STUDY AND SIMULATION OF POWER QUALITY IMPROVEMENT IN DISTRIBUTION NETWORK IN THE CASE OF METEHARA SUGAR FACTORY

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A thesis submitted to the school of electrical engineering and computing of Adama Science and Technology University in partial fulfillment of the requirements for the degree of Masters of Science in electrical power engineering

ADAMA SCIENCE AND TECHNOLOGY UNIVERSITY

SCHOOL OF ELECTRICAL ENGINEERING AND COMPUTING

DEPARTMENT OF ELECTRICAL POWER ENGINEERING

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Declaration

I, the undersigned, declare that this thesis entitled "*Study and Simulation of Power Quality Improvement in Distribution Network in the Case of Metehara Sugar Factory"* is entirely my original work, has not been done or presented for a degree in this or any other universities, and all sources of materials used for the thesis work has been properly referenced.

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Place: Adama

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

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Abstract

Nowadays, Ethiopia has been building a competitive sugar industry which is operated by the supervision of sugar corporation. Those industries need a considerable amount of electric power for their progressive consumption. Metehara Sugar Factory is one of the figurative sugar industries in the country. In this factory the electric power is generated from industrial power stations of non-condensing steam. In non-condensing steam power plants, a continuous supply of fresh feed of water is required. The steam power plant produces steam for industrial purpose besides of producing electric power that achieved by raising the steam in the boilers, expanding it through the turbine and coupling the turbine to the generators which convert mechanical energy to electrical energy. Most of the loads in the industry are nonlinear loads which affect seriously the quality of the power. Therefore, study is needed to identify the level of power quality problems in the company to be able to develop an appropriate mitigation technique. The aim of this study is to evaluate the power quality problem in the factory and to assess the use of D-STATCOM device to reduce the level of the problem.

To prove the power quality, appropriate measurement has been taken by using the power quality analyzing device namely HIOKI-3196 and the measurement data is analyzed by using PQA HiVIEW PRO 9624-50 software, as a result of flexible PC analysis the following specified problem is identified. The measurements of the line to neutral current indicate the harmonic distortion level of 26.20%, 22.58% and 42.95% with major 5^{th} and 7^{th} order harmonics for each phases. In addition to that, the total current harmonics distortion (THD_I) is 54.07%. Even though, an SVC has been installed on the distribution substation, the above problem and the low power factor of 0.54 was recorded.

Modeling and simulation of the DSTATCOM of 10 MVA with phase shifting transformer has been done using DigSilent software version 15.1, accordingly the total harmonics distortion level is reduced to 5.4% and the power factor is improved to 0.95 with an increase of voltage to 225V from the previous value of 200V.

Keywords: Power Quality, Total Harmonics Distortion (THD), Power Factor, D-STATCOM, DIgSILENT, PWM Converter (ElmVSC*).

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Acronyms

AC	Alternating current
ALFC	Automatic Load Frequency Control
ASD	Adjustable Speed Drives
CBEMA	Computer Business Equipment Manufacturers Association
CSI	Current source Inverter
CT	Current transformer
DC	Direct current
DigSilent	Digital Simulation and Electrical Network Calculation
DPF	Displacement Power Factor
DSTATCOM	Distribution Static Compensator
DVR	Dynamic Voltage Restorer
EEP	Ethiopian Electric Power
EPU	Ethiopia Power Utility
FACTS	Flexible AC Transmission system
FIPS	Federal Information Processing Standards
GCT	Gate Commutated thyristor
GTO	Gate Turn-off
HZ	Hertz
HTTP	Hypertext Transfer Protocol
IEC	International Electro Technical Commission
IEEE	Institute of Electrical and Electronics Engineering
IGBT	Integrated Gate Bipolar Transistor
ITIC	Information Technology Industry Council
JRE	Java Runtime Environment
KVA	Kilo Volt Ampere
KVAR	Kilo Volt Ampere Reactive
KW	Kilo Watt
LAN	Local Apparent Noon
LC	Inductor – Capacitor

LCD	Liquid Crystal Display
LCL	Inductor-Capacitor-Inductor
LED	Light Emitted Diode
MB	Mega Byte
MSF	Metehara Sugar Factory
MW	Mega Watt
NPV	Net Present Values
PC	Personal Computer
PCC	Point of Common Coupling
PF	Power Factor
PI	Proportional Integrator
PLL	Phase Locked Loop
PQA	Power Quality Analyzer
PU	Per Unit
PWM	Pulse Width Modulation
RMS	Root Mean Square
SMES	Superconducting Magnetic Energy Storage
SVC	Static VAR Compensator
TCR-FC	Fixed Capacitor Thyristor Controlled Reactor
TDD	Total Demand Distortion
TFT	Thin Film Transistor
THD_I	Total Current Harmonic Distortion
THD_V	Total Voltage Harmonic Distortion
UPFC	Unified Power Flow Compensator
UPS	Uninterrupted Power Supply
VFD	Variable Frequency Drive
VSI	Voltage Source Inverter
VT	Voltage transformer
VSC	Voltage Source Converter

Chapter One

Introduction

1.1 Background

A consistent power supply can be considered as a good quality power. According to manufacture point of view, power quality is defined as characteristic of the power supply that enables the equipment to work properly. According to utility point of view, power quality is defined as reliability or continuity of supply and end show statistics demonstrating that the system is 98% reliable. According to end-user point of view power quality defined as any power problem that is manifested in voltage, current, or frequency deviations that result in failure or misoperation of customer equipment.

Power quality is one of the big issues to be considered, when we referring the Ethiopian power transmission and distribution system, currently our country is building a huge number of substations and relatively high power consuming industry in various parts of the entire regions. Industrial processes use nonlinear loads such as adjustable speed drives (ASD), uninterruptible power supply (UPS), microprocessor based control and power electronic device that is highly sensitive to disturbances and causes for power quality problems. The general classes of power quality problems are categorized as voltage imbalance, voltage fluctuation, power frequency variation, transients (oscillatory transients and impulsive transients), long duration RMS variation, short duration RMS variation and wave distortion. The long duration RMS variation includes over voltage, under voltage and sustained interruption. The short duration RMS variation includes voltage sag, voltage swell and interruption. The wave distortion includes harmonics, inter harmonics, DC-offset, notching and noise. The power quality problems may caused by electrical system design, improper grounding techniques, harmonics or simply just load interactions. The harmonic distortion exists due to the nonlinear characteristics of devices and loads on the power system. The presence of harmonics may affect motors, transformers and wires to heat up excessively finally it can be damage the system [1,2,3].

DSTATCOM (Distribution Static Compensator) is the member of compensating type custom power devices used for load compensation such as power factor correction, load balancing, and harmonic filtering etc. DSTATCOM is a shunt connected device that supply or absorb reactive power and suppressed the effects of poor load power factor, harmonic content, unbalanced load and DC offset [4]. Modern semiconductor switching devices are being utilized more and more in a wide range of applications in distribution network particularly in domestic and industrial loads. Among these, the D-STATCOM is one of the most effective device which is operated based on the principle of voltage source converter [5].

Dig Silent version 15.1 has been used for the simulation studies on the modeled test system. Dig Silent is an abbreviation of "Digital Simulation and Electric Network Calculation Program" which is the most powerful software for power system with an integrated graphical interface and has faster simulation time [6].

1.2 Statement of the Problem

The major power quality problems are an extent variation of voltage, current and the phase displacement between corresponding phase voltage and current at the fundamental frequency, and the degree of unbalance in the different phase voltage and currents in power distribution system due to variation of load. The effects of power quality problems in the industries brings a failure on motor drives, tripping of circuit breakers, overheating of motors, poor power factor problem, fuse blowing, contactor burnouts, and failure on insulation cables etc.

Metehara Sugar Factory(MSF) has two turbo generators to produces total power of 6.36MW. Although, MSF were used the SVC for their power quality improvement, expected quality of power is not achieved yet. The measurements taken from transformer, adjustable speed drive and induction motor side show that power quality problem of total voltage harmonic distortion (THDV), total current harmonic distortion (THDI), neutral current, waveform distortion and poor power factor are above the normal ranges in the industry. There is also power frequency variation that is directly related to the rotational speed of the generators or operation of rotating machinery. Therefore, it is very important to explore solutions to this serious problem of power quality improvement. This thesis focuses on above mentioned power quality problems.

1.3 Objective of the Study

1.3.1 General Objectives

The main objectives of this thesis is to study the major power quality problems in distribution network of Metehara Sugar Factory, and explore and evaluate appropriate mitigation techniques to overcome the problems.

1.3.2 Specific Objective

This thesis targeted to achieve the following specific objectives:

- Assess the power distribution system and the load type existing in Metehara Sugar Factory.
- Identify and evaluate the types of power quality problems and give the possible solutions to the power quality problems.
- Model the distribution system with DSTATCOM, simulate and analyze the designed mitigation techniques to validate their impact on power quality.
- Draw relevant conclusions and recommendations which can help to improve the power quality problem.

1.4 Scope of the Study

The main scope of this study is to deal with power quality improvement in distribution network in Metehara Sugar Factory. This factory has nonlinear loads which introduce harmonics in the system which adversely effects including power factor. For economic operation of a power system, the level of power quality should be properly maintained.

1.5 Significances of the Study

The quality of power can have a direct economic impact on many industrial consumers. Both electric utilities and end users of electrical power are becoming increasingly concerned about the quality of electric power. The term power quality has become one of the most prolific buzzword in the power industry. For Metehara sugar factor implementation of the research result will bring benefits which include:

- Improvement of power quality, power factor and hence increase of efficiency and performances of the factory.
- Reduction of equipment failure due to harmonic distortion.

- Reduction of down time (service interruption) due to loss of synchronism and blackout of alternators.

1.6 Thesis Outline

The thesis is structured as follows;

Chapter One is about the background, statement of problems, objectives, the scope and significance of the study. It focuses on existing system power quality problems and their effect.

Chapter Two deals with the theoretical background and literature review. Here the detailed explanation is given about power quality problems and mitigation techniques to overcome power quality problems. It presents the basic working principle of DSTATCOM along with the control strategy. Finally, the comparison of SVC and DSTATCOM has been done. The research results of different researchers are explained as well in this part.

Chapter Three deals about the methodology of the research, the method of data collection and measuring procedure. Measuring techniques of power quality, behaviors of power quality measuring devices used to take all necessary measurements.

Chapter Four Presents the power quality problems as they examined and identified through various analysis results. Evaluation of total current harmonic distortion (THD_I), total voltage harmonic distortion (THD_V), neutral to ground current flowing, reactive power burden and unbalanced loads at the factory has been done using IEEE-1159 and IEC-61000 power quality standards as a benchmark.

Chapter Five deals with result analysis and discussion about the modeled system which is developed with DigSilent simulation tools and the power quality improvement of the system is tested and it shows that the selected device was mitigated or improved the factory power quality problems.

Chapter Six presents the conclusions of the work along with the future scope and recommendations followed by references.

Chapter Two

Theoretical Background and Literature Review

Theoretical Background

The IEEE has defined the power quality as the set of parameters defining the properties of the power supply as delivered to the user in normal operating conditions in terms of the continuity of voltage and voltage characteristics. Voltage qualities and current qualities are an indicative parameters of power quality. Voltage quality concerns with the deviation of the voltage from the ideal characteristics. Current quality concerns with the deviation of the current from the ideal characteristics. Modern electronic and power electronic devices may become the source and victims of power quality problems. As such the term power quality is used to define the interaction of electronic equipment within the electrical environment. The term electric power quality broadly refers to maintaining a near sinusoidal power distribution bus voltage at rated magnitude and frequency. In addition, the energy supplied to a customer must be uninterrupted from the reliability point of view.

Electric power has been generated by synchronous alternators that are driven by steam turbines. The perfect power supply would be one which always available, always with optimum voltage, frequency and sinusoidal wave shape. Variations in voltage are a frequent occurrence in power distribution networks. The voltage variation according to IEC is ± 5% for low voltage. Most of motors are manufactured to operate in tolerance of ± 5% (IEC). Voltage imbalance is a cause for motor temperature rise and fault. Harmonics, interharmonics, dc offset, noise and notching are a cause for waveform distortions. Power quality provides the solutions to all these problems in a very efficient and optimized way. These problems, if not mitigated would cause heavy economic as well as technical disturbances [1, 2].

2.1.1 Power Quality Issue Categories

Steady state variations refer to rms deviations from the nominal quantities or harmonics. There is internal causes and external causes for power quality problems. The internal causes for power quality problems are large equipment start and/or shut down, improper wiring and grounding, overloaded circuits or harmonics, variation in voltage magnitude and frequency. Variation in magnitude can be due to sudden rise or fall of load, outages, repetitive varying loading pattern in rolling mills, power electronic converters, inverters, lightning etc. The external causes for power quality problems are lightning strikes, equipment failure and weather conditions. The different types of power quality problems are poor load power factor, harmonic contents in loads, notching in load voltages, dc offset in load voltages, unbalanced loads, supply voltage distortion, voltage sag/swell, voltage flicker etc. The sources of poor power quality are [1,2,3]:

- Nonlinear loads
- Arcing loads
- Switching operation
- Reactive loads and unbalance system etc.

2.1.1.1 Short Duration RMS Variation

Short duration voltage variations are almost always caused by fault conditions, the energization of large loads that require high starting currents, or intermittent loose connections in power wiring. The fault condition can be close to or remote from the point of interest. In either case, the impact on the voltage during the actual fault condition is a short duration variation. Changes in current which fall into the duration and magnitude categories are also included in short-duration variations. Depending on the fault location and the system conditions, the fault can be categorizing as:

- Interruption
- Voltage Sags (Dips)
- Voltage Swells.

An interruption occurs when the supply voltage or load current decreases to less than 0.1pu for a period of time not exceeding one minute. The duration of the interruption will depend on the reclosing capability of the protective device. Instantaneous reclosing generally will limit the interruption caused by a non-permanent fault to less than 30 cycles. Delayed reclosing of the protective device may cause a momentary or temporary interruption.

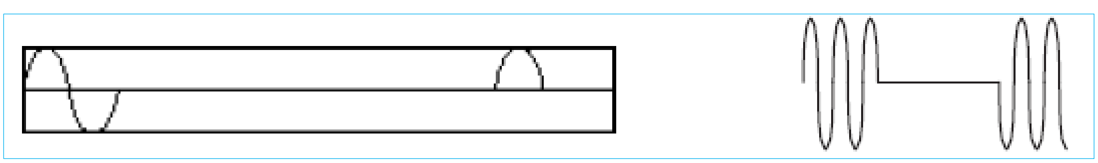

Figure 2.1: Interruption waveform.

Voltage sag is the reduction in a voltage envelope. The duration is usually from one cycle to a few seconds. Usually, sags are caused by fault clearing or switching of heavy load and starting of large motors. An induction motor will draw five to six times its full load current during starting. This lagging current causes a voltage drop across the impedance of the system. The voltage sags are complete or partial for a very short period of time (milliseconds) constitutes a dropout. Typical fault clearing times range from 3 to 30 cycles, depending on the fault current magnitude and the type of overcurrent detection and interruption.

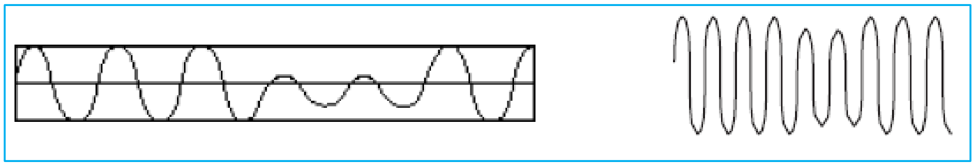

Figure 2.2: Voltage sag waveform.

A voltage swell is an increase in rms voltage or current at the power frequency for durations from 0.5 cycles to one minute. Typical magnitudes are between 1.1 and 1.8pu. Swells can be caused by switching off a large load or switching on a large capacitor bank. Swells are characterized by their magnitude (rms value) and duration. The severity of a voltage swell during a fault condition is a function of the fault location, system impedance, and grounding.

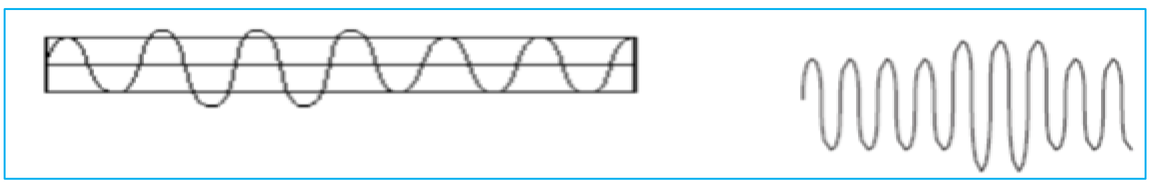

Figure 2.3: Voltage swell waveform.

2.1.1.2 Long Duration RMS Variations

Long duration variations encompass rms deviations at power frequencies for longer than one minute. They are caused by load variations on the system and system switching operations. Depending on the cause of the variation it categorized as:

- Over Voltage
- Under Voltage
- Sustained Interruption

Over voltage is a voltage greater than the rating of a device or component. Over voltages can be the result of switching off a large load and variations in the reactive compensation on the system or switching on a capacitor bank. Poor system voltage regulation capabilities or controls result in overvoltage. Incorrect tap settings on transformers can also result in system overvoltage.

Under voltage is a voltage less than the rating of a device or component. A load switching on and/or a capacitor bank switching off, and overloaded circuit can cause an under voltage until voltage regulation equipment on the system can bring the voltage back to within tolerances.

The decrease to zero of the supply voltage for a period of time in excess of one minute is considered a sustained interruption. Voltage interruptions longer than one minute are often permanent in nature and require manual intervention for restoration.

2.1.1.3 Waveform Distortion

The power system network tries to generate and transmit sinusoidal voltage and current signals, however the sinusoidal nature is not maintained and distortions occur in the signal. The cause of waveform distortions is:

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

Harmonics is a sinusoidal component of an AC voltage that is a multiple of the fundamental frequency (50Hz or 60Hz). Unwanted harmonic currents flowing through the distribution network can causes needless losses. Harmonic distortion exists due to the nonlinear characteristics of devices and loads on the power system. These devices can usually be modeled as current sources that inject harmonic currents into the power system. Harmonic distortion is a growing concern for many customers and for the overall power system due to increasing application of power electronics equipment. Current distortion and voltage distortion levels can be characterized by a total harmonic distortion (THD). The term total demand distortion (TDD) is the same as the total harmonic distortion (THD) except that the distortion is expressed as a percent of some rated load current rather than as a percent of the fundamental current magnitude.

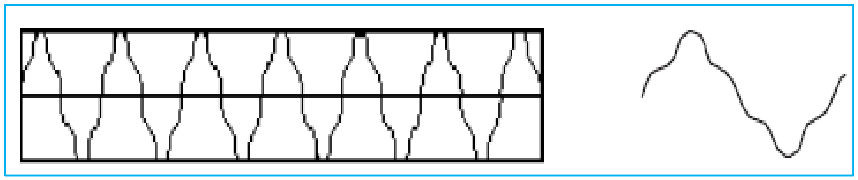

Figure 2.4: Harmonic distortion.

Inter harmonics can be found in networks of all voltage classes. The main sources of inter harmonic waveform distortion are static frequency converters, cyclo-converters, induction motors, and arcing devices. Power line carrier signals can also be considered as inter harmonics.

The presence of a dc voltage or current in an ac power system is termed dc-offset. This phenomenon can occur as the result of a geomagnetic disturbance or due to the effect of half-wave rectification. Incandescent light bulb life extenders, for example, may consist of diodes that reduce the rms voltage supplied to the light bulb by half wave rectification.

Notching is a periodic voltage disturbance caused by the normal operation of power electronics devices when current is commutated from one phase to another. It can damage capacitive components connected in shunt due to high rate of voltage rise at the notches. Since notching occurs continuously (steady state), it can be characterized through the harmonic spectrum of the affected voltage. However, the frequency components associated with notching can be quite high and may not be readily characterized with measurement equipment normally used for harmonic analysis.

Noise is unwanted electrical signals with broadband spectral content lower than 200kHz superimposed upon the power system voltage or current in phase conductors, or found on neutral conductors or signal lines. Noise in power systems can be caused by power electronic devices, control circuits, arcing equipment, loads with solid-state rectifiers, and switching power supplies. Basically, noise consists of any unwanted distortion of the power signal that cannot be classified as harmonic distortion or transients. Noise disturbs electronic devices such as microcomputer and programmable controllers. The problem can be mitigated by using filters, isolation transformers, and some line conditioners.

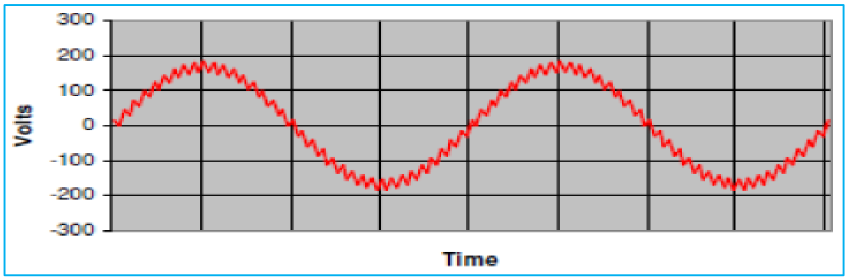

Figure 2.5: Noise waveform.

2.1.1.4 Transients

Transient is a high amplitude, short duration impulse superimposed on the normal voltage or current. It is a voltage or current condition of positive or negative amplitude. A transient is that part of change in a system variable that disappears during transition from one steady-state operating condition to another. It can be classified into two categories:

- Impulsive transient
- Oscillatory transient

An impulsive transient is a sudden, non-power frequency change in voltage, current etc. that is unipolar in nature. The polarity of such a transient can be either positive or negative. Impulsive transients have a very fast rise time and also a very fast decaying time. These transients are mainly caused by lightning strikes. Impulsive transients usually do not conduct far the point of their entry into the power system. The distance to which an impulsive transient travels along a feeder depends on the particular system configuration.

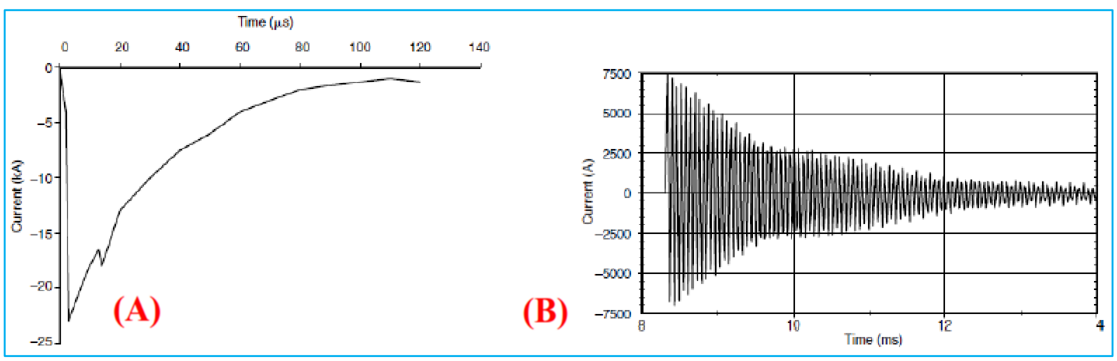

Figure 2.6: (a) Impulsive Transient (b) Oscillatory Transient

2.1.1.5 Voltage Imbalance

Voltage imbalance (or unbalance) is defined as the ratio of the negative or zero sequence components to the positive sequence component. The negative or zero sequence voltages in a power system generally result from unbalanced loads causing negative or zero sequence currents to flow. Imbalance can be estimated as the maximum deviation from the average of the three-phase voltages or currents, divided by the average of the three phase voltages or currents, expressed in percent. The primary source of voltage imbalance less than 2% is unbalanced single phase loads on a three phase circuit.

2.1.1.6 Voltage Fluctuation (Flicker)

Voltage fluctuations are rapid changes in voltage within the allowable limits of voltage magnitude of 0.95 to 1.05pu of nominal voltage. Devices like electric arc furnaces, arc discharge lamps, starting of large motor and welding machines 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 6Hz to 8Hz and is visible to the human eye.

2.1.1.7 Power Frequency Variation

The electric power network is designed to operate at a specified value (50Hz) of frequency. The frequency variations are caused if there is any imbalance in the supply and demand. Large variations in the frequency are caused due to sudden switching of loads [15]. The power system frequency is directly related to the rotational speed of the generators on the system. Frequency variations that go outside of accepted limits for normal steady state operation of the power system are normally caused by faults on the bulk power transmission system, a large block of load being disconnected or a large source of generation going off-line.

Table 2.1: Summary of Power Quality Variation Categories [1,2,3].

Causes	Sources	Effects	Example of power conditioning solution
Impulsive Transient (Transient disturbance)	▪ Lightning ▪ Electrostatic discharge ▪ Load switching ▪ Capacitor switching	▪ Destroys Computer Chips and TV regulator	▪ Surge arresters ▪ Filters ▪ Isolation transformers
Oscillatory Transients (Transient disturbance)	▪ Line/Cable switching ▪ Capacitor switching ▪ Load switching	▪ Destroys Computer Chips and TV regulator	▪ Surge arresters ▪ Filters ▪ Isolation transformers
Sag/Swells (RMS Variation)	▪ Remote system faults	▪ Motor starting and Overheating ▪ Computer failures ▪ ASD shutting down	▪ Ferro resonant transformers ▪ Energy storage technologies ▪ UPS
Interruption (RMS Variation)	▪ System protection ▪ Breaker ▪ Fuses ▪ Maintenance	▪ Loss production ▪ Shutting down of equipment	▪ Energy Storage Technologies ▪ UPS ▪ Backup generators
Under voltage/ Overvoltage (Steady state variation)	▪ Motor starting ▪ Load variation ▪ Load dropping	▪ Shorten lives of motors and lightning filaments	▪ Voltage regulators ▪ Ferro resonant Transformers
Harmonic distortion	▪ Nonlinear loads ▪ System resonance	▪ Overheating transformers and motors ▪ Fuse blow ▪ Relays trip ▪ Meters misoperate	▪ Active or Passive filters ▪ Transformer cancellation of zero sequence components
Voltage flicker	▪ Intermittent load ▪ Motor starting ▪ Arc furnace	▪ Light flicker ▪ Irritation	▪ Static VAR system

2.1.2 Power Quality Mitigation Techniques

The two approaches load conditioning and line conditioning has been used to the mitigation of power quality problems. The load conditioning is mostly related to reactive power compensation techniques it can be broadly classified into two main categories: -

1. Passive techniques
2. Active techniques

The device has been installed for passive techniques are passive shunt L-C filters and power factor correction capacitors. The device has been installed for active techniques are PWM active filters. Passive filters have been most commonly used to limit the flow of harmonic currents in distribution systems. The performances of conventional method (LC filter) is not satisfactory due to the drawbacks. Among the different new technical options available to improve power quality, DSTATCOM have proved to be an important and flexible alternative to compensate for current and voltage disturbances in power distribution system.

2.1.2.1 Power Conditioning Equipment

A power conditioner can be known also as a line conditioner or power line conditioner. It is a device intended to improve the quality of power that is delivered to electrical load equipment. The use of power conditioning equipment is the most common solution to protect the power system network. Most of the power conditioning equipment is voltage monitoring devices as most of the faults that occur in power system are voltage imbalance faults. These devices may be connected at the source side or in the transmission network, or at the load end. In general, these devices are connected at the point of common coupling (PCC) where the load is connected to the supply. This is done as the cost of the power conditioning device increases from load end to source side. There are different power conditioning devices such as [7]: -

1. **Line-voltage regulators**: These are special transformers connected in series with the transmission line designed to regulate the voltage in accordance with the changes in the system. Tap changing transformers, CVT's, buck-boost regulators are the examples for line voltage regulators.
2. **M-G Sets (Motor-generator Sets)**: These M-G sets are installed at the load side in order to supply power to critical loads during the interruptions from the power supply company. In this maintenance and safety are main concern.

3. **Magnetic Synthesizers:** These employ resonant circuits made of inductors and capacitors. They are used to filter the harmonics from affecting the loads, but it is bulky and noisy.
4. **SVC (Static VAR Compensators)**: These also use passive elements like inductors and capacitors. But the use of solid state switches to control the voltage injection increases their efficiency. The switches are controlled such that correct magnitude of voltage is injected at correct point of time so that voltage fluctuations are reduced. But these are expensive.
5. **UPS (Uninterruptible Power Supplies)**: It provides a constant voltage during both voltage sags and outages from a battery or super conducting material. The main parts of an UPS are battery, rectifier and an inverter.
6. **SMES (Superconducting magnetic energy storage)**: SMES stores electrical energy within a superconducting magnet. It provides a large amount of power (750KVA to 500 MVA) within a short time.
7. **Custom Power Devices:** All the above mentioned conventional devices are not suitable to mitigate voltage disturbances effectively. Therefore, there is a need to use new type of devices known as custom power devices. These are power electronic equipment aimed to help in mitigating power quality problems. These are many types like Dynamic Voltage Regulator (DVR), D-STATCOM, auto transformer, UPFC etc. In this thesis a study and simulation of power quality improvement the device of DSTATCOM has been used for improving the power quality.

2.1.3 Static Var Compensator (SVC)

The fixed capacitor bank is the most inexpensive and widely used method of reactive power compensation using one fixed capacitor bank connected to the incoming transformer or switchgear bus. Static VAR Compensators are shunting connected static generators or absorbers whose outputs are varied so as to control voltage of the electric power systems. SVC is connected to Fixed Capacitor Thyristor Controlled Reactor (FC-TCR) configuration. The SVC is connected to a coupling transformer that is connected directly to the ac bus whose voltage is to be regulated. The effective reactance of the FC-TCR is varied by firing angle control of the anti-parallel thyristor. The firing angle can be controlled through a PI (Proportional + Integral) controller in such a way that the voltage of the bus, where the SVC is connected, is maintained at the reference value [8]. One of the applications of SVCs is to balance single-phase loads such as traction loads, so that the negative sequence voltage at the point of common coupling (PCC) is within the limits set by the respective national standards [9].

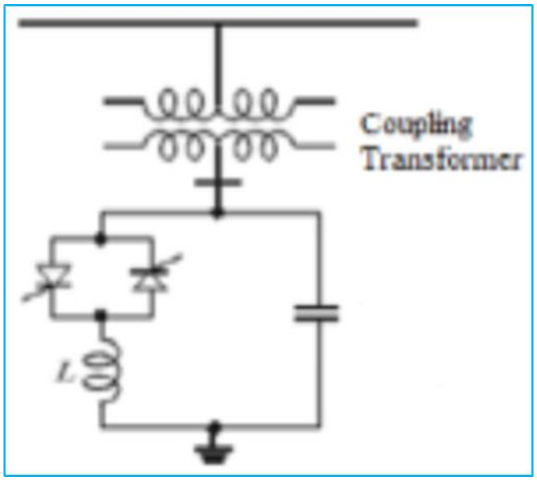

Figure 2.7: Static VAR Compensator (SVC) [8].

The main advantages of SVC over simple mechanically switched compensation scheme is their near instantaneous response to change in the system voltage. For this reason, they are often operated at close to their zero point in order to maximize the reactive power correction they can rapidly provide when required. They are in general cheaper, higher capacity, faster, and more reliable than dynamic compensation scheme such as synchronous condenser.

2.1.4 Distribution Static Compensator (D-STATCOM)

D-STATCOM is a shunt connected reactive power compensation equipment which can generates or/and absorbs the reactive power, control very fast and has the capability to provide adequate reactive compensation to the system. D-STATCOM is basically VSC and CSI based FACTS controller. It is employed at distribution level or at load side, and it works as the IEEE 519-1992 standard limit. Since the electrical power distribution system, it is very important to balance the supply and demand of active and reactive power in the electrical power system. The VSC converts the dc voltage across the storage device into a set of three-phase ac output voltages. These voltages are in phase and coupled with the ac system through the reactance of the coupling transformer. Suitable adjustment of the phase and magnitude of the D-STATCOM output voltages allows effective control of active and reactive power exchanges between the D-STATCOM and the ac system. D-STATCOM can be effectively utilized to regulate voltage for one large motor or for a series of small induction motors starting simultaneously. Induction motor loads draw large starting currents (5- 6 times) of the full rated current and may affect working of sensitive loads [5, 10].

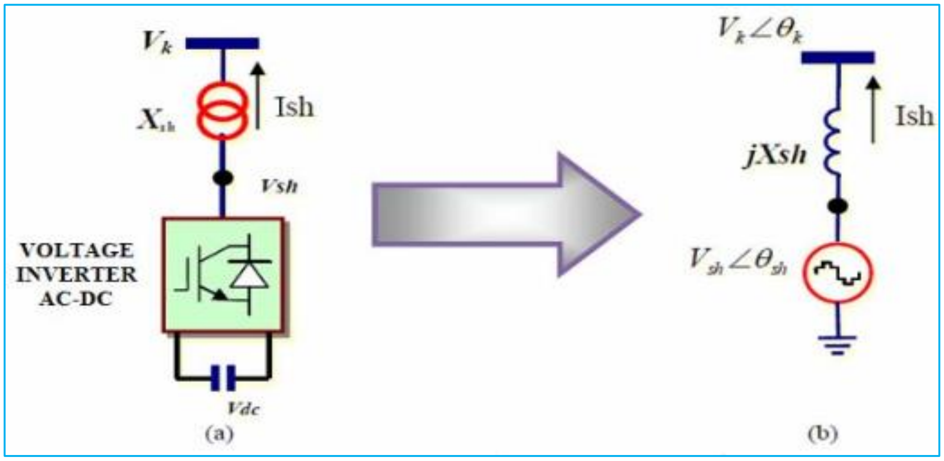

Figure 2.8: (a) Structure of a D-STATCOM, (b) Equivalent circuit [11].

The value of I_{sh} can be controlled by adjusting the output voltage of the converter. The shunt injected current I_{sh} can be written as,

$$I_{sh} = I_L - I_S = I_L - \frac{V_{th} - V_L}{Z_{th}} \tag{2.1}$$

$$I_{sh} < \eta = I_L < -\theta - \frac{V_{th}}{Z_{th}} < (\delta - \beta) + \frac{V_L}{Z_{th}} < -\beta \tag{2.2}$$

Where I_s is source current, I_{out} is output current, V_L is load voltage, I_L is load current and V_{th} is thevenin voltage.

D-STATCOM consist of capacitor, inverter models, PWM control strategy, transformer to match the inverter output to the line voltage, and it has ability to control the magnitude and phase angle of voltage or/and current [21]. A D-STATCOM controller can be constructed based on both voltage source inverter (VSI) topology and current source inverter (CSI) topology. The VSI converters for D-STATCOM are constructed based on multi-level topologies, with or without use of a transformer. These solutions provide support for operation with a high level of terminal voltage. However, in practice the CSI topology is not used for D-STATCOM. The reason for this is related to the higher losses on the DC reactor of CSI compared to the DC capacitor of VSI. VSI based topology has the advantage because an inductance of a coupling transformer can constitute partially or completely, the inductance of AC filter.

2.1.4.1 Components of a D-STATCOM

D-STATCOM consists of voltage source converter (VSC), a dc energy storage device, a coupling transformer connected in shunt to the distribution network through a coupling transformer. D-STATCOM is basically comprised of four major components such as voltage source converter(VSC), controller, energy storage circuit and LCL passive filter [5].

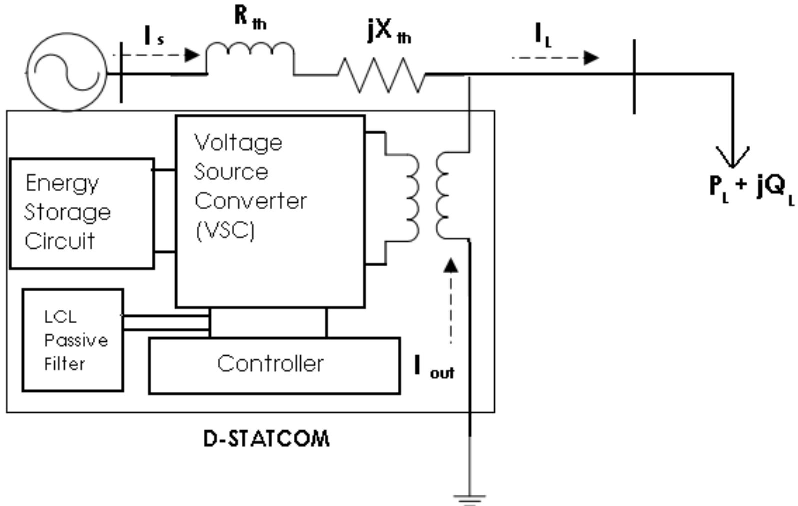

Figure 2.9: Schematic diagram of D-STATCOM [5,19].

$$Z_{th} = R + jX \tag{2.3}$$

The output current will correct the voltage sag by adjusting the voltage drop across the system impedance.

I. Voltage source converter (VSC)

A VSC is a power electronics device which is connected in shunt or parallel to the system, and it can generate a sinusoidal voltage with any required magnitude, frequency and phase angle. It used power electronics switch like IGBT, GTO and etc. VSCs are widely used in adjustable-speed drives. The VSC is used to either completely replace the voltage or to inject the missing voltage. The missing voltage is the difference between the nominal voltage and actual voltage. Normally VSC is not only used for voltage dip mitigation but also for other power quality issues such as flicker and harmonics. VSCs are a forced commutated converter that converts ac voltage into dc voltage and vice versa. The suitable adjustment of magnitude and phase of the DSTATCOM output voltages allows effectives control of active and reactive power exchanges. The semiconducting device in the converter is then switched to get the desired output voltage [5,7,10,12,19,21].

II. Controller

Classical PI control is the most common industrial used technique. This is achieved by a judicious choice of parameters "KP" and "KI" representing the proportional gain and the gain of integral action [7]. The error is processed by PI controller. An error signal is obtained by comparing the reference voltage with the rms voltage measured at the load point. The PI controller process the error signal generate the required angle to drive the error to zero.

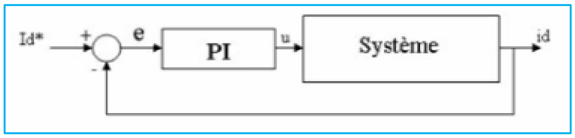

Figure 2.10: PI controller adjusted by analogical [5, 19].

III. Energy storage circuit

The purpose of energy storage is to maintain the dc side voltage of VSC. It carries the input ripple current of the converter. It is the main reactive energy storage element. This DC capacitor could be charged by a battery source or could be recharged by the converter itself [5,19].

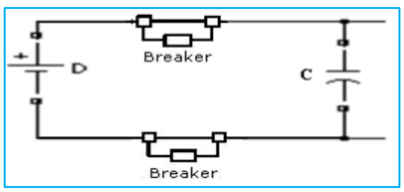

Figure 2.11: Circuit diagram of DC storage [5].

IV. LCL passive filter

The simplest passive filter consisted a series inductor connected to the entrance of the polluting equipment which rectify the capacitive filter output. This is a reliable and low cost solution. However, the inductor is bulky and heavy (due to the iron on its magnetic circuit), which practically limits this solution to low power equipment (less than 600VA).

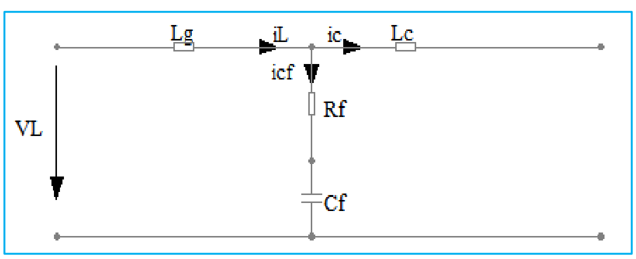

Figure 2.12: LCL passive filter [19].

2.1.4.2 Configuration and Operating Principles of D-STATCOM

The main application of D-STATCOM exhibit high speed control of reactive power to provide voltage stabilization in power system. The D-STATCOM has quicker response time and compact structure as compare to the SVC. The D-STATCOM configuration consists of a DC voltage source, inverter circuit, coupling transformer and control strategy. Such configuration allows the device to absorb or generate controllable active and reactive power.

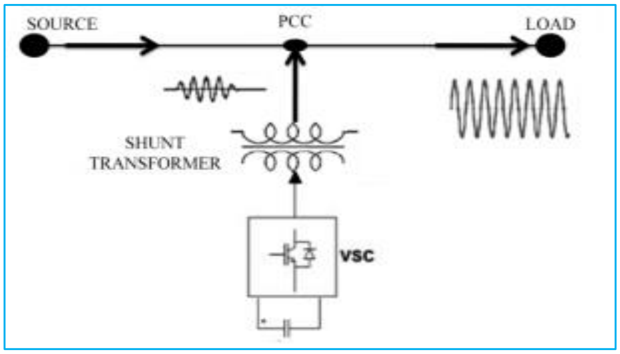

Figure 2.13: Schematic diagram of D-STATCOM [10].

The output terminals of the VSC are connected to the Point of Common Coupling (PCC) through an inductance, which could be a filter inductance of the coupling transformer. The DC side of the converter is connected to a DC capacitor, which carries the input ripple current of the converter and is the main reactive storage element. This capacitor could be charged by a battery source or could be pre charged by the converter itself.

The operating principles of D-STATCOM are based on the exact equivalent of the conventional rotating synchronous compensator. D-STATCOM is works as the IEEE 519-1992 standard limit. The operation of D-STATCOM is as follow:

- When the AC bus voltage magnitude is above that of the VSC voltage magnitude, the AC system see the D-STATCOM as inductance connected to its terminals and the voltage is compared with the AC bus voltage system.
- Otherwise if the VSC voltage magnitude is above that of the AC bus voltage magnitude, the AC system sees the D-STATCOM as capacitance to its terminals.
- If the voltage magnitudes are equal, the reactive power exchange is zero. The value of shunt injected current can be controlled by adjusting the output voltage of the converter.

The voltage regulation at PCC and power factor correction cannot be achieved simultaneously. D-STATCOM is used for voltage regulation at the PCC, the compensation should be such that the supply current should lead the supply voltages; whereas, for power factor correction, the supply current should be in phase with the supply voltages. The phase shift control is used to study the performance of D-STATCOM for power factor correction and harmonic mitigation [5,7,13,20,21].

2.1.4.3 Realization and Control Strategy of D-STATCOM

The aim of the control scheme is to maintain constant magnitude of voltage at the point where a sensitive load is connected and under system disturbances. The generation of proper pulse width modulation (PWM) firing is the most important part of D-STATCOM control and it has a great impact on its compensation objectives, transients as well as steady state performance. A PWM based distribution static compensator offers faster response and capability for harmonic elimination and power factor correction based on phase shift control and indirect decoupled current control [19,21]. All required voltages and currents are measured and are fed into the controller to be compared with the commands. The controller then performs feedback control and outputs a set of switching signals to drive the main semiconductor switches. A D-STATCOM provides fast control of active and reactive powers to enable load compensation, harmonics current elimination, voltage flicker mitigation, and frequency regulation. The control strategies of a D-STATCOM are mainly implemented in the following steps [8]:

- Measurement of system variables and signal conditioning.
- Extraction of reference compensating signals.
- Generation of firing angles for switching devices.

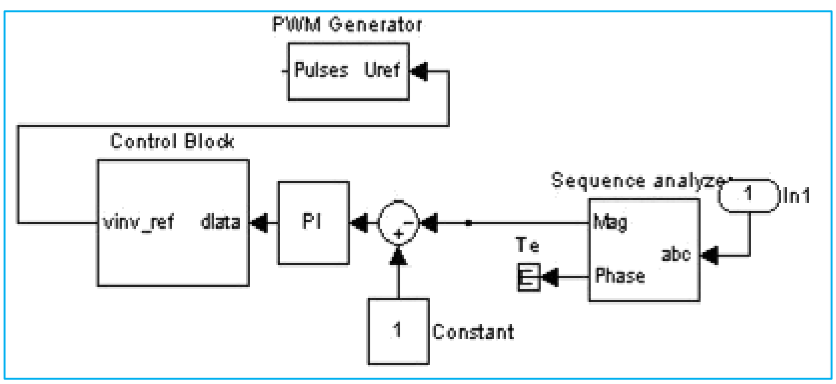

Figure 2.14: Control strategies of D-STATCOM [21].

2.1.5 Comparison of the SVC and D-STATCOM

The factory existing system has static Var compensator (SVC) in order to compensate reactive power however, the compensator did not work effectively, and the value of capacitor was fixed and cannot be changed frequently. The fixed capacitor bank is sized to regulate a 0.9 power factor during maximum operational inductive loading however, in this factory the power factor in each transformer is below the expected value. The SVC and D-STATCOM have a strong influence on power quality improvement. The SVC shows medium performance with respect to overall load compensation. A D-STATCOM provides an integrated solution to the present power quality problems which is faced by existing system.

The D-STATCOM is the best option to inject an unbalanced and harmonically distorted current to eliminate an unbalance or distortion in the load current or the supply voltage as well as the reactive power compensation. A D-STATCOM can eliminate any fluctuation in the load terminal voltage and the voltage of an unbalanced nonlinear and sensitive load can be regulated by this device. A D-STATCOM is a shunt connected reactive power compensation device that is capable of generating and/or absorbing reactive power and that can perform load compensation when connected at load terminals such as power factor correction, harmonic filtering, load balancing in order to improving the quality of the supplied voltage. When the D-STATCOM is connected at the distribution bus, it performs voltage regulation and/or it can hold the bus voltage constant against any unbalance or distortion in the distribution system [4,22]. The performance of voltage sourced converter (VSC) with Pulse-width modulation (PWM) provides a faster control that is required for flicker mitigation purpose [12].

2.1.5.1 Preference of a D-STATCOM as per Economic Perspective

The D-STATCOM device is widely used for power factor correction, load balancing, and load voltage regulation in distribution system. Although significant improvements in the overall power quality can be achieved, the high cost of the D-STATCOM can limit the benefits resulting from its application. The voltage regulation, power factor correction and energy loss reduction are chosen as the main target for the investigation. The process of cost estimation and comparing the different sizes of D-STATCOM is helped us to get the improved performance and the Net Present Values (NPV) for each size including the sum of all benefits and costs of implementing the D-STATCOM [16].

The economic benefits due to energy loss reduction are weighted against the installation cost of the KVar while keeping the voltage profile within defined limits. As per economic aspect it is so obvious that the D-STATCOM is more expensive than SVC. In existing systems, the SVC has been installed at each panels or load terminals, it is prohibitively expensive so that the cost effective method is installing KVar in distribution network with optimal location, type and size.

Table 2.2: Cost Comparison of Various FACTs Device [16,17].

Device	Cost (USD/Kvar)
SVC	34.56
D-STATCOM	165.23 -206.52

The costs of the reactive power source such as D-STATCOM can be divided into two, namely fixed cost and operating costs. The fixed costs mainly consist of the D-STATCOM device cost and the cost to install it including labor hours, footprint of the device, time and so forth. The operating or variable costs are those which allow the D-STATCOM device to work. These operating costs consist of heating losses and maintenance costs etc. In principle, however, the operating costs may differ from year to year.

Table 2.3: Average Costs of Single Power Interruption for Industrial Plants [17].

Plants	Costs
All plants	214.21(Baht)/KW + 303.48(Baht)/KWh
Plants > 1,000 KW max. demand	118.93(Baht)/KW + 106.60(Baht)/KWh
Plants < 1,000 KW max. demand	519.69(Baht)/KW + 918.45(Baht)/KWh

2.1.5.2 Preference of a D-STATCOM as per Load Compensating Perspective

In this thesis, a voltage source converter D-STATCOM based on PWM technique is proposed to mitigate harmonics distortion and improve power factor in distribution system. A STATCOM and D-STATCOM is a shunt connected device that has the same structure however, there is a substantial difference in the operating characteristics. The STATCOM is required to inject a set of three balanced quasi-sinusoidal voltages that are phase displaced by 120°. However, the D-STATCOM must be able to inject an unbalanced and harmonically distorted current to eliminate unbalance or distortions in the load current or the supply voltage. Therefore, its control is significantly different from that of a D-STATCOM. A D-STATCOM is connected in between an unbalanced source and an unbalanced and distorted load to compensate an unbalanced and nonlinear load. An unbalanced and nonlinear load is supplied by an unbalanced voltage source (Vs,) through a distribution panel. The distribution panel feeder has resistance(R) and inductance (L). The terminal voltage(Vt) is applied across the load as well as across the D-STATCOM. The dc voltage (Vdc) is stored in the storage capacitor(C_{dc}) to maintained current tracking and the loss due to R_f is replenished by drawing additional power from the source. The current (i_{dc}) charges or discharges the capacitor(C_{dc}). Thus the deviation of V_{dc} from the reference value V_{ref} at the end of each fundamental frequency cycle gives a good indication of the deviation of the average value of capacitor current i_{dc} from zero [4].

$$V_{dc} = \frac{1}{C_{dc}} \int i_{dc} dt \tag{2.4}$$

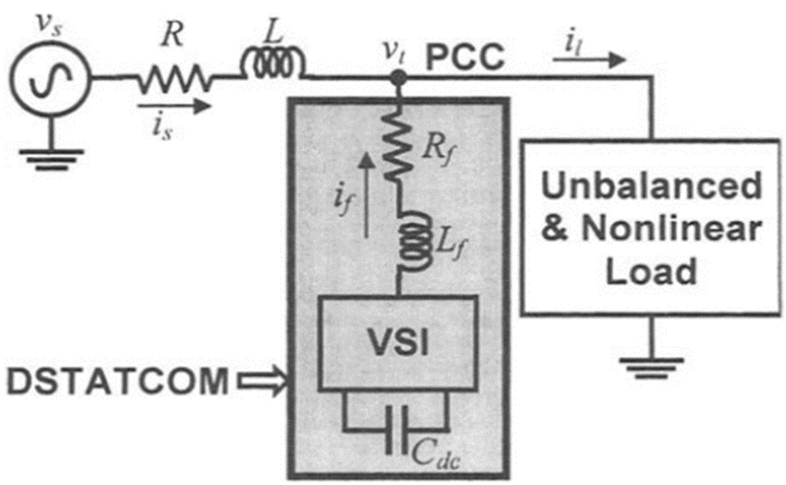

Figure 2.15: D-STATCOM connected to weak supply [4].

The different basic operational principle of the device called SVC and D-STATCOM shows below:

Table 2.4: Comparison of SVC and D-STATCOM [4, 26].

SVC	D-STATCOM
Thyristor based shunt compensator	VSC based shunt compensator
Operates as a shunt connected to control reactive admittance	Functions as a shunt connected synchronous voltage source
It does not provide active power compensation	It provide active power and reactive power compensation
Slow response time	Faster response time
Cost is low	Cost is high
Phase control	PWM control
Capacitive reactive current drops linearly	Constant current characteristics with voltage dip under the limit
High maintenance and service requirements	Low maintenance and service requirements
Low order harmonics are high	Low order harmonics are small
Maximum compensating current is proportional to system voltage	Maximum compensating current is independent on system voltage
Maximum phase delay is one cycle	Maximum delay is negligible

2.2 Literature Review

There are many researches that have study on the different problems related to power quality in distribution network and the methods of improving power quality. And they proposed their best solution to the existing problems. Here a few of them are mentioned below:

In [5], the author explained the power quality improvement methods in distribution line for the purpose of a noval distribution level of voltage control scheme to compensate voltage sag and swell condition. The simulation has been done using MATLAB Simulink of version R2009b; the study shows that the additional of D-STATCOM in distribution line improve the power quality problems due to short duration rms variation. The investigations prove that the voltage sag was mitigated under faults condition and under different type of short circuits. The test system of the study conclude that a D-STATCOM is a promising device and mitigated power quality problems, protects the distribution system from voltage sag and flicker caused by rapidly varying reactive current demand, and it provides leading or lagging reactive power to active system stability, power factor correction and load balancing.

The paper [10], is concerned with the methods of power quality improvement in distribution systems, the role and the performance of D-STATCOM for the purpose of eliminating or overcome the problems of source side like voltage sag and interruption. The work has been carried out by various techniques with D-STATCOM for the purpose of minimizing the problem associated in distribution system such as voltage sag, swell, interruption, total harmonic distortion and low power factor in power system with different condition. The investigator has presented the power quality problems on different condition for nonlinear load and simulated using MATLAB Simulink with comparing the existing power quality problems with and without D-STATCOM.

In [14], the investigator explained the application of D-STATCOM in a three Phase four wire distribution system for the purpose of harmonic elimination and system balance. In their study they try to show the three legs and four leg VSC topology and the performance of D-STATCOM along with a zig-zag transformer using both synchronous reference frame (SRF) and Artificial neural network (ANN) as a solution for power quality issues. The three leg voltage source converter (VSC) based D-STATCOM configuration with a zig-zag transformer has been used for neutral current compensation along with reactive power compensation, harmonic elimination, and load balancing at the PCC. The study shows that the performance of the proposed D-STATCOM system has been validated through simulations using MATLAB Simulink.

The study of Ramesh G B *et al.* [24] presents the improvement of voltage sags, harmonics distortions and poor powers factors using D-STATCOM with LCL Passive Filters in distribution system. The model was based on the voltage source converter (VSC) principles and PWM technique, the simulations has been performed using MATLAB Simulink versions R2009b. The simulation result shows that the power factor has improved, the voltage sag has mitigated and harmonics were eliminated using LCL filter with the D-STATCOM.

Chapter Three

Methodology

The method employed for the study and simulation of power quality improvement has been done by measuring the voltage, current and power, using the device of power quality analyzer namely HIOKI-3196. Also, the power quality problem has been analyzed by PQA HiVIEW PRO 9624-50 software for flexible PC analysis. PQA HiVIEW PRO 9624-50 are graphic based analyzers and equipped with memory so that real time data can be saved.

3.1 Power Quality Investigation Procedures

Collecting of data has been carried out by including careful physical observation, measuring of the whole system, interviewing concerned professionals, referring previously recorded documents. The data monitoring task at the distribution point (low voltage side of distribution transformer) had taken for two weeks, and data measurement has been performed during full operation of the industry. The measurement of power quality has been done as per as IEC 61000-4-30 power quality measurement standard, accordingly many types of power quality problems in existing system has been identified. The standard IEC 61000-4-30 class A define that the measurement methods for each power quality parameter to obtain continuous, non-repeatable and comparable results. It also defines the accuracy of bandwidth, and minimum set of parameters.

The quality analyzer namely HIOKI-3196 has been described the standardize measurements of power frequency, supply voltage magnitude, flicker, harmonics, inter harmonics, voltage sag (dip), voltage swell, interruptions, voltage unbalance, active power, reactive power, apparent power, power factor, negative peak voltage and current, positive peak voltage and current, measurement of under deviation and over deviation parameter etc. Finally, the analysis of power quality has been done according to IEEE 1159-1992 standards and preceded as per IEC 61000-2-4. According to IEC 61000-2-4 power quality could be co-related with voltage, current, frequency, harmonic distortion and power factor.

According to the IEC 61000-4-30 the basic time window for 3cycles (60ms) of 50Hz signal the sampling rate is 9600S/sec, and the analog-digital (A/D) converter provides 1920 samples for each 3cycles (60ms).

Magnitude of supply voltage for 3cycles

$$V_{RMS} = V_1 = \sqrt{\frac{1}{1920}\sum_{n-1}^{1920} V_n^{\ 2}} \tag{3.1}$$

Magnitude of current for 3cycles

$$I_{RMS} = I_1 = \sqrt{\frac{1}{1920}\sum_{n-1}^{1920} I_n^{\ 2}} \tag{3.2}$$

Mean 3-phase voltage (total voltage)

$$V_T = V_{123} = \sqrt{\frac{V_1^{\ 2} + V_2^{\ 2} + V_3^{\ 2}}{3}} \tag{3.3}$$

Mean three phase current (total current)

$$I_T = I_{123} = \sqrt{\frac{I_1^{\ 2} + I_2^{\ 2} + I_3^{\ 2}}{3}} \tag{3.4}$$

Apparent power (VA)

$$S = V_{RMS} I_{RMS} \tag{3.5}$$

Active power

$$P = \sum_{n-1}^{harmMAX} V_n I_n \cos \varphi_{Un} \tag{3.6}$$

Reactive power (Var)

$$Q = \sqrt{S^2 - P^2} \tag{3.7}$$

V_h is the RMS value of the harmonic component h and V_1 is the RMS value of the fundamental component.

$$THD_V\% = \frac{\sqrt{\sum_{h=2}^{\infty} V_h^{\ 2}}}{V_1} * 100 \tag{3.8}$$

THD_I%= percentage of the total harmonic distortion of a non-sinusoidal current waveform.

$$THD_I\% = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^{\ 2}}}{I_1} * 100 \tag{3.9}$$

The IEEE 1159-1992 power quality standards are tabulated in Table 3.1.

Table 3.1: The Range of Voltage Disturbances of Measurement Device System Setting.

S/No	Power quality event	Voltage
1	Over voltage	> 110 %, for > 1 minutes
2	Under voltage	< 90 %, for > 1 minutes
3	Swell	110 % - 180%, for > 1 cycle
4	Sag	< 90 %, for 3- 10 cycle
5	Notch	< 0.5 cycle
6	Momentarily interruption	< 10 %, for 0.5 – 3 second
7	Temporarily interruption	< 10 %, for 3 – 60 second
8	Sustained interruption	< 10%, for > 60 second

3.1.1 Power Quality Measurement Procedure and Device Setting

The internal operating status of HIOKI-3196 is setting, recording and waiting of status until preset time to start measured and analyzed results were displayed to indicate the internal status of the instrument. The internal status is changed by pressing START/STOP button to start/stop recording.

Table 3.2: Internal Operating Status of HIOKI-3196 [15].

Display	Internal status description	Real-time measurement	Recording status
Setting	When turned on, there is no recorded data in the instrument	Possible	Preparation for recording(not recording)
Waiting	Waiting until a preset start time to begin measuring	Possible	―
Recording	Recording has started and measurement data is being saved to the instrument's internal memory(and perhaps to a pc card)	Possible	Recording in progress
Analyzing	Recording has finished and the instrument is ready for analysis of the measurement data in internal memory	Possible	Recording finished

The measurement can be taken by normal measurement or measurement with specified time.

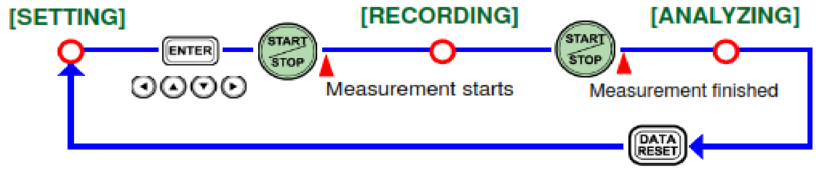

Figure 3.1: Normal measurement step [15].

If the preset measurement start time had already passed, measurement starts immediately.

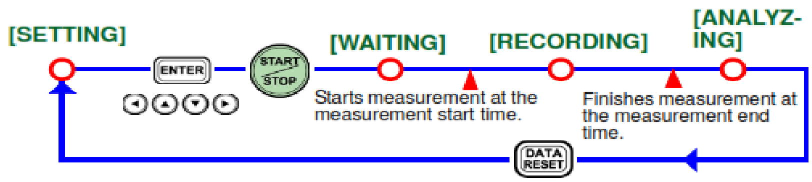

Figure 3.2: Measurement with specified time [15].

The power quality analyzer device has main setting, time plot setting and hardware setting.

- The main settings are contained basic measurement parameter setting such as connection method, voltage and current ranges, VT and CT ratio, clamp sensor, nominal voltage, measured frequency, PLL source, calculation method and fliker.
- The time plot settings are contain recording setting such as time serier or time plot data selection, measurement interval, automatic saving to PC card, real time control, measurement start and end time and repeated recording.
- The hardware settings are used to set the information of display language, beep, screen color, clock setting LAN and RS-232C interface, and automatic hard copy.

Flexible current sensors are convenient when making measurements in a confined space and check clamp sensor set at 9667 and the appropriate current value of either 500A or 5000A.

Table 3.3: System Setting for Measuring Three Phase Four Wire (3P4W) Systems.

System setting	Channel -1,2&3	Channel -4
Wiring	3P4W	AC
Clamp-on sensor	5000A 9667	500A 9667
Voltage range	600V	150V
VT ratio	1	1
Current range	5000A	500A
CT ratio	1	1

The schematic connection diagram of 3P4W quality analyzer from source to loads is depicted in figure 3.4. If the clamp-on sensor is oriented incorrectly, the instrument won't be able to measure power and power factor accurately so that connect the HIOKI-3196 to the power line to be monitored while viewing the connection diagram. Check the proper instrument connection of clamp on current sensors to the VT and CT terminals.

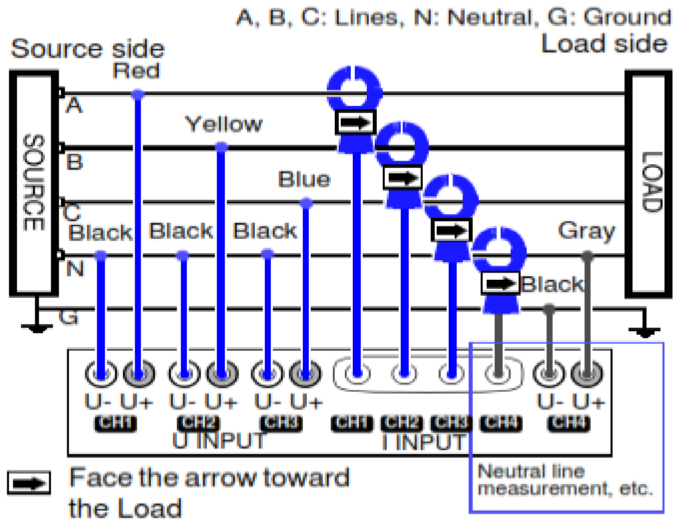

Figure 3.3: Three phase four wire (3P4W) connections [15].

All reference data which needed to feed in to the device

Frequency=50 Hz	V_1=V_2=V_3= 600V (Channel-1,2&3)
V_4=150V (Channel-4)	I_1=I_2=I_3= 5000A 9667(500A, 5000A)
I4= 500A 9667(50A, 500A)	$V_{Reference}$ =380V

The 3P4W unbalanced load is connected to 3P4W supply and the neutral line of the supply side is connected to the load side neutral point. Since the load is unbalanced, the line currents are different in magnitude and displaced from one another by unequal angles. The current in the neutral wire will be the phasor sum of the three line currents. The amount of current flowing in the neutral wire is depend on the magnitudes of line currents and their phasor relation.

$$I_N = I_A + I_B + I_C \qquad (3.10)$$

The wires connected to channel-1,2,3 has been measured phase voltage and phase current. The wire connected to channel-4 measured neutral to ground voltage and current. The three clamp-on sensor has been connected to the three phase load and the remain clamp-on connected to the neutral wire for measuring neutral to ground current respectively. The voltage cord and clamp-on sensor connection status has measure each phase voltage, current, active power, reactive power, apparent power, total harmonic distortion voltage and current, negative and positive peak voltage and current etc.

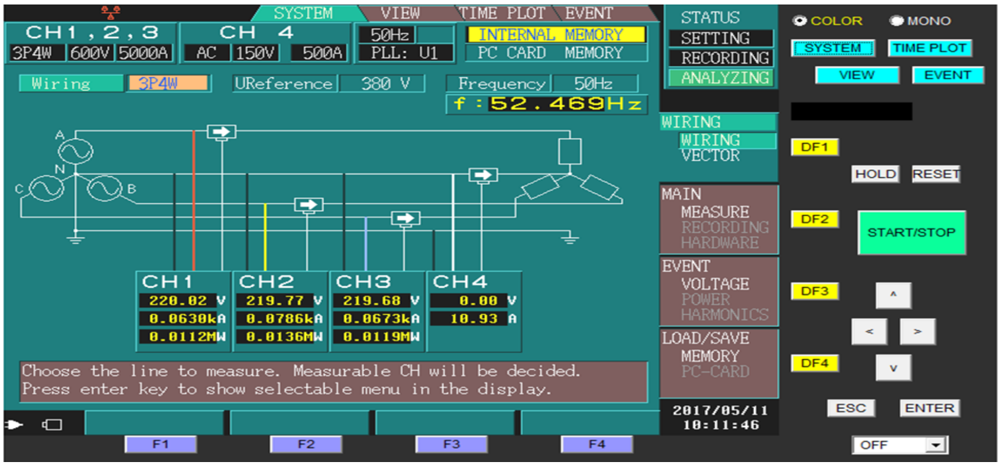

Figure 3.4: Measurement output of 3P4W wiring system connected to transformer.

3.1.2 Power Quality Monitor

Power quality monitoring is the process of collecting, analyzing and interpreting raw measurement data in to useful information. The device which is HIOKI 3196 has been connected with personal computer (PC) by using LAN interface cable controlling system operation and observing the power quality at remote locations using an ordinary web browser of internet explorer by entering the IP address then display the main screen HIOKI 3196 and analyzes measurement data from the PC.

Figure 3.5: Measurement connection on 90 KW rating induction motor.

The internal memory has a storage capacity of 5MB time plot related data and 8MB capacity for storing up to 100 events data sets. The measurement stops when memory becomes full. But, unless otherwise the device is immediately stopped, previously recorded data will be overwritten.

The measurement data which is saved in binary formats through internal memory of HIOKI 3196 has been transferred to PC by using the freeware Down96. The Down96 is application software downloads data which captured in internal memory of power quality analyzer or on the PC card to a PC. Down96 program runs on Java Script, and freeware JRE (Java run time environment). In addition, the power quality analyzer device unit has been installed with firm ware version 2.0 in order to use Down96. The device has a choice of optional clamp-on sensors but for this factory the 9667 flexible clamp-on sensor 500A/5000A rms rating for current measurements has been selected. HTTP server functions were built in instrument settings and data acquisition can be controlled by common internet Web browsers like internet explorer. Finally, further power quality analysis has done by using the optional PQA HiVIEW PRO 9624-50 application software. The application software package of PQA HiVIEW PRO 9624-50 which is used to analyze recorded data with a PC for further data analysis and quick data processing.

Chapter Four

Power Quality Analysis of the Factory

Power quality considers various quality aspects, in particular the current and voltage harmonic levels, the phase displacements between corresponding phase voltages and currents at the fundamental frequency, and the degree of unbalance in the different phase voltages and current. A high level of power quality is understood as a low level of disturbance, agreement on acceptable levels of disturbance [18]. The power distribution systems of the factory had been investigated to diagnosis power quality problems. Every electrical disturbance has an associated waveform which describes its characteristics, and provides important clues to locate the source of electrical problem. The two particular sections were examined in this case study. Firstly, industrial loads supplied from 10 distribution transformers. Secondly, domestic and commercial loads supplied from 19 distribution transformers. Generally, the factory loads have got power from the two steam turbine, one diesel generator and three phase 15KV, 50Hz power from Ethiopian power utility (EPU). The industrial loads supplied from diesel generator and EEP are used as standby power when the factory steam power faces a problem or in case of emergency and startup of the mill and maintenance period.

4.1 Type of Loads in the Factory

The industrial facilities are characterized by the widespread application of nonlinear loads. Nonlinear loads appear to be source of harmonic current in shunt with and injecting harmonic currents into the power system causing harmonic distortion in the voltage. The nonlinear loads in factory can generally be grouped as three phase power converters, arcing devices and saturable devices. Harmonics are generated due to industrials loads such as DC drive, AC drive, saturable device and arcing device such as arc furnaces, arc welders, and discharge type lighting with magnetic ballasts. This thesis is mainly focused on the industrial loads that are supplied from the two turbo generators through 10 step down transformers having 1000KVA rated value and the load has got power from distribution panel. The distribution panels are mainly consisted of electronic variable speed drives, squirrel cage and wound rotor type motors which driving the various drives such as cane unloading equipment, cane carriers, cane preparatory, milling and diffuser plants, pumps, centrifugal machines, crystallizers and agitators, conveyers and air compressors. The industrial loads have been a shunt connected capacitor banks to improve the power quality of the existing system.

4.2 Factory Power Quality Problems on the Industrial Loads Supplied from Turbo Generator

The system structures has two synchronous generators with steam turbine, step down transformers, underground cables, switch board panels, capacitor banks, induction motors, power house, control panels, excitation system and automatic voltage regulators etc. The two synchronous generators had been installed to be fed 3.18MW power from each generator by steam energy coming out from the boiler and the output power is delivered to double bus bar.

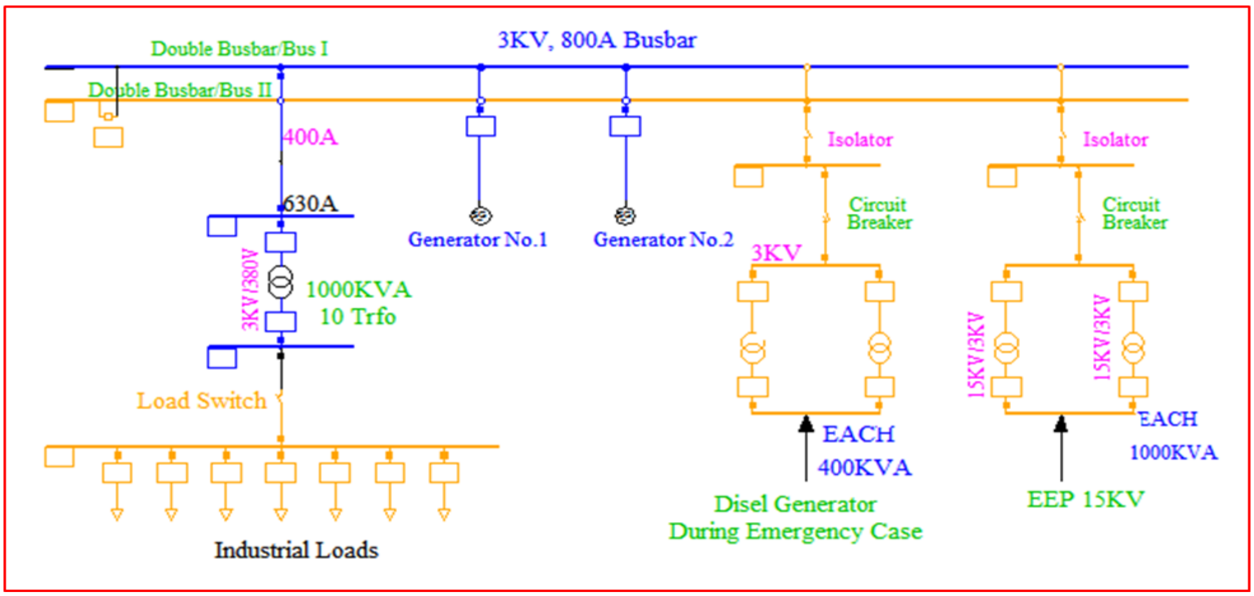

Figure 4.1: Industrial loads outgoing transformers supplied by turbo generator.

4.2.1 Poor Power Factor

Power factor is measured as a ratio of active energy to apparent energy over a specified period. Lower power factor results in higher energy consumption and also causes for voltage drop. The ideal power factor is unity; it cannot be achieved due to the nature of inductive and nonlinear loads which operated at low lagging power factor. The load draws more current for the same load that causes increased in apparent power (KVA) demand and increased I^2R losses. Therefore, upgraded system capacity is needed to supply the same load. The factory had seven SVC that used to compensate reactive power connected to load terminals. Power factor correction is the addition of reactive element in parallel with the load in order to make the power factor closer to unity. The factory loads were supplied from transformer-4, transformer-9 and transformer-10 operated without reactive power compensator, however there is huge centrifuges machines that had been sensitive power electronics devices. Transformer-7 supplies power for five VFD which assigned to drive the motors of band cane carrier, elevator, auxiliary cane carrier, for two belt conveyors of cane handling and milling plant B (tandem B).

Table 4.1: Measured Data at Transformer-7.

Power factor(PF)					**Reactive power(KVar)**			
Time	PF_1	PF_2	PF_3	PF_{sum}	Q_1	Q_2	Q_3	Q_{sum}
11:55:02	0.5406	0.4763	0.4241	0.4824	24.3	19.4	24.0	68.0
12:11:08	0.6344	0.6164	0.5797	0.6104	52.5	49.1	53.0	155.0
12:12:15	0.4818	0.4851	0.4482	0.4714	48.7	46.0	50.0	145.0
12:12:25	0.5182	0.5285	0.4863	0.5106	45.8	42.6	47.1	136.0
14:02:53	0.6300	0.5799	0.5719	0.5939	49.4	53.1	51.1	154.0
14:31:24	0.6286	0.5818	0.5724	0.5943	52.9	56.9	54.8	165.0
Average	0.5722	0.5446	0.5137	0.5438	45.6	44.52	46.67	137.2
Active power (KW)					**Apparent power (KVA)**			
Time	P_1	P_2	P_3	P_{sum}	S_1	S_2	S_3	S_{sum}
11:55:02	15.6	10.5	11.3	37.0	28.9	22.0	26.5	78.0
12:11:08	43.0	38.5	37.7	119.0	67.9	62.4	65.1	195.0
12:12:15	26.8	25.5	25.1	77.0	55.6	52.6	55.9	164.0
12:12:25	27.8	26.5	26.2	81.0	53.6	50.2	54.0	158.0
14:02:53	40.1	37.8	35.6	113.0	63.6	65.1	62.3	191.0
14:31:24	42.8	40.7	38.2	122.0	68.1	69.9	66.8	205.0
Average	32.68	29.92	29.02	91.5	56.28	53.7	55.1	165.2

The maximum power factor measured at this transformer distribution panel was 0.54 which is below EEP's standard limits and hence unacceptable. The transformer draws large lagging currents and large reactive power.

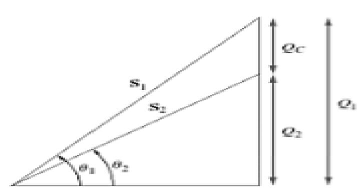

Figure 4.2: Power triangle illustrating power factor correction [25].

Where; pf = $\text{Cos}\theta_1 = 0.54$

$\theta_1 = \cos^{-1}(0.54) = 57.31^0$

$$V = V_m \sin\theta \qquad (4.1)$$

$230 = V_m \sin\theta_1$

$$V_m = \frac{230}{\sin\theta_1} \qquad (4.2)$$

$V_m = 273.28V$

$$V_{rms} = \frac{V_m}{\sqrt{2}} \qquad (4.3)$$

$V_{rms} = 193.238V$

$\omega = 2\pi f = 2 * 3.14 * 50 = 314.15$

The existing system average power factor lag is 0.54 and the target power factor lag is 0.9. If we desire to increase the power factor from $\cos\theta_1$ to $\cos\theta_2$ without altering the real power $P = S_2 \cos\theta_2$ then the new reactive power $Q_2 = P\tan\theta_2$. The reduction in the reactive power is caused by the shunt capacitor, that is

$$Q_{C} = Q_1 - Q_2 = P(\tan\theta_1 - \tan\theta_2)$$

$$Q_{C} = V^2 rms/X_C = \omega C V^2 rms$$

The value of the required shunt capacitance(C) is determined as

$$C = \frac{QC}{\omega V^2 rms} = \frac{P(\tan\theta_1 - \tan\theta_2)}{\omega V^2 rms} \qquad (4.4)$$

$$C = \frac{P(\tan\theta_1 - \tan\theta_2)}{\omega V^2 rms} \qquad (4.5)$$

Where, $\theta_1 = 57.31^0$ and $\theta_2 = 25.84^0$

$$C = \frac{91.5KW[\tan(57.31) - \tan(25.84)]}{(314.15)(193.238^2)}$$

$$C = \frac{91.5 * 1000 * [1.5582 - 0.4842]}{(314.15)(193.238^2)} = 8.377KVar$$

The required capacitor (C) for three phase 91.5KW loads are 8.377KVAR and the rating of capacitor connected in each phases are 2.79KVAR.

$$Q_1 = P\tan\theta_1 = 91.5\ \text{KW} * [\tan(57.31)] = 142.58\ \text{Kvar} = 142{,}580\text{Var}$$

$$Q_C = P[\tan\theta_1 - \tan\theta_2] = 98.271\ \text{KVar} = 98{,}271\text{Var}$$

$$Q_C = Q_1 - Q_2$$

$$Q_2 = Q_1 - Q_C = 142{,}580 - 98{,}271 = 44{,}309 = 44.309\text{KVar}$$

The difference between the new and old reactive power will be:

$$Q_L = Q_1 - Q_2 = 142.58\text{KVar} - 44.309\text{KVar} = 98.271\ \text{KVar} = Q_C$$

The real power (P) dissipated by the load is not affected by the power factor correction because the average power due to the capacitance is zero. An inductor should be connected across the load for power factor correction. The required shunt inductance L can be calculated from:

$$L = \frac{V^2\text{rms}}{\omega Q_L} \tag{4.6}$$

$$L = \frac{193.238^2}{(314.15)(98{,}271)} = 0.0012\ \text{H} = 1.2\ \text{mH}$$

$$Q_L = \frac{V^2\text{rms}}{X_L} = \frac{V^2\text{rms}}{\omega L} \tag{4.7}$$

$$Q_L = \frac{193.238^2}{(314.15)(0.0012)} = 99{,}052.8\text{Var} = 99.05\ \text{KVar}$$

Transformer-8 has been supplied to the load of three VFD drives which runs the inclined, anvil, horizontal of the cane handling and milling plant A (tandem A).

Table 4.2: Measured Data at Transformer-8.

Power factor(PF)					**Reactive power(KVar)**			
Time	PF_1	PF_2	PF_3	PF_{sum}	Q_1	Q_2	Q_3	Q_{sum}
10:08:23	0.7796	0.8016	0.8163	0.7993	62.8	63.7	58.6	185.0
10:12:46	0.4454	0.5242	0.5089	0.4931	64.9	64.2	59.9	189.0
10:42:58	0.7625	0.7797	0.7933	0.7785	74.5	75.5	69.5	220.0
10:43:19	0.4530	0.5045	0.5072	0.4883	66.5	67.5	62.5	197.0
11:17:42	0.7854	0.8083	0.8187	0.8041	65.5	65.2	59.2	190.0
11:40:03	0.5965	0.6647	0.6556	0.6392	56.8	55.5	51.9	164.0
12:37:27	0.5571	0.6413	0.6407	0.6137	21.1	21.3	18.9	61.0
Average	0.6256	0.6749	0.6772	0.6594	58.87	58.98	54.36	172.28
Active power (KW)					**Apparent power (KVA)**			
Time	P_1	P_2	P_3	P_{sum}	S_1	S_2	S_3	S_{sum}
10:08:23	78.2	85.4	82.8	246.0	100.3	106.6	101.4	308.0
10:12:46	32.3	39.5	35.4	107.0	72.5	75.4	69.6	217.0
10:42:58	87.8	94.0	90.6	272.0	115.2	120.5	114.2	350.0
10:43:19	33.8	39.5	36.8	110.0	74.6	78.2	72.5	225.0
11:17:42	83.0	89.4	84.4	257.0	105.7	110.7	103.1	319.0
11:40:03	42.2	49.4	45.1	137.0	70.7	74.3	68.8	214.00
12:37:27	14.1	17.8	15.8	48.0	25.3	27.8	24.7	78.00
Average	53.06	59.28	55.84	168.14	80.61	84.78	79.18	244.43

The maximum power factor measured at this transformer distribution panel is 0.65 which is below EEP's standard limits and hence unacceptable. The loads that supplied from this transformer is nonlinear loads and large inductive loads which cause large lagging currents and large reactive power.

$$Pf = \cos\theta_1 = 0.65 \text{ and } \cos\theta_2 = 0.9$$

$$C = \frac{P(\tan\theta_1 - \tan\theta_2)}{\omega V^2 rms}$$

Where, $\theta_1 = 49.45^0$ and $\theta_2 = 25.84^0$

$$C = \frac{168.14KW[\tan(49.45) - \tan(25.84)]}{(314.15)(193.238^2)}$$

$$C = \frac{168.14 * 1000 * [1.1687 - 0.4842]}{(314.15)(193.238^2)} = 9.811mVar$$

The loss of reactive power from the required capacitor (C) for three phase 168.14KW loads are 9.811mVAR and the rating of capacitor connected in each phases are 2.27mVAR.

$$Q_1 = P\tan\theta_1 = 168.14\ KW * [\tan(49.45)] = 196.519KVAR = 196{,}519VAR$$

$$Q_C = P[\tan\theta_1 - \tan\theta_2] = 115.092\ KVAR = 115{,}092VAR$$

$$Q_C = Q_1 - Q_2$$

$$Q_2 = Q_1 - Q_C = 196{,}519 - 115{,}092 = 81{,}427VAR = 81.427KVAR$$

The difference between the new and old reactive power will be:

$$Q_L = Q_1 - Q_2 = 196.519KVAR - 81.427KVAR = 115.092\ KVAR = Q_C.$$

An inductor should be connected across the load for power factor correction. The required shunt inductance (L) can be calculated from:

$$L = \frac{V^2 rms}{\omega Q_L} \tag{4.8}$$

$$L = \frac{193.238^2}{(314.15)(115{,}092)} = 0.001H = 1\ mH$$

$$Q_L = \frac{V^2 rms}{X_L} = \frac{V^2 rms}{\omega L} \tag{4.9}$$

$$Q_L = \frac{193.238^2}{(314.15)(0.001)} = 118{,}863.36Var = 118.86\ KVar$$

A load's power factor was improved or corrected by deliberately installing a capacitor in parallel with the load as shown in the following figure 4.3 and figure 4.4.

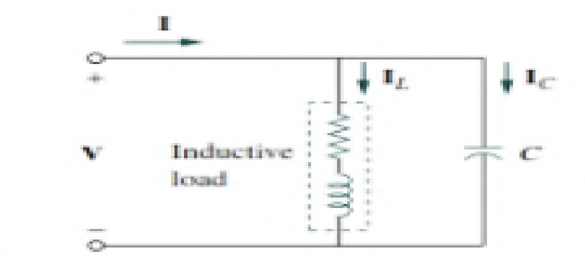

Figure 4.3: Inductive load with improved power factor [25].

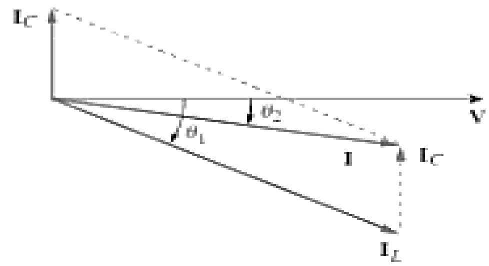

Figure 4.4: Phasor diagram of loading a capacitor in parallel with the inductive load [25].

Power companies charge more for large current because they result in increased power losses by squared factor ($P=I_L^2R$). Therefore, it is beneficial to both the power company and the consumer that every effort is made to minimize current level or keep the power factor as close to unity as possible. Table 4.3 shows the factory average power factor at each transformer.

Table 4.3: Factory Average Power Factor at Transformer.

S.No	Transformer No.	Existing Average Power Factor Lag	Target Power Factor Lag	Minimum Capacitive Load required in KVAR	Loose CT's Ratio to be fixed in Main L.V panel	Remark
1	T1	0.80	0.9	125	1500/5 A	
2	T2	0.80	0.9	175	1500/5 A	
3	T3	0.78	0.9	200	1500/5 A	
4	T4	0.75	0.9	200	1500/5 A	Without SVC
5	T5	0.78	0.9	275	1500/5 A	
6	T6	0.80	0.9	187.5	1500/5 A	
7	T7	0.54	0.9	162.5	750-1500/5 A	
8	T8	0.65	0.9	200	750-1500/5 A	
9	T9	0.78	0.9	100	800/5 A	Without SVC
10	T10	0.50	0.9	100	400-800A	Without SVC

4.2.2 Total Harmonic Distortion (THD_V and THD_I)

Harmonics in power supply systems are the main cause of temperature rise in the equipment and short in service time. This effect attains extremely high values under conditions of resonance amplification of harmonic currents. Among the sources of harmonic voltages and currents in power systems three groups of equipment can be distinguished such as magnetic core equipment, arc furnaces and/or arc welders, and electronic and power electronics equipment [18].

Table 4.4: Total Current and Voltage Harmonic Distortion Measured Value at Transformer-7.

Voltage (V)					**Current (A)**			
Time	V_1	V_2	V_3	V_4	I_1	I_2	I_3	I_4
10:43.02	231.76	231.47	231.80	0.00	43.6	28.3	34.1	10.43
10:43:30	231.35	231.01	231.78	0.00	84.1	38.1	34.8	12.29
10:43:55	231.38	230.99	231.80	0.00	85.4	39.3	34.9	12.10
10:43:57	231.41	230.98	231.76	0.00	82.4	38.9	34.7	12.40
10:44:03	231.52	231.35	231.69	0.00	52.8	28.6	34.5	12.05
10:44:22	231.57	231.44	231.73	0.00	52.8	30.8	34.9	12.38
Average	231.49	231.20	231.76	0.00	66.85	34.00	34.65	11.94
THD_V (%)					**THD_I (%)**			
Time	THD-V_1	THD-V_2	THD-V_3	THD-V_4	THD-I_1	THD-I_2	THD-I_3	THD-I_4
10:43.02	0.86	0.89	1.00	55.02	38.72	23.37	44.46	17.08
10:43:30	0.80	0.86	0.94	46.94	20.07	26.40	41.03	15.57
10:43:55	0.77	0.84	0.91	48.44	20.49	25.25	42.96	12.72
10:43:57	0.78	0.84	0.92	49.28	19.32	23.49	42.54	18.65
10:44:03	0.76	0.79	0.90	57.66	31.34	20.81	43.97	19.06
10:44:22	0.79	0.81	0.94	52.37	27.30	16.18	42.77	19.40
Average	0.79	0.83	0.93	51.61	26.20	22.58	42.95	17.08

According to IEC Standards for current and voltage harmonic limits the maximum permissible total harmonic current distortion (THDI) is 16% but the power quality analysis in table 4.5 has been shows that the total harmonic distortion was 54.07%, it is stay away from reasonable limit and also the line to neutral current were a prominent of 5th and 7th order current harmonics. The value of total demand distortion calculated in terms of total harmonic current distortion:

$$\mathrm{TDD} = \frac{\sqrt{\mathrm{THD_{I1}}^2 + \mathrm{THD_{I2}}^2 + \mathrm{THD_{I3}}^2 + \mathrm{THD_{I4}}^2}}{\mathrm{I_L}} \tag{4.10}$$

$$\mathrm{TDD} = \frac{\sqrt{26.2^2 + 22.58^2 + 42.95^2 + 17.08^2}}{147.44} = 0.39\ \%$$

Where: - THD-I_1, THD-I_2, THD-I_3, THD-I_4 is total harmonic current distortion and I_L is rated load current. When the distorted current in the system is increased, it causes for poor power factor. The power factor with a non-sinusoidal current is

$$\mathrm{PF} = \frac{\mathrm{I}}{\sqrt{1 + \mathrm{THD_I}^2}}\mathrm{DPF} \tag{4.11}$$

$$\mathrm{DPF} = \frac{\mathrm{PF} * \sqrt{1 + \mathrm{THD_I}^2}}{\mathrm{I}} \tag{4.12}$$

According to IEEE 519 harmonic voltage distortion for 69KV and below is limited to 5.0 % total voltage harmonics distortion (THD_V) with each individual harmonic limited to 3%.

Table 4.5: Harmonic Current Limits According to IEC 61000-3-4 [1].

Harmonic order *h*	Max. permissible harmonic current* (%)	Harmonic order *h*	Max. permissible harmonic current* (%)
3	21.6	19	1.1
5	10.7	21	0.6
7	7.2	23	0.9
9	3.8	25	0.8
11	3.1	27	0.6
13	2	29	0.7
15	0.7	31	0.7
17	1.2	33	0.6

The 3rd order neutral to ground harmonic problems at transformer-8 are depicted in figure 4.5.

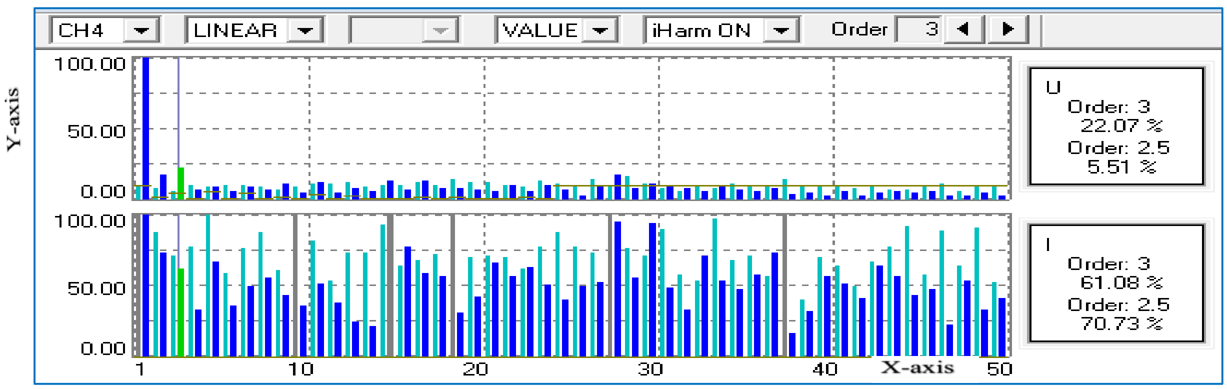

Figure 4.5: Percentage voltage and current harmonics bar graph at transformer-8.

The 5th order harmonics create a counter rotating field, where as the 7th order harmonics create a rotating field beyond the motors synchronous speed. The pulsating torque causes wear and tear on couplings and bearing. The cause of voltage harmonics (V_{harm}) and current harmonics (I_{harm}) above the permissible limit has the effect on increasing the power consumption and thermal losses of induction motor and also missed operation of drives. The 5th order bar graphs of the neutral to ground wire was shown that the voltage harmonics are 12.62% and current harmonics are 49.01% and also, the 7th order bar graph has shown that the voltage harmonics are 9.49% and current harmonics 16.07%. Consequently, the outgoing transformer-8 neutral wires were burned due to 3rd order current harmonics of 61.08% which is generated by nonlinear loads.

4.2.3 Power Frequency Variation

The main causes of power frequency variation are the difference in between active power demand and power generation. It depends on the generator load characteristics and control circuit for automatic load frequency control (ALFC) which includes governor control as well as turbine control. The frequency variation is controlled by proper balance between generations, active power demand and mechanical energy supplied to the prime mover [3]. To maintain stable, efficient, secured and economical operation of the power systems and quality of frequency must achieve the limit of 3% and it lies in between 48.5Hz and 51.5Hz. Also, the frequency of the system directly proportional to the speed of the generator, so that the frequency of the system is decreased when the speed of the generator is reduced.

$$f = \frac{NP}{120} \tag{4.13}$$

Where; f= frequency, N=Speed and P=Number of pole

When the frequency falls below the accepted limit, the generation of active power has been less than the demands of power. When the total generation of active power greater than the demand of power the frequency should rise above the accepted limit. The IEEE standard 1159-1995 says that the quality of power frequency must lies in between 48.5Hz and 51.5Hz., but as described in the following table all values in existing system is beyond allowable margin.

Table 4.6: Power Frequency Variation Measured Value at Transformer-7.

No	Time	Frequency(HZ)
1	10:39:59	52.773
2	10:40:05	52.663
3	10:40:15	52.762
4	10:40:39	52.676
5	10:41:07	52.527
6	10:41:35	52.429
7	10:41:47	52.597
8	10:42:13	52.701

No	Time	Frequency(HZ)
9	10:42:30	52.779
10	10:43:02	52.637
11	10:43:18	52.818
12	10:43:30	53.00
13	10:43:39	52.674
14	10:43:53	52.546
15	10:44:34	52.594

4.2.4 Waveform Distortion

The main causes of voltage and current waveform distortions are harmonics, dc offset, sub-harmonics and interharmonics that have the frequency domain interpretations shown in Table 4.7. In this Table the term n denotes harmonic order, *fo* denotes fundamental frequency of a signal and *f* denotes a particular frequency component of the signal. The term sub-harmonic is loosely called as interharmonics with frequency component less than the fundamental frequency [4]. Waveform distortion is a form of electrical pollution on the network due to feedback of harmonic currents from nonlinear load. Waveform distortion in power system refers to steady state deviation from a sine wave of power frequency.

Table 4.7: Interpretation of Various Harmonics Terms [4].

Term	**A frequency component**
Harmonics	$f = n \times f_o$, for an integer n > 0
DC offset	$f = n \times f_o$, for n = 0
Interharmonics	$f = n \times f_o$, for non-integer n > 0
Sub-harmonics	$0 < f < f_o$

An alternating voltage or current completes 50cycles in one second. The frequency of an alternating quantity is the number of cycle that occurs in one second and it measured in cycle/second (C/S) or Herz (HZ). In figure 4.6 and figure 4.7 an alternating current had been completed 3cycle in 0.06 second.

$$\text{Frequency(f)} = \frac{1}{\text{Period(T)}} = \frac{1}{0.06 \text{ sec}} = 16.67\text{HZ}$$

As the figure 4.6 and figure 4.7 shows the peak values of three phases and neutral to ground currents of 0.25KA/div and 25A/div respectively, but the peak value is not used to specify the magnitude of current. There are interharmonics problems which having the frequency component less than the fundamental frequency. Interharmonics are defined as the frequency that are not integer multiples of the fundamental frequency but presents in the voltage and current waveform.

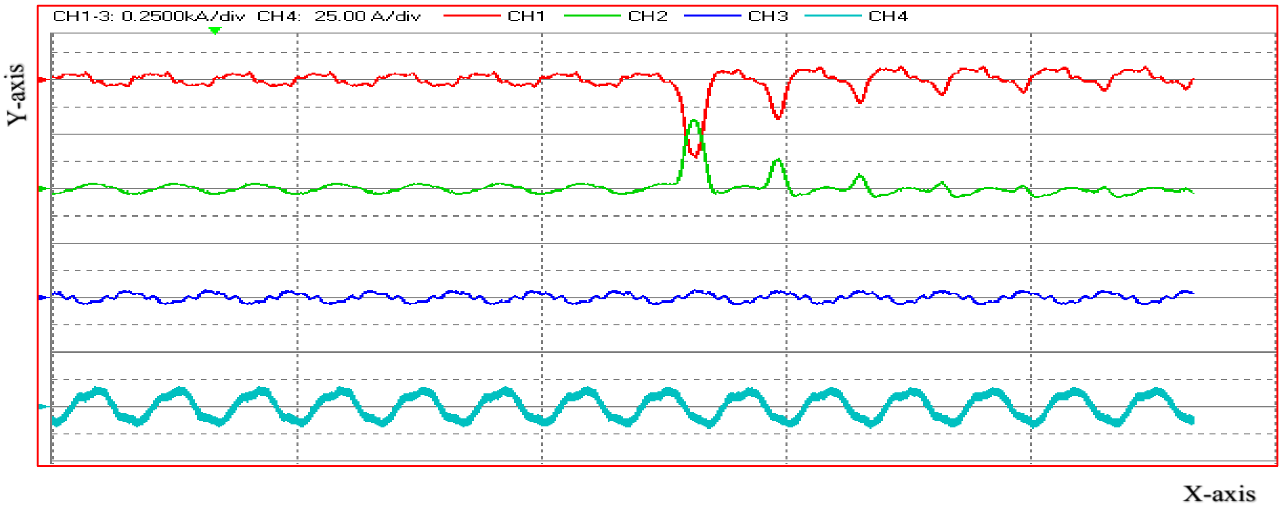

Figure 4.6: Current wave distortion at Transformer-7.

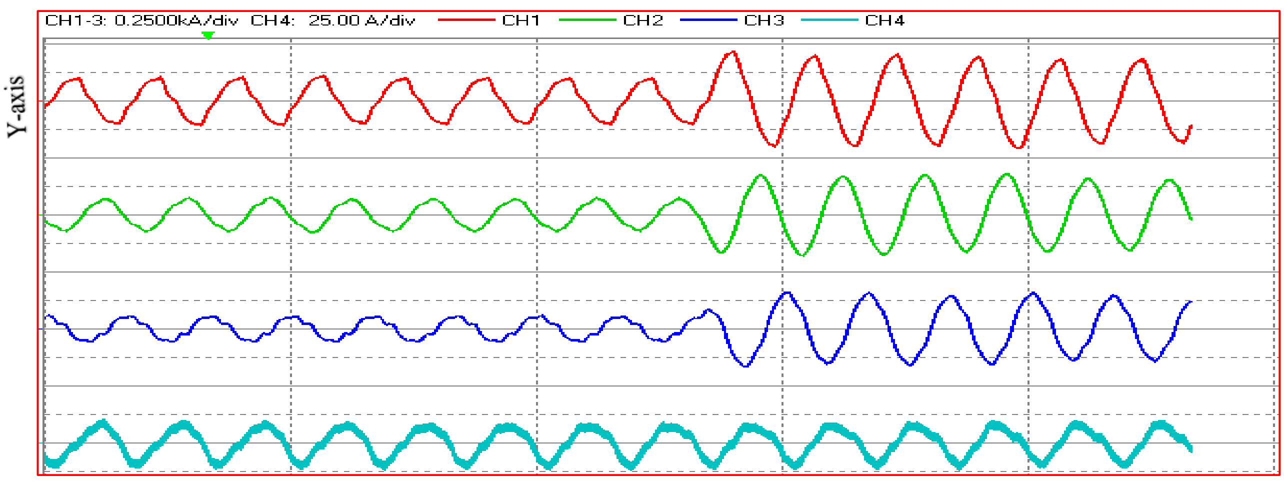

Figure 4.7: Current wave distortion at Transformer-4.

In figure 4.6 and figure 4.7 we have seen that the current wave is distorted or a disturbance happened due to system overloaded. The presence of harmonic distortion has a significant impact in increasing energy consumption. High losses are a cause for increased temperature and faster ageing of the insulation.

4.3 Factory Power Quality Problem Measurement Result at Load Terminals

4.3.1 Asynchronous Motor

The machine mechanical load system is modelled by means of composite model. The composite model has been designed by using the objects of Digsilent software. An asynchronous motor driven machine model (mdm) has power factory objects of the element class (Elm-mdm) with enclosed information about the mechanical load of a motor. Referring the following diagram, asm slot stands for asynchronous machine slot, Xmdm slot is a torque and mdm slot is name of motor driven machine.

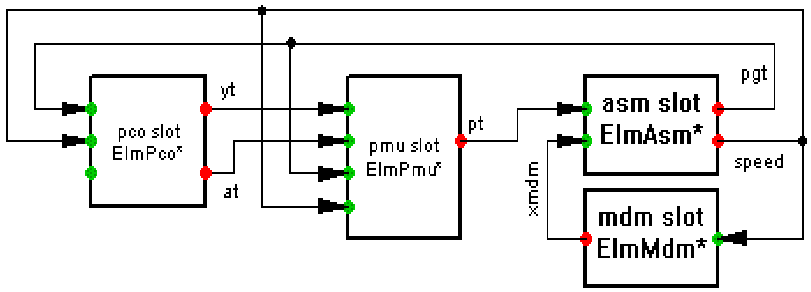

Figure 4.8: Composite frame of asynchronous machine [6].

The load in the factory were above 95% of squirrel cage type induction motor. The measurement has been taken from rotoclon fan. The motor rated power is 90KW and rated current is 167A. The major problem in this motor was operated with poor power factor, speed variation problems due to frequency variation of the system and excessive neutral to ground currents **(**THD-I_4).

Table 4.8: Measured Data at Motor Terminals of Rotoclon Fan.

Voltage (V)					**Current (A)**			
Time	V_1	V_2	V_3	V_4	I_1	I_2	I_3	I_4
17:16:17	222.54	222.55	222.90	1.87	115.4	115.5	116.7	2.62
17:16:25	222.48	222.48	222.48	1.90	114.4	114.6	115.7	2.62
17:17:21	222.34	222.41	222.80	1.88	115.0	115.3	116.3	2.63
17:18:02	222.49	222.53	222.94	1.90	121.4	121.4	122.8	2.65
17:20:42	222.06	222.15	222.52	1.87	119.5	119.6	121.0	2.69
Average	222.38	222.42	222.72	1.88	117.2	117.28	118.5	2.64
THD_V (%)					**THD_I (%)**			
Time	THD-V_1	THD-V_2	THD-V_3	THD-V_4	THD-I_1	THD-I_2	THD-I_3	THD-I_4
17:16:17	0.57	0.60	0.59	4.35	1.59	1.69	1.69	330.20
17:16:25	0.61	0.64	0.64	4.13	1.38	1.47	1.44	405.94
17:17:21	0.58	0.59	0.59	4.12	1.49	1.60	1.56	418.70
17:18:02	0.58	0.61	0.59	3.83	1.06	1.16	1.14	427.52
17:20:42	0.64	0.65	0.66	4.04	1.10	1.19	1.15	329.86
Average	0.59	0.61	0.61	4.09	1.32	1.42	1.39	382.44

4.3.2 Power Quality Problems at Variable Frequency Drives (VFD)

The factory has been used variable speed drive to control the speed of the motor and equipment driven by the motor. The VFD has a power electronics device to vary the frequency of input power to the motor, thereby controlling motor speed. The two feeding table at cane handling and milling plant B, the auxiliary cane carrier motor, the elevator cane carrier motor and the band cane carrier motor have been operated or drive on variable frequency driver. The two feeding table of each motor was the rated power of 30KW, rated current of 58A and the average operating current are 28A. The auxiliary cane carrier motor, elevator cane carrier motor and band cane carrier motor at cane handling and milling plant B were the rated power of 37KW, rated current of 70A and the average operating current of 60A. At cane handling and milling plant-A; the inclined cane carrier, the horizontal cane carrier and the anvil cane carrier motor has been driven with variable frequency drive. The horizontal cane carrier motor and the anvil cane carrier of each motor has the rated power of 11KW, rated current of 22A and the average operating current of 11.5A. The inclined cane carrier motor has the rated power of 18KW, rated current of 34A and the average operating current of 16.2A. The factory boiler-4 induced draft fan motor speed has been controlled by variable frequency drives but sometimes the motor starting torque reduced by using star-delta starting method as optional when the VFD faced a problem. The VFD has been provided for low motor starting current to maintain reduction of thermal and mechanical stresses on motors and belts during starts. But, due to the variation in the speed of motor the VFD could affect the harmonics which produced by existing system. Also, the harmonics by itself can cause some disturbances in entire electrical network.

A. Voltage sags and interruptions

There are many loads that cannot tolerate voltage sag like adjustable speed drives, computers, programing logic controller etc. The voltage sag events must be qualified for the calculation of an index. Usually sag is said to have occurred if the rms voltage in any one phase has fallen below 75% of the nominal value. Voltage Sag below 10% of the nominal value is considered as an interruption. However, the rms voltage starts changing as soon as the sag occurred [4].

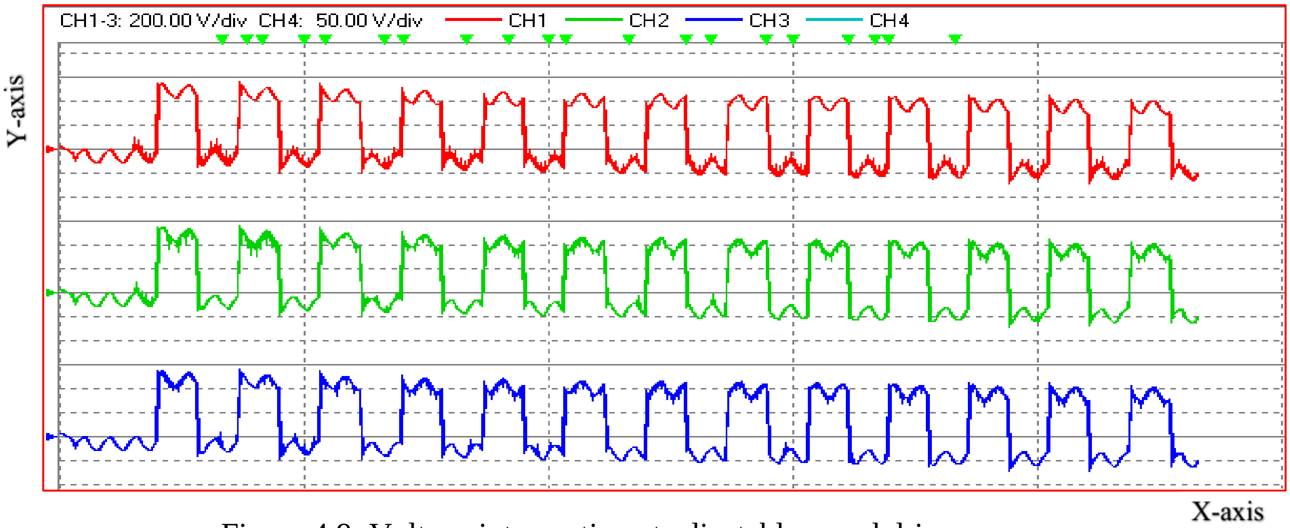

Figure 4.9: Voltage interruption at adjustable speed drives.

The maximum voltage attained by alternating quantity is equal to the voltage of 200V/div times the vertical position so that the magnitude of voltage is equal to 600V. The equation for the instantaneous value is

$$V = V_m \sin \omega t\,, \quad \omega = 2\pi f \ and\ f = \frac{1}{T}$$

$$V(t) = 600 \ \sin 104.7t$$

The Voltage Sag Energy (EVS) is

$$\mathrm{EVS} = \int_0^T \left\{1 - \frac{\mathrm{V(t)}}{\mathrm{V_{nom}}}\right\}^2 \mathrm{dt} \qquad (4.14)$$

Where, V is the magnitude of the instantaneous voltage, V_{nom} is the nominal voltage and T is the duration of sag. This enables the rms measurement settle to steady state value exactly half a cycle following any change in the voltage. However, it takes 10ms (0.01sec) to reach the steady state value therefore we can take minimal value as the sag voltage. The sag magnitude simply indicates the severity of the sag and duration of the time.

$$EVS = \int_0^T \left\{1 - \frac{600 \sin 104.7t}{230}\right\}^2 dt$$

$$EVS = \int_0^T \{1 - 2.6(\sin 104.7t\}^2 \, dt$$

$$EVS = \int_0^{0.01} 1 - \frac{2.6^2}{2}\ [1 - \cos 209.4t]\, dt$$

$$EVS = 0.01 - 3.38[0.01 - 0.018] = 0.037\ or\ 3.7\%$$

Voltage sag below 10% of the nominal value is considered as an interruption. The results show that the phase of channel-2 is jump out due to interruption. Even short dips are sufficient to cause contactors on motor drives to drop out. Stoppage in a portion of a process can destroy the conditions for quality control of the product and require restarting of production.

B. Transients

A transient is that part of change in a system variable that disappears during transition from one steady-state operating condition to another. Transients can be classified into impulsive transients and oscillatory transients. Impulsive transients have a very fast rise time and also a very fast decaying time. Impulsive transients are unipolar and oscillatory transients are bipolar in nature. An oscillatory transient with a primary frequency greater than 500kHz is considered high frequency transients. A transient within the frequency range of 5kHz to 500kHz is considered a medium frequency transient and anything below 5kHz is termed as a low frequency transient [4]. A transient is a disturbance in an AC wave, characterized by a discontinuity of the waveform. These may be of either polarity and are additive or subtractive from the nominal waveform.

$$\text{Frequency(f)} = \frac{1}{\text{Period(T)}} = \frac{1}{0.5 \text{ x } 10^{-6}\text{sec}} = 2\text{MHz}$$

A voltage oscillatory transients are depicted in figure 4.10 has the oscillation frequency of 2MHz and a decaying time constant of 0.5μs. It has three sinusoidal components that get multiplied by a decaying term. The oscillatory transients have been a frequency of 2MHz that be considered as high frequency transients. Oscillatory transients have positive and negative polarity and it's have been showing distinctively by their fast rise time and oscillatory behavior that decays over time. There is a large deviation of the waveform fall in to 0.6879KV for a very short duration of 0.5μs in negative direction. On the voltage/transient waveform the phase at channel-2 out of the system or the second phase has been faced a phase jump.

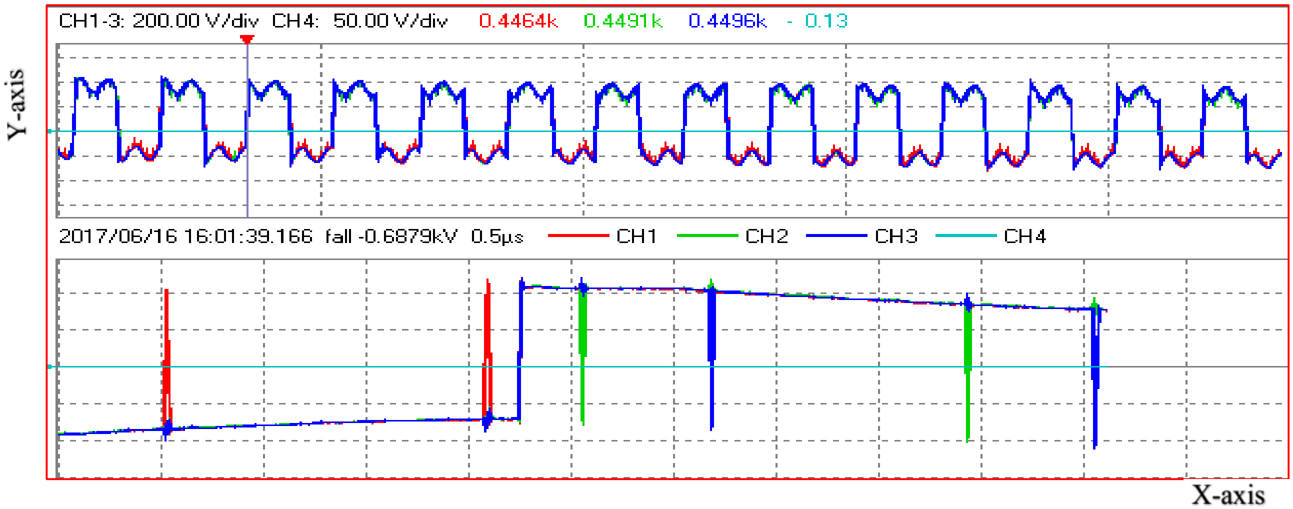

Figure 4.10: Voltage oscillatory transient waveform at adjustable speed drives.

C. Voltage harmonics distortion (V_{harm})

The 3rd order voltage harmonics are 35.11% and current harmonics are 21.75 at Channel-2. The 5th order voltage harmonics are 20.04% and current harmonics are 13.60%. The 3rd and 5th order voltage harmonics problems have been observed at the second phase or at Channel-2 and the phase is out of the system or phase jump happened because of those problems. Due to phase jump the other phase will be overloaded and cause for under voltage problem or other power quality problems.

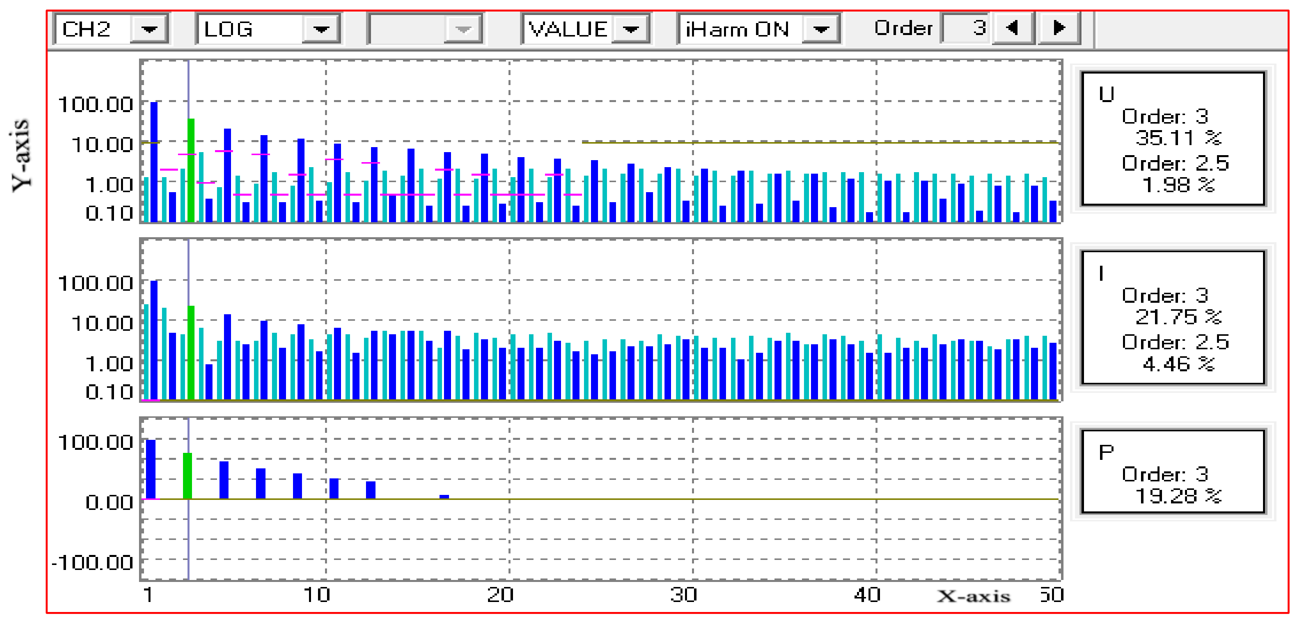

Figure 4.11: Voltage harmonics bar graph at adjustable speed drives.

As the following figure shows, during monitoring of the power quality problems at adjustable speed drives the analysis shows that the transient has repeatedly occurred 55 times, voltage dip 17 times, wave distortion 999 times, power factor problem 53 times, voltage unbalance 54 times, voltage harmonics 999 times, total voltage harmonic distortion 41 times, total current harmonic 84 times and K-factor 197 times.

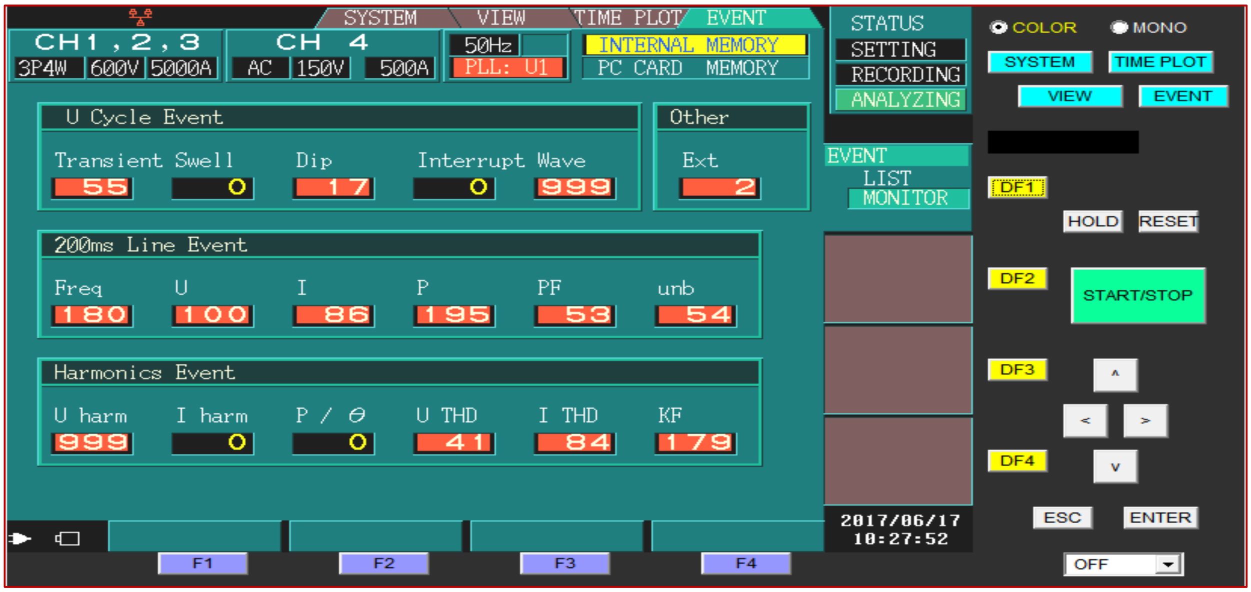

Figure 4.12: Monitoring the power quality problems at adjustable speed drives.

4.3.2.1 Power Acceptability Curves (CBEMA and ITIC Curves)

Computer Business Equipment Manufacturers Association (CBEMA) Curve is representing the withstand capabilities of computers in terms of the magnitude and duration of the voltage disturbance; it had become the de facto standard for measuring the performance of all types of equipment and power systems. Information Technology Industry council (ITIC) curve is representing the withstand capabilities of computers, it has been replaced the curves originally developed by the ITI's predecessor organization and CBEMA. The CBEMA and ITIC curves are quantified the acceptability of supply power as a function of duration versus magnitude of bus voltage disturbances. The two traces of overvoltage and under voltage have been shows as the percentage of bus voltage deviation from the rated voltage against time. The region below the upper trace and above the lower trace is the acceptable range, it defines the tolerance level. An overvoltage of very short duration can be tolerable if it is in the acceptable region. Again a computer may be able to sustain about 5-6% over voltage for a prolonged period of time. Similarly operating below the lower trace is also not permissible. The ITIC curve describes the acceptable range in steps rather than smooth curves used in CBEMA. In addition to these two curves the other power acceptability curves are Federal Information Processing Standards (FIPS) curve for automatic data processing equipment and IEEE standards [1,2,4, 23]. The ITIC curve depicted in figure 4.13 was quantified the voltage tolerance limits of adjustable speed drives voltage variations. The measurement has been taken depending on the disturbance limitation of over voltage, under voltage and the typical break point of ITIC curve for assessing motor contactor and variable frequency drive according to IEEE standard 1159 definition of voltage disturbances.

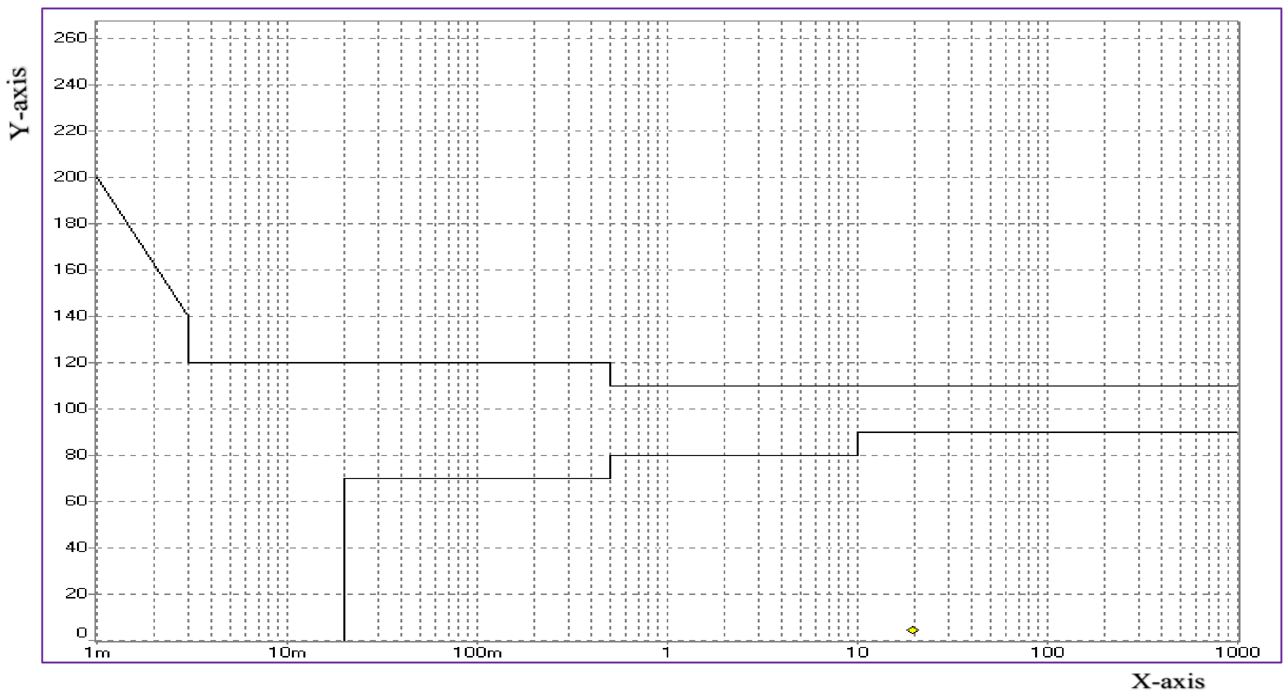

Figure 4.13: ITIC curve measured at 230 phase voltage of the factory adjustable speed drive.

4.4 Factory Power Quality Problems on the Loads Supplied from EEP

The outside transformer mainly consisted a load of computers, printers, copy and faxes machine, washing machines, air conditioners, television, refrigerators, stove, mill, induction motor and etc. The voltage of 15KV was stepped down in to 3KV by two parallel connected transformers individually having 1000KVA. In the irrigation plant the voltage was stepped down in to 0.4KV for continuous usage of irrigation purpose throughout the year.

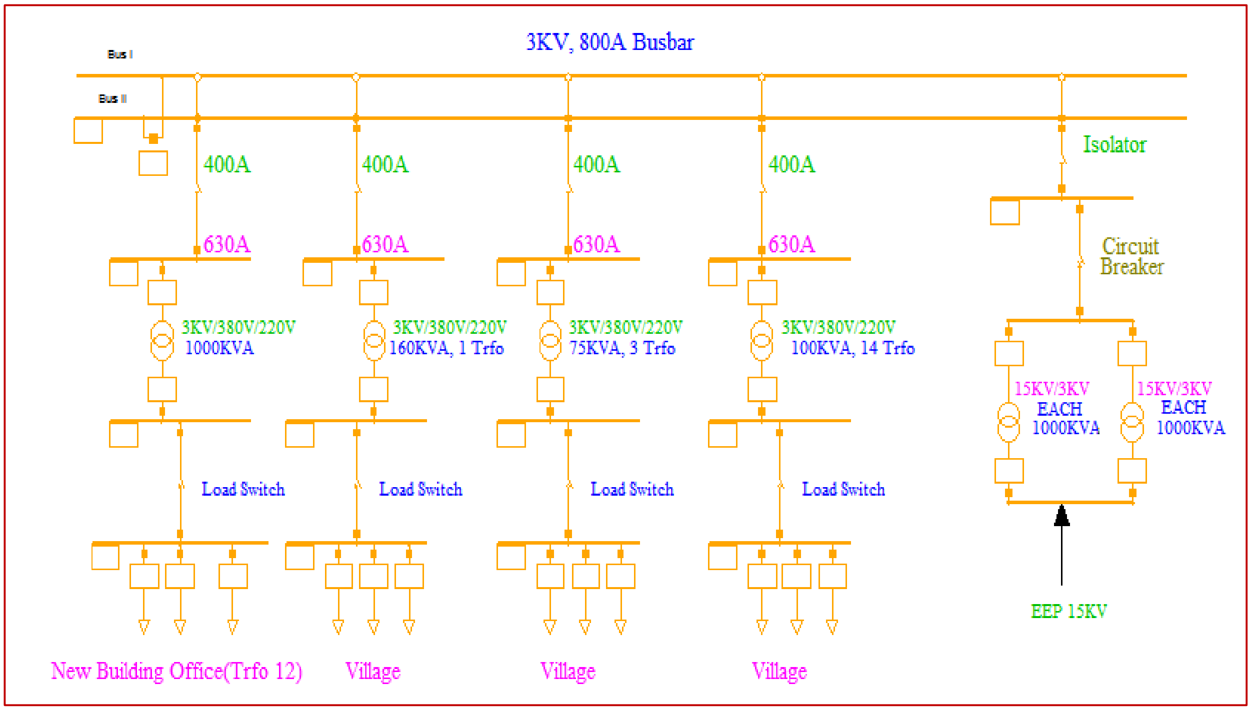

Figure 4.14: Domestic and commercial load outgoing transformers supplied from EEP.

4.4.1 Neutral to Ground Problems

As per IEEE 100 authoritative dictionary of IEEE standard terms, power quality is defined as the concept of powering and grounding electronic equipment in a manner which suitable to the operation of the equipment and compatible with the premise wiring system and other connected equipment.

Table 4.9: Measured Data of Neutral to Ground Wire on Outside Transformer-12.

THD-V_4 (% Voltage harmonics)				THD-I_4 (% Current harmonics)		
Time	3^{rd}	5^{th}	7^{th}	3^{rd}	5^{th}	7^{th}
15:43:14	93.05	60.12	55.07	89.87	20.59	13.30
15:45:40	69.78	41.55	38.56	81.28	19.86	11.16
15:57:04	74.79	41.46	25.14	61.09	12.93	9.89
15:58:24	48.02	38.33	22.54	57.19	11.78	7.93
15:58:28	52.25	36.83	42.31	57.47	11.54	7.82
15:58:29	58.99	46.13	24.46	57.84	12.14	7.54
Average	66.15	44.07	34.68	67.45	14.80	9.60

Figure 4.15 shows that the 3rd order voltage harmonics and current harmonics at neutral wire with percentage values of 98.52% and 57.56% respectively.

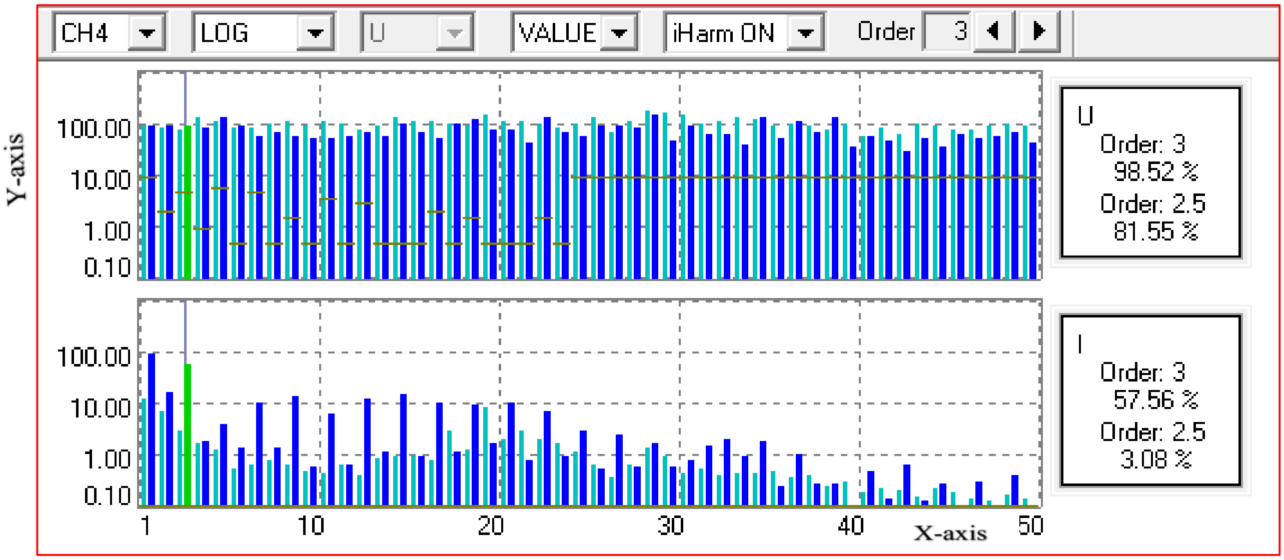

Figure 4.15: Voltage and current harmonics bar graph at neutral to ground wire.

4.4.2 K-Factor Problem

Higher order harmonic currents have a greater influence on the K-factor than lower order harmonic currents. The purpose of measurement of the K-factor when subjected to maximum load the K-factor is larger than the multiplication factor of the transformer [15]. If a company with many offices were uses a poor quality electronic ballasts having poor K-factor, they should install a larger transformer to carry such a heavy load. The K-factor is a number derived from a numerical calculation based on the summation of harmonic currents generated by the nonlinear load. The higher the K-factor, the more significant the harmonic current content [25]. The following is the algorithm used to compute the K-factor according to ANSI/IEEE C57.110 and IEEE Standard 1100-1992:

$$KF = \frac{\sum_{k=2}^{50}(k^2 * {I_k}^2)}{\sum_{k=2}^{50} {I_k}^2} \tag{4.15}$$

Where: k - order of harmonics

I_k - ratio of the harmonic current to the fundamental wave current (%).

The K-factor rating is an index of the transformers ability to withstand harmonic content while operating within the temperature limits of its insulating system and it indicates the power loss using the harmonic rms current for the electrical transformer. A K-factor of 1.0 indicates a linear load with no harmonics. The K-factors of more than 10.0 for nonlinear loads indicated the value is beyond permissible limit. The higher the K-factor, the greater the harmonic heating effects on transformer. As the result of analysis the KF_4 (K-factor at neutral wire) shown in Table 4.10 is not accepted.

Table 4.10: K- Factors Measured Value at Transformer-12.

K-Factor(KF)				
Time	KF_1	KF_2	KF_3	KF_4
15:32:10	3.09	1.42	3.07	23.47
15:43:14	2.56	1.25	2.22	23.12
15:44:27	2.54	1.35	4.57	19.28
15:48:05	2.91	1.48	3.93	20.91
15:57:11	3.66	1.62	5.00	20.03
Average	2.95	1.42	3.76	21.36

4.5 Summary of Industry Power Quality Problems

The overall factory production process and types of loads utilized in the factory are identified. Power quality is an increasingly important issue for industrial loads. Problem with powering and grounding can cause data and processing errors that affect production and service quality. The factory major problems were the imbalance between demand and supply. For example, the ethanol plant is not working due to shortage of power and steam, and it needs more than 600KW power. Metehara Sugar Factory needs a generator that produce maximum of 15MW power and boilers to produce 150-ton steam to overcome the imbalance between supply and demands. Currently the factory operated with two steam generator each generator was produced 2.4MW power but, the system was designed to produce 3.18MW power from each generator.

The measurement of phase voltages, line currents, active power, apparent power, reactive power, power factor, individual harmonic distortion of voltage and currents, total harmonic distortion of voltage and currents have been taken for two weeks in varying time period during the full load and half load operation period of the factory on industrial, domestic and commercial loads which a power supplied by EEP, diesel generators and turbo generators. The average values are compared with the IEEE 1159 – 1995 and IEC 61000 – 2- 4 standards. The major power quality problem has been observed in existing systems are poor power factor, power frequency variations, waveform distortion, excessive current in neutral wire, voltage and current harmonics, total voltage harmonic distortion (THD_V) and total current harmonic distortion (THD_I) at each phases and neutral wire as well. The factory transformer outgoing cable was damaged after the measurement was taken and the analysis has shown that the cause of damaging of the cable is third order harmonics in neutral wire due to nonlinear loads. The 3rd harmonic was prominent on neutral wire, and it is beyond accepted limit consequently the factory have been faced poor grounding system.

Power factor plays a crucial role in the economic operation of any system. Low power factor implies low power utilization, thereby reducing the system efficiency and shorten the life span of electrical appliances. Electricity boards impose a surcharge to the factory if the power factor less than 0.85. Metehara sugar factory have been paid 5,900,317.16 birr for electric power utility in the year of 2016/2017. However, to be more efficient and economical the power factor must be improved by decreasing the harmonic current distortion and also the capacitive part of the filter improve the displacement power factor while the combination of the reactor and the capacitor bank decrease the total harmonic distortion of the current.

Chapter Five

Test System and Simulations Results

5.1 Test System

In this thesis, the D-STATCOM control system as a current source converter including the decoupled control of active and reactive power has been modeled by DigSilent software version 15.1. The active power is proportional to i_d and the reactive power is proportional to i_q which are injected into the system by the D-STATCOM as park's transfomation in equation (5.1) and (5.2).

$$P_{inj} = V_i(i_d cos\theta_i + i_q sin\theta_i) = V_d i_d + V_q i_q \quad (5.1)$$

$$Q_{inj} = V_i(i_d sin\theta_i - i_q cos\theta_i) = -V_d i_d + V_q i_q \quad (5.2)$$

The control of the power injected into the power system reduce to the control of i_d and i_q. The composite frame of the D-STATCOM is depicted in figure 5.1.

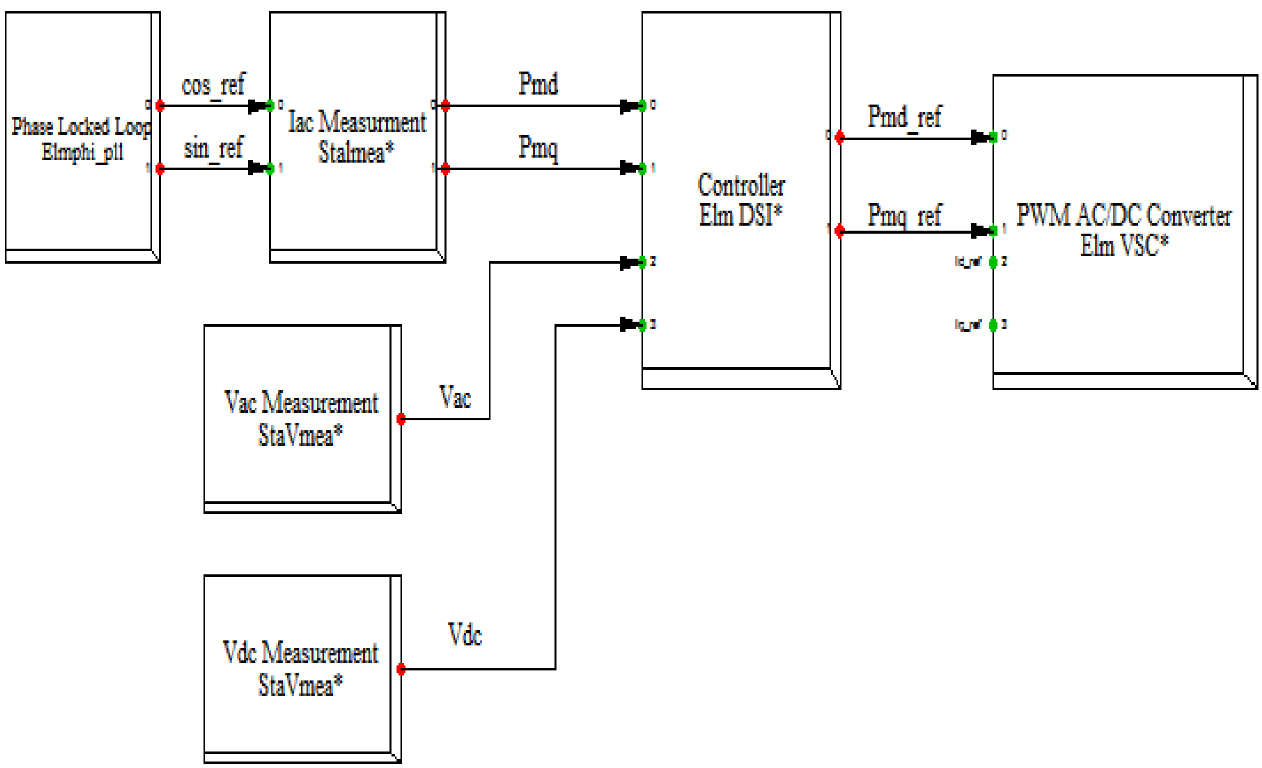

Figure 5.1: A composite frame of D-STATCOM PWM Converter operating as current source.

From the composite frame of a D-STATCOM, the Phase Locked Loop (PLL) which is synchronized the positive sequence component of three phase primary current (I_{ac}) and also the output of the PLL (angle θ=ωt) is used to compute the Ac currents of direct-axis component (i_d) and quadrature-axis component (i_q). The regulation loop consisting of voltage and current regulation. The output of the AC voltage regulator is the reference current (i_q_ref) for current regulator i_q. The i_q is a current in quadrature with voltage which controls reactive power flow. The output of the DC voltage regulator is the reference current (i_d_ref) for current regulator i_d. The i_d is a current in phase with voltage which controls active power flow. The control system modeled for the D-STATCOM is depicted in figure 5.2.

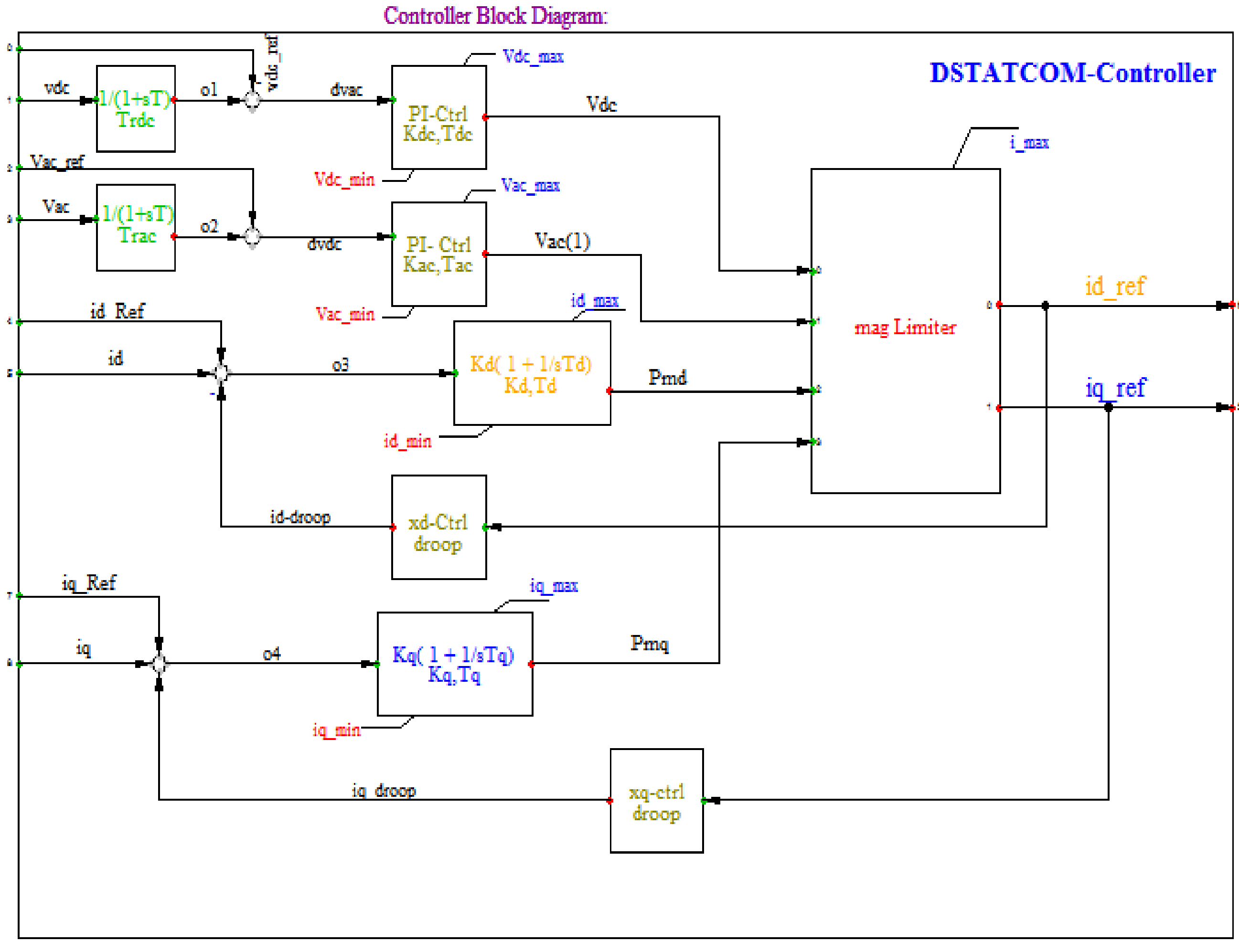

Figure 5.2: Composite control model of D-STATCOM.

In composite control model, when the arrangement of voltage at PCC is more than the voltage at the PWM converter, the reactive current (i_q) flows from bus to the converter then the converter consume reactive power which means the D-STATCOM absorb reactive power. Through the arrangement of voltage at PWM converter is greater than the voltage at PCC, the converter feed reactive current (i_q) to the system and also the D-STATCOM generate reactive power.

The converter's AC current expressed in reference frame which is defined by the input signals cos_ref and sin_ref. The output signals Pmd and Pmq are defined in the same reference frame and transformed back to a global reference frame using the same reference angle.

To evaluate the power quality provided by a D-STATCOM which is connected to week supply, simulation has been performed in DigSilent version 15.1.

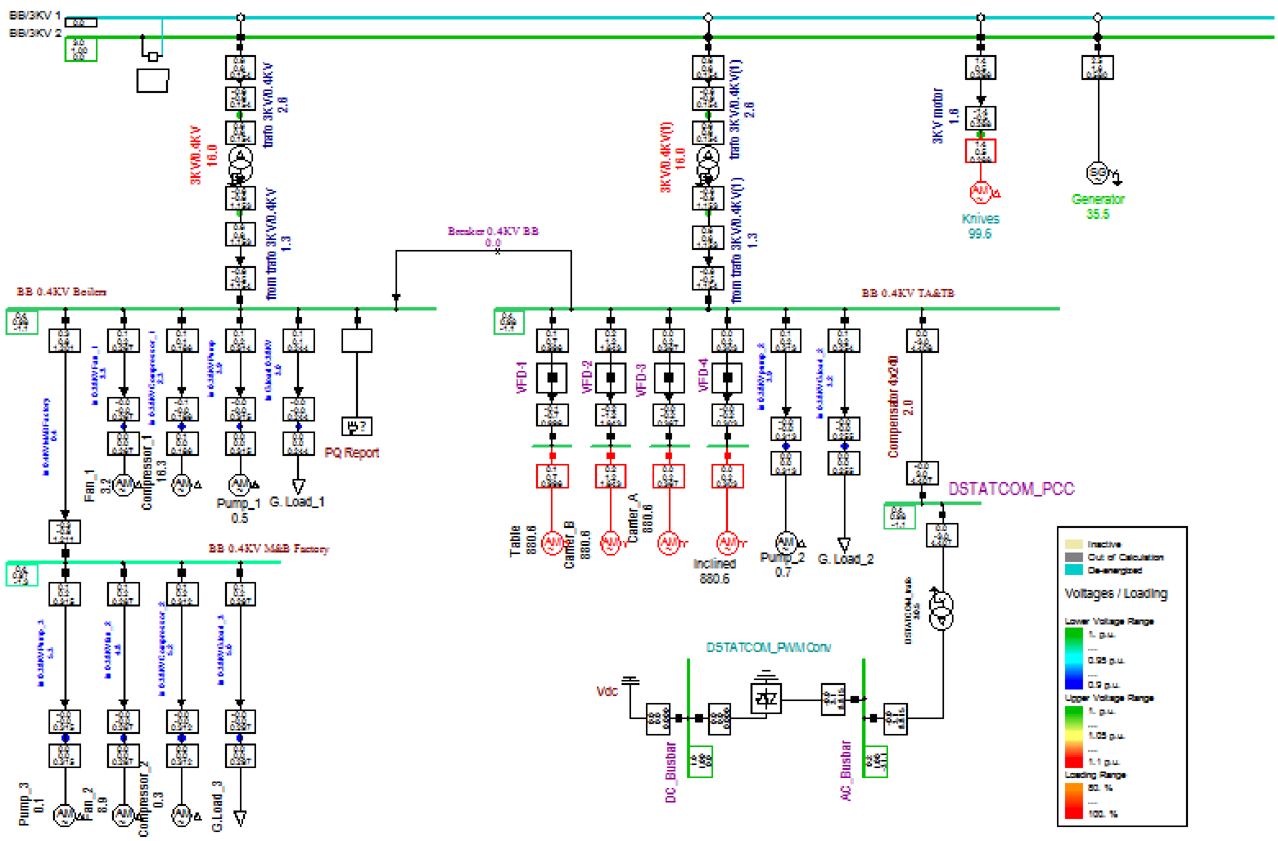

Figure 5.3: The general test system of D-STATCOM connected to industrial network.

The PWM converter is operating as a current source converter when the parameters which built-in integrated current controller K_P, T_P, K_q and T_q are set to zero, and hence the controller is disabled then the output currents id and iq are set equal to the input variable id_ref and iq_ref.

To evaluate the power quality provided by SVC which is connected to week supply, simulation has been performed in DigSilent version 15.1.

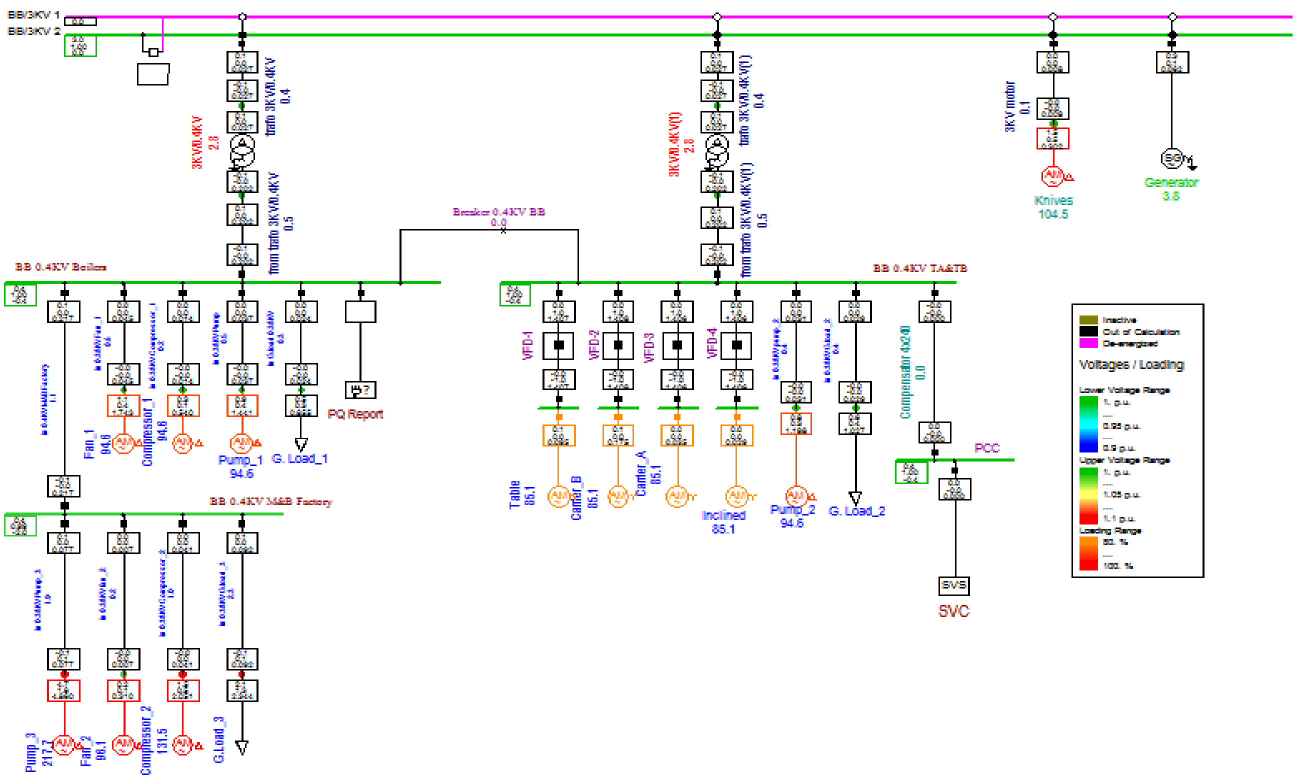

Figure 5.4: The general test system of SVC connected to industrial network.

5.2 Simulation Results

The size of a D-STATCOM was determined by the amount of reactive power to be injected into the system. A 10MVA Y (star)/Z (Zigzag) phase shifting transformer of a D-STATCOM was provided for the required phase displacement between the primary and secondary line to line voltages for harmonic cancellation and also order an electric isolation between the rectifier and the AC supply. A current injected into the system was controlled by D-STATCOM converter using pulse width modulation (PWM).

5.2.1 Harmonic Distortion

The harmonics current injected by the loads were reduced and the fifth order harmonic that found in SVC was eliminated and also the seventh order harmonics was below permissible limit by a D-STATCOM PWM of symmetrical type gate-commutated thyristor (GCT) which is powered by phase shifting transformer. The negative sequence harmonics which is 5^{th}, 11^{th}, 17^{th}, 23^{th}, 29^{th}, 35^{th}, 41^{th}, and 47^{th} harmonics currents were 180° out of phase and canceled out. The magnitude of positive sequence harmonics of 7^{th}, 13^{th}, 19^{th}, 25^{th}, 31^{th}, 37^{th}, 43^{th} and 49^{th} harmonics currents were 1.285%, 1.297%, 1.329%, 1.384%, 1.478%, 1.649%, 2.042% and 3.655% respectively. The total harmonics generated at load side has THD of 54.07% which has been compensated with D-STATCOM in to 5.4% and also the power factor was improved in to 0.95 from 0.54. The D-STATCOM PWM improved the line current THD and satisfied the harmonic guidelines which was set by IEEE standard 519-1992.

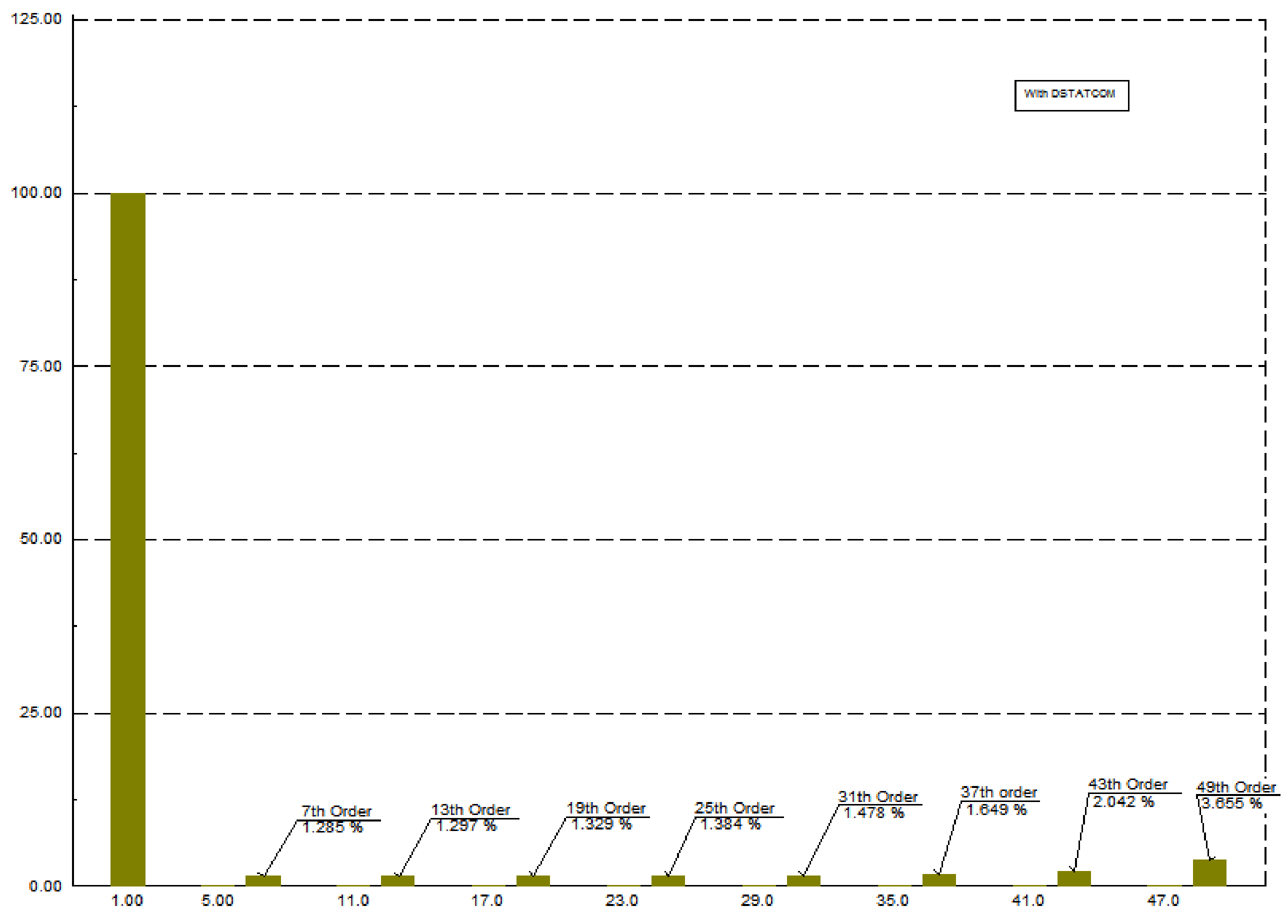

Figure 5.5: n^{th} order harmonic distortion in % with respect to percentage line current THD.

The magnitude of positive sequence harmonics of 13th, 25th, 37th and 49th harmonics currents were 1.297%, 1.384%, 1.649% and 3.655% respectively. The total harmonic distortion was reduced to 4.4% from current harmonics of 54.07% and the power factor was improved into 0.98 from the previous value of 0.65.

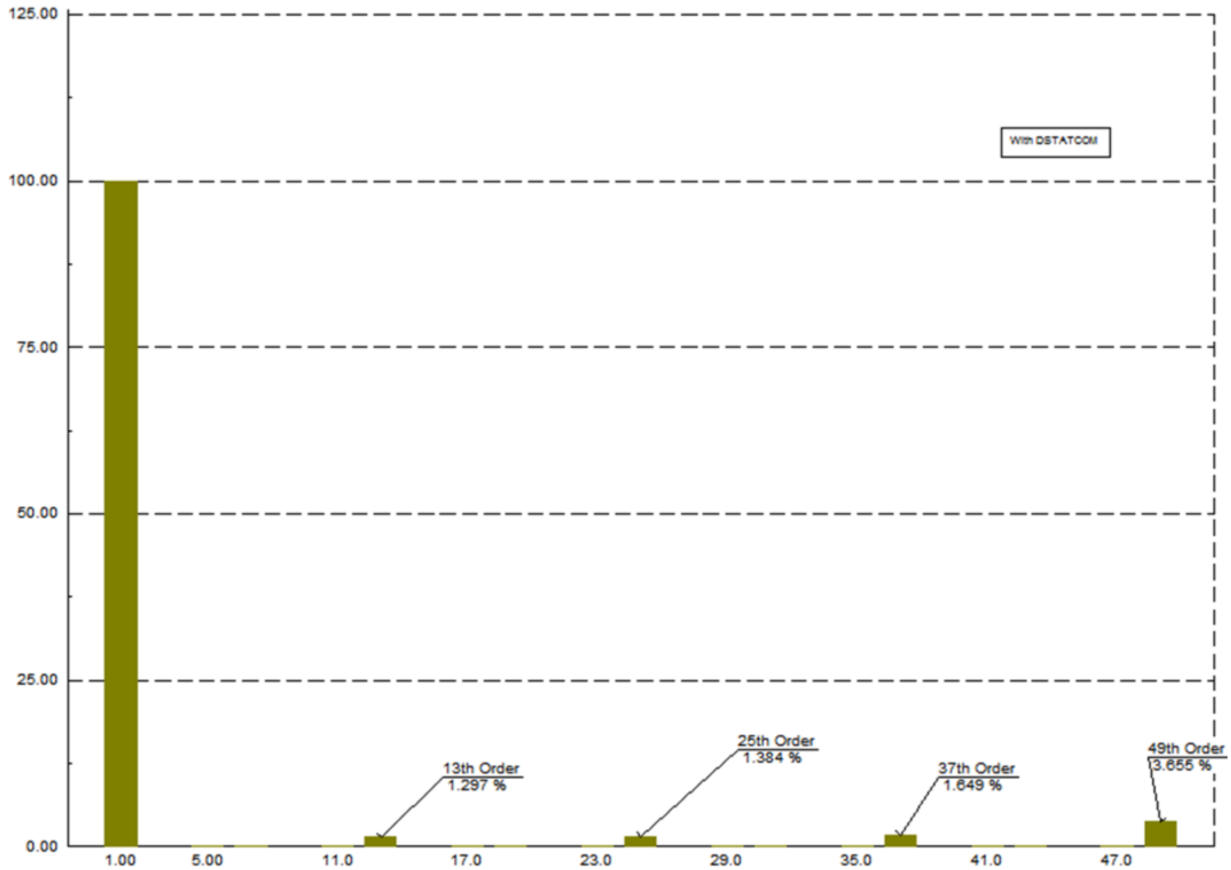

Figure 5.6: n^{th} order harmonic distortion in % with respect to percentage line current THD.

5.2.2 Under Voltage

The nominal voltage magnitude variation according to IEEE 1159-1995 should be ± 10% (207 – 253) V of 230 V. The existing system was operated with SVC, and the measured voltage value 200V, however the D-STATCOM has improved mitigated of the voltage at bus-1 and bus-2 to 225V.

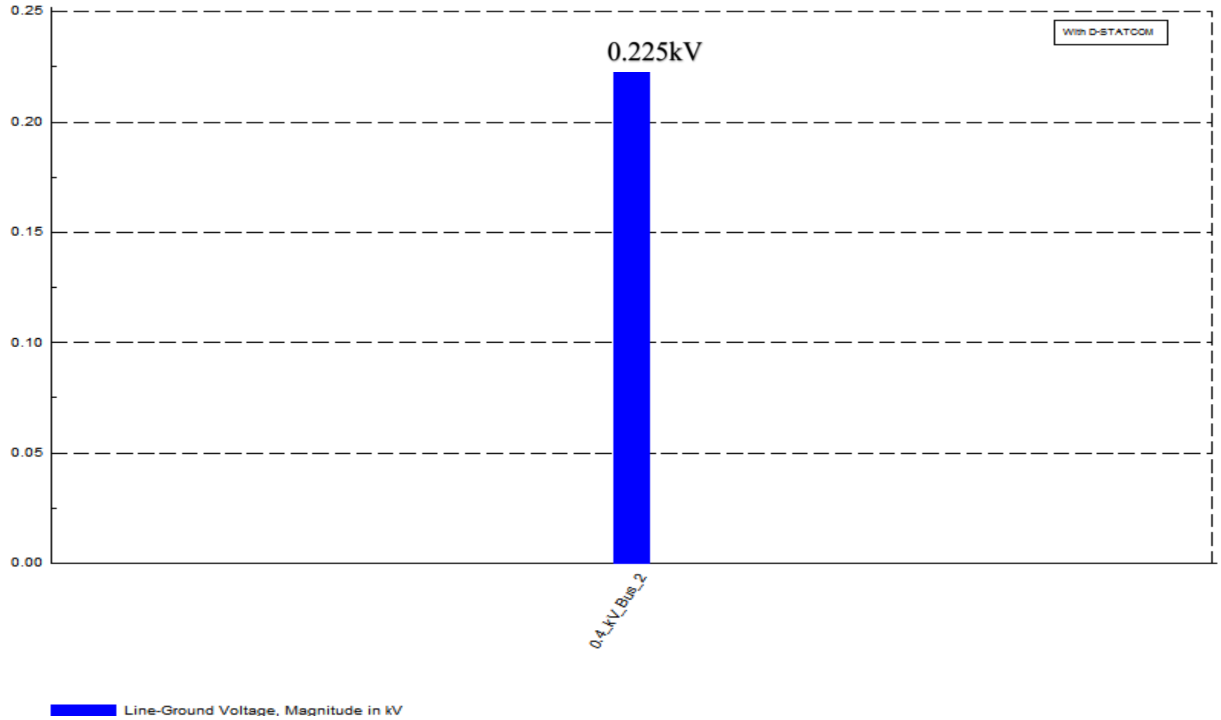

Figure 5.7: Bar-diagram of bus-2 magnitude of phase voltage in kV.

The voltage at bus-3 implies 0.218KV (218V) which is somewhat decreased when compared to voltage at bus-1 and bus-2. The D-STATCOM was installed far away from load bus-3 so that voltage drop happened.

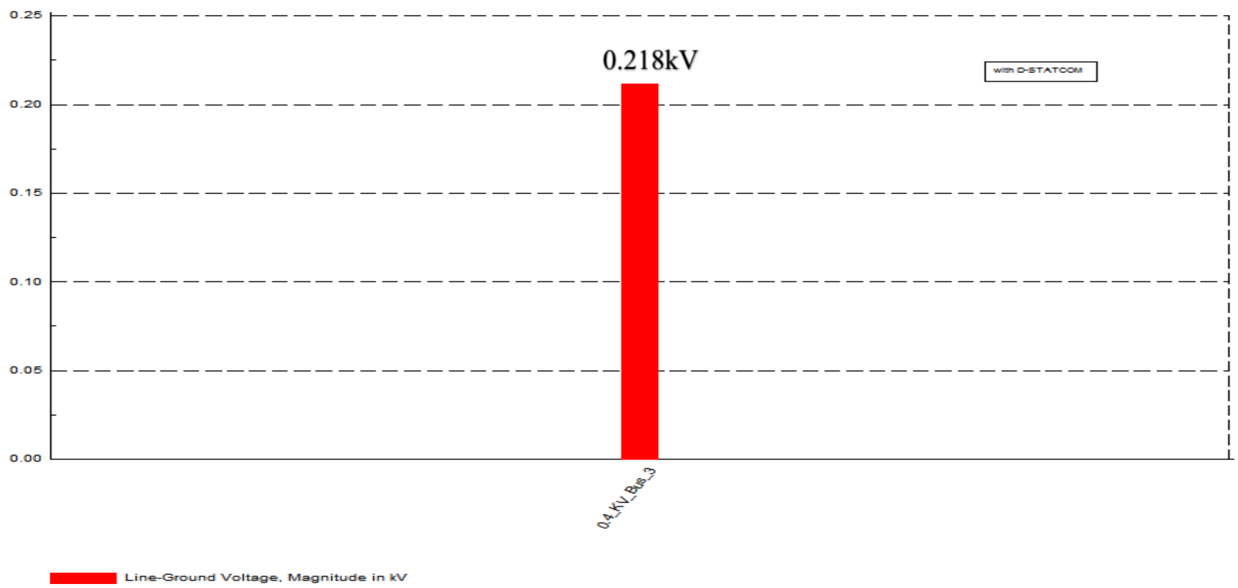

Figure 5.8: Bar-diagram of bus-3 magnitude of phase voltage in kV.

Chapter Six

Conclusion, Recommendation and Future Work

6.1 Conclusions

The necessary investigation has been done by measuring the voltage, current, frequency and power (active and reactive power) using power quality analyzer namely HIOKI-3196. Also, the power quality problem has been analyzed by PQA-HiVIEW PRO 9624-50 software for flexible PC analysis.

The simulation part harmonics has been analyzed in the frequency domain and also harmonic load flow has been done according to IEC 61000-3-6. DigSilent software has given accurate calculated output of harmonic load flow, actual harmonic indices related to current distortion and harmonic losses caused by harmonic source. The result of power quality analysis shows that the presence of excess current harmonic through entire power system. But, those excess current harmonics has been removed by entering the analysis result in PMW to achieve allowable IEC standard.

A 10 MVA Y (star)/Z (Zigzag) phase shifting transformer of a D-STATCOM was provided for the required phase displacement between the primary and secondary line to line voltages for harmonic cancellation and also order an electric isolation between the rectifier and the AC supply. A current injected into the system was controlled by D-STATCOM converter through pulse width modulation (PWM).

The results obtained illustrate that the device controller concurrently eliminated the fifth order harmonics, and also make seventh order harmonics 1.285% which is in the range of permissible limit. The total harmonics generated at load side has THD of 54.07% which has been compensated with D-STATCOM in to 5.4% and also the power factor was improved in to 0.95. The negative sequence harmonics currents were 180° out of phase and canceled out. The suitability of D-STATCOM in enhancing power quality and mitigate the voltage drop or voltage variation at the load bus has been verified by this study.

6.2 Recommendations

As the research shows, the root causes of power quality problem of the factory refers to the imbalance of power supply and power consumption of electrical equipment's which leads to voltage instability. As the existing loads are nonlinear the harmonic distortion has been generated. Due to the presence of harmonic distortion, the system has produced poor power factor. Accordingly, the best recommendation for avoiding all above mentioned problems is the replacement of SVC by D-STATCOM.

Additionally, working on improvement of the following mentioned sensible points may bring the system more sustainable.

- The factory existing sources of energy which is energy from non-condensing steam is not adequate to meet the ever increasing load, and the efficiency of the generator also is below expected value. Therefore, additional energy sources are needed to sustain the industrial load requirement and improve the performance of existing energy source by producing renewable energy.
- As the sensitive devices such as a variable frequency drives were supplied from the same distribution transformer the incremental of harmonic content is expected. So, reducing these harmonic content by segregating sensitive load in to separate transformer is good practice.
- Also, avoid the flow of excessive neutral current by oversizing the conductors.

6.3 Future Work

In Metehara Sugar factory a disturbance has been occurred due to load variation, switching heavy loads and changing the speed of prime mover. These disturbances has been navigated. The systems are dying out quickly when the magnitude of oscillation is small and the system is going to unnecessary frequent load shedding or loss of synchronism when the magnitude of oscillation is very large and they exist for long time, so that it needs further stability study. In this thesis, D-STATCOM has injected the right power into the system and eliminated the unbalance or distortions that has been generated by the nonlinear load, improved also the quality of power. As a future work the study of stability analysis to determine the upper limit of loading before the generators is losing synchronism.

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Appendix

Appendix A_1: Power Quality Standards (IEEE 1159, 1159-1995)

Categories	Typical Duration	Typical Voltage Magnitude
Transients		
Impulsive	50ns<duration<1ms	
Oscillatory	30ms<duration<5us	0-8 p.u
Short Duration Variations		
Instantaneous		
Sag	0.5-30 cycles	0.1-0.9 p.u
Swell	0.5-30 cycles	1.1-1.8 p.u
Momentary		
Interruption	0.5-3 sec	Less than 0.1p. u
Sag	30 cycles-3 sec	0.1-0.9 p.u
Swell	30 cycles-3 sec	1.1-1.4pu
Temporary		
Interruption	3 sec-1 min	Less than 0.1p. u
Sag	3 sec-1 min	0.1-0.9 p.u
Swell	3 sec-1 min	1.1-1.4pu
Long Duration Variations		
Sustained Interruption	Longer than 1 min	0.0 p. u
Under Voltage	Longer than 1 min	0.8-0.9 p.u
Over Voltage	Longer than 1 min	1.1-1.2 p.u
Voltage Unbalance	Steady State	0.5-2 p.u
Wave Form Distortion		
Dc offset	Steady State	0.0-0.1%
Harmonics	Steady State	0.0-20%
Inter harmonics	Steady State	0.0-20%
Notching	Steady State	
Noise	Steady State	0.0-0.1%
Voltage Fluctuation	Intermittent	0.1-7%
Power Frequency Variation	Less than 10 sec	

Appendix A2: Harmonic Current Distortion Limits in % by IEEE 1159-1992

I_{SC}/I_L	$h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h$	TDD
$V_n \le 69$ kV						
<20	4.0	2.0	1.5	0.6	0.3	5.0
20–50	7.0	3.5	2.5	1.0	0.5	8.0
50–100	10.0	4.5	4.0	1.5	0.7	12.0
100–1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0
69 kV < $V_n \le 161$ kV						
<20*	2.0	1.0	0.75	0.3	0.15	2.5
20–50	3.5	1.75	1.25	0.5	0.25	4.0
50–100	5.0	2.25	2.0	0.75	0.35	6.0
100–1000	6.0	2.75	2.5	1.0	0.5	7.5
>1000	7.5	3.5	3.0	1.25	0.7	10.0
$V_n > 161$ kV						
<50	2.0	1.0	0.75	0.3	0.15	2.5
≥50	3.0	1.50	1.15	0.45	0.22	3.75

Values shown are in % of "average maximum load current". I_{SC} is short-circuiting current at the PCC. I_L is the fundamental component of the maximum demand load current at the PCC. It can be calculated as the average of the maximum monthly demand currents or it may have to be estimated. All power generation equipment is limited to these values of current distortion, regardless of actual I_{SC}/I_L.

Appendix B

Appendix B_1: Log Sheet for Turbo Generator No.1

Month	Ampere		MW		Power Factor		K.W.H reading
	Max	Min	Max	Min	Max	Min	
10/11/16	330	206	2.28	0.94	0.88	0.78	920769
20/11/16	539	371	2.40	1.91	0.85	0.77	924582
29/11/16	629	272	2.47	1.30	0.87	0.76	951709
02/12/16	571	428	2.42	1.88	0.82	0.75	930600
10/12/16	571	431	2.48	2.07	0.85	0.77	934858
20/12/16	564	432	2.34	1.92	0.84	0.75	940134
30/12/16	552	410	2.54	1.91	0.86	0.80	945095
01/01/17	600	409	2.48	2.07	0.85	0.77	946174
09/01/17	578	396	2.60	1.88	0.87	0.82	950250
18/01/17	618	339	2.48	1.94	0.83	0.79	955001
26/01/17	584	420	2.48	1.93	0.85	0.80	982500
02/02/17	535	399	2.22	1.83	0.83	0.79	962648
14/02/17	460	223	2.80	1.03	0.86	0.74	968629
22/02/17	511	411	2.17	1.74	0.82	0.74	971378
03/03/17	572	472	2.26	1.16	0.83	0.76	975738
16/03/17	556	399	2.30	1.70	0.85	0.77	982006
29/03/17	536	387	2.34	1.68	0.85	0.77	988599
01/04/17	538	438	2.64	1.87	0.82	0.77	989986
12/04/17	549	396	2.29	1.89	0.90	0.79	995427
17/04/17	542	357	2.16	1.52	0.88	0.78	997870

Appendix B2: Log Sheet for Turbo Generator No. 2

Month	Ampere		MW		Power Factor		K.W.H reading
	Max	Min	Max	Min	Max	Min	
10/11/16	356	234	1.57	1.11	0.86	0.79	943329
20/11/16	537	208	2.26	1.79	0.85	0.79	947152
29/11/16	629	272	2.61	1.30	0.87	0.76	951709
02/12/16	575	425	2.51	1.97	0.88	0.59	953236
10/12/16	582	154	2.58	2.18	0.86	0.78	957630
20/12/16	624	0.77	2.44	2.11	0.84	0.74	963225
30/12/16	562	432	2.51	1.92	0.85	0.81	968324
01/01/17	582	425	2.64	1.99	0.87	0.79	969415
09/01/17	603	411	2.63	1.89	0.85	0.76	973550
18/01/17	569	444	2.56	2.07	0.85	0.79	978232
26/01/17	568	402	2.37	1.91	0.85	0.81	959159
02/02/17	550	409	2.48	1.87	0.88	0.79	986121
14/02/17	468	208	2.12	1.01	0.87	0.85	992324
22/02/17	537	442	2.22	1.91	0.82	0.79	995310
03/03/17	563	326	2.45	2.07	0.85	0.75	999859
16/03/17	577	463	2.49	1.39	0.85	0.78	006667
29/03/17	507	388	2.32	1.79	0.88	0.77	013508
01/04/17	569	421	2.61	1.56	0.89	0.83	015031
12/04/17	573	439	2.27	1.71	0.86	0.72	020836

Appendix C

Appendix C_1: Billing Information of the Factory Ethanol Plant Contract No.003950

Month	Consumption period		Total days	Reading				
	Start	End		Previous	Current	Meter constant	Consumption	Cost in birr
01/04/16	01/03/16	01/04/16	31	8686MW 4247Kvar 1.6	9345MW 4507Kvar 1.6	400	263600MW 104000Kvar 640	152,361.65
01/05/16	01/04/16	01/05/16	30	9345MW 4507Kvar 1.6	10120MW 4605Kvar 1.6	400	310000MW 39200Kvar 640	179,171.57
01/6/16	01/05/16	01/6/16	31	10120MW 4605Kvar 1.6	10704MW 4660Kvar 1.6	400	233600MW 22000Kvar 640	135,027.65
01/07/16	01/6/16	01/07/16	30	10704MW 4660Kvar 1.6	11045MW 4682Kvar 1.6	400	136400MW 8800Kvar 640	78,865.49
01/08/16	01/07/16	01/08/16	31	11045MW 4682Kvar 1.6	11281MW 4700Kvar 1.6	400	94400MW 7200Kvar 640	54,597.89
01/09/16	01/08/16	01/09/16	31	11281MW 4700Kvar 1.6	11634MW 4711Kvar 1.6	400	141200MW 4400Kvar 640	81,638.93
01/10/16	01/09/16	01/10/16	30	11634MW 4711Kvar 1.6	11789MW 4714Kvar 1.6	400	62000MW 1200Kvar 640	35,877.17
01/11/16	01/10/16	01/11/16	31	11789MW 4714Kvar 1.6	11820MW 4716Kvar 1.6	400	12400MW 800Kvar 640	7,218.29
01/12/16	01/11/16	01/12/16	30	11820MW 4716Kvar 1.6	11960MW 4792Kvar 1.6	400	56000MW 30400Kvar 640	33,335.66
01/01/17	01/12/16	01/01/17	31	11960MW 4792Kvar 1.6	13000MW 5089Kvar 1.6	400	416000MW 118800Kvar 640	240,418.37
01/02/17	01/01/17	01/02/17	31	13000MW 5089Kvar 1.6	13885MW 5663Kvar 1.2	400	354000MW 229600Kvar 480	206,597.12

Appendix C2: Billing Information of the Factory/MSF Contract No.999999

Month	Consumption period		Total days	Reading				
	Start	End		Previous	Current	Meter constant	Consumption	Cost in birr
01/04/16	01/03/16	01/04/16	31	4056MW 2619Kvar 10	4117MW 2619Kvar 10	300	36600MW 600Kvar	149,601.61
01/05/16	01/04/16	01/05/16	31	4185MW 2619Kvar 10	4224MW 2654Kvar 40	300	234000MW 210000Kvar	118,706.34
01/6/16	01/05/16	01/6/16	31	4224MW 2654Kvar 40	4273MW 2679Kvar 20	300	294000MW 150000Kvar 1200	120,865.67
01/07/16	01/6/16	01/07/16	30	4224MW 2654Kvar 40	4273MW 2679Kvar 20	300	294000MW 1500000Kvar 1200	120,865.67
01/08/16	01/07/16	01/08/16	31	4273MW 2679Kvar 20	4320MW 2710Kvar 20	300	306000MW 186000Kvar 1200	128,449.20
01/09/16	01/08/16	01/09/16	31	4320MW 2710Kvar 20	4400MW 2761Kvar 10	300	456000MW 306000Kvar 600	188,950.72
01/10/16	01/09/16	01/10/16	30	4400MW 2761Kvar 10	4446MW 2796Kvar 10	300	276000MW 210000Kvar 600	116,679.91
01/11/16	01/10/16	01/11/16	31	4446MW 2796Kvar 10	4520MW 2840Kvar 10	300	444000MW 264000Kvar 600	182,968.79
01/12/16	01/11/16	01/12/16	30	4520MW 2840Kvar 10	4597MW 2890Kvar 10	300	462000MW 300000Kvar 600	191,094.39
01/01/17	01/12/16	01/01/17	31	4597MW 2890Kvar 10	4644MW 2910Kvar 10	300	282000MW 120000Kvar 600	115,276.21
01/02/17	01/01/17	01/02/17	31	4644MW 2910Kvar 10	______	300	276000MW 138000Kvar 600	113,033.69

Appendix D: Weekly/Monthly Report on Electric Consumption Cost

Sugar Corporation	***Company Name:*** ***Metehara Sugar Factory***

1. Electric Consumption Cost of 2015/16

S/n	Month	Cost in birr
1	January	612,213.11
2	December	950,984.41
3	February	530,348.61
4	April	430,150.87
5	May	303,460.89
6	June	374,878.61
7	July	631,576.92
Total		3,833,606.42

2. Electric Consumption Cost of 2016/17

S/n	Month	Cost in birr
1	July	813,410.14
2	August	640,646.61
3	September	816,042.65
4	October	635,091.28
5	November	564,391.78
7	December	627,143.05
8	January	851,591.65
9	February	952,000.00
Total		5,900,317.16

Appendix E: Weekly/Monthly Report on Problems and Electrical Maintenance

Sugar Corporation	***Company Name:*** ***Metehara Sugar Factory***

1. <u>Break down maintenance</u> Year: 2016/2017

S/no	Machine Name	Problem encountered	The given solution
1	First finishing cane knife motor	Overheating	Fixed with cooling system
2	First finishing cane knife motor	Vibration & overloading	Load shedding
3	Power turbine alarmed	Frequency adjustment switch	Adjust the frequency
4	Generator alarmed	Under frequency due to pressure	Load shedding
5	Horizontal bagasse carrier motor	Misalignment	Correct the alignment
6	Bagasse belling machine motor	Bearing got too much hot	Bearing replace
7	River water pumps	Shortage of water in cooler	Ensure sufficient water for cooling
8	ID & FD fan motor	Vibration & bearing damage	Replace the bearing
9	BB machines	Inverter problem	Fixed by resetting the inverter

2. <u>Major problem</u>: a). Burning of factory transformer outgoing cables due to third harmonics on neural to ground wire generated by nonlinear loads. It takes down time of 12 hours to identified and changing the damages of outgoing cables. b). Fault operations of fuse and circuit breaker. c). Problem on frequency adjustment switch and faulty readings of energy meters. d). Power electronics device damaged at centrifugal plant.

3. <u>Remark</u>---------

Prepared by _____________Checked by ______________ Approved by _____________