power quality problems affect other loads and system components such as protection systems, telecommunication systems, and so on. These power quality problems of voltage imbalance and fluctuations even affect good linear loads such as AC motors, especially induction motors, with negative sequence currents and subsequent rotor heating and increased losses and thus resulting in de-rating of these motors. Some additional power quality problems are created because of several physical phenomena in electric equipment such as saturation especially in single-phase induction motors, magnetic ballasts, transformers, voltage regulators based on Ferro resonant and tap changers, and air gap asymmetry in rotating electric motors. They result in the generation of harmonics and increased neutral current. These harmonics and neutral current result in voltage distortion at the neutral terminal, increased losses, and harmonic voltage at the point of common coupling (PCC). With the subsequent advancement, the modern automated controlled electrical loads use solid-state converters because of a number of benefits, namely, energy conservation, reduced size, and reduced overall cost, and so on.

However, even with sinusoidal applied voltage, they draw non-sinusoidal and increased current from the AC mains in addition to the fundamental active power component of current. Some of these nonlinear loads are as follows: [1] [28]

- Fluorescent lighting and other vapor lamps with electronic ballasts
- Switched mode power supplies
- Computers, Xerox machines , medical equipment and television sets
- Printer, scanners, and fax machines
- High-frequency welding machines
- Fans with electronic regulators
- Microwave ovens and induction heating devices
- Variable frequency-based HVAC (heating ventilation and air-conditioning) systems
- Battery chargers and fuel cells
- Electric traction
- Arc furnaces
- Cyclo-converters
- Adjustable speed drives
- Static slip energy recovery schemes of wound rotor induction motors
- Wind and solar power generation

- Static VAR compensators (SVCs)
- HVDC transmission systems
- Magnet power supplies
- Plasma power supplies
- Static field excitation systems

These types of nonlinear loads draw harmonic currents and reactive power component of the current from the single-phase AC mains. Some of them have harmonic currents, reactive power component of the current, and unbalanced currents in the three-phase three-wire supply system. The single-phase distributed nonlinear loads also consist of harmonic currents, reactive power component of the current, and unbalanced currents and excessive neutral current in three-phase four-wire system. These increased currents in addition to the fundamental active power component of current cause increased losses, poor power factor, disturbances to other consumers, communication systems, protection systems, and many other electronics appliances, voltage distortion, voltage spikes, voltage notches, surges, dip, sag, swell in voltages, and so on. Owing to the ever-increasing use of such nonlinear loads in present-day distribution system for obvious reasons, the exhaustive study of these nonlinear loads becomes very relevant to find the proper remedy for mitigation of power quality problems caused by them in the supply system.

Classification of Nonlinear Loads

The nonlinear loads can be classified based on [10]

(i) The use of non-solid-state or solid-state devices, for example, the presence or absence of power electronics converter in the circuits of nonlinear loads

(ii) The use of converter types such as AC–DC converter type, AC voltage controller type, and cyclo-converter type

(iii) Their nature as stiff current fed type or stiff voltage fed type or a combination of both

(iv) The number of phases such as two-wire single-phase, three-phase three-wire, and four-wire three-phase systems.

(a).Non-Solid-State Device and Solid-State Device Type Nonlinear Loads.

The nonlinear loads may be classified based on whether they consist of solid-state devices or any other power converters or not. There are a number of electrical loads that are nonlinear in nature, but they do not involve any power converters. Similarly, there are only some nonlinear loads that consist of solid-state converters. These nonlinear loads are further explained with examples.

- Non-Solid-State Device Type Nonlinear Loads.

As already mentioned, there are many electrical loads in nature that do not consist of any solid-state device or power electronics converter. However, they behave as nonlinear loads when they are connected to AC mains. Most of the electrical machines fall in this category of nonlinear loads. A number of physical phenomena in these electrical machines cause their behavior as nonlinear loads. Typically, the saturation in magnetic material of these machines and electromagnetic devices, skin and proximity effects in conductors, non-uniform air gap in rotating machines, effect of teeth and slotting, and so on result in harmonic currents under steady-state and transient conditions in the AC mains when they are connected to the AC supply system. Some practical examples of these types of nonlinear loads are various types of transformers operating at no load or light load conditions, magnetic ballasts of fluorescent lamps, and single-phase induction motors as they are usually designed with high level of no load current (due to high level of saturation) to reduce the cost and size of these motors. They draw harmonic currents and reactive power component of the current, and also cause excessive neutral current in the three-phase four-wire supply system due to such distributed single-phase nonlinear loads.

- Solid-State Device Type Nonlinear Loads

Many types of electrical equipment consist of different circuits of solid-state devices to process the AC power to suit specific application. They draw non-sinusoidal current from the AC mains and they behave as nonlinear loads. This non-sinusoidal current consists of harmonic currents and the reactive power component of the current along with the fundamental active power component of current. They use various AC–DC converters, AC voltage controllers, cyclo-converters, or a combination of all in their front-end converter. In the single-phase configuration, they draw harmonic currents and reactive power from the AC mains. Examples of single-phase nonlinear loads include both domestic and commercial equipment—among the home appliances are microwave oven, induction heaters, television sets, electronic ballasts-based lighting systems, domestic inverter, adjustable speed drive-based air conditioners, and AC voltage regulator-based fans, whereas the commercial and industrial equipment are computers, copiers, fax machines, Xerox machines, scanner, printers, small welding sets, and so on. In the three-phase, three-wire supply system, they may also draw unbalanced three-phase currents in addition to harmonic currents and reactive power. Some practical loads are three-phase adjustable speed drives, consisting of converter-fed DC motor drives, synchronous motor drives, induction motor drives, and other electric motors used in HVAC systems, wastewater treatment plants, large industrial fans, pumps, compressors, cranes, elevators, electrochemical process such as electroplating and electro-mining, and so on. In the three-phase four-wire supply system, there are many single-phase nonlinear loads connected to AC mains causing excessive neutral current. Distributed single-phase loads on all three phases such as electronic ballasts-based lighting systems, computer loads in high storied buildings, and all other single-phase loads cause burden on the AC mains of harmonic currents, reactive power component of currents, unbalanced currents, and excessive neutral current.

(b). Converter-Based Nonlinear Loads

There are various types of converters used in electrical equipments that behave as nonlinear loads. These nonlinear loads mainly consist of AC–DC converters, AC voltage controllers, cyclo-converters, or a combination of all. These are classified on the basis of these converters, but are not confined to them.

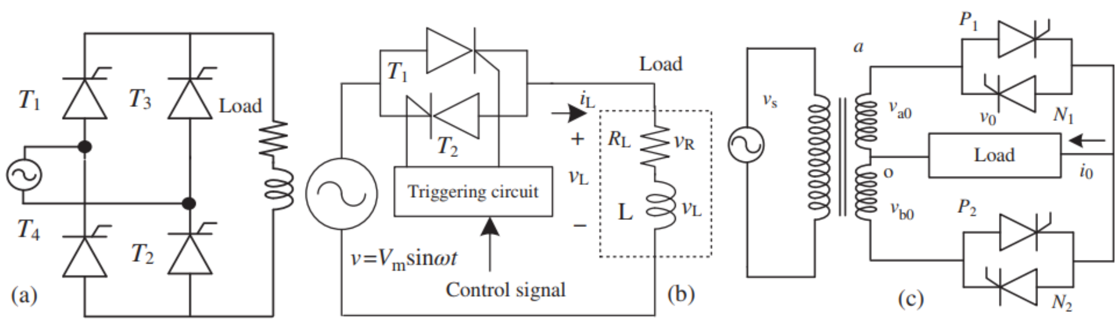

Figure 2.13 various types of current fed nonlinear loads [10]

- AC–DC converter-Based Type Nonlinear Loads

A large number of loads use AC–DC converters as front-end converters ranging from few watts to megawatt rating. These converters are developed in many circuit configurations such as single-phase and three-phase, uncontrolled, semi-controlled, and fully controlled, and half-wave, full-wave, and bridge converter circuits to suit the requirements of specific application. Depending upon the types of filters used for filtering the rectified DC, their behavior varies in a number of ways at the AC mains. Some of the examples of such nonlinear loads include microwave ovens, SMPS, computers, fax machines, battery chargers, HVDC transmission systems, electric traction, adjustable speed drives, and so on. In some cases they draw current with excessive harmonic contents with high crest factor. However, in many cases they draw current with moderate harmonic contents and reactive power with low crest factor, even less than the sine wave. They exhibit poor power factor at the AC mains generally due to harmonics only, but with reactive power as well.

- AC Controllers-Based Nonlinear Loads

Some nonlinear loads use AC voltage controllers for the control of AC RMS voltage across the electrical loads to control the physical process. They draw the harmonic currents along with the reactive power and cause poor power factor. In single-phase distributed loads on three-phase supply systems, they also cause excessive harmonic currents. Some of the examples of such nonlinear loads include AC voltage regulator in fans, lighting controllers, heating controllers, soft starters, speed controllers, and energy saving controllers of three-phase induction motors operating under light load conditions in a number of applications such as hack saw, electric hammers, wood-cutting machines, and so on. They are also used in static VAR compensators (SVCs) in TCRs (thyristor controlled reactors) and so on.

- Cyclo-converter-Based Nonlinear Load

In many applications, cyclo-converters are used to convert AC voltage of a fixed frequency to variable voltage at a variable frequency or vice versa. These cyclo-converters-based nonlinear loads draw harmonic currents not only at higher order harmonics but also at sub harmonics and reactive power and exhibit a very poor power factor at the AC mains. Some of the examples of such nonlinear loads include cyclo-converter fed large-rating synchronous motor drives in cement mills, ore crushing plants, large-rating squirrel cage induction motors, slip energy recovery scheme of wound rotor induction motor drives, VSCF (variable speed constant frequency) generating systems, and so on.

(c). Nature-Based Classification

Most of the nonlinear loads behave as either stiff current fed type or as stiff voltage fed type, or a combination of both. The stiff current fed loads normally consist of AC–DC converters with constant DC current load and a predetermined harmonic pattern in the AC mains with reactive power burden. The voltage stiff loads consist of generally AC–DC converters with a large DC capacitor at the DC bus to provide ideal DC voltage source for the remaining process of solid-state conversion and draw peaky current from the AC mains with high crest factor. Since the analysis of the behavior and remedy for mitigation of power quality problems of these types of loads depend reasonably on this classification, it becomes relevant and important to select a proper compensator.

➢ Current Fed Type of Nonlinear Loads

The stiff current fed types of nonlinear loads generally have predetermined pattern of harmonics and sometimes they have reactive power burden on the AC mains. They have flat current waveform drawn from the AC mains with a low value of crest factor. They typically consist of AC–DC converters feeding DC motor drives, magnet power supplies, field excitation system of the alternators, controlled AC–DC converters used to derive DC current source for feeding current source inverter supplying large-rating AC motor drives, HVDC transmission systems, and so on. Figure 2.13 shows such current fed type of nonlinear load.

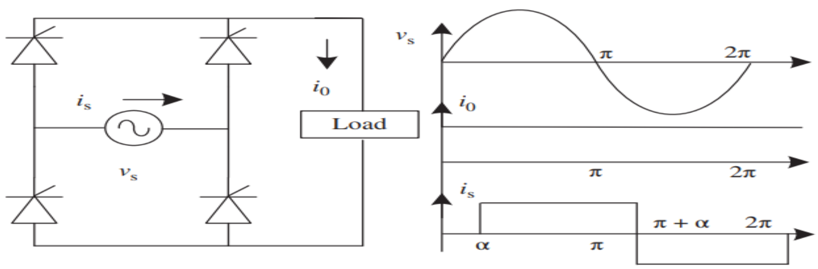

Figure 2.14 shows such current fed type of nonlinear load [10].

➢ Voltage Fed Type of Nonlinear Loads

The stiff voltage types of nonlinear loads behave as sink of harmonic currents. Typical example of such load is an AC–DC converter with a large DC capacitor at its DC bus to provide an ideal DC voltage source for the remaining process of solid-state conversion and it draws peaky current from the AC mains with high crest factor (as shown in Figure 2.15). They generally do not have reactive power requirement, but they have much greater amount of harmonic currents drawn from the AC mains. Examples of such loads include SMPS, battery chargers, front-end converters of voltage source inverter fed AC motor drives, electronic ballasts, and most of the electronic appliances.

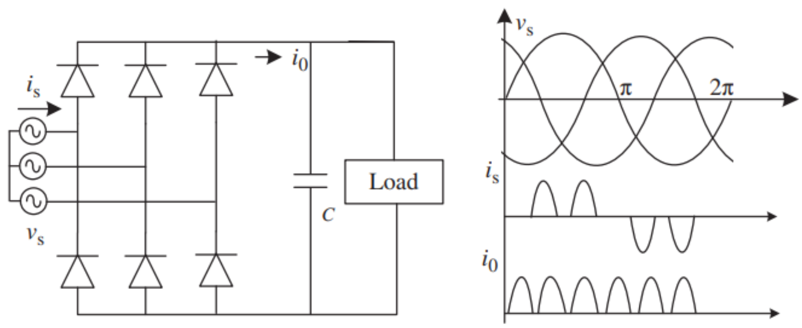

Figure 2.15 Voltage Fed Type of Nonlinear Loads [10]

- Mix of Current Fed and Voltage Fed Types of Nonlinear Loads

The mixed nonlinear loads are combination of current fed and voltage fed types of loads. A group of nonlinear loads and a combination of linear and nonlinear loads fall under this category. Most of the electrical loads consisting of solid-state converters behave as these types of nonlinear loads.

(d) Supply System-Based Classification

This classification of nonlinear loads is based on the supply system having single-phase (two-wire) and three-phase (three-wire or four-wire) systems. There are many nonlinear loads such as domestic appliances that are fed from single-phase supply systems. Some three-phase nonlinear loads are without neutral conductor, such as ASDs (Adjustable Speed Drives), fed from a three-wire supply system. There are many nonlinear single-phase loads distributed on a four-wire, three-phase supply system, such as computers, commercial lighting, and so on.

- Two-Wire Nonlinear Loads

There are a very large number of single-phase nonlinear loads supplied by the two-wire single-phase AC mains. All these loads consisting of single-phase diode rectifiers, semi-converters, and thyristor converters behave as nonlinear loads. They draw harmonic currents and sometimes also the reactive power from the AC mains. Typical examples of such loads are power supplies, electronic fan regulators, electronic ballasts, computers, television sets, and traction. Figure 2.16 shows such voltage fed type nonlinear load.

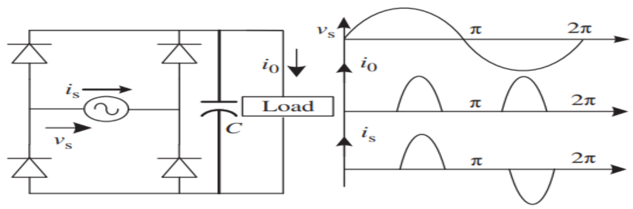

Figure 2.16 shows such voltage fed type nonlinear load.

- Three-Wire Nonlinear Loads

Three-phase, three-wire nonlinear loads inject harmonic currents, and sometimes they draw reactive power from the AC mains and sometimes they also have unbalanced currents. These nonlinear loads are in large numbers and consume major amount of electric power. Typical examples are ASDs using DC and AC motors, HVDC transmission systems, and wind power conversion. Figure 2.17 shows such current fed type nonlinear load.

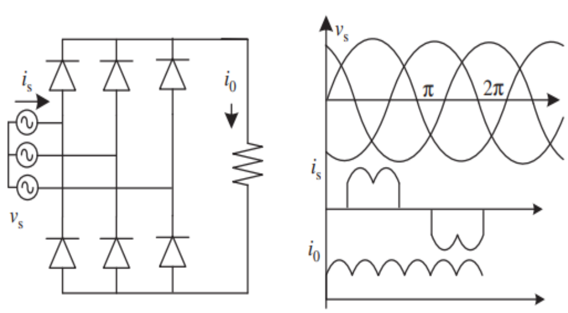

Figure 2.17 shows such current fed type nonlinear load. [10]

➢ Four-Wire Nonlinear Loads

A large number of single-phase nonlinear loads may be supplied from the three-phase AC mains with the neutral conductor. Apart from harmonic currents, reactive power, and unbalanced currents, they also cause excessive neutral current due to harmonic currents and unbalancing of these loads on three phases. Typical examples are computer loads and electronic ballasts-based vapor lighting systems. Besides, they cause voltage distortion and voltage imbalance at the PCC and some potential at the neutral terminal. Figure 2.18 shows such current fed type nonlinear load.

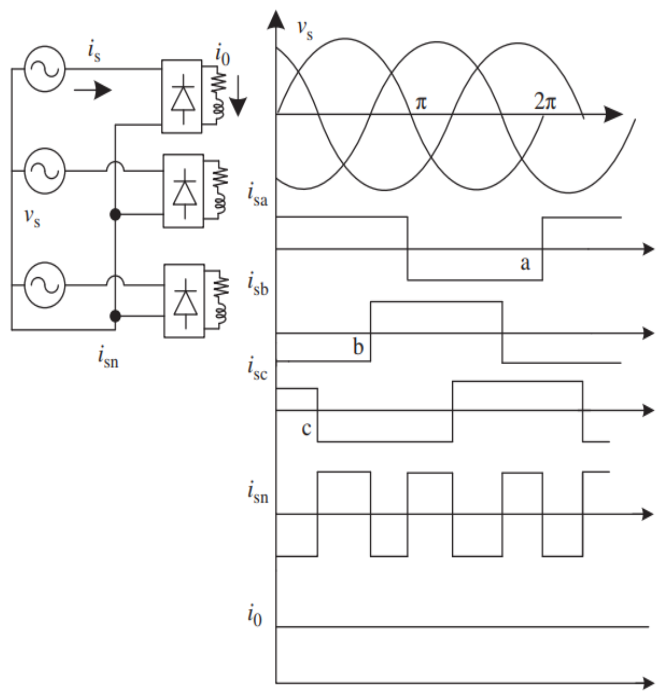

Figure 2.18 shows such current fed type nonlinear load. [10]

2.5 Power Quality Problems Caused by Nonlinear Loads

The nonlinear loads cause a number of power quality problems in the distribution system. They inject harmonic currents into the AC mains. These harmonic currents increase the rms value of supply current, increase losses, cause poor utilization and heating of components of the distribution system, and also cause distortion and notching in voltage waveforms at the point of common coupling due to voltage drop in the source impedance. Some of the effects are as follows: [10] [12].

- Increased rms value of the supply current
- Increased losses
- Poor power factor
- Poor utilization of distribution system
- Heating of components of distribution system
- De-rating of the distribution system
- Distortion in voltage waveform at the point of common coupling, which indirectly affects many types of equipment
- Disturbance to the nearby consumers
- Interference in communication system
- Mal-operation of protection systems such as relays
- Interference in controllers of many other types of equipment
- Capacitor bank failure due to overload, resonance, harmonic amplification, and nuisance fuse operation.

2.6 Passive and Active Power Filters

Active filters are those filter circuits that are designed using transistor and op-amp as their basic components. Along with these elements circuits of active filters also contain resistor and capacitor, but not inductors. Passive filter are those filter circuits that are designed using resistor, inductor and capacitor as their basic components. As shown on Table 2.2 I try to compare the passive and active filters.

Table 2.2 comparisons of active and passive filter

Basis for Comparison	Active Filter	Passive Filter
Composed of	op-amp, transistor etc.	resistor, inductor and capacitor etc.
Cost	High	Comparatively low.
Circuit complexity	More complex	Less complex
Weight	Low	Comparatively bulkier due to presence of inductors.
Q factor	High	Very low
External power supply	Required	Not required
Sensitivity	More sensitive	Comparatively less sensitive.

So, it can be concluded that both active and passive filters have their own region of operation. But active filters are used more than passive filters in the field of communication and signal processing. These thesis works choose passive power filter (single tune shunt passive power) based on these comparisons.

2.6.1 Passive Power Filters

It is designed to be connected in parallel with the nonlinear load to detect its harmonic and reactive current. The PPF technology is a mature technology for providing compensation for harmonic currents and reactive power in AC networks. It has evolved in the past half century with development in terms of varying configurations. Passive filters are also used to eliminate voltage harmonics, to regulate the terminal voltage, to suppress voltage flicker, and to improve voltage balance in three-phase systems. These objectives are achieved either individually or in combination depending upon the requirements and configuration that needs to be selected appropriately. [1]

This section describes the history of development and the current status of the PPF technology. Because of the widespread use of solid-state control of AC power, the power quality issues have become significant. Therefore, the applications of the passive filters have also increased manifold. In view of these requirements, the passive filters are classified based on [1] [12].

(a). Topology (e.g. tuned and damped),

(b). Connection (e.g. series and parallel/shunt), and

(c). Supply system (e.g. single-phase two-wire, three-phase three-wire, and three-phase four-wire) to meet the requirements of various types of nonlinear loads on supply systems.

(a). Topology based classification

PPFs can be classified based on the topology used, for example, tuned filters, damped filters, or a combination of both. The passive tuned filters for shunt and series configurations that are most widely used for the elimination of current harmonics and for reactive power compensation. These are mainly used at the load end because current harmonics are injected by nonlinear loads. These inject equal compensating currents, opposite in phase, to cancel harmonics and/or reactive components of the nonlinear load current at the point of connection. These can also provide the reactive power in the power system network for improving the voltage profile. The passive damped filters for shunt and series configurations are eliminating all higher order harmonics. These are connected before the load either in shunt or in series with the AC mains depending upon the requirements of the nonlinear load for the elimination of current harmonics and for regulating the terminal voltage of the load. The hybrid passive filters as a combination of tuned and damped filters. Another classification of hybrid passive filters includes a combination of shunt and series filters. These are used in single-phase as well as three-phase configurations. These are considered ideal PPFs that eliminate voltage and current harmonics and are capable of providing clean power to critical and harmonic-prone loads such as computers and medical equipment. These can balance and regulate terminal voltages.

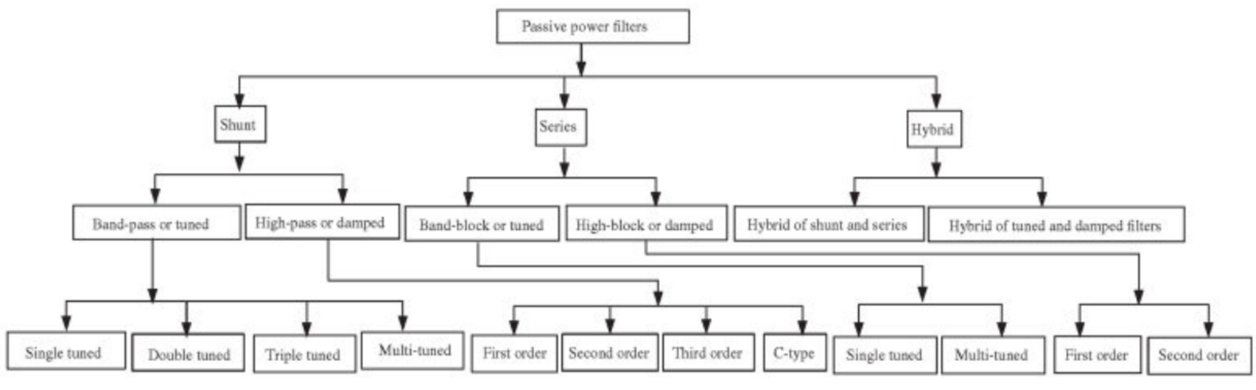

Figure 2.19 Topology based classification of passive power filter [1]

(b). Connection-Based Classification

PPFs can also be classified based on the connection used, for example, shunt filters, series filters, or a combination of both. The combinations of passive series and passive shunt filters are known as hybrid filters. These are mainly used at the load end because current harmonics are injected by nonlinear loads.

➢ Two-Wire PPFs

Two-wire (single-phase) PPFs are used in all three modes, for example, series, shunt, and a combination of both. Figures 2.20 show the configurations of shunt passive filters.

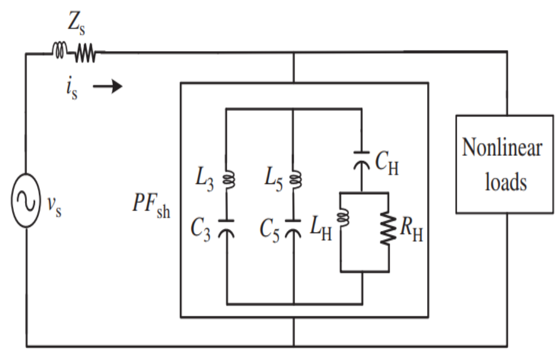

Figure 2.20 single-phase passive shunt filter [1]

➢ Three-Wire PPFs

Three-phase three-wire nonlinear loads such as ASDs are one of the major applications of solid-state power converters and lately many ASDs incorporate passive filters in their front-end design. A large number of publications have appeared on three-wire PPFs with different configurations. All the configurations shown in Figures 2.21 are developed, in three-wire PPFs, with three wires on the AC side and rectifier type nonlinear load.

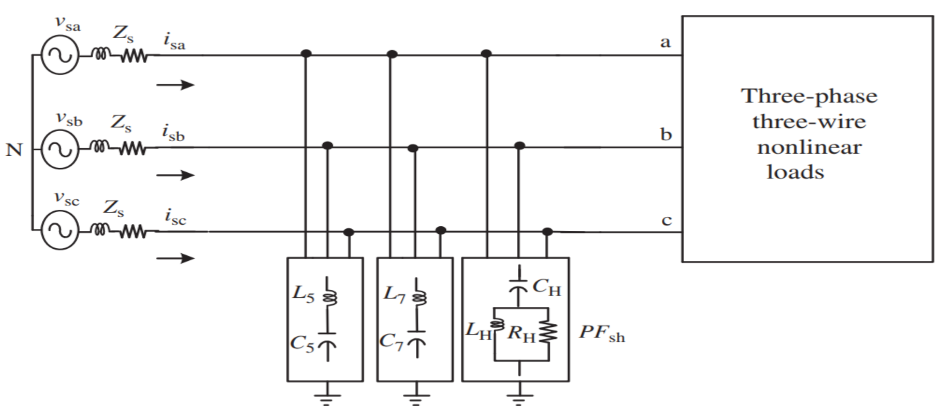

Figure 2.21 three phase three wire shunt passive power filters [1]

➢ Four-Wire PPFs

A large number of single-phase loads may be supplied from the three-phase AC mains with a neutral conductor. They cause excessive neutral current, harmonic and reactive power burden, and unbalance. To reduce these problems, four-wire PPFs have been developed. Figures 2.23 show typical configurations of shunt PPFs. Detailed comparisons of the features of the passive filters are provided for different types of nonlinear loads.

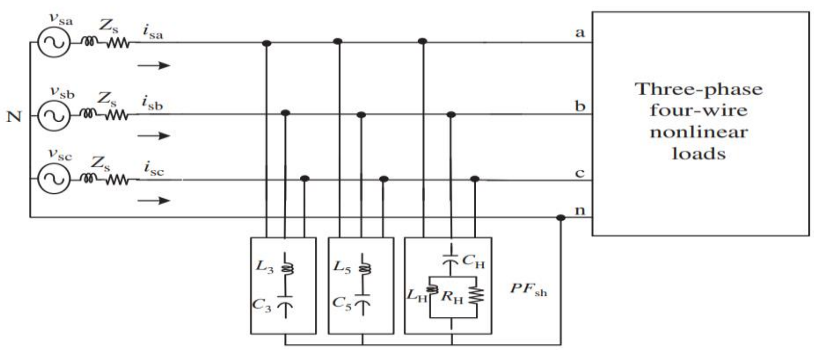

Figure 2.22 three phase four wire shunt passive power filters [1]

(c). Supply System-Based Classification

This classification of the PPFs is based on the supply and/or the load system, for example, single-phase (two-wire) and three-phase (three-wire or four-wire) systems. There are many nonlinear loads such as domestic appliances connected to single-phase supply systems. Some three-phase nonlinear loads are without neutral, such as ASDs fed from three-wire supply systems. There are many nonlinear single-phase loads distributed on three-phase four-wire supply systems, such as computers and commercial lighting. Hence, PPFs may also be classified accordingly as two-wire, three-wire, and four-wire PPFs.

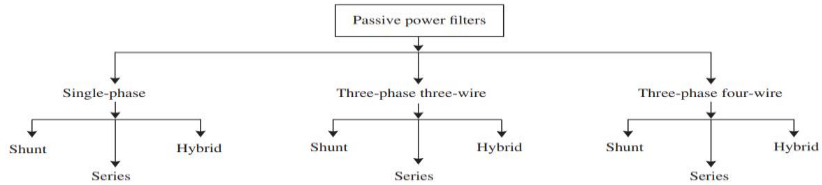

Figure 2.23 Supply-based classification of passive power filters [1]

2.6.2 Principle of Operation of Passive Power Filters

The basic principle of operation of passive power filters may be explained through their objectives, locations, connections, quality, sharpness, rating, size, cost, detuning, applications, and other factors. These are illustrated in the following sections [1].

(a). Objectives

The main objective of passive filters is to reduce harmonic voltages and currents in an AC power system to an acceptable level. The AC passive shunt filters also provide the leading reactive power required in most of the nonlinear loads. The DC harmonic filters are used to reduce only harmonics on the DC bus of the load in the system. The basic operating principle of a passive shunt harmonic filter is to absorb harmonic currents in a low-impedance path realized using a tuned series LC circuit as shown in Figure 2.25. Similarly, the basic operating principle of a passive series filter is to block harmonic currents entering the AC network by a passive tuned parallel LC circuit offering high impedance for harmonic currents as shown in Figure 2.25. Passive shunt filters are connected in parallel to the load and rated for the system voltage at PCC, whereas passive series filters are connected between the AC line and the load and rated for full load current. Passive filters are the engineering solution for harmonic reduction within an acceptable limit and not the elimination of harmonics. In case of passive shunt filters, harmonic voltages are required at PCC to flow the complete harmonic currents in passive series RLC circuits of the shunt filter. The passive shunt connected circuit absorbs a part of harmonic currents into it and a fraction of harmonic currents still flows in the network. Therefore, it only reduces harmonic currents and does not completely eliminate them.

(b). Location

The passive filters are located very close to the loads either on AC or DC lines. Most of the time the passive filters are connected at PCC where loads are connected; however, sometimes they are connected to the tertiary winding of the transformer designed for this purpose at optimum voltage to reduce the cost and to increase effectiveness because of the properly designed leakage reactance of this tertiary winding. Moreover, the passive filters may be used for high-voltage harmonic-producing loads that require transformers and tertiary winding of the same transformer is designed to use the passive filters.

(c).Connection and Configuration

The passive filters are used in shunt, series, and hybrid configurations. The passive shunt filters, which are connected in shunt or parallel to the harmonic-producing loads or network, consist of series RLC circuits tuned at slightly low frequency at which they absorb harmonic currents. For multiple harmonics, multiple tuned series RLC circuits are used to absorb the harmonic currents. However, voltage harmonics are also reduced at PCC due to reduced harmonic currents flowing in the AC network and less harmonic voltage drop at PCC resulting in reduction in harmonic voltages. For reducing the number of series circuits of passive elements, a high-pass filter is used in parallel to other branches to absorb all higher order harmonic currents. This high-pass passive filter uses an additional resistor (*R*H) parallel to the inductor, which is the offered impedance (*R*H) for all higher order harmonics. This resistor has losses because of the harmonic currents. However, higher order harmonic currents are quite low and therefore not much loss is produced in the resistor. Moreover, low-frequency current (fundamental) is mainly confined to the inductor. The passive shunt filters provide leading reactive power at fundamental frequency, which is fortunately an additional requirement of large rating AC–DC converters for which these filters are used. Moreover, size, cost, and weight of the passive shunt filters are decided by AC capacitors that are a part of these filters. Because of these additional advantages, the passive shunt filters are very popular in practice. The passive series filters, which are connected in series with the AC mains and the harmonic-producing loads or network, consist of parallel LC circuits tuned at slightly low frequency at which they have to block harmonic currents [1].

For the mitigation of multiple harmonics, multiple parallel tuned RLC circuits are used to block the harmonic currents. For reducing the number of series connected parallel tuned LC circuits of passive elements, a high-block filter is used in series with other branches to block all higher order harmonic currents. This high-block passive filter uses an additional resistor (RH) in series with the capacitor, which is the lower offered impedance (RH) for all higher order harmonics. This resistor has low losses because of blocking of the harmonic currents; however, higher order harmonic currents are quite low and therefore not much loss is produced in the resistor. Moreover, low-frequency current (fundamental) is mainly confined to the inductor [1].

The passive series filters have lagging reactive power at fundamental frequency, which is an undesired feature, and there is inductive voltage drop at fundamental frequency resulting in poor voltage regulation across the loads. In addition, these passive filters have to be rated for full rated current and their protection becomes an additional requirement. Therefore, the passive series filters are not very popular in practice. A hybrid passive filter, consisting of one branch of a series passive filter and remaining elements of passive shunt filters, is considered a very popular passive filter in the distribution system. It also avoids the drawbacks of the series filter by using shunt filters and demerits of shunt filters are overcome by a series filter.

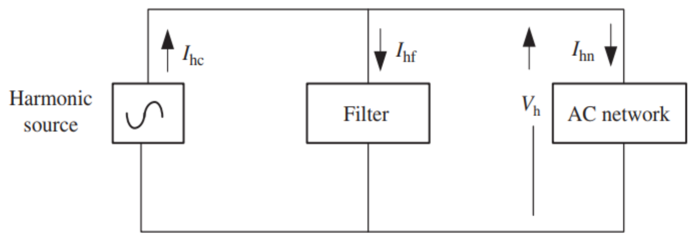

Figure 2.24 circuit for computation of harmonic currents and voltages on the AC side [1]

(d). Sharpness of Tuning of Passive Filters

This is one of the important properties of the passive filters. It is quantified in terms of a quality factor of the inductor (Q) and is known as sharpness of tuning of the passive filter. A passive shunt filter is considered to be tuned corresponding to a frequency at which its inductive reactance is equal to its capacitive reactance. Passive shunt filters tuned at lower frequencies are sharply tuned and have a high value of quality factor, typically 10–100 and preferably between 30 and 60. Other types of passive shunt filters, known as damped filters and high-pass filters are tuned for high frequencies and have a low value of quality factor, typically 0.5–5 and preferably between 1 and 2. The high-pass passive filters offer low impedance over a broad band of frequency bandwidth.

(e). Cost of Passive Filters

The cost of the passive filter is reasonable and sometimes it reaches 15–20% of the equipment for which it is used; therefore, the cost factor should be taken into account while designing the passive filters. Moreover, it has some power losses, which must also be considered in its design. The cost of the passive filter may also be partially supplemented to the reactive power supplied by it. These filters are sometimes designed based on a minimum cost filter. An overall minimum cost filter is a minimum capital cost filter, which adequately reduces harmonics at least cost with some or part of reactive power. A minimum cost filter has to consider the cost of losses along with capital cost of the filter. The major part of the capital cost (about 60%) is the cost of the power capacitors; therefore, a reasonable cost reduction may be achieved by proper selection of its capacitors. Detailed discussions on the cost of these filters are given in the design of these filters.

2.6.3 Shunt Passive Power Filters

Passive shunt filters are connected in parallel to harmonic-producing loads to provide low-impedance paths for harmonic currents so that these harmonic currents do not enter supply systems and are confined to flow in the local passive circuits preferably consisting of lossless passive elements such as inductors (L) and capacitors (C) to reduce losses in the filter system. Practically, capacitors may have very low internal power losses; however, inductors have reasonable resistance and other losses (core loss if the core is made of a ferromagnetic material). Therefore, losses in the inductors cannot be neglected and are considered as an equivalent resistance connected in series with the inductors. It is also represented in terms of quality factor of the inductor. It can be a notch filter sharply tuned at one particular frequency, which is also known as a single tuned filter. It is a simple series RLC circuit, in which R is the resistance of the inductor as shown in Figure 2.26a. The value of the capacitor, also known as the size of the filter, is decided by the reactive power requirements of the loads and its inductor value is decided by the tuned frequency. Therefore, these types of tuned or notch filters provide harmonic current and voltage reduction and power factor correction because of capacitive reactive power at fundamental frequency as this filter circuit behaves as capacitive impedance at fundamental frequency. The resistance of the reactor (inductor) decides the sharpness of tuning and is responsible for limiting the harmonic current to flow in the passive filter. Normally, the notch filters are used at more than one tuned frequency and may have more than one series RLC circuit for multiple harmonics. Sometimes two tuned filters are combined in one circuit. It is known as a double tuned or double band-pass filter, as shown in Figure 2.26c, having minimum impedance at both the tuned frequencies. The main use of the double tuned filter is in high-voltage applications because of reduction in the number of inductors to be subjected to full line impulse voltages. More than two tuned filters (triple and quadruple) can also be combined in one circuit, but no specific advantage is achieved and there is difficulty in adjustment [1].

Moreover, more than two tuned filters are rarely used in practice and only in a few applications. Other types of passive filters, shown in Figure 2.26b and d, are known as high-pass filters that absorb all higher order harmonics. They are also known as damped filters as they provide damping due to the presence of a resistor in the circuit. These filters have higher losses, but fortunately at high frequencies not much higher currents and power losses are present in the loads. These can be first-order simple series *RC* circuits. These help to improve the voltage profile at the point of common coupling (PCC) even for very high frequencies. Normally, a second-order high-pass filter is used as it also reduces the harmonic components in the system. It consists of an external resistor in parallel to the inductor and a capacitor connected in series with the *RL* circuit. Third-order high-pass filters are also used sometimes, for reducing the losses and for better filtering characteristics. There are many other types of passive shunt filters, such as automatically tuned filters (by automatically varying capacitor or inductor values), C-type filters, and composite filters used as a combination of these filters. However, the passive filters have problems of resonance with the source impedance, fixed compensation, and poor power factor at light loads due to excessive leading reactive power injection.

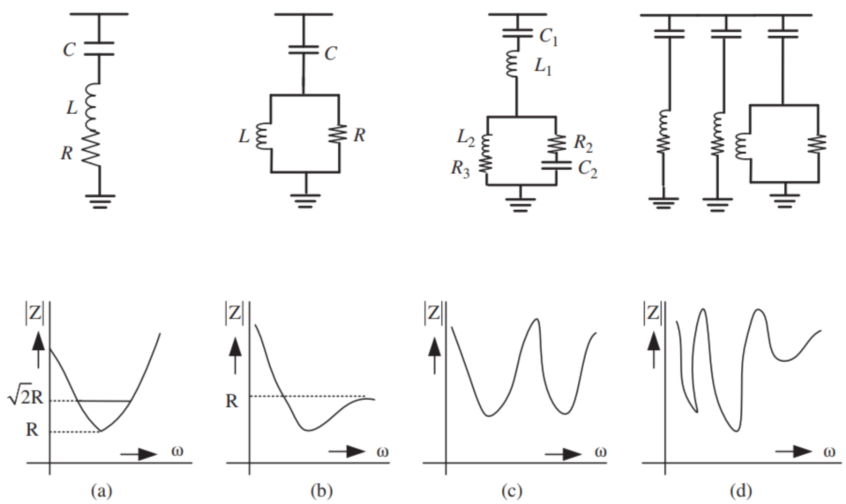

Figure 2.25 Common types of passive shunt filters with impedance–frequency plots: (a) band-pass; (b) high-pass; (c) double band-pass; (d) composite.

2.7 Effects of PQ on some Textile Machinery

(a). Effects of PQ on Weaving –Knitting.

Textile weaving covers a very wide range of products. Most of the garments, surface coverings of the sitting set in our rooms, tulle and curtains, carpets, towels in the bathrooms, and even the airbags in our cars are of fabrics manufactured through textile weaving or knitting. Today's weaving and knitting machines are high technology machines. They include tens of sensors, driver controlled ac and dc electrical machines, communications cards, CPU units, touchscreens, Ethernet cards and encoders. These equipments operate at different voltage values. If any interruption, in the machines at the weaving room occurs for any reason, it can take up to 4 h for the machinery park to return to the acceptable performance values. Thus, any short-term or long-term interruption means a direct manufacturing loss. These machines which are sensitive to sinusoidal form of electrical power can shut down if a voltage drop, voltage sag and voltage fluctuations occur. These machines include special encoders used for position determination and interruptions without any reason can lead to the breakdown of this device (values approximately $500) and its replacement means at least 2hr of interruption. Voltage sags can result in excess current drawings, which cause the engines operating at approximately 6kW to draw higher currents, leading to the break-down of electronic cards driving such engines. Such cards cost approximately $2500 and their replacement may take minimum 2hr. High current and voltage harmonics and the other distortions can cause such machines to stop. Harmonics shorten the life of all electrical and electronic equipments in the machines. They cause break-downs, resulting in repair costs and manufacturing losses. They also shorten the depreciation periods of the machines, leading to increasing costs and thus losses [10].

2.8 Literature Review

Power quality is a set of electrical boundaries that allows a piece of equipment to function in its intended manner without significant loss of performance. In other words power quality problem is any power problem manifested in voltage, current, or frequency deviations that result in failure or mal-operation of customer equipment. IEEE Standard 1159 defines power quality as "the concept of powering and grounding sensitive equipment in a manner that is suitable for the operation of that equipment" [7] [25].

Now-a-days the customers use large number of devices at their installations that consist of power electronics. The residential customers use different domestic appliances such as televisions, video cassette recorders, microwave ovens, personal computers, heating ventilation air conditioning equipment, dishwashers, dryers etc. The business and office equipment include workstations, personal computers, copiers, printers, lighting etc. On the other hand, the industrial customers use programmable logic controllers (PLC), automation and data processors, variable speed drives, soft starters, inverters, computerized numerical control tools and so on. Presently, many customers use compact fluorescent lamps (CFL) for lighting their installations. Many of these devices are quite sensitive to power quality disturbances [8].

Case studies and surveys in different countries around the world have been done to estimate the impacts of poor power quality to the customers. Manufacturers of electrical and electronic equipment and end users of electric power are challenging utilities to upgrade the quality of their electric power supplies. Utilities on the other hand are forcing end-users to mitigate the quality of electric current they draw. The issue of power quality has reached up to making national regulations in some countries. The following are some of the works done before on power quality problems and mitigation techniques [7] [11].

Shazly A. Mohammed, Abdel-Moamen M.A. and B. Hasanin [2]. Did analysis, modeling and simulation of Dynamic Voltage Restorer (DVR) for compensation of voltage quality disturbances. Accordingly, DVR provides the most commercial way to mitigate voltage sag by injecting voltage as well as power in to the system. Finally they found DVR handled both three phase balanced and unbalanced solutions without any difficulties. They injected appropriate voltage component to correct rapidly any disturbances in the supply voltage to keep the load voltage balanced and constant at the nominal value.

Prakash sundaram1, Shimi S.L. Dr.S.Chatterji [3]. Published a paper entitled "Reduction in Harmonics in Marble Industry" on an industry found in India. After measuring the harmonic components of current, they found that the 5th harmonic content was beyond the IEEE limits, and then design the harmonic filter. After installation of harmonic filter at Arihant Marble Industry, measurement were done again and found that 5th harmonic content was below IEEE limits. They found shunt harmonic filters are economical way of mitigating harmonics.

Hussein Mohamed El-Eissawi Fathi, [4], investigates and mitigates the power quality problems in nuclear installations. Normally electrical power is supplied to the installations via two sources and each source is designed to carry the full load. The assessment of power quality was performed at the nuclear installations for both sources at different operating conditions. In both sources there were several disturbances, which exceeded the thresholds of the power quality standards defined by IEEE Std. 1159 - 1995. Effective and economic mitigation techniques were suggested to the power quality problems occurred.

M. Davudi, S. Torabzad, B. Ojaghi [5] has presented a paper on Analysis of Harmonics and Harmonic Mitigation Methods in Distribution Systems, using Electromagnetic Transient Analysis Program (ETAP).

Muhammad Yasir, [6], proposes generic evaluation approach for estimating the financial impact of voltage sag events on customer operations. The proposed technique is based on the event tree method. Using this approach, it is possible to consider the impacts of operational failure of various sensitive equipment involved in the customer operations on the financial losses expected from voltage sag events. A methodology, based on the developed approach, is also proposed for analyzing the effectiveness and practical viability of various voltage sag mitigation solutions. A quantitative case study is conducted in the thesis to illustrate the applicability of the proposed approach.

Shady A. El-Kashlan and Hussein El-Desouki Saied [7] 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.

Michella Weverink[8] published a paper on Mitigation of Voltage Sags in Industrial Power Plants with Medium Voltage DC Distribution System. His study focus on how to mitigate the voltage sags in industry.

Alexandre Nassif, [9], presents an evaluation of the relative severity of the harmonic currents from power electronic-based home appliances and the impact of the discrepancy of the harmonic current phase angles. An investigation is carried out on the common filter topologies, and the most cost-effective topologies for mitigating harmonics are identified. As many of the larger harmonic loads also generate inter harmonics, inter harmonics have become prevalent in today's medium-voltage distribution system. Mitigation cannot be carried out until the inter harmonic source location is known. A method for inter harmonic source determination is proposed and then verified through simulation and field measurement studies. Moreover, a comparative assessment was made to find out the applicability of various mitigation options. The method can be applied by customers to select the most economical mitigation option for their operations.

M. Bayrak A. S. and Yilmaz [10], present the Effects of power quality on manufacturing costs in textile industry. He analyzed by cost wise the effect of power quality problem.

M.K.Pradhan, **Kamlesh Keharia**, **Rajesh Darapu**, **B. Mariappan**, [12], presents a case study of application of solid-state harmonic filter to improve electric power quality and reduce energy consumption in textile industries. Detailed studies were carried out in various textile firms in India and the effects of poor power quality especially harmonics were analyzed on the productivity and energy consumption. Harmonic current generated by nonlinear loads like motors driven by Variable Frequency Drives (VFD) cause power system heating and add to user power bills. The harmonic related losses are present in the power cables, bus bars linking the loads with source, the power transformer itself. A more serious effect of harmonic loads served by transformer is due to an increase in winding eddy current losses. The heat generated due to harmonics must be removed in order to save electrical energy, thus leading to savings in the utility bill. The paper is a case study where a 1.5 MVA transformer used for powering the spinning section of a textile mill. The current harmonics is recorded with & without using the harmonic filter. The power parameters are recorded on both the primary & secondary side of transformer to demonstrate how the harmonic filter can reduce the effects of harmonics and save energy.

S.V Ravi Kumar and S.Siva Nagaraju [15] worked on simulation of D-STATCOM and DVR in power systems. They described the techniques of correcting supply voltage sag, swell and interruptions in a distributed system. In their work they used DVR to inject voltage in series with the system voltage and D-STATCOM to inject current into the system to correct the voltage sag, swell and interruption. Finally they found that DVR provide relatively better voltage regulation capabilities and also observed that the capacity for power compensation of DVR and D-STATCOM depends on the rating of storage devices.

Nexant SARI, [22], found that the main economic impact of power interruptions, both planned and unplanned, is the loss of output in the industrial sector. These losses can be as high as US$ 81 million annually (0.65%of GDP) under a typical scenario (300 hours of planned outages) of imposing power interruptions such as those experienced during 2001. Also the impact due to unplanned outages can be as high as US$ 47 million (0.38%of GDP) in a typical year having 100 hours of unplanned outages. This is a significant economic loss especially in comparison to the 4.5 %to 5%average GDP growth that has taken place in Sri Lanka during the last few years. The economic losses due to planned and unplanned power interruptions can also be expressed in other forms. One commonly used measure is the economic loss (in US$) per unit of supply (kWh); identified as the cost of un served energy. These findings emphasize the importance of reducing both planned and unplanned interruptions.

Franz Alois Hemetsberger, [23], identifies power quality problems in the isolated Porgera Mine System located in the Highlands of Papua New Guinea. For the problems identified, recommendations are suggested to improve the power quality. The voltage sag caused by the starting of large motors is investigated with measured data from the mine and simulated using a power-system-computer-aided-design-software (PSCAD/EMTDC) to observe the extent of the sag throughout the system. The extent of sags from faults is also simulated including some mention of harmonics propagation. Results of the project include the total harmonic voltage distortion being within IEEE standards, characterization of the measured voltage sags, the severity of the sag throughout the system, identification that some sags fall below tolerance curves for sensitive equipment according to the CBEMA curve and correct mitigation techniques available for the problems identified. It was found that line conditioning practices at the mine are adequate but advised that for further expansion a further voltage study be carried out.

CHAPTER THREE

Research Methodology

3.1 Research Approach

The research methodologies flows literature review, interview with company electrical personnel, collection of data by using power quality analyzer MICROVIP3 plus. By comparing the existing PQ problems to IEEE Standard 1159-1995 and finding the solution for the problems. MATLAB/SIMULINK software modeling and simulation of power quality problems have been carried out for the modeled networks & based on the above steps the Conclusion and Recommendation has been made in this thesis work.

Shortly the following diagram shows the methodology that has been followed in this thesis work.

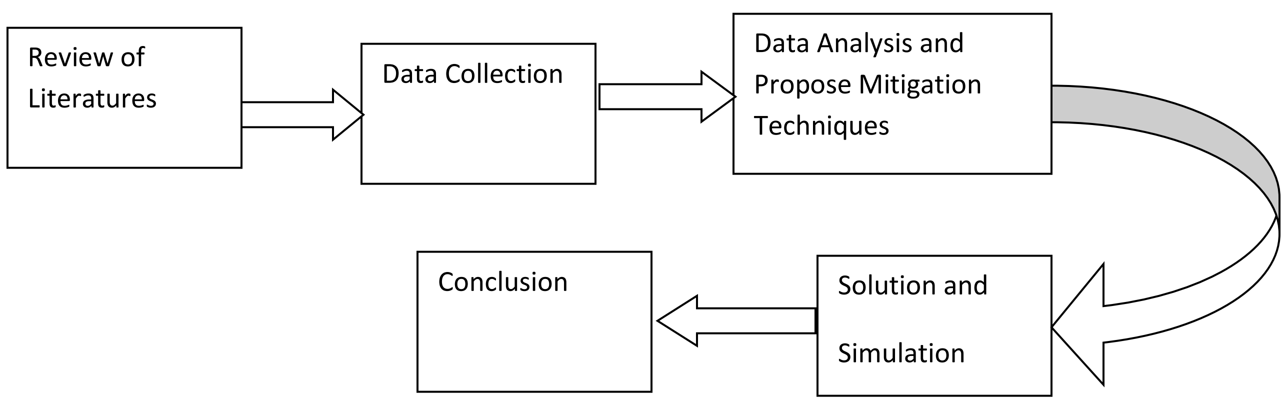

Figure 3.1 Methodology Diagram

3.2 Review of Literatures

These thesis work reviewed books and paper has been done before and all source help me to understand about the power quality problems. Power quality is a set of electrical boundaries that allows a piece of equipment to function in its intended manner without significant loss of performance. In other words power quality problem is any power problem manifested in voltage, current, or frequency deviations that result in failure or mal-operation of customer equipment. IEEE Standard 1159 defines power quality as "the concept of powering and grounding sensitive equipment in a manner that is suitable for the operation of that equipment". The specific power quality problems that need to be evaluated will be different from customer to customer. A review of the types of equipment used by the customer, process requirements and economic impacts of problems will lead to a list of problems that need to be studied. They can include possible problems with both the utility distribution system and the customer facilities [7] [13] [25].

There are a number of power quality problems in the present-day fast-changing electrical systems. The main causes of these power quality problems can be classified into natural and man-made in terms of current, voltage, frequency, and so on. The natural causes of poor power quality are mainly faults, lightning, weather conditions such as storms, equipment failure, and so on. However, the man-made causes are mainly related to loads or system operations. The nonlinear loads cause a number of power quality problems in the distribution system. They inject harmonic currents into the AC mains. These harmonic currents increase the rms value of supply current, increase losses, cause poor utilization and heating of components of the distribution system, and also cause distortion and notching in voltage waveforms at the point of common coupling due to voltage drop in the source impedance. Some of the effects are as follows: [10] [12]

3.3 Data collection

The data collection process has been done by power quality analyzer (MICROVIP3 Plus). The device has the ability to measure High speed voltage quality parameter, RMS voltage quality parameters, Power quality parameters, 3-Phase quality parameters, Harmonic quality parameters and distortion factors simultaneously. The MICROVIP3 PLUS is a low cost, class 1 (IEC1036) high technology portable analyzer for both single phase and three phase systems, manufactured by ELCONTROL ENERGY and supplied complete with three 1000A clip-on CTs. voltage leads and all accessories in strong carry case.

Figure 3.2 MICROVIP3 Plus

CHAPTER FOUR

Description of the Study Area

4.1 Site Description

ETUR Textile PLC Factory is one of subsidiary company of Yüksel Tekstil, TURKIYE**.** The company is one of the pioneers of textile industry in Turkey, established in 1960 GC and start exporting to the world market since 1978 GC by the name Yüksel Tekstil**.** ETUR Textile PLC was established by 2010 GC in Ethiopia, Oromia Regional State at 6KM south of Adama town on the 60000 sq.m area with a geographical reference of 8.49N, 39.23E. It is a sign of Ethiopian and Turkey partnership.

ETUR is re-cycling about 6000 tons of fabric remnants and about 1000 tons cotton spinning leftovers every year which are the production leftovers would have polluted environment. Because of re -cycling

- ETUR has not dyeing and finishing process and there is no chemical consumption in the process,
- Saves 29.9 million cubic meters of water and 300.000 Kwh electric powers
- They have 6.4MW capacity.
- Around 800 employee in thier factory

Company principle is; "The Earth is not a Heritage for Humans but Entrusted to us by Our Grandchildren". The company proud of saving the enviroment since 1978 by re-cycling hard and soft all textile wastes much before enviroment concept established by any other institution in the world.

A. Fiber Preparation, Blending and Conditioning;

Etur has 9 lines of Fiber preparation lines and conditioning metal boxes to reach optimum mixture of different fibers in the blend for proper quality of Re-Cycled yarn spinning.

Figure 4.1 Fiber Preparations, Blending and Conditioning

B. Carding & Drawing;

In the carding section there are 36 carding machines and 9 drawing frames. The carding machines are much more complicated from regular carding machines, designed for especially re-cycling and in addition to this the selling prices of these specially designed cards approximately 2 times more expensive than regular carding machines. In addition to carding machines there are 10 special designed drawing frames to ensure yarn sliver quality.

Figure 4.2 Carding & Drawing

C. Re-Cycled Open End Yarn production:

ETUR is manufaturing Re-Cycled yarns with 3792 Rotors, 36 carding frames and 10 drawing frames with sliver regulator together with self-developed fiber blending machineries to reach maximum level of yarn quality.

Figure 4.3 Re-Cycled Open End Yarn productions

Etur has the capability to produce yarn counts starting from Nm 1/1 (Ne 0,60/1) to Nm 50/1 (Ne 30/1) In single, 2 plies and multi folds in different blends;

- ✓ Cotton / Polyester
- ✓ Cotton / Acrylic
- ✓ Cotton / Viscose
- ✓ Cotton / Bamboo
- ✓ Cotton / Polyamide

- ✓ Cotton / Wool / Other Synthetic Fibers
- ✓ Cotton / Flax / Other Synthetic Fibers
- ✓ And also any other blends required by customers.

End-Use of Etur Manufactured Re-Cycled Yarns ;

- ✓ Circular and Flat-Bed Knitting (Sweaters, T-Shirts, Sports Wear)
- ✓ Hosiery (Sport Socks, Men's, Lady's and Children's Socks) Weaving (Warp and Weft)
- ✓ Fleecing
- ✓ Hand Knitting
- ✓ Home Textile -Curtains, Bath and Door Mats, Bed Sheets
- ✓ Upholstery Fabrics
- ✓ Carpets
- ✓ Tufting
- ✓ Door & Bath Mats
- ✓ Floor Mops
- ✓ Cotton Blankets
- ✓ Bed and Sofa covers
- ✓ Table Clothes and Napkins

CHAPTER FIVE

Data Collection, Analysis of Power Quality Problems and Proposed Mitigation Techniques

5.1 Introduction

Background of different power quality problems and review of Literatures have been discussed in the chapter two. The major causes of problems and options to reduce them are highlighted with reference to different Authors. Under this chapter, data have been collected and analyzed. After analysis of the data, mitigation solutions have been proposed. The collected data have been analyzed and the levels of the disturbances have been compared with international standards. Data have been collected from the secondary winding of transformer with respective ratings of 1250KVA, 15/0.38KV, and 6% impedance. Recycling line with an electrical load of capacity 102.709kVA and power factor of 0.814

5.2 Data Collection and Analysis

5.2.1 Wave form distortion data Analysis

IEEE 519-1992 was developed to evaluate harmonic voltages and currents at a point of common coupling (PCC) between the end user and the utility supply system. The PCC is the location where another customer can be served from the system [5] [23]. The standard allows for the same procedure to be applied by the customer at other locations within a facility but different current limit values could apply in these cases. The waveform distortion is principally characterized by its spectral contents which are investigated using Fourier transform expressed as [1].

$$F(t)=F_o+\sum_{h=2,4,6..}^{\infty}\left(Fh\ cos(h*\omega ot+\varphi h)\right)+\sum_{h=1,3,5..}^{\infty}(Fh\ sin(h*\omega*t+\varphi h)) \quad (5.1)$$

whereas:

F (t) - voltage/Current waveform

F_0 - Dc-component

F_h - Spectral content

h - Harmonic

ωo - Fundamental angular frequency

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

The effect of the harmonic contents on the distortion of the sinusoidal waveform can be observed from the above equation, equation (5.1) 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. Using the Fourier series expansion, we can represent a distorted periodic wave shape by its fundamental and harmonics [1] [6] [10].

$$U(x) = \mathrm{Udc} + \sum_{n=1}^{\infty} (\mathrm{U(n)s}\sin(\mathrm{n\omega t}) + U(n)c\cos(n\omega\mathrm{t}))n = 1 \tag{5.2}$$

The coefficients are obtained as follows:

$$U(n)s = \frac{1}{\pi}\int_0^{2\pi} u(t)\sin(n\omega\mathrm{t})d\omega\mathrm{t} \tag{5.3}$$

$$U(n)c = \frac{1}{\pi}\int_0^{2\pi} u(t)\cos(n\omega\mathrm{t})d\omega\mathrm{t} \tag{5.4}$$

Where n is an integer and $\omega = \frac{2\pi}{\mathrm{T}}T$ is the fundamental period time. It is also common to use a single quantity, the total harmonic distortion (THD), as a measure of the effective value of harmonic distortion. Mathematically, THD values of voltage and current, THDU and THDI, respectively, are given as follows:

$$THD_U = \frac{\sqrt{\sum_{N=2}^{\infty} U^2(n)}}{U(1)} * 100 \tag{5.5}$$

$$THD_I = \frac{\sqrt{\sum_{N=2}^{\infty} I^2(n)}}{I(1)} * 100 \tag{5.6}$$

Effective value

$$Urms = \sqrt{\frac{1}{T}\int_0^T U(t)^2 dt} = \mathrm{U}\,(1)\sqrt{1+THD^2}u \tag{5.7}$$

$$Irms = \sqrt{\frac{1}{T}\int_0^T I(t)^2\, dt} = \mathrm{I}(1)\sqrt{1+THD^2}_{\mathrm{I}} \tag{5.8}$$

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

$$TDD = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_L} * \ 100 \tag{5.9}$$

whereas: I_h is the harmonic currents,

I_L is the rated load-current.

Table 5.1 Harmonic current limits for individual end users from IEEE standard 159-1992

V≤69KV						
I_{sh}/I_L	h<11	11<h<17	17<h<23	23<h<35	35<h	TDD
<20	4	2	1.5	0.3	0.3	5
20-50	7	3.5	2.5	0.5	0.5	8
50-100	10	4.5	4	1.5	0.7	12
100-1000	12	5.5	5	2	1.0	15
>1000	15	7	6	2.5	1.4	20

whereas:

I_{SC} - Short circuit current at the point of common coupling.

I_L - Maximum demand loads current (fundamental frequency component) at the point of common coupling.

$$I_L = \frac{P}{\sqrt{3} * PF * KV} \quad (5.10)$$

$$I_{SC} = \frac{U_{20}}{\sqrt{3} * Z_T} \quad (5.11)$$

$$\text{Short circuit ratio} = \frac{I_{SC}}{I_L} \quad (5.12)$$

whereas:

U_{20} - Nominal voltage with the secondary side of transformer open

I_{sc} - Short circuit current of the transformer

%Z-Percentage transformer impedance

P - Load demand

PF - Power Factor

The tables of individual harmonic component limits apply to the odd harmonic components. Even harmonic components are limited to 25% of the limits in the tables. Current distortion which results in a dc offset is not allowed. The total Demand Distortion (TDD) as defined previously;

$$TDD = \sum_{h=2}^{hmax} Ih^2 / IL \quad (5.13)$$

whereas:

I_h - Magnitude of individual harmonic components (RMS, amps)

H - Harmonic order

I_L - Maximum demand load current (RMS amperes) defined above.

Table 5.2: Harmonic voltage limits, IEEE standard 519-1992

Utility bus voltage	Maximum individual harmonic component (%)	Maximum THD (%)
<69kv	3.0	5.0
39kv -137.9kv	1.5	2.5
138kv	1	1.5

IEEE Standard for Shunt Power Capacitors (IEEE Standard 18-1992) specifies the following continuous capacitor ratings:

- 135 percent of nameplate kVAr
- 110 percent of rated RMS voltage (including harmonics but excluding transients)
- 180 percent of rated RMS current (including fundamental and harmonic current)
- 120 percent of peak voltage (including harmonics)

5.2.2 Data collected from Transformer.

Table 5.3: Voltage data from transformer

No of measurement	Frequency	V1 RMS	V2 RMS	V 3 RMS	V 1 THD	V 2 THD	V 3 THD	V Unbalance
	Hz	V	V	V	%	%	%	%
1	50.1	200	199	198.9	2.6	3	3	0.3
2	50.1	200.6	199.6	199.6	2.6	2.9	3	0.2
3	50	202.4	201.3	201.4	2.7	3	3	0.2
4	50.1	204.4	203.4	203.6	2.7	3	3	0.2
5	50.1	203.3	202.2	202.3	2.7	2.9	3	0.2
6	50.1	204.5	203.5	202.7	2.3	2.5	3	0.2
7	50.1	204.9	203.8	203.9	2.7	3	2.5	0.2
8	50.1	205	203.5	205.1	2.7	3	3	0.2
AVERAGE	50.1	203	202	202	2.6	2.9	2.9	0.2

The table 5.3 shows the voltage distortion level and RMS value of each phase taken from the transformer of the feeder of recycling section; the measurement on individual phases. The average full load measurement shows that the THDv is 2.6%, 2.9% and 2.9% for the respective phases. As per IEEE standard the voltage distortion should be below 3% for individual harmonic components and below 5% for total harmonic distortion. The figure in the table implies there is no sign of significant voltage distortion. The voltage unbalance limit at the terminal of the motors in the industry should be below 1% as per IEEE standard. The unbalance greater than 1% makes motor operation difficult in which the motors are over heated and forced to function below their rated power. Again the measurement taken at the terminal of the motors indicates the voltage unbalance is not beyond the standard. The average measured supply frequency is 50.1 Hz which in is the range of acceptable limit.

Table 5.4: Current data from transformer

No of measurement	A1 RMS	A2 RMS	A3 RMS	A1 THD	A2 THD	A3 THD	A Unbalance
	A	A	A	%	%	%	%
1	167.5	170.6	166,4	30.1	31.9	29	0.8
2	169	171.5	167.3	30.6	32.5	29.3	0.8
3	169.4	171.7	167.8	33	34.8	31.9	0.9
4	170.1	173	168.4	31	32.9	29.7	0.9
5	170.4	172.8	169	31.1	33	29.8	0.7
6	170.5	172.6	169	31.3	33.2	30.1	0.6
7	169	171	167.4	30.9	32.8	29.8	0.7
8	170.4	170.7	170.2	34.2	35.7	33.6	0.6
AVERAGE	170	171	168	31.5	34.4	30.4	0.75

The table 5.4 shows RMS current, THD_I per phase and unbalances between the phases for different readings. The reading in the table shows average values of the parameters at the bottom. The average current unbalance value is 0.75% which is not beyond limit value given by standard, 10%. But the THD_I measured shows there is high value of distortion.

Table 5.5: Average real power and power factor data measured on transformer

Average power					Average power factor			
W1	W2	W3	W total	VA total	PF1	PF2	PF3	PF mean
27994.45	27952	27658.85	83605.3	102709	.822	.806	.814	.814

Table (5.5) shows single phase and three phase average real power, apparent power and power factor reading as indicated in the table. As the data taken from the transformer implies the average power factor of the three phases is low, 0.814. The factory has been penalized by Ethiopian Electric Utility (EEU) for the low power factor. Therefore the power factor should be corrected so that the efficient use of power is ensured and also for factory to escape from penalty.

Table 5.6 RMS value of individual harmonic currents and voltages

Harmonic components	h=1	h=3	h=5	h=7	h=11	h=13	h=17
RMS current(pu)	1	0.01875	0.25	0.225	0.0356	0.01863	0.01875
Voltage (pu)	1	0	0.0140	0.0170	0.0100	0.0040	0.0048

5.3 Proposed Mitigation Techniques

5.3.1 Removing Harmonics and Compensating Reactive Power.

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 [8]. 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.

Design of shunt harmonic filter to reduce current harmonic distortion

The design procedure of single tuned shunt harmonic filter is:

1. Calculate the value of the capacitance needed to improve the power factor and to eliminate any penalty by the electric power company.

2. Choose a reactor to tune the series capacitor to the desired harmonic frequency
3. Calculate the peak voltage at the capacitor terminals and the RMS reactor current.
4. Choose standard components for the filter and verify filter performance to assure that capacitor components will operate within IEEE-18 recommended limits

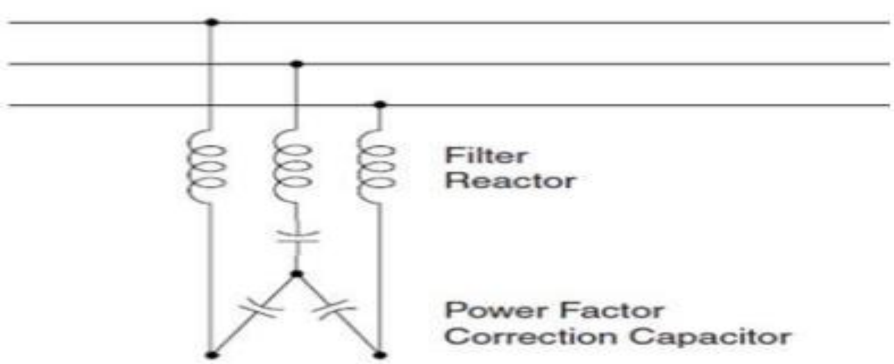

Figure 5.1: Harmonic filter and power factor correction configuration [1]

Most harmonic flow analysis on power systems is performed using steady-state, linear circuit solution techniques. Harmonic sources, which are nonlinear elements, are generally considered to be injection current sources into the linear network models. They can be represented as current injection sources or voltage sources. For most harmonic flow studies, it is suitable to treat harmonics sources as simple sources of harmonic currents [7].

Modeling of nonlinear loads

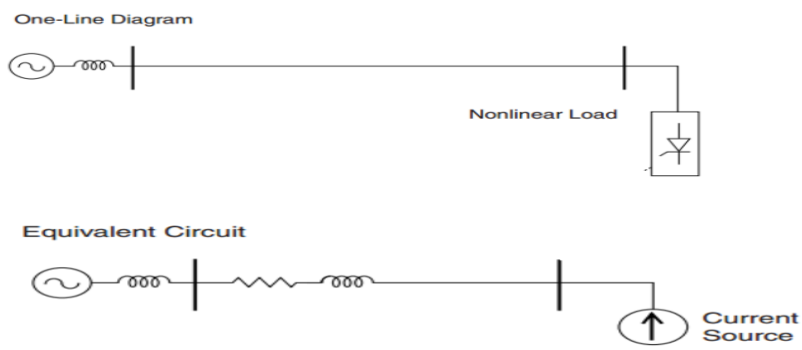

Figure 5.2: Representation of nonlinear loads as a current source for analysis [8]

Power factor correction

Power factor is defined as the ratio between the active component P and the total value of the apparent power S. [1]

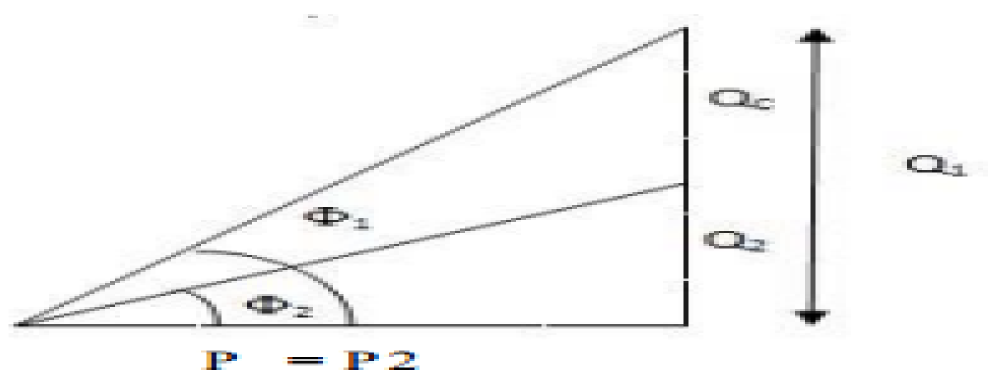

Figure 5.3 Phasor representations before and after power factor corrector [28]

$\tan(\varphi 1) = Q1/P \rightarrow Q1 = P*\tan(\varphi 1)$ (5.14)

$\tan(\varphi 2) = Q2/P \rightarrow Q2 = P*\tan(\varphi 2)$ (5.15)

$Q2 = Q1 - Qc \rightarrow Qc = Q1 - Q2$ (5.16)

$Qc = P[\tan(\cos^{-1}(PF1)) - \tan(\cos^{-1}(PF2))]$ (5.17)

whereas:

P - Active power

Q1 - Reactive power before power factor correction

φ1 - Phase displacement angle before power factor correction

Q2 - Reactive power after power factor correction

φ2 - Phase displacement after power factor correction

Qc - Reactive power for power factor correction

Qc - Reactive power for power factor correction

Some inductive loads need much reactive power from the utility supplying electric power. But this has a limit how reactive power to be sent from the utility. The rest is to be generated near to the load requiring it. This is known as power factor improvement. Improving the power factor means taking the necessary steps to increase the power factor in a defined section of the installation by locally delivering the necessary reactive power so that the value of the current and consequently of the power flowing through the upstream network can be reduced, at the same time required output power. In this way, the lines, the generators and the transformers can be sized for a lower apparent power. Thus, this improvement of power factor is known as power factor correction (PFC).For what said above, the main advantages of power factor correction can be summarized as follows: [1] [28]

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

Utility companies will provide a limited amount of reactive power at no cost, however, customers with high reactive power loads are charged for the additional power. They call this additional charge a power factor penalty (or power factor surcharge PFS). The target power factor is the power factor; a consumer must obtain to avoid paying a power factor penalty.

Ethiopian electric power utility set the target power factor which vary anywhere from 85% to 100%.

Voltage Rise at End User Bus

The voltage rise from placing capacitors on an inductive circuit is a two-edge's word from the power quality standpoint. If the voltage is low, then the capacitors provide an increase to bring the voltage back into tolerable limits. However, if the capacitors are left energized when the load is turned off, the voltage can rise too high, resulting in a sustained overvoltage. The voltage rise by the end user from the installation of capacitors is approximated by the following equation [8].

$$\%\Delta V = kVArcap * Z_T(\%)/kVAT \quad (5.18)$$

whereas:

$\%\Delta V$ - Percentage rise in voltage

kVArcap- Capacitor bank rating

kVAT - Step down transformer rating

$Z_T(\%)$ - Step down transformer impedance,%

This formula assumes that the transformer is the bulk of the total impedance of the power system up to the point at which the capacitor is applied

5.3.2 Design of Power Factor Corrector and Passive Power Shunt Filters

The analysis and design of passive power filters are normally considered together. It needs the data and nature of the nonlinear load for which a passive filter is to be designed and then a step-by-step procedure is adopted to design the passive filter. The passive shunt filter basically consists of a series combination of an inductor and a capacitor tuned to a particular frequency and it acts as a low-impedance path for that harmonic. In a single-phase system, the third and fifth harmonic filters are designed using a series tuned filter and a high-pass filter is designed using a second-order damped filter. In a three-phase system, the fifth and seventh harmonic filters are designed using a series tuned filter and a high-pass filter is designed using a second-order damped filter. Initially, the size of the capacitors is calculated from the reactive power requirement (QC) of the load. The absolute value of capacitance (C_n) is calculated as

$$\mathrm{Cn} = \frac{\mathrm{Qc}}{\mathrm{m\omega Vs2}} \quad (5.19)$$

where m is the number of branches in the passive filter for all the phases *V*s. Is per-phase fundamental voltage across it, and ω is the fundamental frequency of the supply. To trap the nth harmonic current, the inductance for the *n*th-order filter is calculated as

$$\mathrm{Ln} = \frac{1}{\mathrm{n2\omega 2Cn}} \quad (5.20)$$

The series resistance for the inductor of the *n*th-order filter is calculated as

$$\mathrm{Rn} = \frac{\mathrm{n\omega Ln}}{\mathrm{Qn}} \quad (5.21)$$

where: Q_n is the quality factor of the inductor of the nth-order filter, which is normally considered as $10 < Q < 100$. Mostly electrical energy is generated, transported and consumed as alternating current because of some practical reasons (e.g. the possibility to use transformations). However, alternating current has also some drawbacks. One of those is the need for reactive power that has to be supplied together with the active power.

The active power delivers the useful energize, the reactive power does not contribute to this. Nevertheless, it is an essential part of the total power: almost any system element generates or consumes reactive power. The compensation of reactive power can happen both in series connection as in shunt connection. Filtering the dominant harmonics frequency can reduce the effect of harmonics on equipment. In this case, the three phases shunt passive single tune filter fifth and seventh harmonic (5^{th} &7^{th}) design is discussed in this thesis work.

(a). Filter design and Power Factor upgrading

The whole filter design procedures have been discussed in chapter three. In this section the design activity is the issue to be concentrated on by considering the main steps

Select a tuned frequency for the filter

Filtering should start at the lowest harmonic frequency generated by the load which is (5^{th} &7^{th}) harmonic in this case. The filter will be tuned slightly below harmonic frequency of the concern (5^{th} &7^{th}) to allow tolerances for the filter components and variation in system impedance [1]. This prevent the filter from acting as a direct short circuit for the offending harmonic currents, reduce duty on the filter components, and minimize the possibility of dangerous harmonic resonance should the system parameters change and cause the tuning frequency to shift. This will also overcome detuning effect of filter due to higher value of shift & allow providing low impedance path to harmonic current.

Computing capacitor bank size and the resonant frequency

The source impedance will always have a tendency of affecting the system resonant condition [1]. This total source impedance will be so much has impact that resonant condition of system will be just before the tune frequency & operate the filter with some neighboring frequency. When there are multiple harmonic filters connected in the system, the resonant of filter circuit will affect the all harmonic filters. The filter size is based on the load reactive power requirement for the power factor correction. The total apparent power on the feeder for Recycling section is 102.7kVA with the bus voltage of 380V and 0.814 power factor lagging. The dominant harmonic currents are the 5th and the 7th harmonic current as it can be seen from the analysis done above. This feeder is supplied with 1250 kVA Transformer of 6% impedance. The filters upgrade the power factor to 0.96 in addition to filtering harmonic components. The tuned frequencies for the filters are selected to 5th and 7th harmonics. From 102.7kVA three phase capacity each phase has capacity of 34.24kVA by assuming equal sharing of the load for each phase. Adding 30% extra capacity for the design for the safety reasons each phase will have a capacity of 44.512 kVA at power factor of 0.814.

The reactive power drawn by each phase becomes:

$$\text{Q1} = 44.512 kVARsin\,(cos^{-1}(0.814) = 25.855\text{KVAr} \quad (5.22)$$

$$\text{Q2} = 36.24 kVARsin\,(cos^{-1}(0.96) = 15.285\text{KVAr} \quad (5.23)$$

Required compensation for the filter and the power factor correction is

$$QCompensation = Q1 - Q2 \quad (5.24)$$

$$QCompensation = 10.57 kVAr$$

To filter out the n^{th} harmonics the parameters should be calculated

$$X_{ch} = X_{lh} = \frac{1}{\omega Ch} = \omega Lh \quad (5.25)$$

whereas:

X_{ch} - Capacitive reactance for the h_{th} filter

X_{lh} - Inductive reactance for the h^{th} filter

C_h - Capacitance value for the h^{th} filter

L_h - Inductance value for the h^{th} filter

The filters are required to inject 10.57 kVAr reactive powers at the fundamental frequency, neglecting other harmonics. Since the filters (5^{th} and 7^{th}) are two parallel single tuned, the capacitor corresponding to the h^{th} harmonic filter can be shared corresponding to the magnitude of the harmonic current approximately by the following equation.

$$Q_h = Q_c * \frac{I_h}{\sum_1^h Ih} \quad (5.24)$$

whereas:

Q_n - Reactive power to be generated by the h_{th} filter

Q_c - Total reactive power needed to be generated

I_h - Magnitude of the h_{th} harmonic current

h - Harmonic number

From equation (5.13), the 5^{th} and 7^{th} harmonic share should be calculated according to equation (5.14) and (5.15)

$$Q_5 = KVAR * \frac{I_5}{I_5+I_7} = 10.57\text{kvar}*\frac{31.8}{31.8+27.9} = 6.63\text{kvar} \quad (5.25)$$

$$Q_7 = KVAR * \frac{I_7}{I_5+I_7} = 10.57\text{kvar}*\frac{27.9}{31.8+27.9} = 4.94\text{kvar} \quad (5.26)$$

Depending on the above equation the filters are designed as follows

Design of fifth harmonic filter

Capacitor of 6.63kVAr reactive power is required to filter out the 5th harmonic. It should be tuned at 4.7th harmonic because of the reasons stated under filter design procedure number 1. The net wye-equivalent filter reactance (capacitive) is determined by

$$X_{Filter} = X_{ch} - X_{lh} = \frac{(KV)^2}{MKVAr} = \frac{(0.38)^2}{0.00663MVAr} = 21.78\Omega \tag{5.27}$$

$$X_{cap} = (h)^2 * X_L = (4.7)^2 X_L \tag{5.28}$$

The desired capacitor reactance can be calculated as follows

$$X_{cap} = (h)^2 X_{Filter} * \frac{1}{(h)^2-1} = \frac{(4.7)^2 X_L}{(4.7)^2-1} = 22.81\text{ohm}$$

$$X_{Filter} = X_{Cap} - X_L \tag{5.29}$$

$$C_{Cap} = \frac{1}{2\prod X_{CCap}} = \frac{1}{2*\pi*50*22.81} = 0.0001395\text{F} \tag{5.30}$$

Computing filter reactor side

$$X_{Lfund} = \frac{X_{cap}}{(h)^2} = \frac{22.81}{(4.7)^2} = 0.986\ ohm \tag{5.31}$$

$$L = \frac{X_{Lfund}}{2\pi*50} = \frac{0.986}{2\pi*50} = 0.0031385H \tag{5.32}$$

Quality factor of the filter (Q)

$$Q = \frac{hX_L}{R} \tag{5.33}$$

whereas:

h is tuning harmonic

X_L is inductance of the filter

R is resistance of the inductor

Typical value of Q for the filter that are used in industry ranges from 15 to 80 [4]
The larger the Q value the sharper the tuning of the filter. Assuming Q=50

To achieve X_{Cap} (capacitor reactance) at the given rated voltage, the capacitor has to be rate:

$$R = \frac{hX_L}{Q} = \frac{5*0.0031385}{50} = 0.00031385\ ohm \qquad \text{from (5.33)}$$

Reactance of the transformer

$$X_t = \frac{0.06*(0.38)*0.38)}{MVA} = 0.007\ ohm \qquad (5.34)$$

$$L_t = \frac{0.007}{2*3.14*50} = 0.00002228H$$

Evaluating of filter duty requirements for both harmonics

Evaluation of filter duty requirement typically involves capacitor bank duties. IEEE -18 standards for shunt power capacitors is used as the limiting standard to evaluate these duties. These duties are:

- ✓ Fundamental duties
- ✓ Harmonic duties and
- ✓ RMS current and peak voltage duties

Fundamental duty

In this step, the fundamental frequency operating voltage across the capacitor bank is determined as follows: The apparent reactance of the capacitor and reactor at the fundamental frequency is

$$X_{fund} = \left|X_{Lfund} - X_{cap}\right| = |0.986 - 21.78| = 20.794\ ohm \qquad (5.35)$$

Fundamental frequency filter current is:

$$I_{fund} = \frac{V/\sqrt{3}}{X_{fund}} = \frac{380/\sqrt{3}}{20.794} = 10.55A \qquad (5.36)$$

The fundamental frequency operation voltage across the capacitor bank is:

$$V_{(1-1)fund} = \sqrt{3} * I_{fund} * X_c = \sqrt{3} * 10.55 * 21.78 = 398V \quad (5.37)$$

Harmonic duty requirement

In this step the maximum harmonic current expected in the filter is computed. This current has two components: harmonic current produced by the non-linear load and harmonic current from the utility side. The measured data shows the nonlinear load produces 25% fifth harmonic of the fundamental current, harmonic currents in ampere produced by the load would be as follows:

$$I_h = I_h(pu) * \frac{KVA}{\sqrt{3} * KV_{actual}} = .25 * \frac{102.70}{\sqrt{3} * .38} = 39A \quad (5.38)$$

Harmonic current contributed to the filter from the source side is estimated as follows. Neglecting the utility impedances the voltage distortion on the utility system will be limited by the impedance of the service transformer and the filter only. Fundamental frequency impedance of the service transformer is:

$$X_{Tfund} = Z_T(\%) * \frac{(KV)^2}{MVA_t} = 0.06 * \frac{(0.38)^2}{1.25} = 0.007\ ohm \quad (5.39)$$

$$X_{T(5th)} = 5 * 0.007 = 0.035\ ohm$$

Harmonic impedance of the capacitor is

$$X_{(Cap-wye)harm} = \frac{X_{(Cap-wye)}}{h} = \frac{21.78}{5} = 4.356\ ohm \quad (5.40)$$

Harmonic impedance of the reactor is

$$X_{L(harm)} = 5 * X_{L(fund)} = 5 * 0.986 = 4.93\ ohm \quad (5.41)$$

Utilities are expected to supply pure sine wave voltage. But this cannot be expected because of solid state protective devices and energization of transformers involved in the power system. Assuming the voltage distortion on the utility system 1%, the estimated amount of the fifth and seventh harmonic current contributed to the filter from the source side would be:

$$I_{h(utility)} = \frac{Vh(utility) * KVAactual}{\sqrt{3} * (X_{T_{harm}} + X_{Lharm} - X_{(Cap-wye)}harm} = 0.01 * \frac{380}{\sqrt{3}(0.035 + 4.93 - 4.356)} = 3.6A \quad (5.42)$$

The sum of the harmonic current produced by the load and that contributed from the utility side will be:

$$I_{htotal} = I_5 = 39A + 3.6A = 42.6A \quad (5.43)$$

The harmonic voltage across the capacitor can computed as follows:

$$V_{cap(L-L)} = \sqrt{3} * I_{htotal} * \frac{X_{(Cap-wye)}}{h} = \sqrt{3} * 42.6 * \frac{4.356}{5} = 64V \quad (5.44)$$

Evaluation of total RMS current and peak voltage requirement

Total current passing through the filter

$$I_{rms\,total} = \sqrt{\left(I_{fund}\right)^2 + (I_h)^2} = \sqrt{10.55^2 + 42.6^2} = 43.89A \quad (5.45)$$

Assuming the harmonic and fundamental components add together, the maximum peak voltage cross the capacitor is:

$$V_{(L-L\,)cap,peak} = V_{(L-L\,)cap,fund} + V_{(L-L\,rms\,)harm} = 398 + 64 = 462V \quad (5.46)$$

RMS voltage across the capacitor is

$$V_{cap(L-L\,rms)total} = \sqrt{\left(V_{(1-1)Cfund}\right)^2 + \left(V_{Cap(L-L)harm}\right)^2} = \sqrt{398^2 + 64^2} = 403V \quad (5.47)$$

The total KVAr seen by the capacitor is

$$KVAr_{cap(wye)\,total} = \sqrt{3} * I_{rms\,total} * V_{Cap(L-L)total} = \sqrt{3} * 43.89 * 403 = 30.64KVAr \quad (5.48)$$

Evaluation of capacitor rating limits

IEEE Standard for Shunt Power Capacitors (IEEE 18-1992) specifies the following continuous capacitor ratings for both harmonics respectively:

Table 5.7: Comparison of capacitor performance to IEEE-18 recommended limits for 5th harmonic filter on transformer.

Duty	Definition	Limit (%)	Actual value	Actual value (%)
Peak voltage	$\frac{\boldsymbol{V_{1-1cap(max,peak)}}}{\boldsymbol{V_{rated}}}$	120	462/400	115
RMS voltage	$\frac{\boldsymbol{V_{1-1Cap(RMS,total)}}}{\boldsymbol{V_{rated}}}$	110	403/400	100
RMS current	$\frac{\boldsymbol{I_{RMS,total}}}{\boldsymbol{I_{rated}}}$	180	43.89/28.9	151
KVAr	$\frac{\boldsymbol{KVA_{rCap(max)}}}{\boldsymbol{KVA_{rated}}}$	135	30.64KVAr/20KVAr	153

Evaluate filter frequency response.

The filter frequency response is now evaluated to make sure that the filter does not create a new resonance at a frequency that could cause additional problems. The harmonic at which the parallel resonance below the notch frequency will occur is computed as follows. This assumes the service transformer reactance dominates the source impedance (line impedance and transformer impedance) [8].

$$h_o = \sqrt{\frac{X_{cap}}{X_T * X_{L\,fund6}}} = \sqrt{\frac{22.81}{0.007*0.986}} = 4.8$$

Design of seventh harmonic filter

Capacitor of 6.63kVAr reactive power is required to filter out the 7th harmonic. It should be tuned at 6.7th harmonic because of the reasons stated under filter design procedure number 1. The net wye-equivalent filter reactance (capacitive) is determined by

$$X_{Filter} = X_{ch} - X_{lh} = \frac{(KV)^2}{MKVAr} = \frac{(0.38)^2}{0.00494MVAr} = 29.23\Omega \tag{5.49}$$

$$X_{cap} = (h)^2 * X_L = (6.7)^2 X_L \tag{5.50}$$

The desired capacitor reactance can be calculated as follows

$X_{cap} = (h)^2 X_{Filter} * \frac{1}{(h)^2-1} = \frac{(6.7)^2 X_L}{(6.7)^2-1}$ =29.9 ohm

$$X_{Filter} = X_{Cap} - X_L \quad (5.51)$$

$$C = \frac{1}{2\prod XC_{Cap}} = \frac{1}{2*\pi*50*22.9} = 0.0001065 \text{ F} \quad (5.52)$$

Computing filter reactor side

$$X_{Lfund} = \frac{X_{cap}}{(h)^2} = \frac{22.9}{(6.7)^2} = 0.666\ ohm \quad (5.53)$$

$$L = \frac{X_{Lfund}}{2\pi*50} = \frac{0.666}{2\pi*50} = 0.0021202\ H \quad (5.54)$$

Quality factor of the filter (Q)

$$R = \frac{hX_L}{Q} = \frac{7*0.0021202}{50} = 0.00029680\ ohm \quad (5.55)$$

Reactance of the transformer is already calculated before

Evaluating of filter duty requirements for both harmonics

Fundamental duty

$$X_{fund} = \left|X_{Lfund} - X_{cap}\right| = |0.666 - 29.9| = 29.234\ ohm \quad (5.56)$$

Fundamental frequency filter current is:

$$I_{fund} = \frac{V/\sqrt{3}}{X_{fund}} = \frac{380/\sqrt{3}}{29.234} = 7.5A \quad (5.57)$$

The fundamental frequency operation voltage across the capacitor bank is:

$$V_{(1-1)fund} = \sqrt{3} * I_{fund} * X_c = \sqrt{3} * 7.5 * 29.9 = 388V \quad (5.58)$$

Harmonic duty requirement

In this step the maximum harmonic current expected in the filter is computed. This current has two components: harmonic current produced by the non-linear load and harmonic current from the utility side. The measured data shows the nonlinear load produces 22% seventh harmonic of the fundamental current, harmonic currents in ampere produced by the load would be as follows:

$$I_h = I_h(pu) * \frac{KVA}{\sqrt{3}*KV_{actual}} = .22 * \frac{102.70}{\sqrt{3}*.38} = 31A \quad (5.59)$$

Harmonic current contributed to the filter from the source side is estimated as follows. Neglecting the utility impedances the voltage distortion on the utility system will be limited by the impedance of the service transformer and the filter only. Fundamental frequency impedance of the service transformer is:

$$X_{Tfund} = Z_T(\%) * \frac{(KV)^2}{MVA_t} = 0.06 * \frac{(0.38)^2}{1.25} = 0.007ohm \quad (5.60)$$

$$X_{T(7th)} = 7 * 0.007 = 0.049\ ohm \quad (5.61)$$

Harmonic impedance of the capacitor is

$$X_{(Cap-wye)harm} = \frac{X_{(Cap-wye)}}{h} = \frac{29.9}{7} = 4.27\ ohm \quad (5.62)$$

Harmonic impedance of the reactor is

$$X_{L(harm)} = 7 * X_{L(fund)} = 7 * 0.986 = 4.662\ ohm \quad (5.63)$$

Assuming the voltage distortion on the utility system 1%, the estimated amount of the fifth and seventh harmonic current contributed to the filter from the source side would be:

$$I_{h(utility)} = \frac{Vh(utility)*VAactual}{\sqrt{3}*(X_{T_{harm}}+X_{Lharm}-X_{(Cap-wye)}harm} = 0.01 * \frac{380}{\sqrt{3}(0.049+4.662-4.27)} = 5A \quad (5.64)$$

The sum of the harmonic current produced by the load and that contributed from the utility side will be:

$$I_{htotal} = I_7 = 31A + 5A = 36A \quad (5.65)$$

The harmonic voltage across the capacitor can computed as follows:

$$V_{cap(L-L,rms)harm} = \sqrt{3} * I_{htotal} * \frac{X_{(Cap-wye)}}{h} = \sqrt{3} * 36 * \frac{4.27}{7} = 38V \quad (5.66)$$

Evaluation of total RMS current and peak voltage requirement

Total current passing through the filter

$$I_{rms\ total} = \sqrt{\left(I_{fund}\right)^2 + (I_h)^2} = \sqrt{36^2 + 5^2} = 36A \tag{5.67}$$

This is the RMS current of rating required for the filter reactor

Assuming the harmonic and fundamental components add together, the maximum peak voltage cross the capacitor is:

$$V_{(L-L\ )cap,peak} = V_{(L-L\ )cap,fund} + V_{(L-L\ rms\ )harm} = 388 + 38 = 426V \tag{5.68}$$

RMS voltage across the capacitor is

$$V_{cap(L-L\ rms)total} = \sqrt{\left(V_{(1-1)Cfund}\right)^2 + \left(V_{Cap(L-L)harm}\right)^2} = \sqrt{388^2 + 38^2} = 390V \tag{5.69}$$

The total KVAr seen by the capacitor is

$$KVAr_{cap(wye)\ total} = \sqrt{3} * I_{rms\ total} * V_{Cap(L-L)total} = \sqrt{3} * 36 * 390 = 24.317KVAr \tag{5.70}$$

Evaluation of capacitor rating limits

Table 5.8 Comparison of capacitor performance to IEEE-18 recommended limits for 7th harmonic filter on transformer.

Duty	Definition	Limit (%)	Actual value	Actual value (%)
Peak voltage	$\frac{V_{1-1cap(\,max,peak)}}{V_{rated}}$	120	476/400	119
RMS voltage	$\frac{V_{1-1Cap(\,RMS,total)}}{V_{rated}}$	110	398/400	100
RMS current	$\frac{I_{RMS,total}}{I_{rated}}$	180	20/14.5	140
KVAr	$\frac{KVA_{rCap(\,max)}}{KVA_{rated}}$	135	13.787KVAr/10KVAr	135

Evaluate filter frequency response.

$$\sqrt{\frac{29.9}{0.007+0.666}} = 6.7$$

6.7th harmonic is slightly less than fifth harmonic and the severity of parallel resonance would be less compared to if it would be at 7th harmonic.

5.4 Modeling and Simulation of Single Tune Passive Shunt Power Filters

A model is a representation of the construction and working of some system of interest. It similar to the system but simpler than the system it represents. The three phase model of the loads of the factory can be represented as shown in Figure (5.11). The model contains voltage source coming from the utility, impedance of the service transformer, impedance of the line and the loads. The loads are represented with the current sources. Harmonic sources, which are nonlinear elements, are generally considered to be injection of current sources into the linear network models. They can be represented as current injection sources or voltage sources [2]. For most harmonic flow studies, it is suitable to treat harmonics sources as simple sources of harmonic currents. The designed shunt harmonic filters have been integrated in to the system to improve the distorted waveforms. Simulation results have been shown and explained in accordance to the result obtained. The Matlab Simulink modeling is used to determine the improvement obtained; through simulation. The simulation results are shown in figure (5.12) up to (5.15). Both current and voltage harmonics have been simulated before and after the integration of shunt harmonic filters.

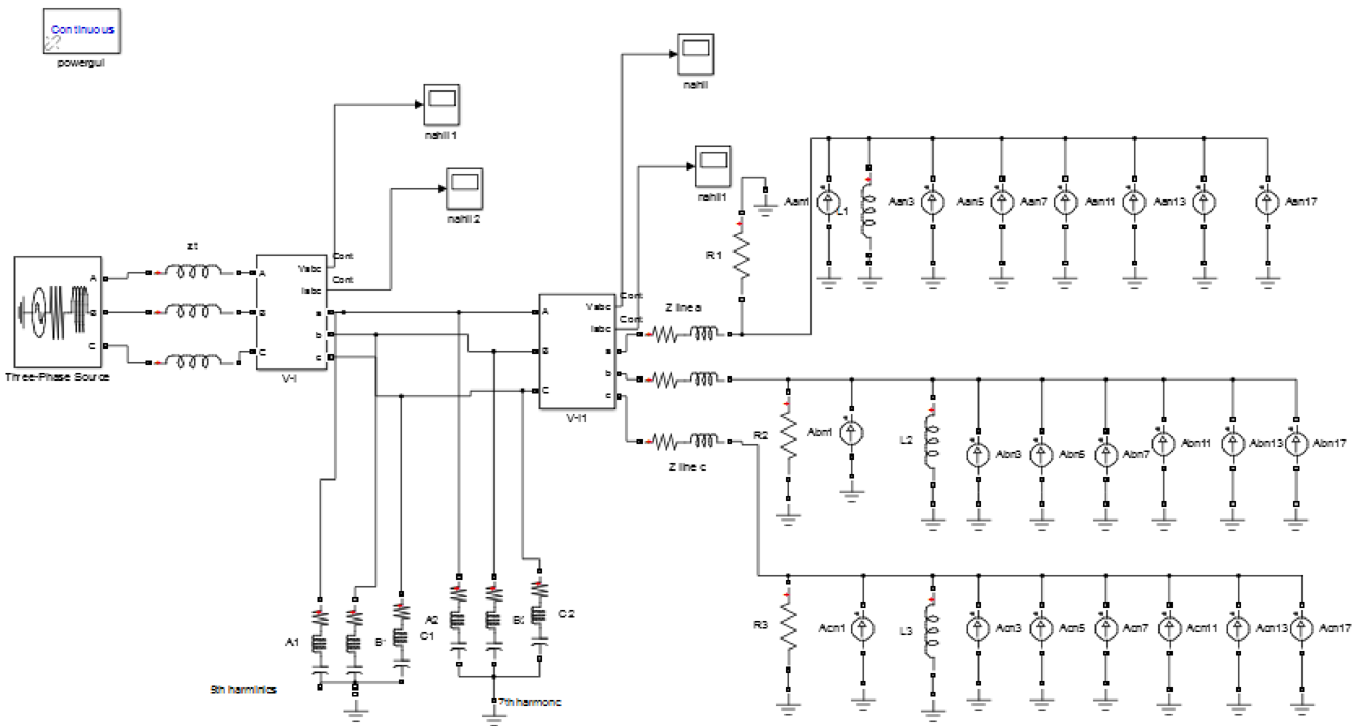

Figure 5.4 Circuit diagram of the model

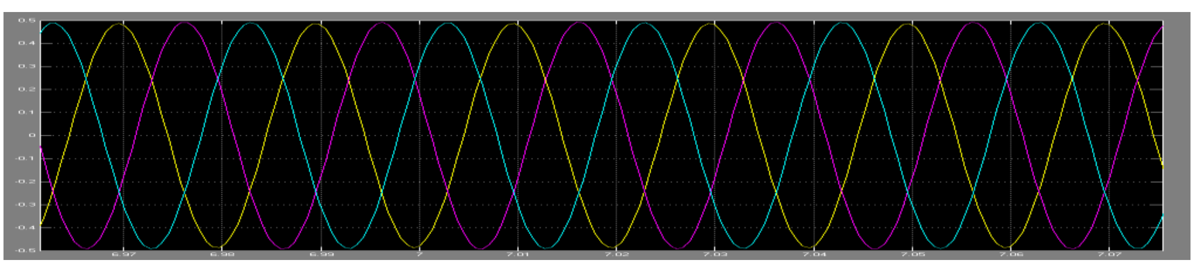

Figure 5.5 Simulated wave shape of voltage with filter

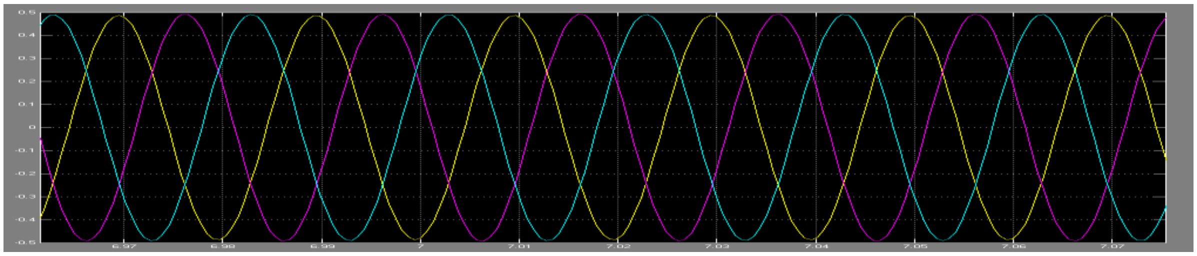

Figure 5.6 Simulated wave shape of current with filter.

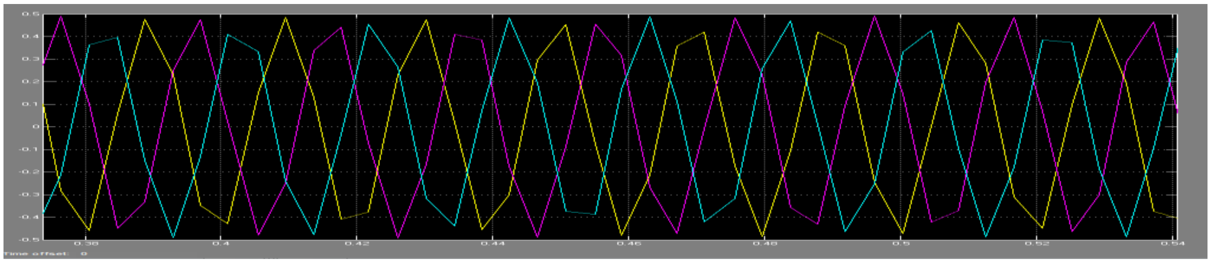

Figure 5.7 Simulated wave shape of current without filter

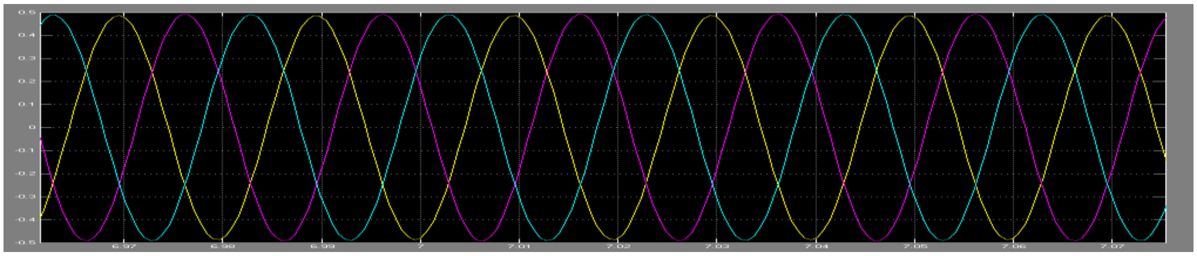

Figure 5.8 Simulated wave shape of voltage without filter

CHAPTER SIX

Conclusion and Recommendation

Based on the results of the power quality assessments carried out at ETUR Textile, the following major conclusions are drawn. In this chapter, useful recommendations are forwarded.

6.1. Conclusions.

This thesis work described some of power quality problems starting with review of literatures; previous research works and collection and analysis of data. Measurements have been conducted to assess the power quality problems at the factory. Mostly this thesis focused on harmonics and power factor correction analyses have been performed to identify the level of the power quality problems. Then respective solutions have been presented. From the analysis, it is seen that current THD in the range of 34.4% and voltage THD in the range of 2.9% were measured from the system. The dominant harmonic components are identified to be 5^{th} &7^{th} harmonics. The gathered data also showed that the factory has been working with poor power factor, 0.814. Harmonics cause nuisance tripping of circuit breakers, over heating of motors, generators, transformers, over loading of neutrals and in some cases increases shutdown time in production, thereby affecting negatively the economics of the industry. Mostly factory like textile needs good power quality because the process of production took around 2 hour to start by full capacity if any kind of power quality problem happened. The analysis made also shows as the company has harmonic distortion and relatively poor power factor. The Ethiopian Electric Utility charges the factories and industrial customers for the reactive power consumption when the PF is less than 0.85. The factory has been paying a much amount of money for the poor power factor in addition with the power quality problem they face with production loss. Single tuned shunt harmonic filters have been designed to limit the harmonic current injections within tolerable range and to improve power factor. Using the designed mitigation techniques the power factor is upgraded to 0.96 and the dominant harmonics (5^{th} &7^{th} orders) are reduced to 0.15% to solve the existing power quality problem.

6.2 Recommendation.

The following recommendations are forwarded.

- The Ethiopian Electric power and Ethiopian electric utility should work a lot on the whole power system, from generation to distribution to reduce power quality problems and especial attention should be given to power interruption problem which has been a day to day problem for the end users.
- Factories need to assess the power quality status of their supply system and sensitivity of their equipment to the power quality problems by install reasonable and appropriate mitigation techniques , if not the consequence is more than the power quality problem happened for example resonance effect is the best indicator.
- Ethiopian Electric Utility must give special attention to rehabilitation and automation of the distribution system.

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