Harmonics Analysis in Power Distribution Network and Its Mitigation Techniques (Case study of Metahara Sugar Factory)

Nafyad Deme Urga

A Thesis Submitted to

The Department of Electrical Power and Control Engineering

School Of Electrical Engineering and Computing

Presented in partial fulfilliment of the requirement for the degree of Masters in Electrical Power and Control engineering (Power System Engineering)

Office of Graduate Studies

Adama Science and Technology University

September, 2022

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DECLARATION OF STUDENT

I hereby declare that this Master Thesis entitled "**Harmonics Analysis in Power Distribution Network and Its Mitigation Techniques (Case study of Metahara Sugar Factory)**" is my original work. That is, it has not been submitted for the award of any academic degree, diploma, or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Nafyad Deme Urga	_______________	_______________
Name of student	signature	Date

RECOMMENDATION OF ADVISOR

I ,the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled "**Harmonics Analysis in Power Distribution Network and Its Mitigation Techniques (Case study of Metahara Sugar Factory)**", prepared under my guidance by **Nafyad Deme Urga** submitted in partial fulfillement of the requirements for the degree of master's of Science in Electrical Power and Control Engineering (Power System Engineering). Therefore, I recommend the submission of a revised version of the thesis to the department following the applicaeble procedures.

Dr.Milkias Berhanu	______________	______________
Name of Advisor	signature	Date

APPROVAL PAGE

I ,the advisor of the thesis entitled "**Harmonics Analysis in Power Distribution Network and Its Mitigation Techniques (Case Study of Metahara Sugar Factory)**" and developed by **Nafyad Deme Urga** hereby certify that the recommendation and suggestions made by the board of examiners are approppprietely incorporated into the final version of the thesis.

Dr.Milkias Berhanu	______________	_____________
Major Advisor	signature	Date
________________	_________	___________
Co-advisor	signature	Date

We the undersigned members of the board of examiners of the thesis by open defense by **Nafyad Deme Urga** have read and evaluated the thesis proposal entitled "**Harmonics Analysis in Power Distribution Networks and Its Mitigation Techniques (Case Study of Metahara Sugar Factory)**" and examine during the open defense. This is therefore,tocerify that the thesis is accepted for partial fulfillement of the requirement of the degree of Master of science in Electrical Power and Control Engineering (Power System Engineering).

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Internal Examiner	Signature	Date
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Final approval and acceptance of the thesis proposal is contingent upon submission of its final copy to the office of postgraduate studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SDC).

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LIST OF ACRONYMS AND ABBREVIATIONS

AC	Alternative Current
ANSI	American National Standard Institute
APF	Active Power Filter
ASD	Adjustable-Speed-Drive
BPT	Power balance Theory
CDC	Dc link Capacitor
CPD	Custom Power Device
CSD	Current synchronous Theory
DSTATCOM	Distribution Static Compensator
DVR	Dynamic Voltage Restorer
EEU	Ethiopian Electric Utility
EMC	Electro Magnetic Compatibility
ESA	Ethiopian Standard Agency
FCT	Field Controlled Transistor
FFT	Fast Fourier Transformation
GTO	Gate turn-off Transistor
HCC	Hysteresis Current Control
HVDC	High Voltage DC
ID	Forced draft
IEC	International Electro-technical Commission
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistor
IJRASET	International Journal for Research on Applied Science& Engineering Technology
IPR	Instantenous Reactive Power Theory
KVAR	Kilovolt Ampere Reactive

LPF	Low pass Filter
MOSFET	Metal oxide Field Effect Transistor
MSF	Metahara Sugar Factory
NECE	National Electro-technical Committee of Ethiopia
NEMA	National Electrical Manufactures Association
PCB	Printed circuit board
PCC	Point of Common Coupling
PFC	Power Factor Controller
PID	Proportional-Intigrator-DerivativeController
PI	Proportional-Intigrator Controller
PLL	Phase-locked Loop
PWM	Pulse Width Modulation
RMS	Root mean square
SA	Secondary/Auxiliary
SRF	Synchronoues Reference Frame
STS	Static Transfer switch
SVC	Series VAR Compensator
SVPWM	Space Vector Pulse Width Modulation
TCD	Total cane crushed perday
TDD	Total Demand Distortion
THD_I/THDv	Total Harmonics Distortion of current/voltage
UPQC	Unified Power Quality Conditioner
UPS	Uninterruptable Power Supply
VAR	Volt Ampere Reactive
VDC	DC link Voltage
VFD	Variable Frequency Drive
VSC/VSI	Voltage Source Converter/Inverter

LIST OF SYMBOLS

%Z	Percentage of Impedance
Dpf	Displacement Power Factor
F	Farad
f	Frequency
f_0	Natural frequency
H	Henery
Ha	Harmonics in phase A
Hb	Harmonics in phase B
Hc	Harmonics in phase C
I	Current
I f	Full load phase current
I_{comp}	Compensating Current
I_{harm}	Harmonics Current
IL	Load Current
I_{ref}	Reference Current
Isc	Short Circuit current
Isc	Short circuit current
I_{sw}	Switching Current
Ki	Integral gain
Kp	Proportional gain
Kv	Kilovolt
Kw	Kilowatt
Mw	Mega watt
n	Integer
Pp	Peak to peak

Q	Reactive power
Qc	Compensator Reactive Power
V	Voltage
V f	Full load phase Voltage
V_{harm}	Harmonics voltage
V_{sw}	Switching Voltage
X	Reactance
Xsc	Short circuit Reactance
Xtr	Transformer Reactance
Ztr	Transformer Impedance

ABSTRACT

Providing clean power to the utilities is important for reliable and healthy operation of electrical equipments of the end users. In this era the advancements in industrial control technology is in the growing pace and using of non-linear load introduce non-linear characteristics in the network. This study presents the analysis of harmonics distortion in Metahara Sugar Factory (MSF) power distribution network and design DSTATCOM with synchronuous reference frame (SRF) control theory for harmonics mitigation for the results exceeded the limits stated in IEEE and IEC standard requirements.

The ratio of short circuit current to maximum load current (Isc/IL) at each transformer Point of Common Coupling (PCC) hasbeen computed.The HIOKI 3196 Power Quality Analyzerwas used to monitor and collect real-time data at PCCsof each transformer. Mesuared, computed and analyzed real data showedthat there is total harmonics current distortion (TDD) at distribution transformer#2,6,7,8 and#11 found 13.58%, 34.79%,10.28%, 8.41% and 24.80% respectively. The 5^{th} and 7^{th} order are the dominant individual harmonics current distortion found at these transformers' PCCs. Distribution network system modeling and simulations with DSTATCOM and bridge rectifier for non-linear load representation have done by using MATLAB/SIMULINK and the simulation results showed that the total harmonics current distortions substaially reduced to 3.17%,3.82%,3.59%,3.44% and 4.04% for tansformer#2,6,7,8 and 11 respectively, which is below recommended harmonics limits stated in IEC and IEEE ducuments.It is found important to implement the proposed harmonic current mitigation device at PCC of identified transformers distribution panels to mitigate harmonic current and improve system power factor and conduct further study on harmonics problem in relation with resonant frequency at installed capacitor banks in power distribution network of the factory.

Keyterms:*Point of common coupling (PCC), total harmonic distortion (THD), harmonics mitigation,power quality analyzer and MATLAB/SIMULINK.*

CHAPTER ONE

INTRODUCTION

1.Backgroundof the study

Electrical energy is the most efficient and popular form of energy and the modern society is heavily dependent on the supply of electricity. In recent times electric utilities (commercial and residential), academic and research centers, manufacturering sectors , agro-processing industries and other end users of electric power are becoming increasingly concerned about the quality of electric power because it is very important for the efficient functioning of the end user equipments. Harmonic currents are present in modern electrical distribution systems caused from non-linear loads such as adjustable speed drives, electronically ballasted lighting and the power supplies of every computer, copier, and fax machine and much of the telecom equipment used in modern offices. The widespread and growing of these loads been greatly increased the flow of harmonic currents on facility distribution systems and has created a number of problems. These problems include overheated transformers, motors, conductors, and neutral wires,nuisance breaker and relay trips,voltage distortion, which can cause sensitive electronic equipment to malfunction or fail, and elevated neutral-to-ground voltage, which can cause local area networks to malfunction. Single-phase electronic loads generated harmonics at all odd multiples of the fundamental, but the most dangerous of these are usually the "triplen" harmonics that have frequencies multiples of the third harmonic. Triplens add together in the neutral on the secondary side of a delta-wye transformer and can cause very high neutral currents. In conventional transformers, triplen harmonics are transferred to the primary (delta) winding, of this transformer is thus spared from having caused excessive losses in the transformer.

Three-phase loads do not generate triplen harmonics. As a result, harmonic problems in industrial facilities dominated by three-phase loads will most often result from currents flowing at the 5th , 7th, 11th, 17th, 19th ,etc. In a three-phase power distribution system, the 5th and 7th harmonics are the most predominant causes of distortion and heating problems. These harmonics will easily cause standard distribution transformers to overheat of neutral conductors and may burn at the worst conditions.

One of the main responsibilities of a utility system is to supply electric power in the form of sinusoidal and currents with appropriate magnitudes and frequency for the customers at point of common coupling (PCC).Many choices are available to mitigate harmonic distortion including line reactors, harmonic traps, 12-pulse rectifiers, 18-pulse rectifiers, and low pass filters. Some of these solutions offer guaranteed results and have no adverse effect on the power system, while the per formance of others is largely dependent on system conditions. Operation analysis and technical appraisal of these solutions are studied (M. Davudi et al.,2011).

In older days passive filters using tuned LC components were in very much used for theimprovement of power quality by removing voltage and current harmonics. But due to their high cost, resonance problems, large size, and many more these filters are not in much use in the present day. All these problems are now improved by the use of active power filters (APF) and more advanced hybrid filters using several new technologies (Kidanemariam, 2021).

This implies power factor correcting capacitor bank unit able to generate resonant frequency(parallel resonant). And if observed harmonics order (say 5^{th}) frequency are close to each other 5^{th} and 7^{th} harmonics distortion will be amplified.

By adding some typical sizes of power factor correction capacitors resulted in the magnification of the 5^{th} and 7^{th} harmonic components, which in turns makes it even more difficult to meet the IEEE Std519-1992 harmonic current standards. Power factor correction capacitors should not be used without turning reactors in case the adjustable speed drives are greater than 10% of the total plant load (Sinku, 2015).

1.1 Statement of the problem

Different years test and operational data records on maintenance documents of Metahara Sugar factory showthat there is overheating of panels' bus bars, cables, transformers & motors, blown of fuses, burning of motor's stator coil, noise of transformers, failures of power cables, tripping of circuit breakers and nuisance tripping of protection relays in different parts of sugar processing plants of the factory. Following the observation of recorded operational and test data preliminary study has been done on factory power distribution network that focusing on the analysis of power quality problems using HIOKI 3196 Power Quality Analyzer. The findings of preliminary study on power quality issuesshowed that there exist power quality problems like harmonics and inter-harmonics, voltage unbalance, voltage sag, voltage swell, power frequency deviation, poor power factor, k-factor and flicker.Variable frequency drive (VFD) is contemporary technology that used to control speed of motors in wide range and known for energy saving. But, it introduces non-linear characteristics in the network which inturn produce substantial amount of harmonics.Arc welding, electronics devices and switch mode power supply, saturated magnetic core are of some devices are common sources of harmonics including VFDs which has the greater share in generating harmonics in power distribution network.

The presence of harmonics in power distribution system might causes voltage & current distortion which leads to ageing of electrical appliances, lead to mal-functioning & damages to electrical apparatus. This would results in operational down time and decrease the life time of the equipments or machineries. This resultedthe decrease product and productivity of the factory.Therefore it found important to analysis and quantify the level of harmonics in factory distribution networkin depth. After in depth analysis and quantification of harmonics level it must avoided or reduced below the recommended practices and requirements standards stated in IEEE and IEC limits.

Thus, this thesis work is aimed to in-depth analysis of harmonics and its level that can be generated by non-linear loads and design and suitable mitigation technique.

1.2 **Motivation**

In metahara sugar factory the gradual replacement of old machineries by contemporary machineries has been in increasing pattern. Due to the gradual introduction of those contemporary machineries (especially VFD) to existing system leads the introduction of different loads including nonlinear loads. During independent project work the preliminary study on power quality issues showed that there are power quality problem different type. Among the problems harmonics and inter-harmonics, voltage unbalance, voltage sag, power frequency deviation, poor power factor, k-factor, flicker in factory's distribution networks. The presence of harmonics on power system causes voltage & current distortion which leads to ageing of electrical appliances & damages to electrical apparatus. This results in factory operation down time and decrease the life time of the equipment/machineries which in turns decrease product and productivity of the factory. Thus this motivates me to plan to in-depth investigation/analysis of harmonics among the other power quality issues in this MSc thesis work.

1.3. Objective of the study

1.3.1 General objective

The main objectives of this thesis work are to carry out a detail study on Harmonics and Its Mitigation Techniques focusing on power distribution networks in the case of metahara sugar factory.

1.3.2 Specific objectives

- To Perform measurements at common point of coupling using Power Quality analyzer and determine the total harmonics distortion of current and voltage level (THD_I and THDv) as well as TDD at each PCC
- To compare the results of the measurement with IEEE Std519-1992,IEEE Std519-2014 limits ,IEC61000-2-2 and IEC61000-3-4 standards.
- To Model, design and simulation of the system with and without DSTATCOM of the existing system underconsideration using MATLAB-Simulink model

1.4 Scope of the study

Detail study of harmonics at each service transformers found in cane handling, boiler and sugar processing plants have been done using the device called HIOKI 3196 Power Quality Analyzer. Harmonics order, total current and voltage harmonics distortion at PCC of distribution transformer were identified. Appropriate harmonics mitigation technique was designed and simulated with MATLAB/SIMULINK tool. This thesis work does not include the analysis of harmonics in residential utilities and irrigation power distribution system of the factory.Implementation of desgnedharmonics mitigation technique require campany top management commitment.

1.5 Significance of the study

In the first place from actual investigating the total current harmonics distortion (THDI) and total voltage harmonics distortion (THDv) will help the factory to have information about the problem in power supply network is encountering and getting prepare to solve it by implementing proper harmonics mitigation technique.

In doing so the efficiency and performance of their equipment will be increased and failure of equipment will be minimized. This will saves money lost due to poor power quality which causes production loss, damage to sensitive electronic devices and reduction of equipment efficiency. Secondly having thorough study of this particular power quality problem being in the real place in which actual problem easily analyzed knowledge will be gained.

Thirdly, this thesis work would laid ground for further study on the area of under consideration.

Finally factory's biggest goal which is the product and productivity improvement would be enhanced by reducing system and machinery failure and related downtime.

1.6 Organization of the Thesis

This thesis work presents harmonics analysis and design harmonics mitigation technique hence DSTATCOM with Synchronuous Reference Frame (SRF) control theory for total and individual harmonic current distortionin the case of Metahara Sugar factory.Measured, computed as well as simulation values of harmonics distortion were compared with selected International and National Standards. The thesis is organized into five chapters.

Chapter one:Containsthe introductory part of thethesis,background of the study,statement of the problem,objectives of the study,scope of the study and significant of the study.

Chapter two: Presents the review different reseachpapers of different authors related to the concept of this thesis.This chapter also presents the definition of harmonics and harmonics related terms. Power quality as well as harmonics categories, sources of harmonics as well as sequences of harmonics and harmonics standards are the other concept related to this study were discussed in this chapter.

Chapter three:Describes the general background of Metahara Sugar Factory,power generation and generation control overview as well as methodology of the study.Mathematical modeling of system with mathematical computation were done on all considered distribution transformer is presented in detail.In this chapter detail study of harmonics mitigation techniques, MATLAB/SIMULINK model of base system as well as model of base system with DSTATCOM, design of DSTATCOM with SRF control theory were done in this chapter.Description of power quality monitoring equipment used for this study is also presented in this section.

Chapter four:Contains the results and discussion and the details of real-time data, computed data as well as simulation results in compirson of IEEE and IEC standards for any deviation from stated limits.

chapter five: Conclusion, recommendation and suggestion of future work from this study were discussed in chapter**.** Result verification of all collected data also checked for their validation is presented in this chapter.

CHAPTER TWO

LITERATURE REVIEW

2.1 Theoretical background

2.1.1 Waveform distortion

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. There are five primary types of waveform distortion, namely DC offset, harmonics, interharmonics,notching and noise.

Harmonic distortion is a growing concern for many customers and for the overall power system due to increasing application of power electronics equipments. Harmonic current distortion originates from the nonlinear characteristics of devices and loads on the power system. Voltage distortion is the result of harmonic distorted currents passing through the linear, series impedance of the power delivery system. It is also common to use a single quantity, the total harmonic distortion (THD), as a measure of the effective value of harmonic distortion. Many adjustable-speed drives (ASD) will exhibit high THD values for the input current when they are operating at very light loads. This is not necessarily a significant concern because the magnitude of harmonic current is low, even though its relative distortion is high. To handle this concern for characterizing harmonic currents in a consistent fashion, IEEE Std519-1992 defines another term, the total demand distortion (TDD) which is one of harmonics index. This term is the same as the total harmonic distortion except that the distortion is expressed as a percent of some rated load current rather than as a percent of the fundamental current magnitude at the instant of measurement (Tadiwos, 2018).

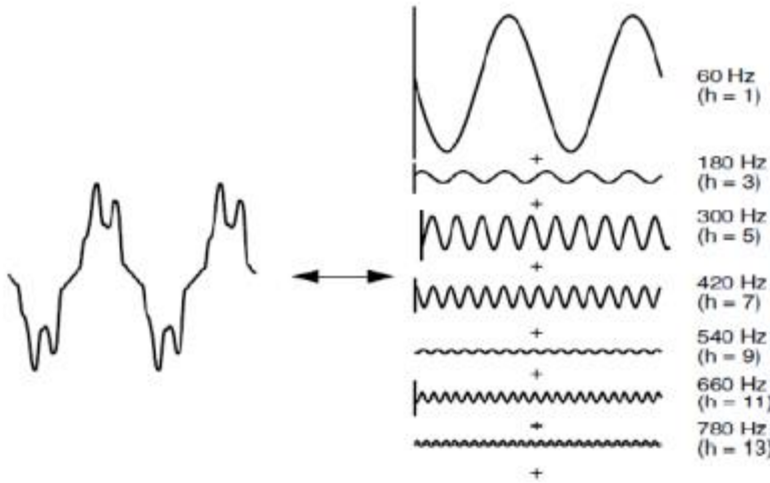


Figure 2.1: Fourer series representation of a distorted waveform taken from (Kidanemariam, 2021).

2.1.2 Definition of harmonics and related terms

Harmonics is a sinusoidal component of an AC voltage that is a multiple of the fundamental frequency (50Hz or 60Hz) of system frequency. Unwanted harmonic currents flowing through the distribution network can causes needless losses. Harmonic distortion exists due to the non-linear 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. Harmonics voltages and/or currents are multiples integral of the fundamental frequency that always greater than the fundamental frequency. Harmonics are the byproducts of modern electronics. Especially prevalent wherever the large number of personal computers, adjustable speed drives (ASD), and the other type of equipment that draw the current in short pulses.

2.1.3 Inter harmonics

Interharmonicsof voltages or currents having frequency component that have no integral multiples of fundamental frequency at which supply system designed to operate at frequency 50Hz or 60Hz. Inter harmonics can be found in all networks of all voltage classes. The main sources of inter harmonics wave form distortion are static frequency converters, cyclo-converters, induction furnaces and arcing devices (Tadiwos, 2018).Uneven distribution of flux in air gap of rotating machine generates harmonics.

2.1.4 Notching

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

2.1.5 DC offset

The presence of a dc voltage or current in an ac power system is termed as 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.

2.1.6 Noise

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. That is why study of harmonics is becoming one of current area of research (Poornima S. & K.George, 2016).The main causes of voltage and current waveform distortions are harmonics, dc offset, sub-harmonics or inter-harmonics that have the frequency domain interpretations shown in Table 2.1. In this table the term 'n' denotes harmonic order 'f_o' denotes fundamental frequency of a signal and 'f' denotes a particular frequency component of the signal. The term sub-harmonic is loosely called as inter-harmonics with frequency component less than the fundamental frequency (Kidanemariam, 2021). Basically, noise consists of any unwanted distortion of the power signal that cannot be classified as harmonic distortion or transients.

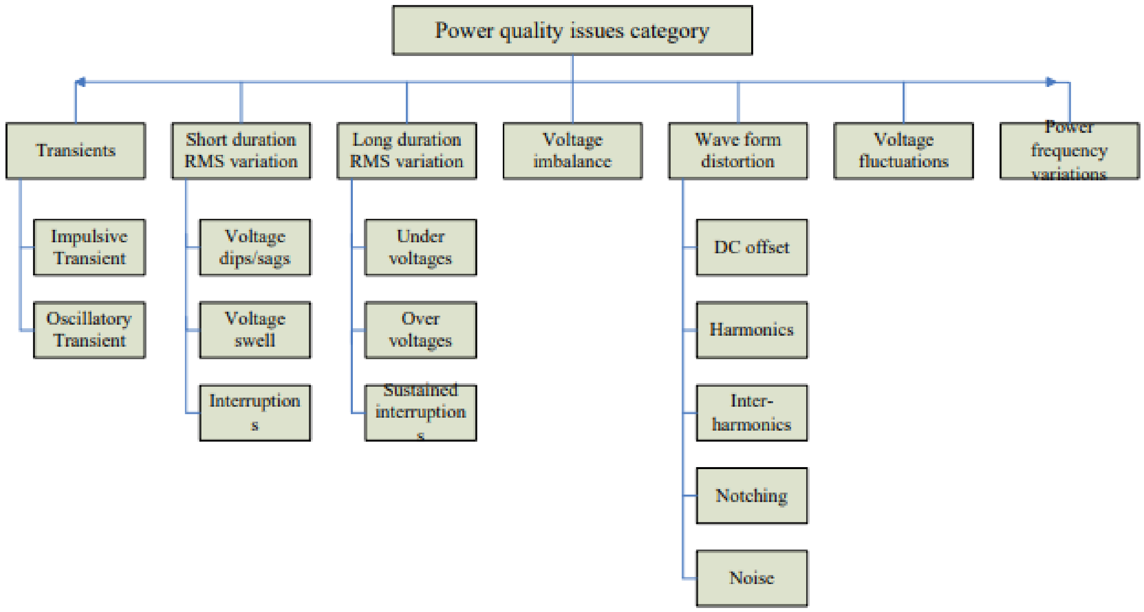


Figure 2.2: General power Quality issues categories taken from (Kidanemariam, 2021).

Table 2.1:Interpretation of different tems of waveform distortion (Poornima S.& K.George, 2016).

Terms	Frequency components
Harmonics	f=n*fo, for an integer n>0
DC offset	f=n*fo, for n=0
Interharmonics	f=n*fo, for non-integer n=0
Sub-harmonics	0<f<fo

2.1.7 Category of harmonics

Based on the order in which harmonics occurred in the power system network harmonics can be categorized as even and odd harmonics. Even harmonics (e.g., 2nd, 4th…) are not a concern to most installations as they cancel each other out and add a minor distortion amount to total line current. In contrast, odd harmonics (e.g., 3rd, 5th…) add a significant amount of wave form distortion to the non-sinusoidal and fundamental currents and are a major concern to most installations. Harmonics can also be categorized as individual and total harmonics distortion based on the percentage of distorted wave form of current and voltage in the network of submission of each phases and addition of distorted phases.

2.1.8 Sources of harmonics

Harmonics-related problems on electric utility distribution systems are usually created by primary-metered customers. The significant harmonics are almost always 5^{th}, 7^{th},11^{th} or 13^{th} with the $5^{th}$and 7^{th} harmonics orders being the problem of adjustable speed drives (ASD) in most instances. As six switches or six pulses are used the harmonics which are dangerous to the system are 5^{th} and 7^{th} order harmonics. Harmonics are produced by nonlinear loads or devices that draw nonsinusoidal currents. An example of a nonlinear load is a diode, which permits only one-half of the otherwise sinusoidal current to flow. Another example is a saturated transformer, whose magnetizing current is no sinusoidal. But, by far the most common problem-causing nonlinear loads are large rectifiers and ASDs. Non-linear load current waveshapes always vary somewhat with the applied voltage waveshape. Typically, the current distortion of a nonlinear load decreases as the applied voltage distortion increases thus somewhat of a compensating effect. As a result, most nonlinear loads have the highest current distortion when the voltage is nearly sinusoidal and the connected power system is “stiff” (i.e., low impedance) (Grady, 2012). Nonlinear loads appear to be sources of harmonic current in shunt with and injecting harmonic currents into the power system. For nearly all analysis it is sufficient to treat these harmonic producing loads. These non-linear loads are current source and voltage.These non-linear load includes power semiconductors, electronics devices, arcing equipment (arc welding and arc furnace), switchingpower supplies/especially heavy loads, switching switch mode power supplies, uninterruptable power supply (UPS), discharge lamps, electronics ballast.As these non-linear load introduced into the distribution network they inject non-linear characteristics of the whole system. Major problem related to harmonics disturbance is harmonic resonance which magnify harmonics distortion to the level that can damage the equipment or cause the equipment cause malfunction. Power factor correction capacitors in distribution system are the main cause of harmonics resonance (Tadiwos, 2018). 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 weldingand electronic and power electronics equipment (Kidanemariam, 2021).

Power Quality problems can lead to poor power quality which may occur because of increased losses, undesirable and abnormal nature of equipment, problem of interference (Prasad & Akella,2017).

2.1.9 Sequence of harmonics

What is harmonics sequence?

Harmonic sequence is the phase rotation relationship with respect to the fundamental component. Harmonics sequence can be categorized as positive sequence, negative sequence and zero sequence harmonics.

Positive sequence harmonics (4th, 7th, 10^{th},… $(6n+1)^{th}$ have the same phase rotation as the fundamental component. These harmonics circulate between the phases and causing excessive heating effect.

Negative sequence harmonics (2nd, 5th, 8th ……… $(6n-1)^{th}$ have the opposite phase rotation with respect to the fundamental component. These harmonics circulate between the phases cause motor torque problem/torque pulsation.

Zero sequence harmonics(3rd, 6th, 9th, ….. $(6n-3)^{th}$ do not produce a rotating field. These harmonics circulate between the phase and neutral or ground. These third order or zero sequence harmonics, unlike positive and negative sequence harmonic currents do not cancel each other but add up arithmetically at the neutral bus. Hence adds voltage and/or current in neutral or ground wire causing heating and failure of that conductor (Poornima S.& K.George, 2016).

2.1.10 Effects of harmonics in electrical power distribution network

The impact of harmonic currents on transformers is more serious than on conventional conductors because the resistive skin effect is enhanced within closely-spaced transformer windings. Good engineering practice calls for the derating of transformers that serve nonlinear loads to an equivalent 80% of nameplate kVA (Dagnew, 2018).

- Overload and overheating in distribution system (in transformers, cables, motors, capacitors) due to increase in rms value of current
- Overload of neutral conductor due to (3^{rd} order-triplen) harmonics current(if exist)
- Overload and torsional oscillation of motors and generators due to 5^{th} order harmonics
- Distortion of supply voltage capable of distorting sensitive loads like computer and control systems.
- Premature failure or operation of protective devices (such as fuses and relays)
- Disturbance of communication networks and telephone lines (interference)

- Inaccuracy of demand and watthour meter (measuring equipment)
- Corruption and loss of data, overheating or damage to sensitive equipment,
- Overheat of capacitor banks and fire accident in capacitor bank
- Mal operation of timing circuits-false reading of digital clock and false figure reading of controllers
- Gradual damage of motor shaft due to parasite effect
- High power losses and increased temperature of cable and faster ageing of the insulation.

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 miss operation of drives (Tadiwos, 2018).

2.1.11 Preliminary observation of case studysite and problem identification

Physical observation on the system under consideration have been carried out since 2016/17GC factory operation campaign and later on the problem was defined during mini project work (which was the basefor this case study).

The following problems areidentified that encountered in power distribution system of different plants and considered as the base for this study.

- Failure of power factor correcting capacitor, contactors and HRC fuses which connect the capacitors to the bus bar that have led to fire accidents in one of installed capacitor bank in 2021GC. (Normivak power panel)
- Transformer#1 power panel capacitor out of service due to the failure /burnt of fuse in the panel
- Overheating and burn out of conductors and terminal connectors like power and control cable in different plant of the factory
- Distribution transformers terminals problems (four transformers till middle of 2022). That means once on transformer#03, once on transformer#05, twice on transformer#09 (that means once on transformer terminals andonce fire accident raised from transformer high tension side terminals on 25/01/2022)

- Repeated burn out stator coil of electric motors which are operating at their less or at their rated capacity.
- Failure of some electrical parts and units including VFD (variable frequency drives), control printed circuit boards (PCBs) and Panels, different type of fuses.
- Failure of different input and output cards of controllers in the different plants

2.1.12 Probable symptoms of harmonics seen in factory

As per different close observation done on analysis of harmonics in power distribution network along with the literatures reviewed regarding the indicators of probable harmonics indicators the following points were investigated as an indicators of harmonics problem in the factory.

Those indicators are what have been being observing in metahara sugar factory of sugar production plants (Source:from factory repair books):

It should be noted that all these points are not necessary the symptoms harmonics problems

- Failure of expensive printed circuit boards (PCBs) of different controllers
- Failure of VFD inverters-phase loss
- Burnt of electric motors stator coil
- Corruption of different software
- Fire accidents in power factor correction equipment
- Nuisance tripping of circuit breakers and protective relay
- Frequent blown of both power and control fuses
- Burnt of neutral conductors/other cable in the network
- False figure readings of controllers
- Overheating of transformers, motor, power cables and busbars.

2.1.13 Overloaded Neutral Conductors

In a three-phase, four-wire power distribution system, the sum of the three phase currents returns through the neutral conductor. Positive and negative sequence components sum to zero at the neutral point, but zero sequence components are purely additive in the neutral and/or ground conductor. Power system engineers are accustomed to the traditional rule that “balanced three-phase systems have no neutral currents.” However, this rule is not true when zero sequence harmonics (i.e., primarily the 3rd harmonic) are present (Grady, 2012). Therefore itdoes burnt neutral conductor. Sizing of neutral conductors which able to take into account the issue of zero sequence harmonics is required.

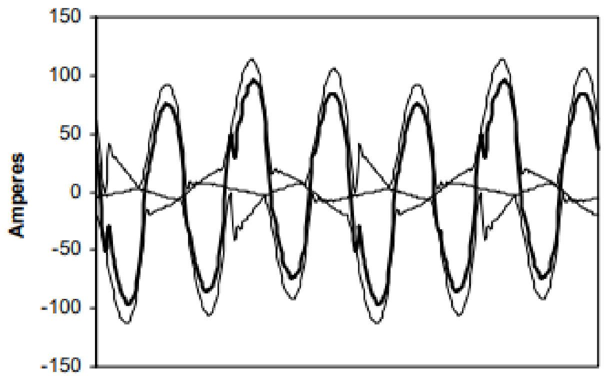


Figure 2.3: %THDI$_4$ sum of currents in A,B,C in neutral conductor (**bold curve**) (Grady, 2012).

2.1.14 Harmonics problem of variable frequency drives (VFD)

The factory has been using variable speed drive that account about 36% of factory total load to control the speed of the motor hence equipment driven by the motor through different suitable transmissions. The VFD uses a power electronics device/power semiconductorused to vary the frequency of input power to the motor, thereby controlling motor speed. In sugar production plants (from extraction to weighting of sugar) there are different VFD driven units (Table 3.5A in Appendix A). Those include, the two cane feeding table at cane handling plant A and B, three cane carries at cane handling of plant A and B, feed water pump#3 driving, mill number 3 driving at new milling plant, Secondary/auxiliary (SA) fan of boiler number four, forced drought fan (ID) of boiler number four, five bagasse feeders of boiler number four, six screw bagasse feeder of boiler number one, two and three two for each boiler, one for OC filter drum drive and five for Broadbent batch sugar processing machines at centrifugal plant.Even though VFD able to provide low motor starting current to maintain reduction of thermal and mechanical stresses on motors and connected transmission during starts that length motors life. But its counter product is that VFD could affect the power network by generating harmonics due to its non-linear in their nature that adversely affect the network if its level is beyond acceptable limits.

2.1.15 Capacitor banks, resonant frequency and harmonic magnification

A major concern arising from the use of capacitors in power system is the possibility of system resonance. Higher harmonics will flow to capacitors that are low impedence to high frequencies. The reactance of capacitor bank decreases with frequency and the bank therefore acts as a sink for higher harmonics currents. This effect increases the heating and dielectric stresses on the system underconsideration.

Frequent switching of nonlinear magnetic components such as transformers and reactors can produce harmonics currents that will add to the loading of capacitors.

Parallel resonance occur when the system inductive reactances and capacitive reactances are equal at the same frequency. If the combination of capacitor banks and the system inductance results in parallel resonance near one of the characteristics harmonics generated by the nonlinear loads that harmonics current will excite the tank circuit thereby causing causing an amplified current to oscillate between the energy storage in the inductance and energy storage in capacitance.Series resonance is a result of a series combination of capacitor banks and line or transformer inductances.Series resonance presents a low impedance path to harmonic currents and tend to trap any harmonic current to which it is tuned. That is why power factor correcting capacitor bank is complained for harmonics amplification. Distribution system frequency response characteristics are dominated by the interaction of shunt capacitance and system inductances. Besides capacitor banks, capacitance of insulated cables can influence system resonances (Hartmann et al.,1993). The connection of PFC capacitors (without reactor) results in the amplification of harmonic currents at the busbar level and an increase of the voltage distortion. Capacitors are linear reactive devices and consequently do not generate harmonics. The installation of capacitors in a power system (in which the impedances are predominantly inductive) can, however result in a total or partial resonance occurring at one of the harmonic frequencies. Because of harmonics, the current I_c circulating through the PFC capacitors is higher compared to the situation where the only fundamental current is present. Therefore it is required that h_o be minimum for f_o far from dangerous harmonics frequencies.The factory has seven series VAR compensator (SVC) without anti-resonant unit that installed to compensate reactive power connected to load terminals. Even though the aim of this thesis work is not about reactive power compensation it is important to put brief understanding about the effect of these power factor correcting steps of capacitor in generating resonant frequency hence resonance current that lead to harmonics current amplification.

Resonance occurs when the harmonic currents injected by nonlinear loads interact with system impedance to produce high harmonic voltages. In (Grady, 2012) it was stated that resonance can cause nuisance tripping of sensitive electronic loads and high harmonic currents in feeder capacitor banks. In severe cases, capacitors produce audible noise and sometimes bulge.

Parallel resonance occurs when the power system presents a parallel combination of power system inductance and power factor correction capacitors at the nonlinear load. The product of harmonic impedance and injection current produces high harmonic voltages. Series resonance occurs when the system inductance and capacitors are in series, or nearly in series, from the converter point of view. For parallel resonance, the highest voltage distortion is at the nonlinear load. However, for series resonance, the highest voltage distortion is at a remote point, perhaps miles away or on an adjacent feeder served by the same substation transformer. Usually, the feeder voltage distortion is high near the harmonics source, but when there are many shunt capacitors, remote points may also have high voltage distortion. It is desirable, but perhaps impossible to turn off all shunt capacitors when the measurements are made.Resonant currents which are created by current harmonics and different filtering topologies of the power system can cause capacitor failures and/or fuse failures in capacitor or other electrical equipment (Sinku, 2015).PFC stages have traditionally been utilized to improve the electrical power quality of EPS by emulating an input resistance for all system frequencies, so that in the case of a sinusoidal grid voltage the input current is sinusoidal with very high-frequency harmonic distortion, linked to the switching ripple. However, this resistor emulator behavior will result in line current harmonics in the case of harmonically distorted grid voltages,which would contribute to maintain THDV levels at the Point of Common Coupling (PCC) (M.Lopez-Martin et al., 2018).

Basic configuration of a tuned 3-φ capacitor bank for power factor correction and harmonic treatment that prevents of current harmonic magnification (Equ.2.1).

Harmonic voltages produce exaggerated harmonic currents in capacitors because of the inverse relationship between capacitor impedance and frequency.Capacitors with excessive harmonic currents often produce a load humming noise (Grady, 2012).

Capacitors are linear reactive devices and consequently do not generate harmonics.If the natural frequency response of the capacitor bank / power system reactance combination is close to a particular harmonic, then partial resonance will occur with amplified values of voltage and current at the harmonics frequency concerned. In this particular case the elevated current will cause overheating of the capacitor, with the degradation of the dielectric due to voltage stress, which may result in its eventual failure.The order of ho of the natural resonant frequency between the system inductance and the capacitor bank is given by:

$$h_o=\sqrt{(Ssc/Q)} \qquad (2.1)$$

Where, Ssc=the level of system short circuit power (KVA) at the point of connection of the capacitor, Q=Capacitor bank rating in kvar,h_o=the order of natural frequency f_o, (i.e. $f_o= h_o *50$ for a 50Hz system).

In order to allow the system owner or operator to control the system impedance characteristics to reduce voltage distortion when necessary, users should not add passive equipment that affects the impedance characteristic in a way such that voltage distortions are increased. In effect, such actions by a user could amount to producing excessive voltage harmonic distortion. Such passive equipment additions (that lead to undesirable system impedance characteristics) should be controlled by the user in the same manner as current harmonic-producing devices operated by the user (Halpin et al., 2014).

Figure 2.4: Burnt capacitor bank main fuses at Normivak panel in 2017 factory operation year

2.1.16 Consideration of K-factor for distribution transformer

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.

The K-factor is a number derived from a numerical calculation based on the summation of harmonic currents generated by the nonlinear loads. The higher the K-factor, the more significant the harmonic current content. The following is the algorithm used to compute the K-factor according to ANSI/IEEE C57.110 and IEEE Standard 1100-199. K-factor for each phases and neutral conductor can de designated as kf1, kf2, kf3 and kf4 respectively.

$$KF = \frac{\sum_{k=2}^{50}(k^2 * I_k{}^2)}{\sum_{k=2}^{50} I_k{}^2} \qquad \text{……………………………(2.2)}$$

Where ‘k’ is order of harmonics and

‘I_k’ is ratio of harmonics currents to the fundamental waveform in (%).

The higher the k-factor value the higher heating effect of harmonics current on transformer (Poornima S. & K.George, 2016).

2.1.17 Experiencing effect of harmonics in cable, motor and transformer

Harmonics currents in motor can give rise to high audible noise emission as compared with sinusoidal excitation. Harmonics also produce the resultant flux distribution in air gap which can cause and enhance a phenomenon called cogging (refusal to start smoothly) or crawining very high slip in induction motor.The harmonics components thus affect machine efficiency and can also affect the torque developed. Harmonic pairs such as the fifth and seventh harmonics have the potential for creating mechanical oscillation in turbine-generator combination of motor-load system. The mechanical oscillation result when oscillating torques caused, by interaction between harmonics currents and fundamental frequency magnetic field, excite a mechanical resonant frequency. For instance the fifth and seventh can combine to produce a torsional stumulas on generator rotor at the sixth harmonics frequency. If the frequency of mechanical resonance exists close to the frequency of electrical stumulas high-stress mechanical forces can be developed.The effect of harmonics in transformer is twofold:current harmonics cause an increase in copper losses and stray flux losses and voltage harmonics cause in iron losses. The overall effect is an increase in transformer heating as compared to purely sinusoidal (fundamental) frequency operation. The transformer losses caused by both harmonics voltage and harmonics currents are frequency dependent. The losses increases with inceasing frequency and therefore higher frequency components can be more important than lower frequency components in causing transformer heating. In general the higher frequency harmonics occur with diminished amplitude which tends to cancel their greater effect. Cables that is subjective to ordinary harmonics current are prone to heating. When current waveform that rich in high frequency harmonics is flowing in cable the equivalent AC resistance for cable raisedeven higher amplifying heating loss (Kidanemariam, 2021).

2.1.18 Effects of harmonics distortion on electronics and measuring equipments

Power electronics equipments is susceptable to misoperation caused by harmonics distortion.

These equipment is often dependent upon accurate determination of voltage zero crossing or other aspects of the voltage wave shape. Harmonics distortion can result in a shifting of voltage zero crossing or the point at which one phase-to-phase voltage become greater than another phase-to-phase voltage. This are critical points for many types of electronics circuit controls and misoperation can be resulted from these shifts. Phase imbalance caused by harmonics distortion can cause erroneous operation of energy meters and instrumentation devices. There has recently been a great emphasis on revitalizing industry with more automation and more modern equipment. This usually means electronically controlled, energy-efficient equipment that is often much more sensitive to deviations in the supply voltage than were its electromechanical predecessors (Tadiwos, 2018).

2.1.19 Effects of harmonics in protection and switching equipments

Harmonics current can increase losses in switchgear,thereby reducing steady state current carrying capability and shortening the life some insulating componets. Fuses suffer dearating because of the heat generated by harmonics during normal operation. There are currently no standards for the level of harmonics current that switching devices or fuses are required to interrupt or carry. All tests are performed at rated supply frequency. In addition to this relay respond differently to different wave shape that arises from different harmonics distortion of currents it faces. Harmonics effects imposed on all types of equipments cannot be perfectly correlated to a few or simple indices. Moreever the harmonic characteristics of the utility circuit seen from the PCC often are not known accurately. Accordingly a good engineering judgements are required on a case-by-case basis and this recommendation in no way overrides such judgements (Hartmann et al.,1993)

2.1.20 Harmonics Indeces

The two most commonly used indices for measuring harmonics content of a waveform are total harmonics distortion (THD) and total demand distortion (TDD).The THD is a measure of the effective value of the harmonics component of a distorted waveform related to the fundamental. This index can be calculated either for voltage or current. Current distortion levels can be characterized more effectively by TDD factor which is calculated relative to maximum demand load current rather than fundamental of present sample (Tadiwos, 2018).

The percentage of Total harmonic Distortion of voltage, total harmonics distortion of current and Total Demand Distortion can be calculated using equiation (2.4) through equ.(2.7).

$$THD_V = \frac{\sqrt{\sum_{V_2}^{\infty} V_h^2}}{V_1} \times 100\% \quad \text{……………………………(2.3)}$$

$$THD_I = \frac{\sqrt{\sum_{I_2}^{\infty} I_h^2}}{I_1} \times 100\% \quad \text{…………………………………(2.4)}$$

$$TDD = \frac{\sqrt{\sum_{I_2}^{\infty} I_h^2}}{I_L} \times 100\% \quad \text{…………………………………(2.5)}$$

$$TDD = \frac{\sqrt{ha^2+hb^2+hc^2}}{Peak\ Demand\ current}$$ ………………………..(2.6)

Equation (2.5) shows Total Demand Distortion of current perphase whereas equ.(2.5) used to calculate TDD of three phase current. And multiplying equation (2.6) by 100 percentage of TDD can be achieved.

Where, V1 and I1 are fundamental voltage and current at system frequency, Vh and Ih are harmonic voltage and current , ha ,hb, hc are phase A,B and C harmonic current factor respectively. IL is the maximum demand load current at fundamental system frequency.

High order harmonics are usually negligible when considering THD, but they cause an added reactive power absorbing ,whichmeans they should be considered in power factor correction (Jdeed, 2018). The importance of power quality issues that poor power quality leads to unnessary westage of power and economy which creates financial burden on suppliers and customers (E.Hossain et al., 2018).

2.1.21 Economic effect of harmonics and Mitigating Measures

From a customer's perspective, the most common economic justification of harmonics mitigation is in minimizing down-time due to nuisance tripping of senstive loads.From a loss perspective, harmonics can be considered as a reduction in power factor hence machinery inefficiency as produced power is not effectively utilized.

$$pf_{true} \approx \frac{dpf_1}{\sqrt{1+THD_I^2}}.$$ ……………………………………….(2.7)

Thus, the true power factor of nonlinear loads is limited by THDI . Consider a nonlinear load with perfect displacement power factor (dpf1). This implies as current harmonics distortion increases power factor will degrade as well. The power factor comparison presents a rather optimistic picture, because harmonic currents actually cause more losses per ampere than do fundamental currents. Voltage harmonics have been shown to cause additional losses in motors, transformers and distribution system as well.Voltage harmonics induce harmonic currents that increase motor losses and insulation temperature. In system failure perispective, sudden failure of electronics and electrical equipments there will be tremidiuos economics loss as it force one to change spare in place of failed electrical/electronics devices which will add production cost to the company.

Therefore mitigation of harmonics current and voltage that beyond the recommended standard in economically and technically feasible way is recommended for the seek of system safe and smooth performance hence retain company product and productivity. Power factor is one of the most economic consideration of harmonic effect as poor power factor due to harmonics distortion lead to power factor penality and under performance of the system(Grady, 2012).

2.1.22 Power quality standards

The purpose of power quality standards is to protect utility and end-user equipment from failing or mal operation when the voltage, current or frequency deviates from normal values (Poornima & Jois, 2016). These standards protect by setting measurable limits as to how far the voltage, current or frequency can deviate from normal values. Moreover, power quality standards help utilities and customers to gain agreement on what are acceptable and unacceptable levels of service. The increasing concern on power quality issues resulted in a lot of power quality monitoring and case studies being done by different utilities and consumers around different parts of the world. This increasing need for power quality monitoring has driven the requirement for standards that describe measuring methods and how the different power quality parameters are calculated and interpreted. As a result, a lot of international standards related to power quality have been formulated by different standard organizations and put into work. There are known national and/or internationally accepted guidelines on power quality problem limits as standards must be obeyed by government, different organizations and person in using and delivering power to the consumers in their power network.

Such organization includes the Institute of Electrical and Electronics Engineers (IEEE), European Union Standards organization (CENELEC), International Electro-technical Commission (IEC), American National Standard Institute (ANSI), National Electrical Manufactures Association (NEMA) and so on as written in (IEEE Std 519-1992). In this study, mostly the IEC and IEEE standards requirements and recommendations and definitions were used for this thesis work for the matter that their widely used in academic and research areas and they are high level of completeness to characterize all the major electrical phenomena comprising power quality.

2.1.22.1 IEC Standards For Power Quality

International Electro-technical Commission (IEC) was founded in 1906. The IEC is the world's leading organization for the preparation and publication of international standards for all electrical, electronic, and related technologies (Kidanemariam, 2021). The IEC family, with 84 member countries and 87 affiliate member countries (developing countries), spread across more than 97% of the world's population. IEC standards have been adopted by the European Committee for Electro technical Standardization (CENELEC) and many other countries all over the world. The IEC has defined a category of standards called Electromagnetic Compatibility (EMC) Standards that deal with power quality issues. These standards are broken down into six parts: General (IEC 61000-1-x), Environment (IEC 61000-2-x), Limits (IEC 61000-3-x), Testing and Measurement Techniques (IEC 61000-4-x), Installation and Mitigation Guidelines (IEC 61000-5- x), Generic and Product Standards (IEC 61000-6-x). IEC standards for each power quality parameter are not given on a single publication rather they are separated into several publications which fall into different parts of the standard and also for different levels of current and voltage. For example, the IEC standard relating to harmonics limits generally fall in parts 2 and 3 which includes:

- IEC 61000-3-4 (1998): Limitation of Emission of Harmonic Currents in Low-Voltage Power Supply Systems for Equipment with Rated Current Greater Than 16A
- IEC 61000-2-2 (1993): Compatibility Levels for Low-Frequency Conducted Disturbances and Signaling in Public Low-Voltage Power Supply Systems.

The IEC standards related to harmonic distortios are discissed below. Network According to IEC 61000-2-2 (Habte, 2018).

Table 2.4: Compatibility Levels for Individual Harmonic Voltages in the Low-Voltage Public (Hartmann et al.,1993)

Not multiple of 3		Multiple of 3			
Odd order h	Harmonic voltage (%)	Odd order h	Harmonic voltage (%)	Even order h	Harmonic voltage (%)
5	6	3	5	2	2
7	5	9	1.5	4	1
11	3.5	15	0.3	6	0.5
13	3	21	0.2	8	0.5
17	2	>21	0.2	10	0.2
19	1.5			12	0.2
23	1.5			>12	0.2
25	1.5				
>25	$0.2 + 1.3 \times 25/h$				

*The THD of the supply voltage including all harmonics up to the 40th order shall be less than 8 %.

Table 2.3: Individual harmonics current limits according to IEC 61000-3-4 (Habte, 2018).

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

These IEC 61000 EMC standards, presented in tables 2.1 and 2.2 are used to check the compatibility levels of the voltage and current distortion in all power panel or PCC of each transformer in the Metahara sugar factory.

2.1.22.2 IEEE Standards For Power Quality

The IEEE is a professional association formed in 1963 from the amalgamation of the American Institute of Electrical Engineers and the Institute of Radio Engineers. The institute is the world's largest association of technical professionals with more than 420,000 members in over 160 countries around the world (Hartmann et al.,1993).The IEEE Standards Association (IEEE-SA) is an organization 21 within IEEE that develops global standards in a broad range of industries.

The most often quoted harmonics standard in the U.S. is IEEE 519, "Recommended Practices and Requirements for Harmonic Control in Electric Power Systems." IEEE 519 attempts to establish reasonable harmonic goals for electrical systems that contain nonlinear loads. The objective is to propose steady-state harmonic limits that are considered reasonable by both electric utilities and their customers. The underlying philosophy is that

- customers should limit harmonic currents,
- electric utilities should limit harmonic voltages,
- both parties share the responsibility for holding harmonic levels in check.

IEEE 519 applies to all voltage levels, including 120V single-phase residential service. While it does not specifically state the highest-order harmonic to limit, the generally accepted range of application is through the 50^{th} harmonic order. Direct current, which is not a harmonic, is also addressed and is prohibited. Since no differentiation is made between single-phase and three phase systems, the recommended limits apply to both. It is important to remember that IEEE 519 is a recommended practice and not an actual standard or legal document. Rather, it is intended to provide a reasonable framework within which engineers can address and control harmonic problems. It has been adopted by many electric utilities and by several state public utility commissions (Grady, 2012).

Some of the standards developed by IEEE which are related to power quality phenomena are:

- IEEE Standard 1159-2009: Recommended Practice for Monitoring Electric Power Quality.
- IEEE Standard 1159.3-2003: Recommended Practice for the transfer of power quality data.
- IEEE Standard 519-1992: Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems.

- IEEE Standard 519-2014: Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems (Revised version of IEEE Std 519-1992)

Table 2.2:Current distortion limits for general distribution systems 120V through 69KV (Hartmann et al.,1993)

Maximum harmonics current distortion in percent of IL						
Individual harmonic order (odd harmonics)[a,b]						
Isc/IL	3≤h<11	11≤h<17	17≤h<23	23≤h<35	35≤h<50	TDD
<20[c]	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

Note: Even harmonics are limited to 25% of the odd harmonic limits above. Current distortions that result in a direct current offset; for example, half wave converters are not allowed.

In Table 2.1 *"I"* is for 6-pulse rectifiers. For converters higher than 6 pulse, the limits for characteristic harmonics are increased by a factor of $\sqrt{q/6}$, where q is the pulse number, provided that the amplitudes of non-characteristic harmonics are less than 25 percent.

*All power generation equipment is limited to these values of current distortion, regardless of actual (I_{SC}/I_L) ratio. Where, I_{SC} =Maximum short circuit at PCC and I_L=Average Maximum demand load current (fundamental frequency component at PCC).

Table 2.3: Voltage harmonics distortion limits (Halpin et al., 2014).

Bus voltage v at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
V≤1.0kV	5.0	8.0
1kV<V≤69kV	3.0	5.0
69kV<V≤161kV	1.5	2.5
161kV<V	1.0	1.5[a]

High-voltage systems can be have up to 2.0% THD where the cause in an HVDC terminal whose effects will have attenuated at points in the network where future users may be connected. Among those standards IEEE and IEC are the most commonly and frequently used standards for power quality limits. To specify it more IEEE 519-1992, IEEE 519-2014 and IEC 61000-2-2/-3-4 are common standards that explain and set limits about power quality limits and recommendations/specifically harmonics distortion limits. The IEEE standard 519-1992 limits the level of harmonics at the customer service entrance or Point of Common Coupling (PCC). And these thesis work which aimed at harmonics was made as reference for limits of any deviations.

2.1.22.3 Ethiopian Standard Agency (ESA)

ESA is a governmental non-profitable organization and the sole national standards body which represents Ethiopian interest in economic, social, and environmental aspects concerning standard benefits across the international and regional arena. ESA has three core business areas which mainly focus on the standard formulation, training, and technical support and organizing and disseminating standards, conformity assessment procedures and technical regulation for the customers.

Ethiopia has no national standard for limiting the level of harmonic distortion on electrical system. Moreover, the National Electro-technical Committee of Ethiopia (NECE) under the Ethiopia Standards Agency (ESA), which is responsible to approve and adopt international IEC standards to national standard, did not adopt the IEC 61000: EMC standards related to power quality phenomena for national use.National Electro-technical Committee of Ethiopia (NECE) was established in November 2012 under ESA with an expert group from five different organizations: ESA, Addis Ababa University, Ethiopian Electric Utility, Ministry of Energy, and Ethiopian Conformity Assessment Enterprise. NECE, together with the Technical Committees on different fields, is the responsible body within the ESA, for the approval and adoption of IEC standards for national use. Ethiopia, as one of the affiliates plus member countries of IEC, has adopted 251 IEC standards through NECE, out of the free 400 standards allowed for national adoption by such member countries. Unfortunately, NECE has not adopted the IEC 61000: EMC standards related to power quality phenomena as a national standard still now (when this research work is prepared).

Ethiopian Energy Authority (EEA) is another organization possibly concerned with standards associated with electrical power quality. As per the information gathered from the authority staff, the EEA is in the process of preparing a national “Grid Code” which may contain some electrical power quality standards

Generally, IEEE 519-1992, IEEE Std519-2014 and IEC 61000-2-2/-3-4 are common standards that explain and set limits about power quality limits and recommendations/specifically harmonics distortion limits. The IEEE standard 519-1992 limits the level of harmonics at the customer service entrance or Point of Common Coupling (PCC). And these thesis work which aimed at harmonics was made as reference for limits of any deviations.

2.2 Reviewed Research papers

Nowadays there are a lot of power quality problems happening in the utilities as well at the end users of the electric powers due to the power electronic devices i.e. nonlinear loads, load switching, system faults, motor starting, load variations, intermittent loads and arc furnaces and arch welding as well as electronics and magnetic ballasts. Due to the increment of the power quality problems, there are researches have been done on the issue of electric power quality problems in distribution systems in different parts of the world (Kidanemariam, 2021).

Different studies or research papers have been done on harmonics analysis and mitigation techniques by different scholars at different time. There are many relevant papers on scope of this study. Among the relevant studies the following paper workswhich are relevant to this thesis work was revieved.

Henock Habte(2018), study was done on “Power Quality Assessment and Mitigation in distribution System (A case study at Adama Spinning Factory)’. This thesis work was focused on harmonics current and harmonics voltage analysis but only up to 11^{th} order due the limitation of used harmonics measuring device called DELAB NV8s PFC which only measure harmonics up to 11^{th} order. The researcher mainly pinpoint out the effects of adjustable Speed Drive (ASD) on current and voltage harmonics distortion as most loads connected to each feeder in the factory are this type load. MATLAB/SIMULINK model was used for simulating the system with and without proposed current harmonics mitigation technique. IEEE 519-2014 and IEC 61000-2-2/3-4 guidelines was utilized by the researcher. In this study the researcher identified that there is current harmonics distortion on three transformers among existing four transformers in the factory and the level of investigated current harmonics found exceed the stated limits. As a result proposed compensator called DSTATCOM of current control mode and control theories of IRP and SRF which is used to extract reference current from the compensator that used for both harmonics current mitigation and power factor improvement. The limitation of measuring harmonics only up to 11^{th} orderwas identified and this gap was filled by measuring and monitoring harmonicsusing the instrument HIOKI 3196 Power Quality Anayzer during this thesis work.

Netsanet Tadiwos (2018),study was done on “Study and simulation of power quality improvement in distribution network in the case of Metahara sugar factory.” The instrument called ‘HIOKI 3196 Power Quality Analyzer” was used in recording and analyzing real time data in the plants under operation.The study have been covered by taking measurement at ten transformers at the point of common Coupling (PCC).The study was focused on harmonics generating non-linear loads in the factory. According to this thesis workthe analysis on transformer#07 shows the average individual phase voltage harmonics is 0.79%, 0.83%, 0.93% and 51.61% for V1, V2, V3 and V4 respectively. In the same way average total and individual phase current harmonics is 26.20%, 22.58%, 42.95% and 17.08% for I1, I2, I3 and I4 respectively. According to IEC Standards for current and voltage harmonic limits the maximum permissible total harmonic current distortion (THDI) is found 16%.The study was also explain the components of D-STATCOM was deeply explained for realization of the device performance.Comparison of SVC and D-STATCOM was also done in different perspective before selecting D-STATCOM for identified power quality problems.The DigSilent application software was used in simulating D-STATCOM for its effectiveness of proposed mitigation of identified power quality problems specifically harmonics distortion and poor power factor of the network. The investigator fails to explain the effect of harmonics for additional installation of VFD driven loads in the factory and further study on power quality issues. In this thesis work eventhogh it was stated that the measurement was done at ten transformers' PCC of the factory, it fail to present the results for each transformer. This gap was filled by taking the measurement for individual and total current distortion by using the same instrument.

Jhuma and Ashutosh (2018) the study was done on "Reduction of harmonics by active and passive harmonics filters" and published on internationally known campanycalled Journal on Research on Applied Science and Engineering Technology(IJRASET). The study has been focused on investigation, analysis and mitigation of harmonics generated by electronics power converters. Fast Fourier Transformation (FFT) is the method and MATLAB/SIMULINK model were used in the analysis of harmonics (individual and total) of current and voltage and simulation of designed harmonics filter for 3kw load taken into consideration. Passive filter was designed and recommended to decrease distortion by shifting the resonance point in the power network taken into consideration.Transformer overloading and magnetization of non-linear loads on it was stated as source of harmonics in power distribution network.

The effect of harmonics in the electrical power system includes the loss of data, overheating device or damage to sensitive equipment and more heating of capacitor banks.The Maximum frequency harmonics may also cause interference to nearby which telecommunication system. Harmonic current is isolated by using harmonic filters in order to protect the electrical equipment from getting damaged due to harmonic voltage distortion.

AC line reactor filter and DC-link inductor filter are the two purely inductive type filters. AC line reactors offer a considerable magnitude of inductance that alters the shape or form factor the current waveform drawn by the rectifier bridge.

The study was limited to the designed passive harmonics filter for two pulse diode rectifier only and did not considered 6-pulse and higher pulse harmonics generating devices. The drawback of passive filters as well as the comparison between active and passive filters did not explained.

Fisseha Kidanemariam (2021),the study was done on power quality improvement by using Unified Power Quality Conditioner (UPQC) at National Tobacco Enterprise of Ethiopia. The measurement was done at each distribution transformer common coupling and modeled by using MATLAB/SIMULINK application software tool. The study was focused on voltage source Converter (VSC) with the capacitor DC-link at each PCC of two distribution transformers of the factory.The instrument called FLUKE3.33/3.34 Energy and Power Quality Analyzer was used for data collecting purpose. The study has been identified different power quality problems like voltage sag and voltage swell, current and voltage harmonics distortion, flicker, voltage and current unbalance.

Following the identification of power quality problems the level of those power quality parameters were compared with IEEE Std 519-2014 limits. As per the writerthere is THDI distortion that is above stated limit for distribution transformer#2 (630KVA) while THDv is within stated limits for loads on both transformers of the factory.Total Harmonics current distortion seen on distribution transformer#1(1250KVA) found within the considered standard limits.

Eventhough the percentages of harmonics current and voltage seen from the simulation results the researcher lacks to explain the effect of harmonic currents found flowing through neutral conductor.

CHAPTER THREE

MATERIALS AND METHODOLOGY

3.1 Background of case study

Ethiopian Sugar Corporation (ESC) has been making heavy investments in the country's sugar sector. The corporation was established by councils of minister under proclamation No.192/2003E.C was aimed in the construction of ten new sugar factories. Among sugar factories found under Ethiopian Sugar Corporation, metahara sugar factory (MSF) is the one. The factory is found in Oromia regional state East shoaFantale district near Metahara city at Merti village which is 208 kilo meter from the capital city Addis Ababa. The precise loacation of Metahara Sugar Factory is at $8^0$50'00.5"N and $39^0$55'19.2"E and 966m asl. The partial cut view of the estate is seen on Figure 3.1 below as taken from Google Earth.

The factory is the second oldest sugar factory before the renewal of Wonji and shoa sugar factories as Wonji-shoa sugar factory. There are 9 camps surrounding the factory estate. Merti is the head quarter of the factory in which sugar production plants (boiler and power plant, cane handling, milling, clarification, evaporation, vacuum, centrifugal) and ethanol plant found at. The factory has designed production capacity of 5000 TCD (tons of cane crushed per day).

Figure 3.1:Actual bird view of case study area (Metahara Sugar Factory)-Source:Google Earth.

3.1.1 Electric Power sources of the factory

The factory is currently using three power sources namely its own source electric power of steam power plant having two generating units having 3.18MW installed capacity, diesel generators and 15kv line of Ethiopian Electric Utility (EEU) of 1MW installed capacity. The two generating units supply sugar production plants' machineries loads (extraction and process houses),one 625KVA diesel generator that used to supplies emergency lighting of the factory and feed water pump#1 drive motor (to save boilers by cooling them down) when sudden total blackout might happened and EEU line is absent as well through common bus bar and step up/dowmtransformer from 0.4kv to 3kv and connected to 3kv bus bar via bus coupler.

Head quarter, Ethanol and biocompostplant ,residential houses of all camps, deep well pump drive motors and irrigation pumps are supplied from 15Kv feeder of EEU line which is medium voltage feeder line after stepping it down to 380V. The total power demand excluding irrigation, Ethanol and biocompostplant ,factory resident camps and head quarter residential loads of the factory is 5.8MW. But the power demand is increasing as steam driven mill turbines are being changed to motor driven mill and unplanned additional load is being installed.Currently there are twelve low voltge feeders in sugar production plants and the distribution feeder have the size 1000kVA each except the 12^{th} distribution transformer which is two parallel connected 400kVA (Figure 3.2).

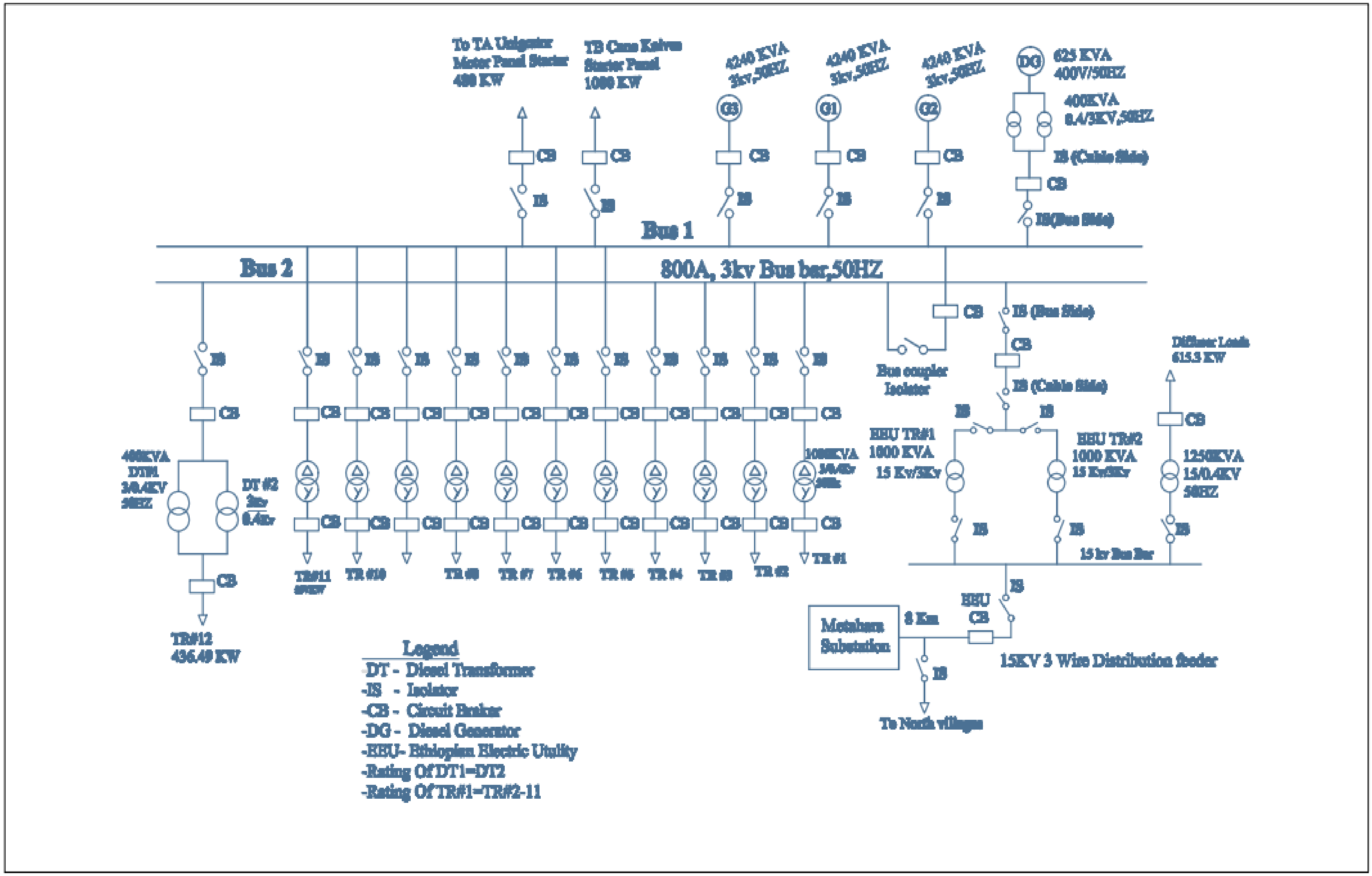


Figure 3.2: Modified Single line line diagram of Metahara Sugar Factory power generation and distribution network (2022GC)

Figure 3.3:Metahara Sugar Factory side view of Alternator-gearbox-turbine assembly(unit #1)

Figure 3.4:Metahara Sugar Factory partial view of power generation control room

Figure 3.5:Metahara Sugar Factory partial view of power house

3.1.2 Description of factory Source and load category and Primary data collection

The factoryhas 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.The industrial facilities are characterized by the widespread application of nonlinear loads.

The nonlinear loads such as AC to DC rectifiers produce distorted waveforms (Prof. C.Veeresh & Amin, 2021). Harmonics are present in waveforms that are not perfect sine waves due to distortion from 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 satureable devices. Harmonics are generated due to industrials loads such as DC drive, AC drive, satureable device and arcing device such as arc welders and discharge type lighting with magnetic ballasts (Poornima S. & K.George, 2016). It is known that electrical motors have playing a vital role in the industry hence in the factory. In Metahara Sugar Factory about 95% of the load is inductive type which consist of squirrel cage and wound rotor induction motors. Resistive and capacitive loads also exist in the factory. Specific existing factory loads by category. Electrical motors both (squirrel cage and wound rotor type), Arc welding (generator and transformer) type welding machines, fluorescent lamps (having electronics and magnet bllast), LED lighting units, High pressure sodium lamps, Mercury lamps,different controllers, heating resistors,AC drives/VFDs or/and voltage source converters and office equipments. Of these load categories the AC induction motors and variable frequency drive (VFD) are the most dominant loads in this factory. There are total number of 26VFDs in number (frequency converters) units with power ratings ranging from 2.2Kw to 400Kw are connected to the distribution network which account total of 3290.7kw which is about 36% of total load of the factory to be drived and installing new VFDs increasing is increasing from the time to time. As a modern production facility, the factory uses technologically advanced and energy efficient machineries and drives, which are sensitive to deviation in the supplied power quality and have a tendency to distort source voltage and current of pure sine wave. The distribution of these VFDs on each distribution transformer is presented in Table 3.3A more harmonic distortion levels are likely to present on transformers#T2,T6,T7,T8 and T11 for the fact that higher total number and installed capacity of VFDs are connected to these transformers. Almost all transformers have installed capacitor banks for power factor improvement at their respective power panel or MDB (main distribution board) of the feeders

(Table 3.1A).Those transformers include transformer number 01,02,03, 05, 06, 07 and 08 power panels). Each capacitor bank panels are equipped with EPCOS type automatic Power Factor Controller (PFC) units, which monitors the instantaneous power factor (cos φ) and correct when it falls below the targeted 0.90 by connecting different size capacitors to the network step by step. However, almost 50% of these installed capacitor bank units are not factional due different problems on the installed units. The capacitor steps are pre-designed based on the targeted average power factor of the factory. As stated on the PFC manufacturer product profile there will be self-resonant frequency of the resonant circuit, formed by the power factor correction capacitors in conjunction with the feeding transformer, is typically between 250 and 350Hz, i.e. in the region of the 5^{th} and 7^{th} harmonics for 50Hz frequency system respectively.

The focus area of this study is to analysis and investigate harmonics of non-linear loads mainly on feeders supplying VFD driven loads at respective PCC (transformer#2,4, 6, 7,8,10 and 11) and to roughly study resonance effects that might raised from capacitor banks in the factory which expected to intensify the harmonics current hence voltage distortion in the distribution network.Factory load data (VFD driven and non VFD driven loads) have been collected and tabulated Table 3.1A and VFD driven load table 3.4A collected from realible source respectively.

3.1.3 Mathematical calculation of Isc/IL ratio for each distribution feeder

Transformers are specified by their output voltage, kVA rating, percent impedance (%Z), and X/R ratio. The transformers are modeled by their series resistances and leakage reactance. The magnetizing current, Shunt admittances and core losses are neglected, as is the case in most power system analysis.

There are 12 (twelve) delta-wye step-down distribution transformer of rating ten of them 1000KVA each and two of them 400KVA each in the factory. As X/R ratio is not always found on transformer nameplate it is important to get it from IEEE Std 141-1993 (page 184). From the graph in this standard for 1000KVA and 400KVA X/R ratio value is approximately found as 6 and 5 respectively. From respective transformer nameplate the %Z for 1000KVA transformers is 3.89 while 4.26 for 400KVA transformers. The purpose of this mathematical modelling is to calculate and come up with the ratio of Isc to IL that used to determine the range in which harmonics distortion level found by comparing with IEC and IEEE standards.

Where, Isc is maximum short circuit current at PCC where as IL is the maximum demand load current (fundamental frequency component) at the PCC under normal load operation condition.The ratio of (Isc/IL) is determined as follows.

Distribution Transformer number 01

Rating=1000KVA, 50Hz 3kv/0.4kv %Z=3.89

Ipri=182.78A   Isec=1443A (perphase)   Vector group: Dyn5

The impedance of the transformer, Ztr can be calculated from the percentage impedance by using equation.

Ztr=%Z× (KV) ^{2}×10/(KVA)   (3.1)

Ztr= (3.89) × (0.4) ^{2}×10/ (1000) =6.224E-3 ohm

By using the relation X/R=6 implies Xtr=Rtr×6 and $Z^2=R^2+X^2$,Xtr=0.0129ohm and Rtr=0.0778ohm.

The percentage of transformer reactance is calculated using eqn.

%Xtr=KVA×Xtr/10(kv)^2 (3.2)

Hence, %Xtr=KVA×Xtr/10(kv)^2=1000×0.0129/10×(0.4)^2=8.0625

Isc=IFL×100/%Xsc=IFL×100/%Xtr or   Isc/IL=MVA $_{Sc}$/MVA $_{D}$

Isc=IFL×100/%Xsc=IFL×100/%Xtr=721.1×100/(8.0625)=8943.88A

The short circuit ratio (Isc/IL) is determined as

Isc/IL=8943.88A/721.1A=12.41   (3.3)

DistributioTransformer number 02

Rating=1000KVA, 50Hz 3kv/0.4kv %Z=3.90

Ipri=182.78A   Isec=1443A (per phase)   Vector group: Dyn5

The impedance of the transformer, Ztr can be calculated from the percentage impedance by using equation (1).

Ztr=%Z×(KV)^2×10/ (KVA) (3.4)

Ztr= (3.90) × (0.4)^2×10/ (1000) =6.24E-3 ohm

By using the relation X/R=6 implies Xtr=Rtr*6 and $Z^2=R^2+X^2$,Xtr=0.0129ohm and Rtr=0.0778ohm.

%Xtr=KVA×Xtr/10(kv)^2 (3.5)

Hence, %Xtr=KVA×Xtr/10(kv)^2=1000×0.0129/10×(0.4)^2=77.4

Isc=IFL×100/%Xsc=IFL×100/%Xtr (3.6)

Isc=IFL×100/%Xsc=IFL×100/%Xtr=1200.29×100/(77.4)=1550.76A

The short circuit ratio (Isc/IL) is determined as

Isc/IL=1550.76A/1200.29A=1.3 (3.7)

Distribution Transformer number 03

Rating=1000KVA, 50Hz 3/0.4kv %Z=5.37

Ipri=182.78A Isec=1443A Vector group: Dyn5

The impedance of the transformer, Ztr can be calculated from the percentage impedance by using equation below.

Ztr=%Z×(KV)^2×10/(KVA) (3.8)

Ztr= (5.37) × (0.4)^2×10/ (1000) =8.592E-6 ohm

By using the relation X/R=6 implies Xtr=Rtr×6 and $Z^2=R^2+X^2$,Xtr=1.4125E-3ohm and Rtr=8.475E-3ohm. Hence

%Xtr=KVA×Xtr/10(kv)^2 (3.9)

$\%Xtr=KVA \times Xtr/10(kv)^2=1000 \times 8.475E\text{-}3/10 \times (0.4)^2=5.2968ohm$

$Isc=IFL \times 100/\%Xsc$ (3.10)

$Isc=IFL \times 100/\%Xsc=IFL \times 100/\%Xtr=1248 \times 100/(5.2968)=23561.4A$

The short circuit ratio (Isc/IL) is determined as

$Isc/IL=23561.4A/1248A=18.88$ (3.11)

Distribution Transformer number 04

Rating=1000KVA, 50Hz 3/0.4kv %Z=5.37

Ipri=182.78A Isec=1443A Vector group: Dyn5

The impedance of the transformer, Ztr can be calculated from the percentage impedance by using equation below.

$Ztr=\%Z \times (KV)^2 \times 10/(KVA)$ (3.12)

$Ztr=(3.94) \times (0.4)^2 \times 10 \times (1000)=6.304E\text{-}3$ ohm.

By using the relation X/R=6 implies $Xtr=Rtr \times 6$ and $Z^2=R^2+X^2$,Xtr=6.218E-3ohm and Rtr=1.0364E-3ohm.

$\%Xtr=KVA \times Xtr/10(kv)^2$ (3.13)

Hence, $\%Xtr=KVA \times Xtr/10(kv)^2=1000 \times 6.218E\text{-}3/10 \times (0.4)^2=3.8863ohm$

$Isc=IFL \times 100/\%Xsc=IFL \times 100/\%Xtr$ (3.14)

Hence, $Isc=1438.21 \times 100/(3.8863)=37007.18A$

The short circuit ratio (Isc/IL) is determined as

$Isc/IL=37007.18A/1438.21A=25.73$ (3.15)

Distribution Transformer number 05

Rating=1000KVA, 50Hz 3/0.4kv %Z=3.89

Ipri=182.78A Isec=1443A Vector group: Dyn5

The impedance of the transformer, Ztr can be calculated from the percentage impedance by using equation below.

Ztr=%Z× (KV) ^{2}×10/ (KVA) (3.16)

Ztr= (3.89) × (0.4) ^{2}×10/ (1000) =6.224E-3 ohm

By using the relation X/R=6 implies Xtr=Rtr×6 and $Z^2=R^2+X^{2,}$,Xtr=0.0129ohm and Rtr=0.0778ohm.

%Xtr=KVA×Xtr/10(kv)^2 (3.17)

Hence, %Xtr=KVA×Xtr/10(kv)^2=1000×0.0129/10×(0.4)^2=8.0625

Isc=IFL×100/%Xsc (3.18)

Hence, Isc=1245.34×100/(8.0625)=15446.08A

The short circuit ratio (Isc/IL) is determined as Isc/IL=15446.08A/1245.34A=12.40 (3.19)

Distribution Transformer number 06

Rating=1000KVA, 50Hz 3/0.4kv %Z=3.91

Ipri=182.78A Isec=1443A Vector group: Dyn5

The impedance of the transformer, Ztr can be calculated from the percentage impedance by using equation below.

Ztr=%Z× (KV) ^{2}×10/ (KVA) (3.20)

Ztr= (4.91) × (0.4) ^{2}×10/ (1000) =7.856 E-3ohm

By using the relation X/R=6, Xtr=Rtr*6 and $Z^2=R^2+X^{2,}$,Xtr=0.0775ohm and

Rtr=1.2915E-3ohm.

$\%Xtr=KVA\times Xtr/10(kv)^2$ (3.21)

Hence, $\%Xtr=KVA\times Xtr/10(kv)^2=1000\times 7.749E\text{-}3/10\times(0.4)^2=4.8431ohm$

$Isc=IFL\times 100/\%Xsc=IFL\times 100/\%Xtr$ (3.22)

$Isc=IFL\times 100/\%Xsc=IFL\times 100/\%Xtr=1110.68A\times 100/(4.8431)=22933.25A$

The short circuit ratio (Isc/IL) is determined as

$Isc/IL=22933.25A/1110.68A=20.65$ (3.23)

Distribution Transformer number 07

Rating=1000KVA, 50Hz 3/0.4kv %Z=4.01

Ipri=182.78A Isec=1443A Vector group: Dyn5

The impedance of the transformer, Ztr can be calculated from the percentage impedance by using equation below.

$Ztr=\%Z\times (KV)^2\times 10/(KVA)$ (3.24)

$Ztr=(4.01)\times(0.4)^2\times 10/(1000)=6.416\ E\text{-}3ohm$

By using the relation $X/R=6$ implies $Xtr=Rtr\times 6$ and $Z^2=R^2+X^2$, ,Xtr=0.0633ohm and

Rtr=0.0105ohm.

$\%Xtr=KVA\times Xtr/10(kv)^2$ (3.25)

Hence, $\%Xtr=KVA\times Xtr/10(kv)^2=1000\times 0.0633/10\times(0.4)^2=39.5625$

$Isc=IFL\times 100/\%Xsc=IFL\times 100/\%Xtr$ (3.26)

$Isc=IFL\times 100/\%Xsc=IFL\times 100/\%Xtr=682.41\times 100/(39.5625)=1724.89A$

The short circuit ratio (Isc/IL) is determined as

$Isc/IL=1724.89A/682.41A=2.56$ (3.27)

Distribution Transformer number 08

Rating=1000KVA, 50Hz 3/0.4kv %Z=4.01

Ipri=182.78A Isec=1443A Vector group: Dyn5

The impedance of the transformer, Ztr can be calculated from the percentage impedance by using equation below.

Ztr=%Z× (KV) ^{2}×10/ (KVA) (3.28)

Ztr= (4.01) × (0.4) ^{2}×10/ (1000) =6.416 E-3ohm

By using the relation X/R=6 implies Xtr=Rtr×6 and $Z^2=R^2+X^2$, ,Xtr=0.0633ohm and

Rtr=0.0105ohm.

Hence, %Xtr=KVA×Xtr/10(kv)^2=1000×0.0633/10×(0.4)^2=39.5625

Isc=IFL×100/%Xsc=IFL×100/%Xtr (3.29)

Isc=IFL×100/%Xsc=IFL×100/%Xtr=266.57×100/(39.5625)=673.79A

The short circuit ratio (Isc/IL) is determined as

Isc/IL=673.79A/266.57A=2.53 (3.30)

Distribution Transformer number 10

Rating 1000KVA, 50Hz 3/0.4kv %Z=4.17

Ipri=182.78A Isec=1443A Vector group: Dyn5

The impedance of the transformer, Ztr can be calculated from the percentage impedance by using equation below.

Ztr=%Z×(KV) ^{2}×10/ (KVA) (3.31)

Ztr= (4.17) × (0.4) ^{2}×10/ (1000) =6.672E-3ohm

By using the relation X/R=6 implies Xtr=Rtr×6 and $Z^2=R^2+X^2$, ,Xtr=6.58E-3ohm and

Rtr=1.0969E-3ohm.

$\%Xtr=KVA\times Xtr/10(kv)^2$ (3.32)

Hence, $\%Xtr=KVA\times Xtr/10(kv)^2=1000\times 6.58E\text{-}3/10\times(0.4)^2=4.1125$

$Isc=IFL\times 100/\%Xsc=IFL\times 100/\%Xtr$ (3.33)

$Isc=IFL\times 100/\%Xsc=IFL\times 100/\%Xtr=1174.51\times 100\times(4.1125)=28559.5A$

The short circuit ratio (Isc/IL) is determined as

$Isc/IL=28559.5A/1174.51A=24.32$ (3.34)

Distribution Transformer number 11

Rating=1000KVA, 50Hz 3/0.4kv %Z=4.03

Ipri=182.78A Isec=1443A Vector group: Dyn5

The impedance of the transformer, Ztr can be calculated from the percentage impedance by using equation below.

$Ztr=\%Z\times (KV)^2\times 10/(KVA)$ (3.35)

$Ztr=(4.03)\times(0.4)^2\times 10/(1000)=6.672E\text{-}3ohm.$

By using the relation X/R=6 implies Xtr=Rtr×6 and $Z^2=R^2+X^2$, ,Xtr=6.448E-3ohm and

Rtr=1.0969E-3ohm.

$\%Xtr=KVA\times Xtr/10(kv)^2$ (3.36)

Hence, $\%Xtr=KVA\times Xtr/10(kv)^2=1000\times 6.448E\text{-}3/10\times(0.4)^2=3.9948$

$Isc=IFL\times 100/\%Xsc=IFL\times 100/\%Xtr$ (3.37)

$Isc=IFL\times 100/\%Xsc=IFL\times 100/\%Xtr=654.70\times 100/(3.9948)=16388.81A$

The short circuit ratio (Isc/IL) is determined as

$Isc/IL=16388.81A/654.70A=25.03$ (3.38)

Distribution Transformer number 12

Rating=800KVA (Two 400KVA parallel connected small trasformers), 50Hz 0.4kv/3kv and vice-versa. %Z=2.5

Ipri=168A Isec=663.19A Vector group: Dyn5

The impedance of the transformer, Ztr can be calculated from the percentage impedance by using equation

$$Ztr = \%Z \times (KV)^2 \times 10 / (KVA) \quad (3.39)$$

Ztr= (2.5) × (0.4)^2×10/ (800) =5E-3ohm.

By using the relation X/R=5 implies Xtr=Rtr×5 and $Z^2=R^2+X^2$, ,Xtr=5.88324E-3ohm and

Rtr=9.8054E-4ohm.

$$\%Xtr = KVA \times Xtr / 10(kV)^2 \quad (3.40)$$

Hence, $\%Xtr = KVA \times Xtr / 10(kV)^2 = 800 \times 5.8832\text{ E-3}/10 \times (0.4)^2 = 2.9416$

$$Isc = IFL \times 100/\%Xsc = IFL \times 100/\%Xtr \quad (3.41)$$

Isc=IFL×100/%Xsc=IFL×100/%Xtr=663.5×100/(2.9416)=22555.75A

The short circuit ratio (Isc/IL) is determined as

$$Isc/IL = 22555.75A/663.5A = 34 \quad (3.42)$$

Therefore **Isc/IL** ratio for loads on each transformer has been calculated in such away and tabulated in the appendix A table 3.2A.The purpose of calculating the ratio of Isc/IL at each PCC is to compare possible harmonics current level be generated by nonlinear loads comparing IEEE and IEC standards rather the actual harmonics currunts at each PCC.

3.2 Real time data collection

Following mathematical calculation real time data have been taken by using the device called HIOKI3196 Power Quality Analyzer at each transformers low tension distribution panel which is the individual point of Common coupling for each transformer except transformer#12 that was held insufficient electrical loads.

3.2.1 Harmonic Distortion Assessment procedure

Harmonics measurements are performed to characterize the level of harmonics generation for existing non-linear loads in given power distribution networks.

Procedure in power quality problems and/or harmonics distortion power distribution network will be:

1) Performing actual harmonics measurement in existing system at least for a week at PCC
2) Evaluate measured results and compare with given standards. Calculating ratio of Isc/IL in order to use the current distortion limits stated in (IEEE 519-2014 and IEEE Std 519-1992 and IEC 61000-2-2/3-4 and others.
3) If the value of the measurement does not meet the standard selected by selected standards mitigation devices/technique will be selected. Possible mitigation technique will be evaluated and selection of optimum one that fit the system will be selected
4) Modeling the system under consideration evaluating selected technique and simulation will be carried out to check the overall of system response with and without selected harmonics mitigation technique(s).

Where to take the measurement? At PCC.

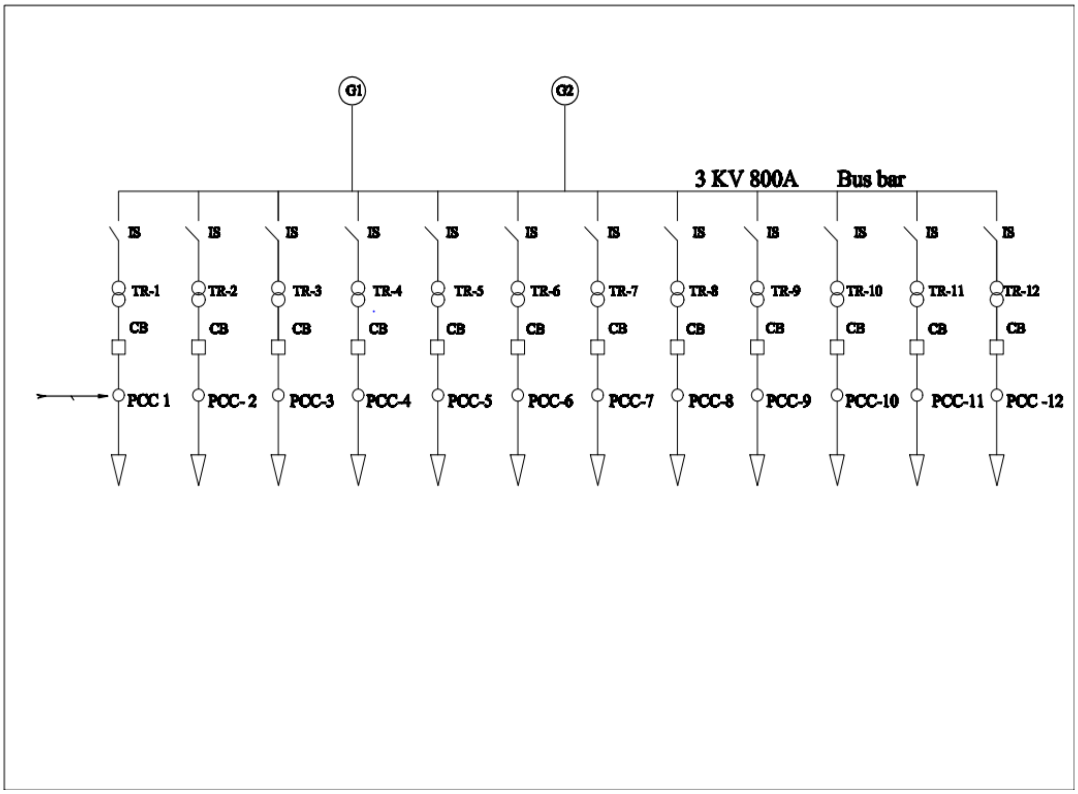
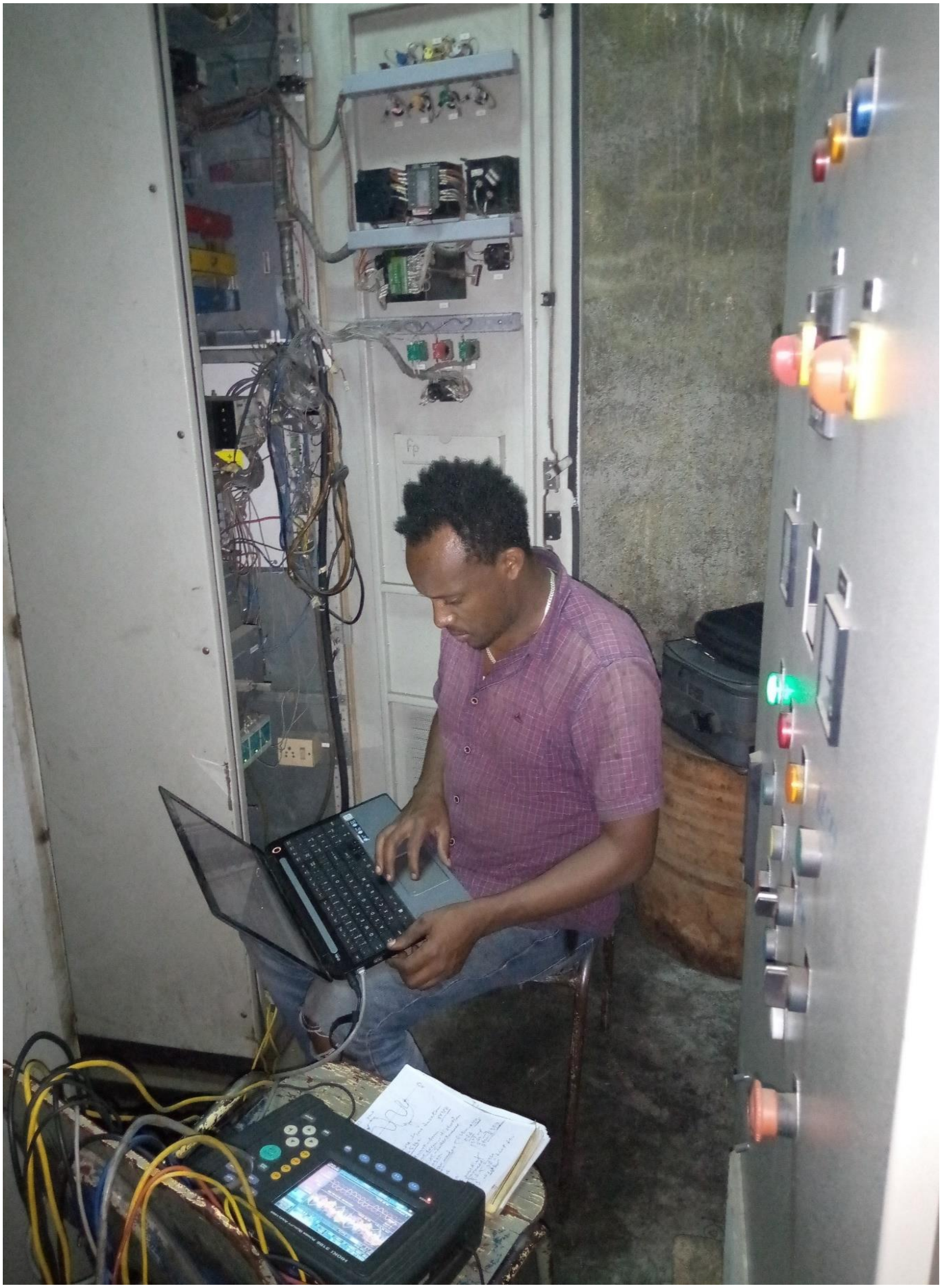


Figure 3.6: Partial show of factory single line diagram to show where real time data were taken.

Figure 3.7: Indoor type distribution transformer#02 at boiler plant (Metahara Sugar Factory)

Figure 3.8: Partial view of boiler ID#04 fan VFD panel and load monitoring .



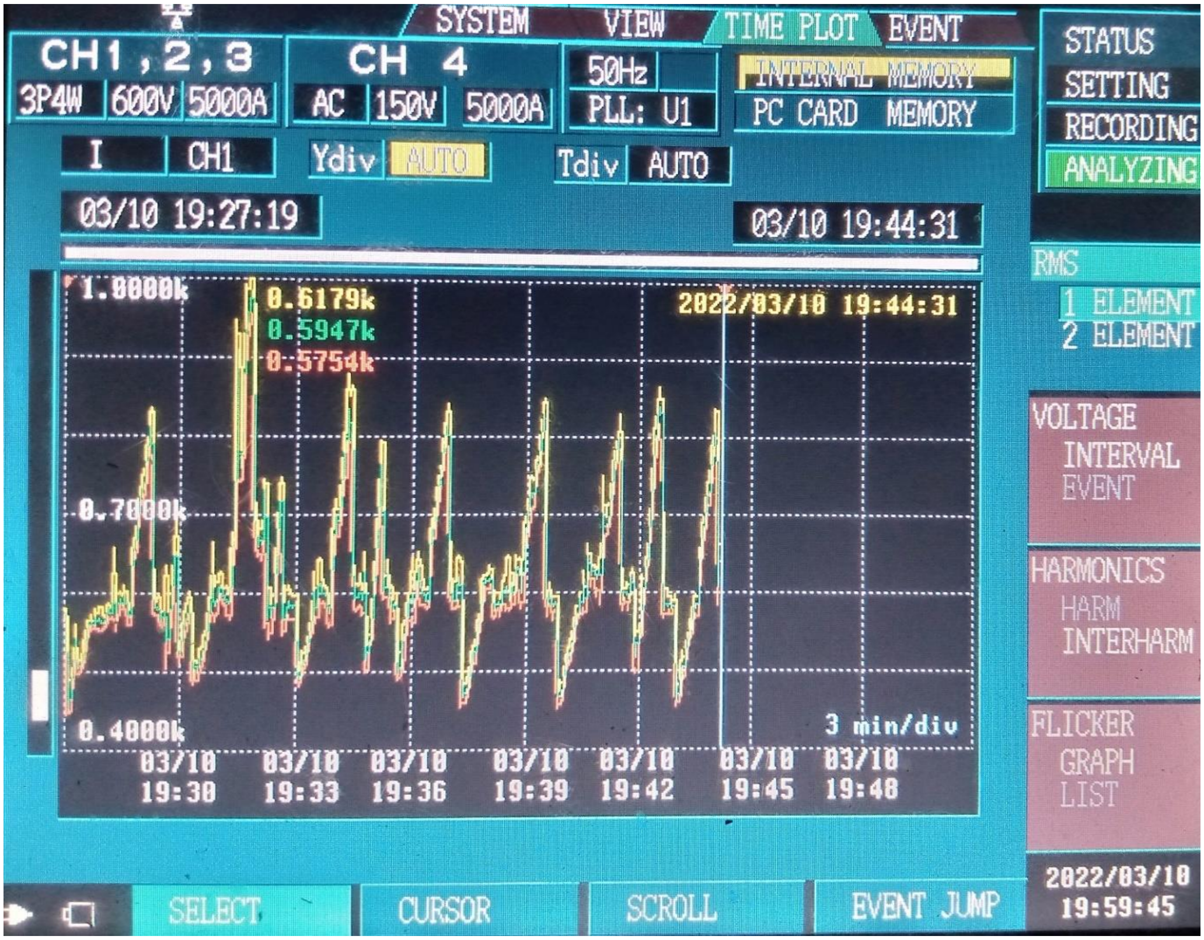


Figure 3.9: Current harmonics distortion waveform **in phase A** on transformer#06 (as sample)

3.2.2 Modeling and Design of Distribution Network Mitigation Techniques

Factory power distribution system consisting of source, measuring units, circuit braekers, distribution transformers and connected lump sum of load was partially modeled with MATLAB/SIMULINK for seek of clarity of the distribution network. The actual illustration is found in Fig 3.16.

3.2.3 Partial Model of Metahara Sugar Factory Power Distribution Network (Existing)

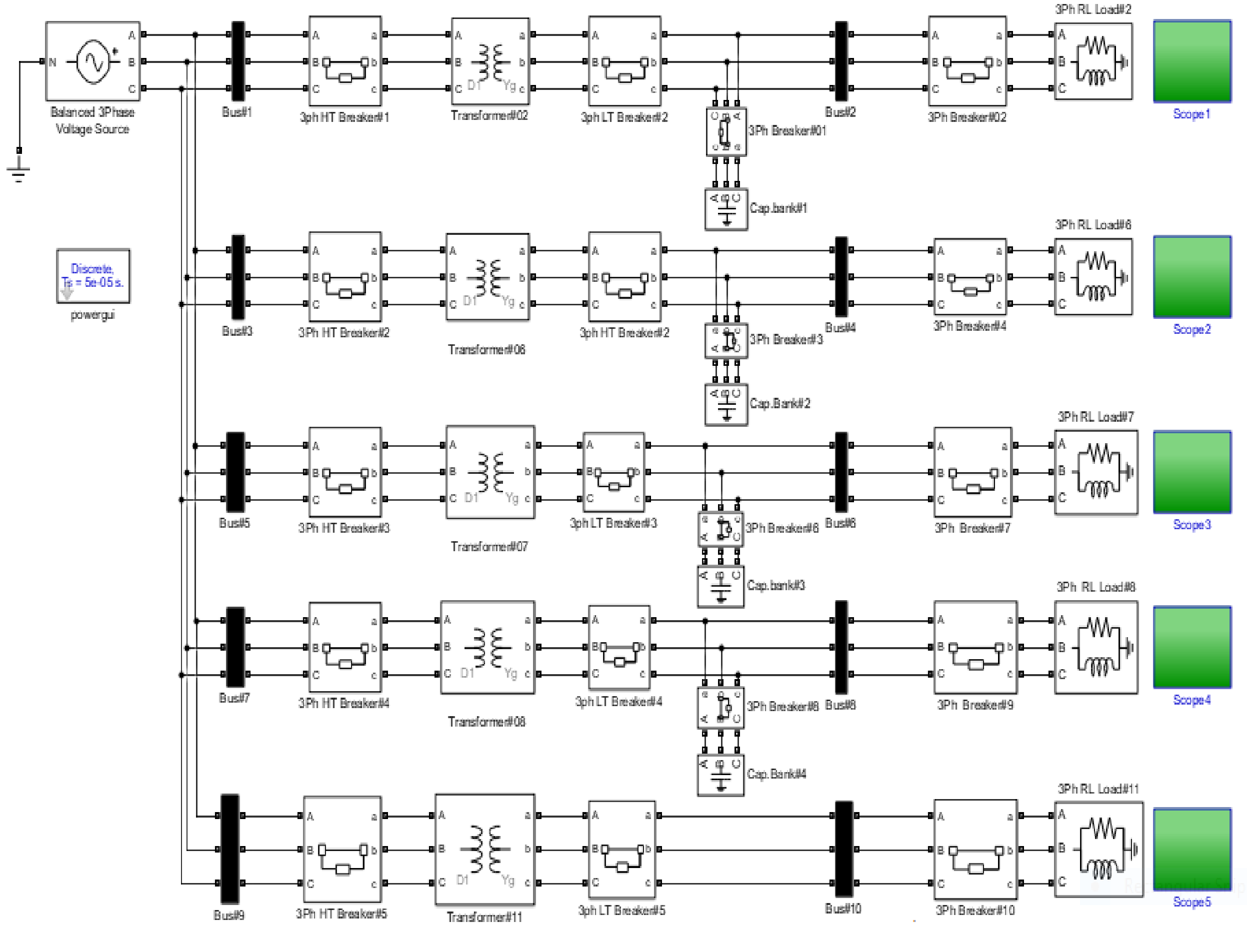


Figure 3.10:SIMULINK model of partial power distribution network of Metahara Sugar Factory (for power panel of transformer#2,6,7,8 and 11).

Figure 3.10 shows partial modeling of existing power distribution network was purposely made for the seek of avoiding modeling complexity and for this reason only five selected power distribution transformers and connected distribution power panel (which mitigation of harmonics current is the concern) were selected and included. Transformer number 11 is newly relocated transformer to balance machinery loads of the factory. As it can seen from Figure 3.10 capacitor bank did not installed to this transformer as this transformer is temporarly installed and relative feed small load compared to the other distribution transformers in the factory.

3.3 Modeling and Design of Mitigation Techniques

The power quality problems in power distributions systems are not new, but the awareness of the customers, utilities and equipment manufacturers has increased in recent years. Starting from the time of awareness and identification of power quality problems a lot of conventional solutions, which typically use passive elements, have been proposed and implemented in different parts of the world. Even though these solutions have existed for a long period of time in the field of electrical power engineering, they do not always respond correctly and perform as expected on the modern power system. Economic and technical limitations have to taken into account before implementation of power quality problem mitigation technique or method. Mitigating techniques has to be implemented on a system when the distortion levels exceed the limits set by different standard organizations in order to avoid failure of equipments both in the utility and customer premises.On the other hand only optimum/feasible solution should be implemented. Passive filters consisting of tuned L-C component have been widely used to suppress harmonic distortions. Even though these passive filters have low initial cost and high efficiency, they also have various drawbacks like instability, fixed compensation, resonance with supply as wellas loads and utility impedance (Habte, 2018).The level of power quality required is essential in mitigating power quality problems. Line reactors, DC chokes, 12-pulse converters and broadband and harmonic trap filters do reduce harmonic current and voltage to some extent but may not reduce to the level below the values stated in (Hartmann et al., 1993) & (Halpin et al., 2014) recommendation and practices.

Generally,there are two major approaches namely load conditioning and line conditioning has been used to the mitigation of power quality problems (specifically harmonics distortion).The 5^{th} order harmonic filtering is usually adequate to solve most distribution system harmonic problems. However, in some cases it may be necessary to add 7^{th} , 11^{th} , and 13^{th} harmonic filters, in that order (Grady, 2012). The load conditioning is mostly related to reactive power compensation techniques it can be broadly classified into two main categories namely passive techniques using passive filter and active techniques using active filters.Active filter is a new and promising technology, but there are as yet few distribution feeder installations. Active filters are power electronic converters that inject equal but, opposite distortion to yield more sinusoidal voltage waveforms throughout a network. Shunt active filters are used to compensatecurrent harminics of nonlinear loads to perform reactive power compensation and balance the imbalance currents. It senses the load current and injects a current into the system to compensate current harmonics or reactive load.

In general term Harmonics mitigation /controlling harmonics in power system will be done by doing one or more of the following points to the system under study.

1) Adding different type of passive and/or active filters either to take out harmonics current or block harmonics current from the system or supply harmonics current locally
2) Reducing harmonics current produced by loads-reducing harmonics generating loads
3) Modifying the frequency response characteristics of the systems by filters, inductors or capacitors.

The analysis of measurements carried out in Metahara Sugar Factory power distribution network in the previous chapter shows that current harmonic distortion levels which exceeds the limits set by IEC and IEE standards, are present on transformers T2, T6, T7, T8 and T11. There are a number of devices and techniques available to control harmonic distortion in an electrical system. The analysis of measurements carried out in Metahara Sugar Factory power distribution network in the previous chapter shows that current harmonic distortion levels which exceeds the limits set by IEC and IEEE standards, are present on transformers T2, T6, T7, T8 and T11. Therefore there is required that to design and simulate suitable harmonics mitigation technique for those distribution transformers.

3.3.1 Custom Power Devices

The term custom power device (CPD) refers to the use of power electronic controllers for distribution systems to enhance the quality and reliability of power that is delivered to customers.They have good performance at medium distribution levels and most are available as commercial products.The CPDs are basically of two types network reconfiguring type and compensating type. The complete classification of CPDs is shown in Figure 3.1.These are power electronic equipment aimed to help in mitigating power quality problems. These are many types of CPD like Dynamic Voltage Regulator (DVR), D-STATCOM, auto transformer, UPFC etc.

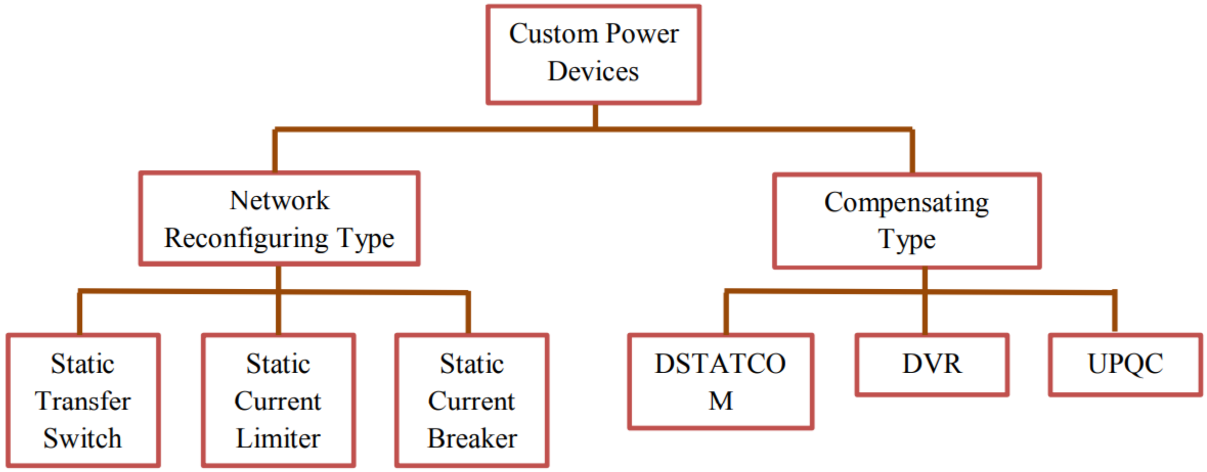


Fig.3.11General classification of custom power devices (CPD) (Habte, 2018).

3.3.2 Reconfiguring Type CPDs

The network reconfiguring equipment can be normal thyristor or gate turn-off thyristor base. The Static Current Limiter/ Static Circuit Breaker are usually used for fast current limiting and current breaking during faults. On the other hand, the Static Transfer Switches (STS) are used to promptly transfer load to an alternate feeder to protect a load from voltage sag/swell or fault in the supplying feeder. Uninterruptable Power Supply (UPS) is also categorized as a network reconfiguring type CPD, which is used to mitigate voltage dip and short duration interruptions (Habte, 2018).

The compensating CPDs are used for active filtering, load balancing, power factor improvement and voltage regulating (sag/swell). These devices are mainly three types:Distribution STATCOM, Dynamic Voltage Restorer and Unified Power Quality Conditioner. Distribution Static Compensator (DSTATCOM) is a shunt connected device, designed to inject unbalanced and harmonically distorted current to distribution line via coupling inductor to eliminate unbalance or distortions in the load current or the supply voltage. It can also perform voltage regulation when connected to a distribution bus. In this mode it can hold the bus voltage constant against any unbalance or distortion in the distribution system. Generally, DSTATCOMs can be used in distribution networks for load current balancing, flicker effect compensation, current harmonic distortion compensation and power factor improvement. The single line diagram of DSTATCOM is shown in Figure 3.2.

3.3.4 Unified Power Quality Conditioner (UPQC)

UPQC is a very versatile device that can inject unbalanced and distorted current in shunt and voltage in series simultaneously in a dual control mode. Therefore it can perform both the functions of load compensation and voltage control at the same time. Applications of UPQC include VAR compensation, harmonic suppression, current balancing, active/ reactive power control, voltage balancing and voltage regulation (Habte, 2018).

The most popular Active Filter is the parallel or shunt type.The active filters can predict the load requirements and consequently they exhibit very good dynamic response. Among the different new technical options available to improve power quality is distribution Static synchronous compensator (DSTATCOM) have proved to be an important and flexible alternative to compensate current harmonics and voltage disturbances in power distribution system (Poornima & Jois, 2016). Besides this the introduction and developments of IGBTs the DSTATCOM has got a real boost and at present and considered as ideal solid-state device. As stated in (Singh & Raj, 2012) the effectiveness of DSTATCOM depends upon used control algorithm for generating the switching signals for the voltage source converter and value of interfacing inductors.

In this thesis work design and simulation of power quality (specifically for harmonics) improvement the device called distribution Static Synchronoues Compensator (DSTATCOM) has been selected for harmonics current distortion improvementare required at distribution transformers #02,06,07,08 and#11 PCCs whose magnitude in percentage of is found beyond the limits stated in IEC and IEEE standard documents recommendation and requirements.

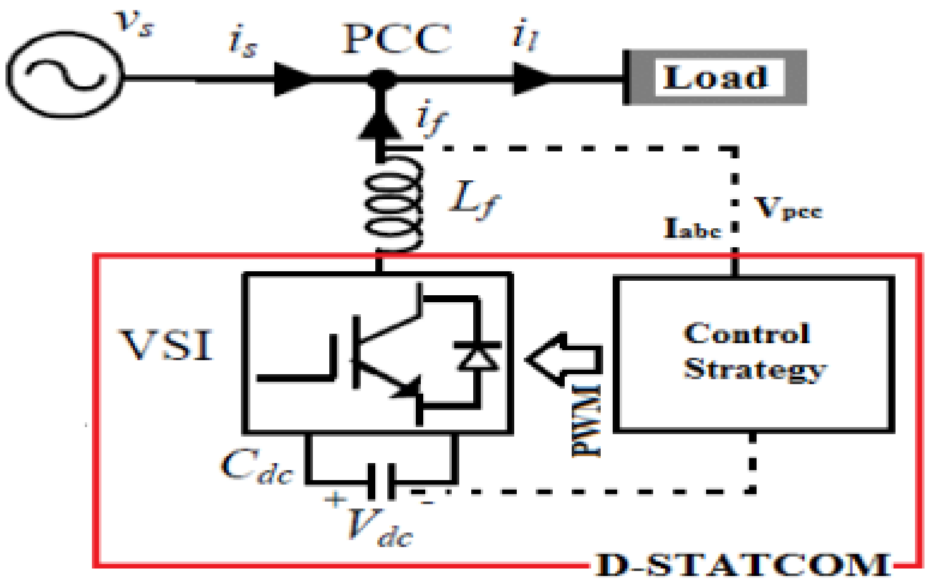


Figure3.12:Schematic diagram of DSTATCOM (Sinku, 2015).

There are two modes of DSTATCOM operation namely load compensation in current-control mode and voltage regulation in voltage-control mode. Since the main concern of this study is harmonic distortion, the DSTATCOM in current control mode is used for load compensation, i.e. current harmonic compensation. This device is shunt connected to the power distribution network through a coupling inductance that is usually realized by the transformer leakage reactance. In general, the DSTATCOM can provide power factor correction, harmonics compensation and load balancing. The major advantages of DSTATCOM compared with a conventional static VAR compensator (SVC) include the ability to generate the rated current at virtually any network voltage, better dynamic response and the use of a relatively small capacitor on the DC bus. The size of the capacitor does not play an important role in steady-state reactive power generation, which results in a significant reduction of the overall compensator size and cost (Singh & Raj, 2012). The DSTATCOM mitigates power quality problems by injecting current to the system. DSTATCOMs for three-phase four-wire systems with neutral conductor have been successfully developed at the customer end for unbalanced systems (Kullan et al., 2016).

Three-phase four-wire DSTATCOM are used to improve the power Quality in three phase four-wire distributrion systems. The three-phase four-wire system are for the compensation of neutral current along with the power quality compensation in supply current. The number of power electronic switches is less here compared to three-phase three wire DSTATCOM (Sree Jyothi et al., 2021).

3.3.5 Design of DSTATCOM for Harmonic Current Distortion Mitigation

The DSTATCOM is shunt connected power electronics based device. It is connected near the load side at the distribution system. It is six pulse voltage Converter, which converts a DC voltage into AC out putvpotageinorder to compensate the active and reactive power that is needed by the system as well as to correct current and voltage distortion. The topology for this purpose is DC voltage source.In this topology the DSTATCOM consists of DC voltage source inverters (VSI) using 6 IGBT's, dc capacitor, ripple filter and a reactance of coupling transformer (Poornima S. & K.George, 2016). As one can see from Figure 3.2 above schematic diagram of DSTATCOM it is connected between source and load) in shunt manner.

3.3.5.1 Design of DC Bus Voltage

The minimum DC bus voltage of voltage source Inverter (VSI) should be more than twice of the crest of AC electrical syatem's phase voltage and given by the following formula.

$$VDC=2\sqrt{2}VLL/\sqrt{3}m \quad (3.43)$$

Where, VLL is system line to linevoltage and m is modulation index. The parameter 'm' is equal to unity for the system under normal operation (SunInnovative Research Center). Hence as normal system operation considered the value of modulation indexis selected as unity (m=1).

Therefore VDC voltage will be

$$VDC1=2\sqrt{2}VLL/\sqrt{3}m=2\sqrt{2}*400/\sqrt{3}*1=653.2V$$

However, due to the dead-band and transition durations of the switching device, the attaineable voltage at the selected DSTATCOM output terminal will be smaller than the estimated one in practice. As a result,the DC bus voltage of magnitude to safe value 700V is selected.

This is because of drawing the ten transformer is found not possible and not important for the case of time and space constraints (i.e only the transformers on which measured harmonics current distortion that found out of the standard and feed variable frequency drive loads).

3.3.5.2 Design of DC Bus Capacitance

The capacitor at the DC side of the DSTATCOM is responsible for supplying the current harmonics and the fluctuations caused by the compensation of the reactive power. The switching losses and the coupling inductor losses force the DC capacitor to discharge. On the other hand the average value of the voltage across the capacitor terminals must be kept at a constant value in order to the capacitor perform its duty. The voltage across the capacitor is regulated by absorbing or releasing active power into the electrical network.

The amount of transient energy required during load changes determines the DC bus capacitance value.Because the energy stored in the capacitor is used to supply the load's energy requirement for a portion of a power cycle, the relationship is expressed as:

$$1/2(V^2\,DC - V^2\,DC1)C\,Dc = k13VIat \qquad (3.44)$$

Where,VDC is the maximum voltage and VDC1 is the minimum allowed DC bus voltage reduction during the transients, ‘t’ is the time when the backup is required for transient, ‘a’ is the overloading factor ,V is phase voltage, ‘I’ is phase current, ‘k1’ is variation of energy during dynamics and CDc is the DC bus capacitance value. Therefore from equation (3.44) the value of CDC is calculated as follows:

And using the values of each parameter as, VDC=700V, VDC1=653.2V, t=30ms, a=25%, Vphase=220.6,Iphase=536A and variation of energy during dynamics is taken as 10%(k=0.10)

From eqn.(3.44) and numerical values of stated parameters DC-link capacitor capacitance for each DSTATCOM have been calculated and numerical values are presented as follows:

CDC2=42mF, for DSTATCOM#02.Similary CDC6=41.66mF, for DSTATCOM#06, CDC7=27.64mF for DSTATCOM#7,CDC8=31.3mF for DSTATCOM#8 and CDC11=25.25mF forDSTATCOM #11.

3.3.5.3 Design of AC coupling inductor

Selection of AC inductor (Lr) depends of VSI depends on the current ripple Icr,pp, switching frequency and DC bus voltage and given by the following equation:

$$Lr=\sqrt{3}*m*Vdc/(12afsIcr,pp) \qquad (3.45)$$

Using equation (3.45) coupling inductor was calculated for each DSTATCOM to be connected at respective PCC.

First peak to peak ripple current calculation was done by taking measured average fundamental phase current from each DSTATCOM.

If=Icr,pp2=10%*Iphase=0.10*536=53.6A (for DSTATCOM#02).And similarily peak to peak AC to DC voltage conversion ripple current for selected DSTATCOM inverter used for transformer#6,7,8 and 11 are 51.75A, 53.5A,39.86A and 31Amps respectively.

Now,Lr2=$\sqrt{3}*$m*Vdc/(12afsIcr,pp)=$\sqrt{3}*$1*700/(12*1*1.25*5e3*53.6)=0.30mH(for DSTATCOM#02).And similary, perphase coupling inductor for each DSTATCOM used on transformer#6,7,8 and 11 PCC is 0.31mH, 0.302mH, 0.406mH and 0.52mH respectively.

3.3.6 Inverter Design

3.3.6.1 Selection and Design of switching Devices of Inverter

Voltage source inverter (VSI) in a DSTATCOM is used to generate the compensating three phase AC currents at any required magnitude, phase and frequency. It consists of power semiconductor switches and DC link capacitor. The power semiconductor device can be a Metal Oxide Field Effect Transistor (MOSFET) or Gate Turn-Off (GTO) thyristor or Insulated Gate Bipolar Transistor (IGBT) or Field Controlled Thyristor (FCT) based on the specific application requirements. Gate turn-off thyristors are recommended for high voltage application with lower switching speeds. On the other hand, MOSFETs have very low switching losses but are not suitable for very high voltage applications. IGBTs and MOSFETs are the preferred devices for distribution system applications as they can carry fairly large current and has fast switching characteristics and low losses. These two power semiconductor devices are also selected for realizing the VSI of the DSTATCOM proposed for this study. Switching devices are selected based on their capabilities switching frequency and load withstand capacity. The two common parameter that must be considered are current rating and voltage level and calculated using the following formula.

Vsw=(VDC+Vd) (3.46)

Vd=10%of overshot in DC link voltage under dynamic conditions.

Where , Vsw and Isw are voltage source inverter (VSI's) IGBT switch voltage and switching current rating that indicate insultation level of the swichcontact cover and switch contact ratings respectively and given by the following equation.

V_{sw}=(700+0.1*700)=770v (for each IGBTs used in design of VSI used for current compensating purpose of selected transformers load).

Isw=1.25(Icr,pp+Ipeak) (3.47)

Isw_2=1.25(Icr,pp+Ipeak)=1.25*(53.6+536)=737Amps (for DSTATCOM#02). And similarly switching rating of IGBTs used for current compensating device VSI for transformers number 6, 7, 8 and 11 are 711.56A, 735.63A, 548.08A and 426.25A respectively. This implies that the IGBTs contact should be rated at this designed ampere.

3.3.6.2 Selection of Inverter topology and modulation Technique

It is also important to consider the level of inverter going toused for designed DSTATCOM. The total harmonics distortion of the 7-level inverter produce less harmonics than the 5-level. Thus, by increasing the number of levels of inverter, the distortion will be reduced (Jhuma & Ashutosh, 2018). Therefore it is important to use the higher of level of inverter is recommended if the cost does not be the factor. Three phase voltage source 4level sinusoidal PWM type of inverter has been selected for required purpose and compareable advantage with lower level of invertes like the issues of switching losses as it built from minimum power components compared to convertional 4level NPC inverter as well as two modes of operations (2level and 4level) as required, high quality voltage waveform and higher efficiency. Selection between SVPWM and PWM inverter is based the comparison of the complexity of computation state vector (SVPWM) inverter requires more cost of implementation (Nessereddin et al.,2017).

3.3.6.3 Design of kVA rating of VSI of DSTATCOM

It is important to determine the rating of kVA of voltage source Inverter size that will be used in current compenstating purpose. PWM type voltage source inverter is selected for this thesis work.The series lossless (ideal) VSI's kVA rating is calculated by using the following formula.

$$KVA=3*Vphase(Av.rms)*Ifull\ load/(1000) \quad (3.48)$$

Where, V_{phase}(Av.rms) and I_{full}load are rms value of phase voltage and phase current of VSI used in DSTATCOM. Rms I_f for each transformer harmonics compensating DSTATCOM is calculated as follows.

$$If=p/\sqrt{3}*(VLL) \quad (3.49)$$

$I_{f2}=p/\sqrt{3}*(VLL)=671.5e3/(\sqrt{3}*400)=969.22A$ (for DSTATCOM#2). And similarly perphase full load current on transformer#6, 7, 8 and 11 are 907.42A, 440.84A, 197.51A and 547.33A respectively. Using equation (3.48) VSI's kVA rating used for each transformer (DSTATCOM be used for harmonic compensation purpose at each selected PCC) calculated as follows.

VSI's of DSTATCOM kVA rating for Transformer#2 PCC

kVA=3*220.67V*969.22A/(1000)=641.63. And similarly kVA of VSI for transformer#6, 7, 8 and 11PCCs is 616.95kVA, 298.23kVA, 134.33kVA and 376.51kVA respectively.

3.3.6.4 Inverter Maximum input DC voltage and Maximum out put AC voltage

The main draw back of voltage Source Inverter (VSI) is that the maximum voltage obtained can never exceed the DC-link voltage(Nessereddin et al., 2017). The peak DC link voltage across the inverter brigde is by

$$V_{dc\,peak}=1/(1-2D)*V_{dc} \tag{3.50}$$

Where, Vdc is Dc-link voltage and D is inverter duty cycle and D=0.15.

$V_{dc\,peak}=1/(1-2D)*V_{dc}=1/(1-2*0.15)*700=1000V$

Maximum inverter output phase voltage is given by

$$V_{maxinv\,out}=1/2*Ma*B*V_{dc} \tag{3.51}$$

Where, Ma is modulation index and B is duty cycle constant. And then,

$V_{maxinv\,out}=1/2*Ma*B*V_{dc}=1/2*1*\sqrt{2}*700=495V$

3.3.6.5 Machematical calculation of instantaneous reactive power being injected at PCC

The instantaneous reactive power being injected at PCC by the DSTATCOM for improving harmonic distortion and system performance of the network is given by the following equation.

$$QC=(V_{pcc})^2/X-(V_{pcc}V_i)*\cos\alpha/X \tag{3.52}$$

Where, Vpcc is phase voltage at point of common coupling, Vi isinverter peak out putvoltage, XL is branch circuit and transformer reactance and α (angle alpha) is phase difference between voltage at Pcc and inverter voltage.

Therefore the instantaneous reactive power (QC) to be by DSTATCOM at point common coupling calculated as follows (refer table 3.3A in appendix A for reactance value of each network).

Mvar Vaue of DSTATCOM#1 to be Injected at Pcc#1 (Transformer#02 PCC)

By using equation (3.52) theinstanteous reactive power to be injected at selected PCCs have been calculated as follows.

QC1=$(Vpcc1)^2/X-(Vpcc1*Vi)*\cos\alpha/X$, for DSTATCOM of PCC1 and Cosα ismaximum at alpha of zero degree and $\cos(0^0)=1$.This implies that the phase angle between voltage at point of common coupling and inverter voltage is zero(capacitive mode) or no phase difference between them.

QC1=$(220.67)^2/(0.0682)-(220.67)*(495)*\cos(0^0)/(0.0682)=887.63$KVAR.

Similarly ,

MvarVaue of DSTATCOM#2 to be Injected at Pcc#2 (Transformer#06 PCC)

QC2 =$(Vpcc2)^2/X-(Vpcc2*Vi)*\cos\alpha/X$, for DSTATCOM of PCC2

QC2=$(226.63)^2/(0.5265e\text{-}3)-(226.63)*(495)*\cos(0^0)/0.5265e\text{-}3)=3817.93$MVAR.

Mvar Vaue of DSTATCOM#3 to be Injected at Pcc#3 (Transformer#07 PCC)

QC3 =$(Vpcc3)^2/X-(Vpcc3*Vi)*\cos\alpha/X$, for DSTATCOM of PCC3

QC3 =$(225.5)^2/0.1197-(225.5)*(495)*\cos(0^0)/(0.1197)=507.70$kVAR

Mvar Vaue of DSTATCOM#4 to be Injected at Pcc#4 (Transformer#08 PCC)

QC4=$(Vpcc4)^2/X-(Vpcc4*Vi)*\cos\alpha/X$, for DSTATCOM of PCC4

QC4=$(226.70)^2/(0.071)-(226.70)*(495)*\cos(0^0)/0.071)=856.67$kVAR

Mvar Vaue of DSTATCOM#5 to be Injected at Pcc#5 (Transformer#11 PCC)

QC5=$(Vpcc5)^2/X-(Vpcc5*Vi)*\cos\alpha/X$, for DSTATCOM of PCC5

QC5=$(229.2)^2/(9.148e\text{-}3)-(229.2)*(495)*\cos(0^0)/9.148e\text{-}3)=6.65$MVAR

3.3.7 Selecting Control theories for designed DSTATCOM

A control mechanism is required to generate the gate pulse for the voltage source convert so that the chosen mitigation device can execute its function. The DSTATCOM is controlled using a variety of time domain and inverter so that the chosen mitigation device can execute its frequency domain control techniques. These control methods are used to create reference currents and voltages in order to regulate the VSC with a pulse. Since frequency domain control algorithms are sluggish, wasteful, and require a lot of computation, they are not as good as time-domain control algorithms for real-time control of these compensators. Some of the time-domain control algorithms are: Synchronous reference frame (SRF) theory, Instantaneous symmetrical component theory, Instantaneous reactive power theory (IRPT), Current synchronous detection (CSD) approach, Power balance theory (BPT) and others.

Among all of the existing time-domain algorithms the SRF algorithm shows significant advantage the othercontrol theories for its simple design,increased speed of control and employ fewer computations which makes it more likely to be implemented practically.By lowering the number of computations necessary, SRF-based control reduces the overall complexity of the control system (Al-Haddad et al., 2015). As a result, this control theory is used in this study as it is the better compared to others.

3.3.8 Reference current generation and control of DSTATCOM

The DSTATCOM is common among custom power devices(CPD) used for harmonics current compensation and used for mitigating of other power quality problems.In this study, synchronized reference frame theory is used to manage the DSTATCOM's VSC gate pulse generation.

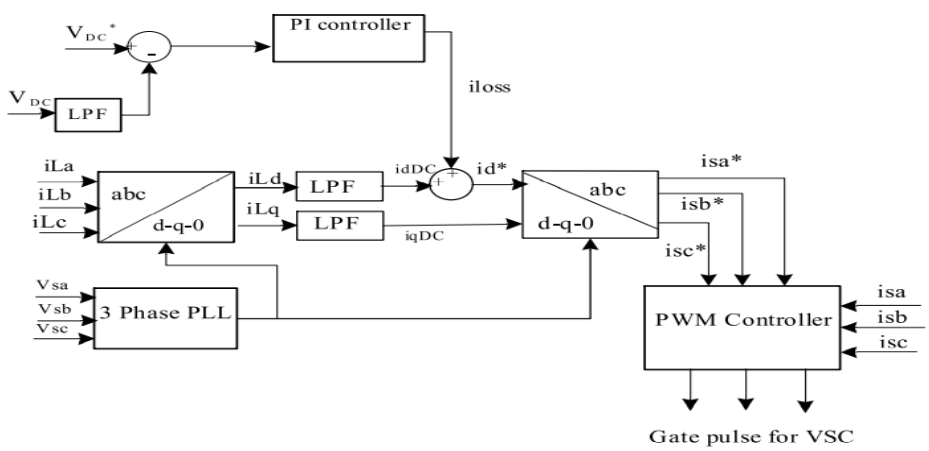


Figure 3.13:Block diagram of SRF based control theory of DSTATCOM (Al-Haddad et al., 2015)

As it can be seen from Fig.3.19 the final out put of the block is three phase gate pulse that used to trigger VSI of DSTATCOM. Measurements of voltages at PCC (vsa, vsb, vsc), Load currents (iLa, iLb, iLc) and the to trigger VSI of DSTATCOM. Measurements of voltages at PCC (vsa, vsb, vsc), Load currents (iLa, iLb, iLc) and the

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \mathrm{Cos}\,\theta & \mathrm{Cos}(\theta-\frac{2\pi}{3}) & \mathrm{Cos}(\theta+\frac{2\pi}{3}) \\ -\mathrm{Sin}\,\theta & -\mathrm{Sin}(\theta-\frac{2\pi}{3}) & -\mathrm{Sin}(\theta+\frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{3.53}$$

DC bus voltage (VDC) are all detected as feedback signals of the selected control unit. Park's transformation is used to convert the load currents in the three phases from measurement block to the dq0 frame (Al-Haddad et al., 2015) see matrix equation.(3.53) above.

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \text{Cos}\,\theta & \text{Sin}\,\theta & 1 \\ \text{Cos}(\theta - \frac{2\pi}{3}) & \text{Sin}(\theta - \frac{2\pi}{3}) & 1 \\ \text{Cos}(\theta + \frac{2\pi}{3}) & \text{Sin}(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} \qquad (3.54)$$

The inverse Park's Transformation in which three phase load current be feeded to three phase PWM controller of the control unit is given by the matrix equation (eqn.3.54) as shown above. Phase-locked loop (PLL) is required for synchronization of right hand side parameters of Park's transformation and inverse Park's Transformation Matrix signals with the instantenuousvoltage level at selected PCC whereas, Low-pass filters (LPFs) are employed to extract the DC components of iLd and iLq (current ripples) from these d–q current components that happens during voltage conversion. Fundamental and DC components of d-axis and q-axis current is given in eqn.(3.55) and eqn.(3.56) below respectively.

$$i_{Ld} = i_{dDC} + i_{dAC} \qquad \text{……………….………..(3.55)}$$

$$i_{Lq} = i_{qDC} + i_{qAC} \qquad \text{……………………….(3.56)}$$

The main aim of the control strategy implemented to control a D-STATCOM used for voltage mitigation is to control the amount of reactive power exchanged between the STATCOM and the supply bus. When the PCC voltage is less than the reference (rated) value then the D-ATACOM generates reactive power and when PCC voltage is more than the reference (rated) value then the D-ATACOM absorbs reactive power(Kumar N, 2014).

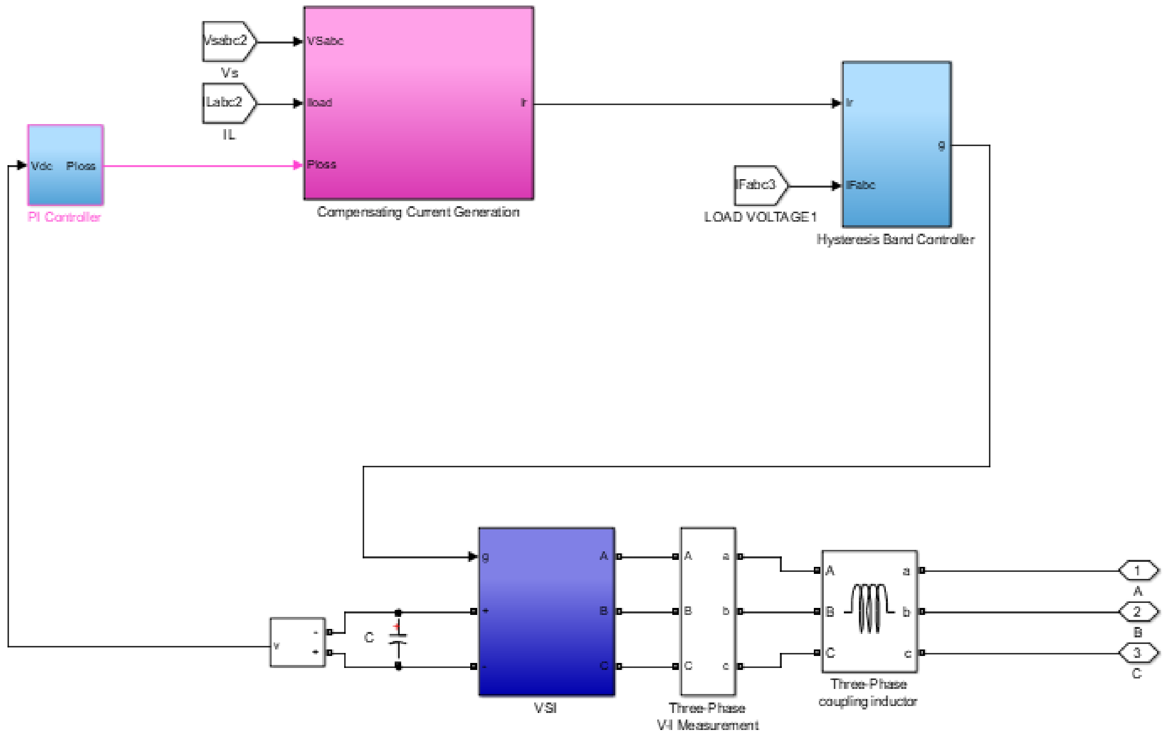


Figure 3.14: MATLAB/SIMULINK Model of VSI type DSTATCOM

3.3.9 Hysteresis Current Control

Hysteresis Current Control (HCC) is a stable, fast and accurate method of generating switching pulses for producing the compensating current in shunt CPDs. To generate the compensator current (Icomp) a hysteresis band ±h is used so that, If $Icomp \geq Iref$ + h, then the compensator current has to be lowered by applying a negative voltage across the output. This is accomplished by turning on the switches on the negative dc line of the inverter. If $Icomp \leq Iref$ −h, then the compensator current has to be raised by applying a positive voltage across the output. This is accomplished by turning on the switches on the positive dc line of the inverter (Sinku, 2015).

The tracking performance of the hysteresis current control method is inversely proportional to the load inductor and the size of the hysteresis band and directly proportional to the magnitude of dc voltage. As the number of switching increased to get a better tracking, the inverter losses will become higher. The MATLAB/SIMULINK model of the hysteresis current control technique is shown in Figure 3.22 below. A hysteresis band of [-h, h] = [-0.1, 0.1] is used for the simulation in this study.

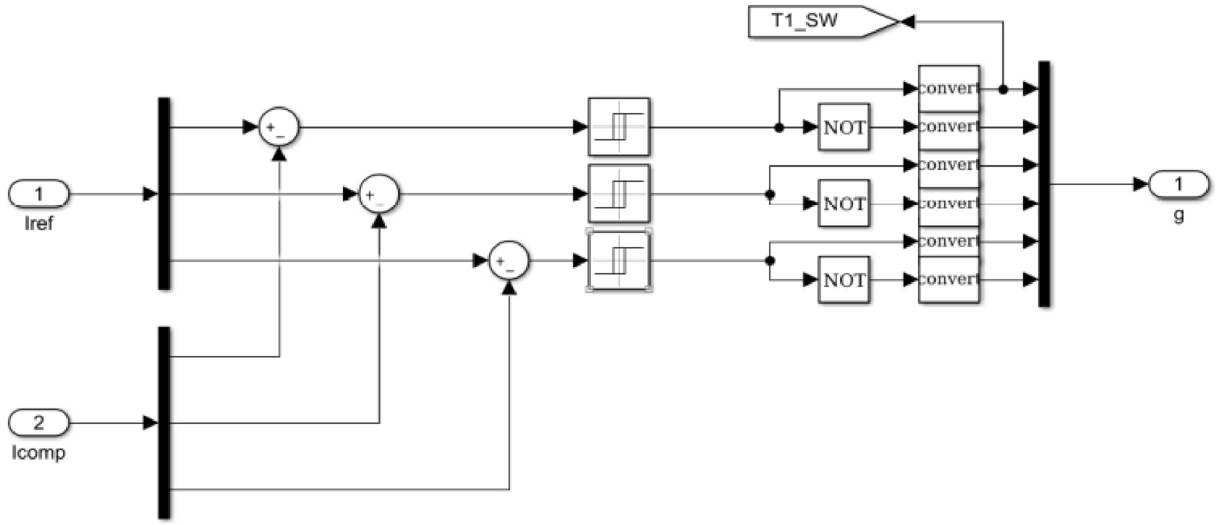


Figure 3.15:SIMULINK Model of Hysteresis Current Control (Sinku, 2015)

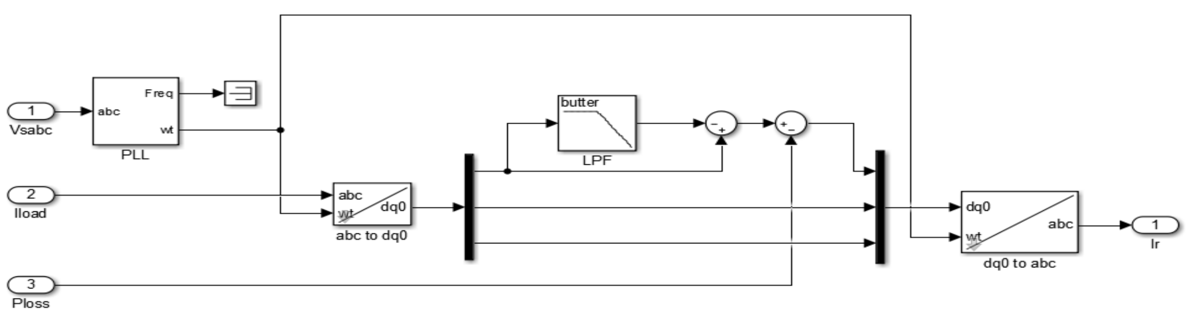


Figure 3.16: SIMULINK Model for Synchronouos Reference Frame (SRF) of DSTATCOM controller (Sinku, 2015).

The SRF controller extracts dc quantities by a low-pass filter, therefore, the non-dc quantities (harmonics) are separated from the reference signal (Dr.P.Vend Katesh et al.,2021).

In the shunt active power filter controlling and generating reference signals first the load currents are converted from abc to the dq0frames. The PLL (phase-locked Loop) signal is obtained from PCC voltages for the generating fundamental unit vectors for the conversion of sensed currents to the dqo reference frame.The PCC voltages are converted to the rotating reference frame usingthe abc–dq0 conversion using the Park’s transformation with unit vectors ($cos\theta$, $sin\theta$) derived from the supply currents using a PLL for generating of fundamental unit vectors (Kidanemariam, 2021).

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Partial model of Factory Power distribution network with DSTATCOM

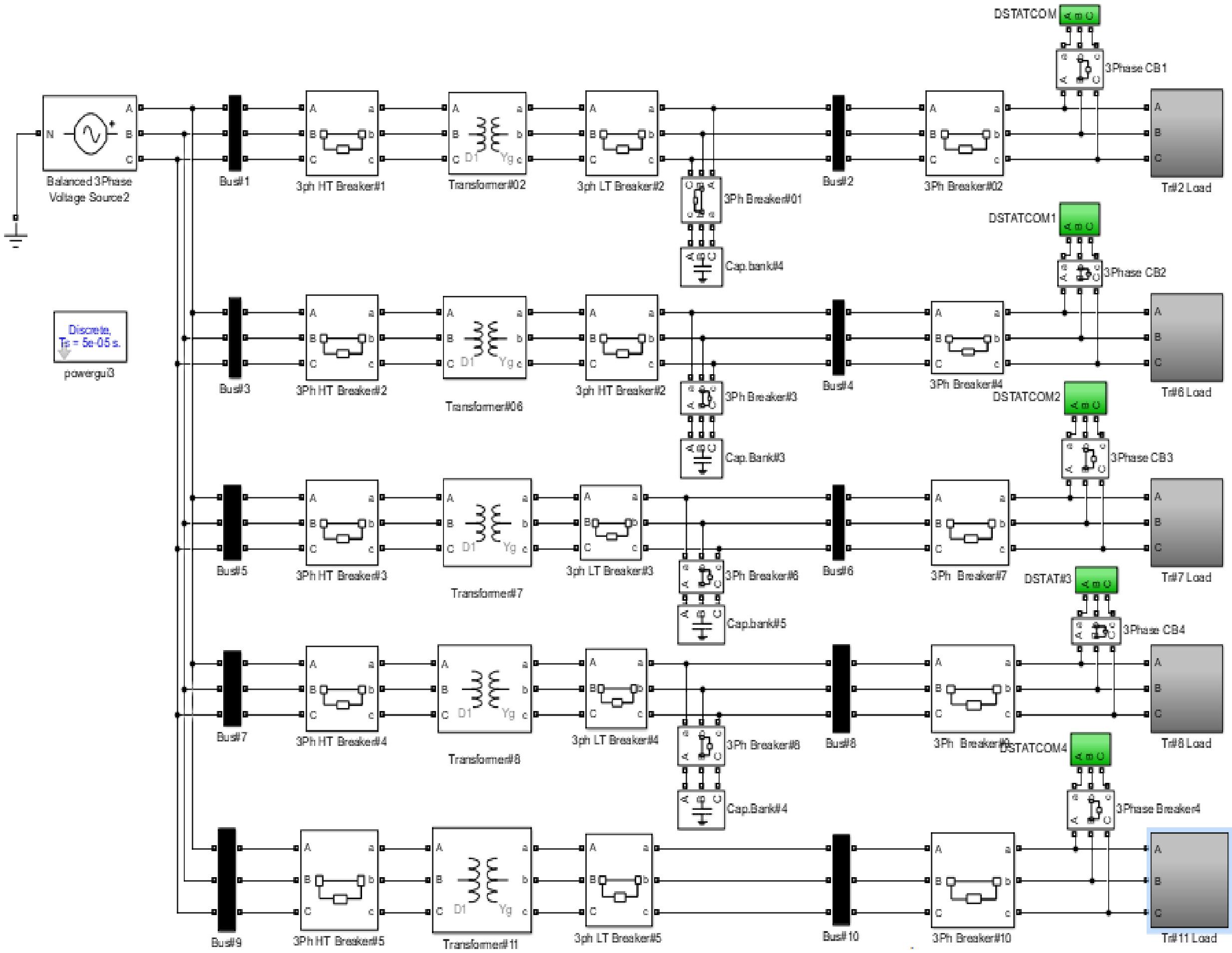


Figure 4.1: Factory partial SIMULINK model with DSTATCOM (Transformer#02,06,07,08 and 11)

Figure 4.1 shows selected part of power distribution system of the factory is modeled with selected current harmonics mitigation device. As it can be seen from this figure transformer#02,transformer#06, transformer#07 and transformer#08 have connected capacitor bank that was installed for power factor correction purpose.

Capacitor bank did not connected at transformer#11 distribution panel as this transformer is temporarily installed here for the purpose of load minimization from transformer#10.

4.2 Simulation Results of SIMULINK Model for selected Distribution Panels

Modeling and simulation was made in MATLAB software and the simulation results with and without designed harmonics mitigation techniques have been done for five selected power distribution panels in the factory.

The Fast Fourier Transform Techniques been used for harmonic distortion spectrum analysis.

It is a real-time, very fast method of performing a spectrum analysis that permit the evaluation of a large number of function. Multichannel analog-digital conversion and micro or mini computers are used for real-time data acquisitionWh. en the waveform is recorded with suitable bandwidth using either analog or digital techniques the Fast Fourier Transform (FFT) calculation of harmonics components,the conversion of engineering units the calculation of stastics and the plotting and printings of the results can be performed off-line in the laboratory using suitable facilities (Kidanemariam, 2021).

The following simulation results found by connecting nonlinear load that represented by bridge rectifier at PCC in combination with linear load connected to each selected transformer power distribution panel for the investigation of harmonic distortion from non-linear load and checking the effectiveness of selected and designed harmonics mitigation device (i.e DSTATCOM for this thesis).

4.2.1 Simulation Result of Transformer#02 Distribution Panel

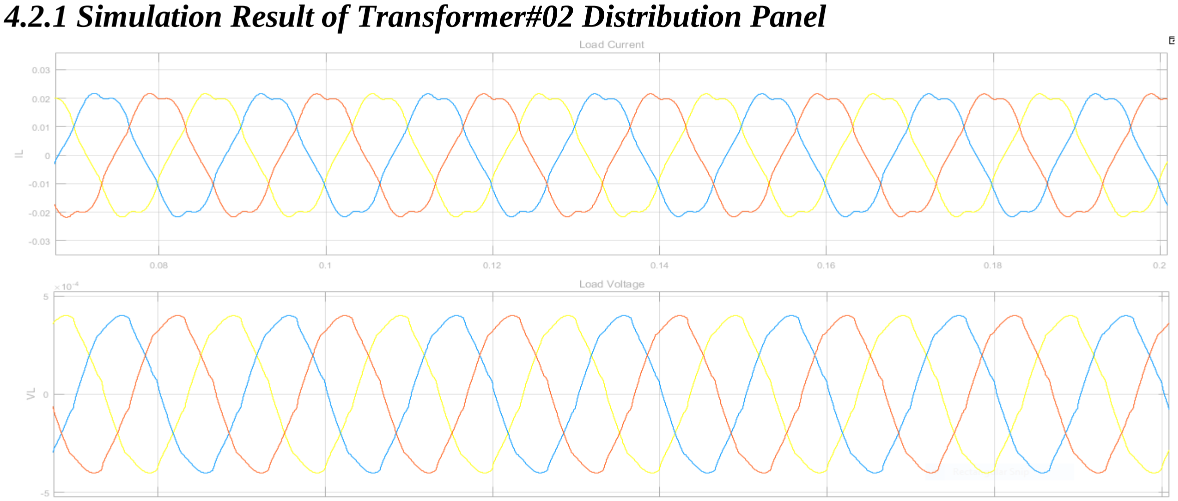


Figure 4.2:Load current and load voltage combined waveform for transformer#02 distribution panel without DSTATCOM

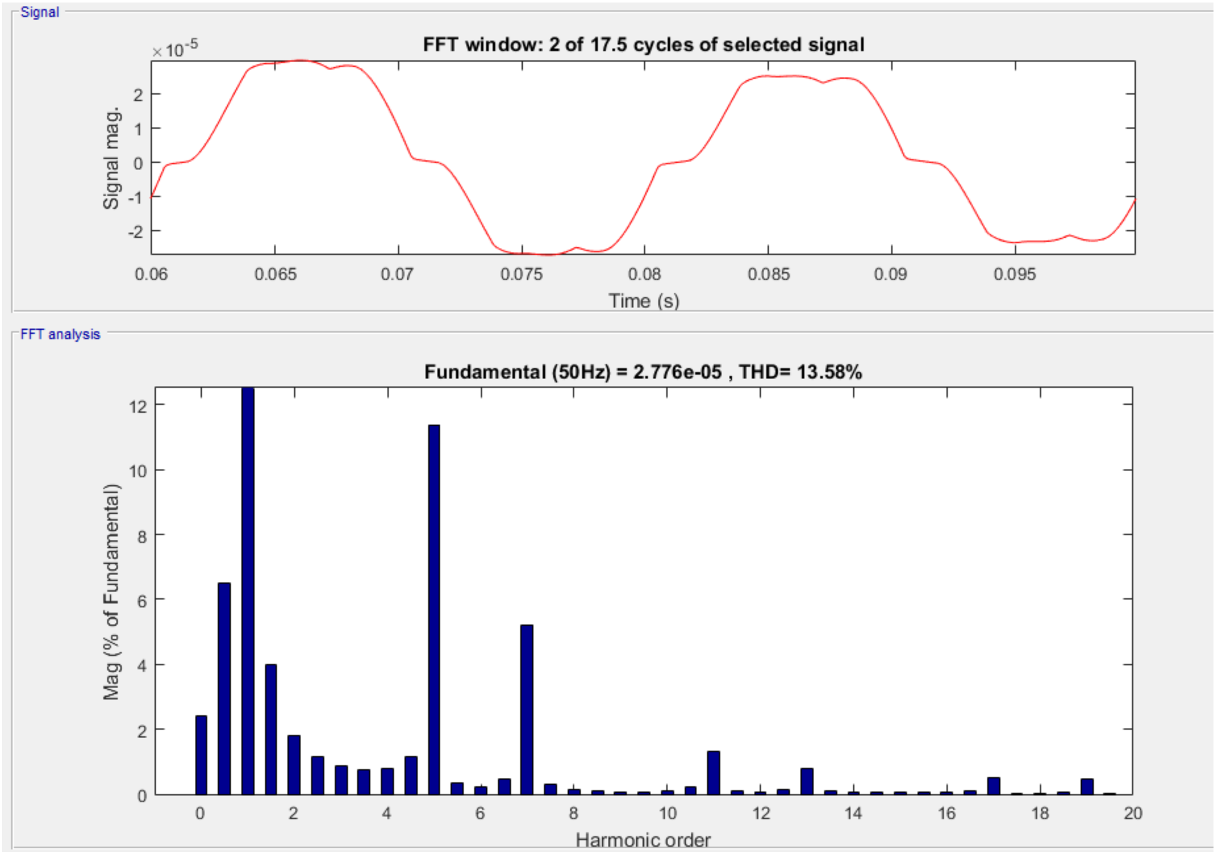


Figure 4.3:Harmonic spectrum of load current for transformer#02 distribution board without DSTATCOM,THDIload=13.58%

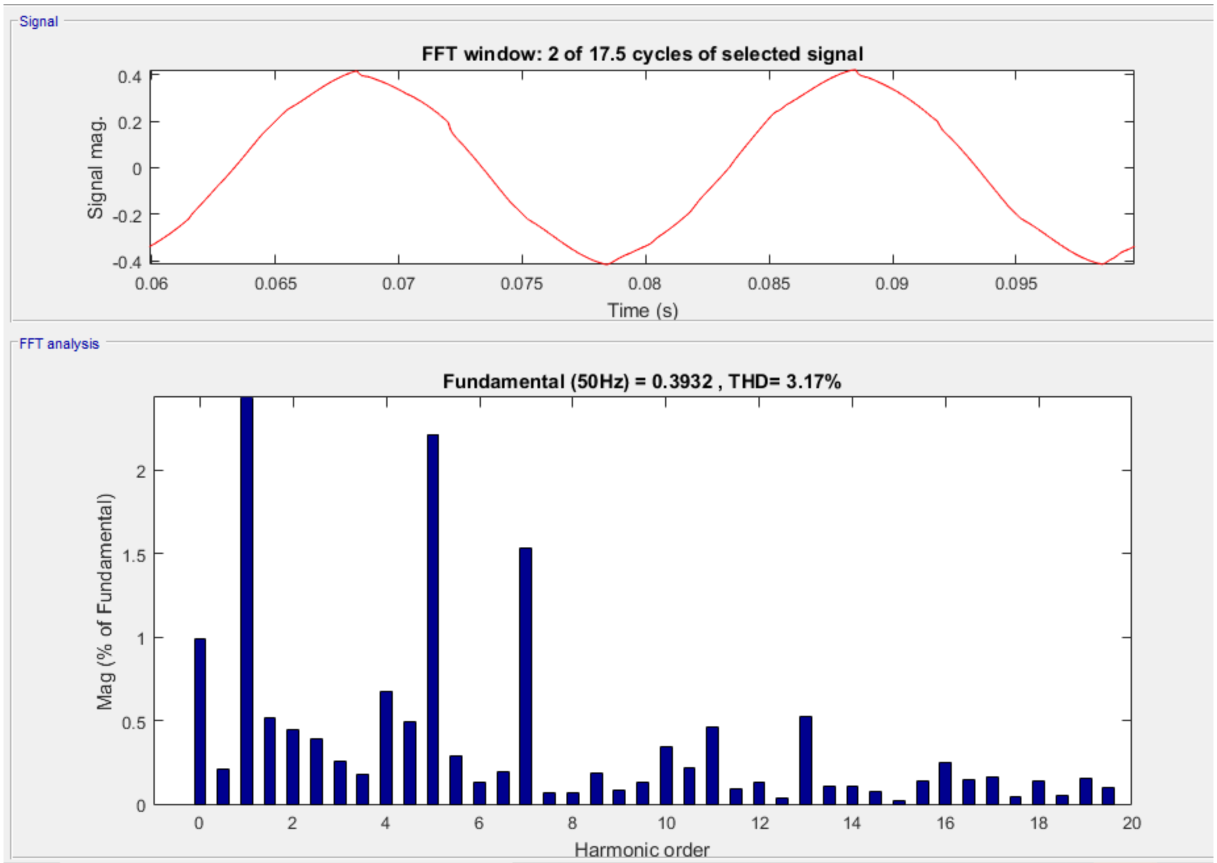


Figure 4.4:Harmonic spectrum of load current at transformer#02 distribution board with DSTATCOM,THDIload=3.17%

From figure 4.4 it can be seen that the percentage of load current THD value is achieved through tuning PI and PID controllers gains by trial and error and the values of these controller gains at which THD of load current 3.17% foundkp=0.08 and ki=0.0008 for PI controller and kp=45, ki=70 and kd=1.75 for PLL's PID controller. More precise and optimum values of these controllers gain can be obtained by tuning them more and more. For this study as load current total harmonics distortion THD_{IL} found below considered standard limits, further tuning of these controlles is not important.

4.2.2 Simulation Result of Transformer#06 Distribution Panel PCC

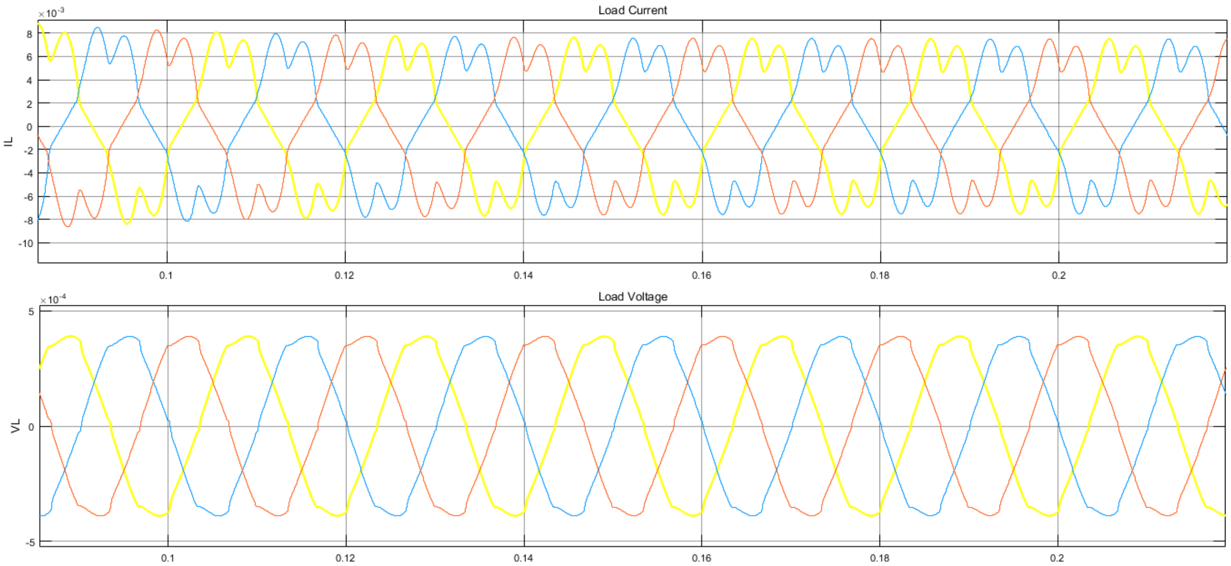


Figure 4.5:Load current and load voltage combined waveform for transformer#06 distribution panel without DSTATCOM`

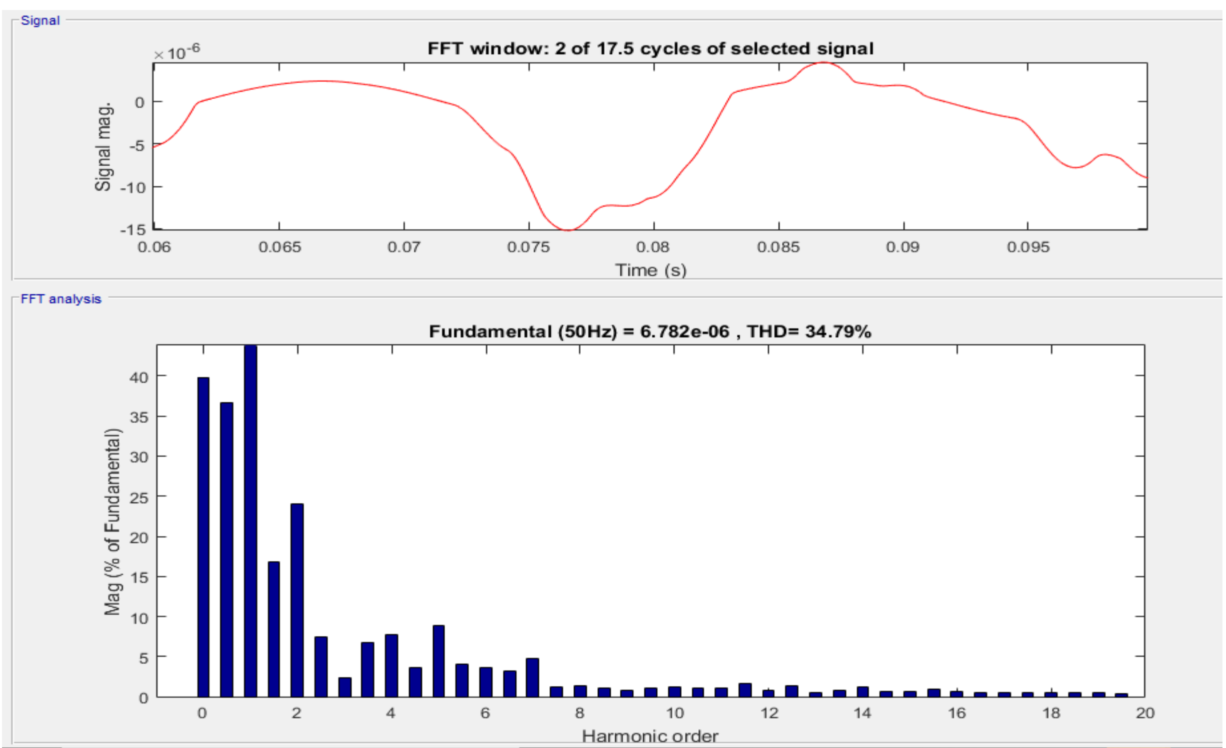


*Figure 4.6:*Harmonic spectrum of load current at transformer#06 distribution board without DSTATCOM,THDIload=34.79%

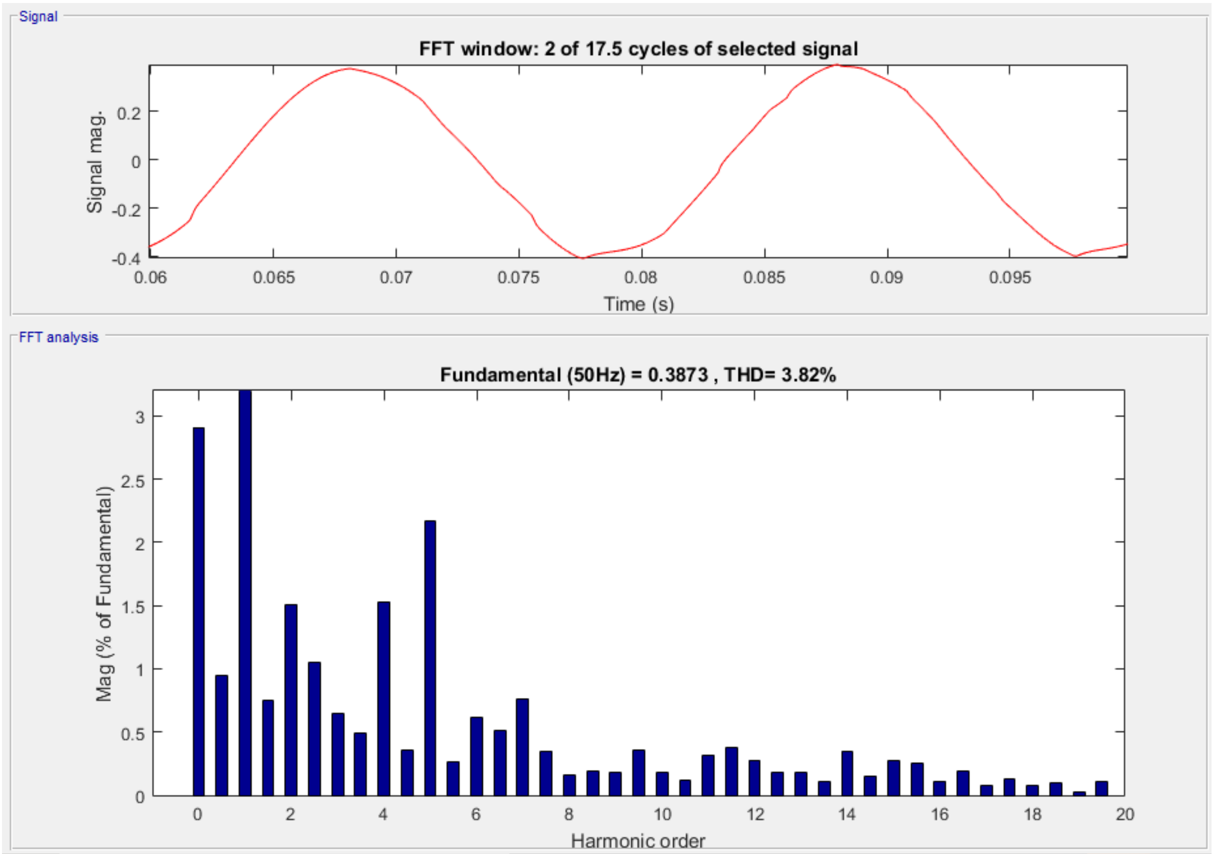


Figure 4.7: Harmonic spectrum of load current at transformer#06 power distribution board with DSTATCOM,THDIload=3.82%

As it can be seen from Figure 4.7 percentage of load current THD value is achieved through tuning PI and PID controllers gains by trial and error and the values of these controller gains at which THD of load current 3.82% foundkp=0.08 and ki=0.008 for PI controller and kp=65, ki=105 and kd=2.5171 for PLL's PID controller. More precise and optimum values of these controllers gain can be obtained by tuning them more and more. For this study as load current total harmonics distortion THD_{IL} found below considered standard limits, further tuning of these controlles is not important.

4.2.3 Simulation Result of Transformer#07 Distribution Panel PCC

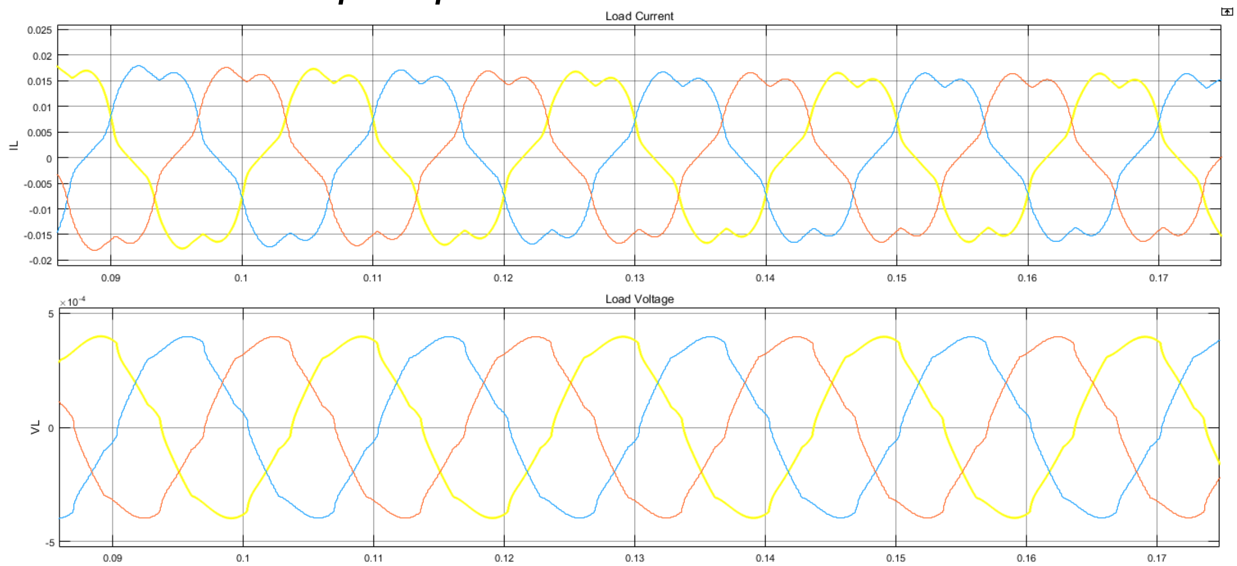


Figure 4.8:Load current and load voltage combined waveform for transformer#07powerdistribution panel without DSTATCOM,THDIL

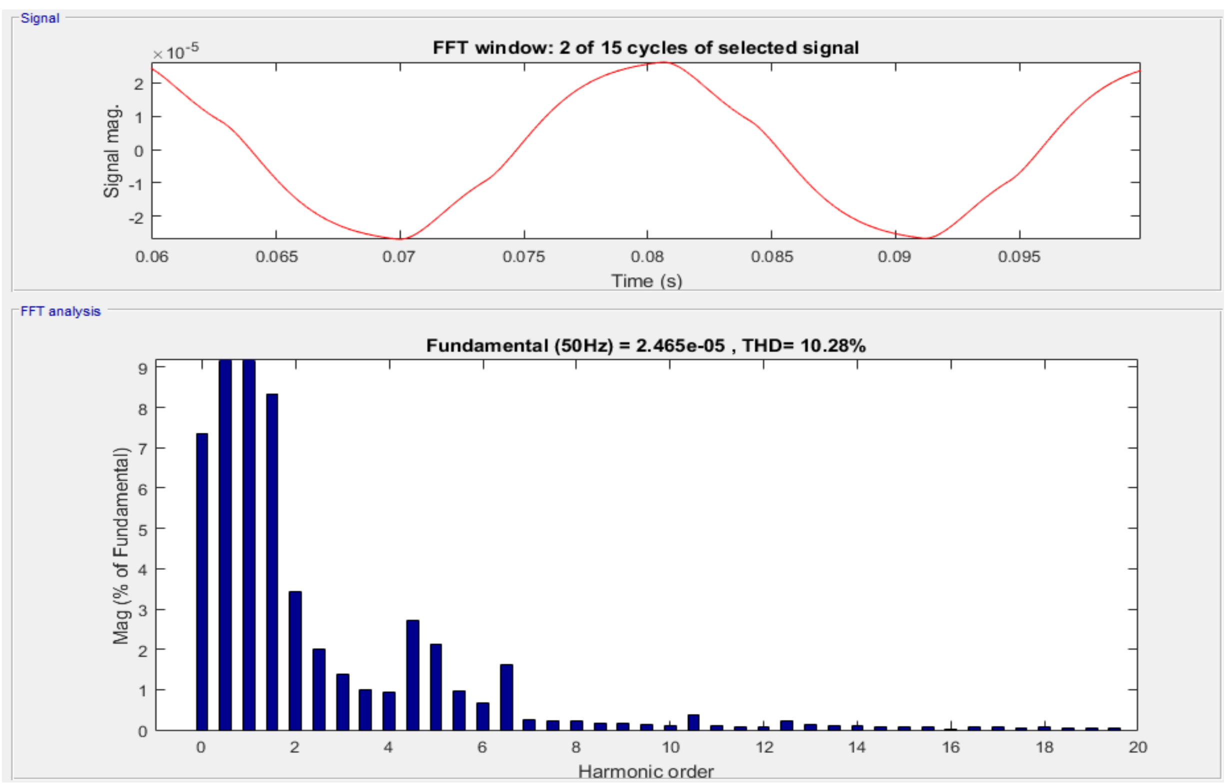


*Figure 4.9:*Harmonic spectrum of load current at transformer#07 distribution board without DSTATCOM,THDIload=10.28%

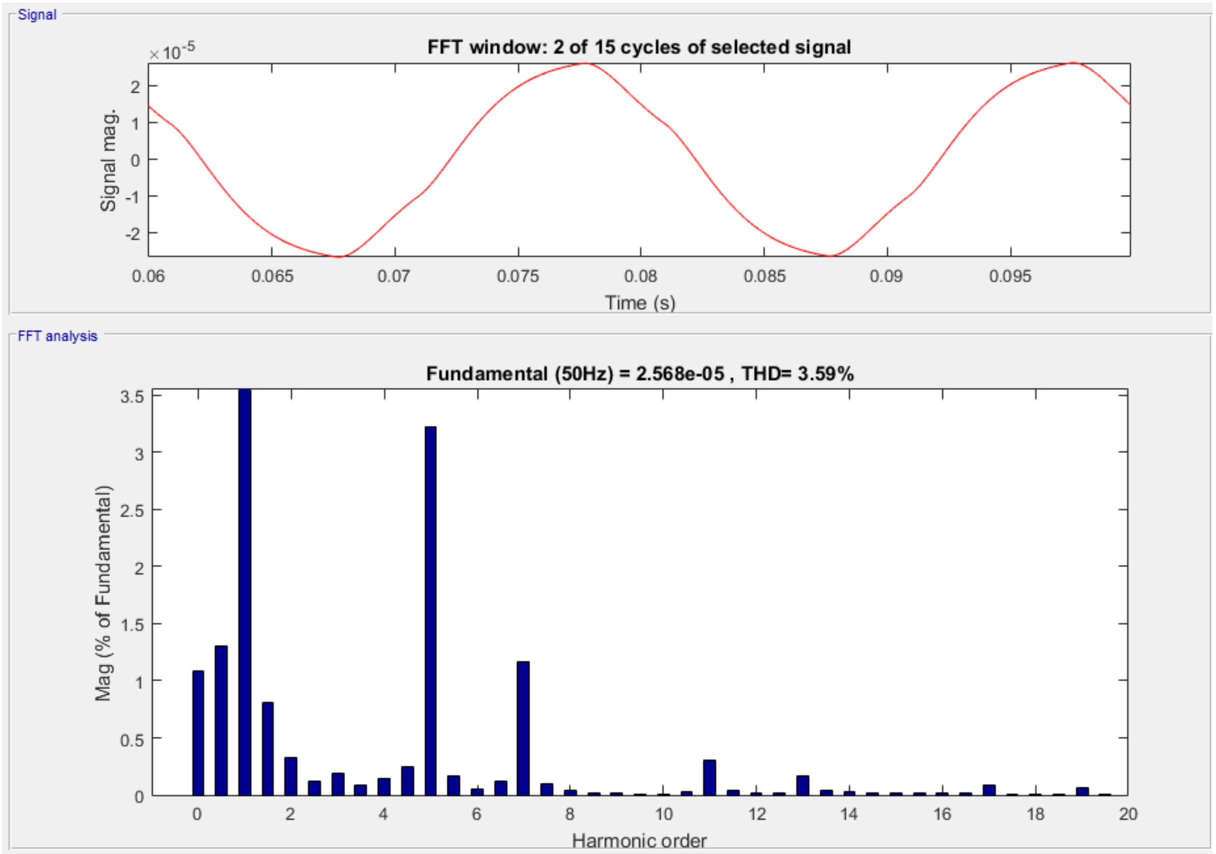


Figure 4.10 Harmonic spectrum of load current at transformer#07 power distribution board with DSTATCOM,THDIload=3.59%

From figure 4.10 it can be seen that the percentage of load current THD value is achieved through tuning PI and PID controllers gains by trial and error and the values of these controller gains at which THD of load current 3.59% foundkp=0.08 and ki=-0.05 for PI controller and kp=-6, ki=145 and kd=-0.505 for PLL's PID controller. More precise and optimum values of these controllers gain can be obtained by tuning them more and more. For this study as load current total harmonics distortion THD_{IL} found below considered standard limits, further tuning of these controlles is not important.

4.2.4 Simulation Result of Transformer#08 Distribution PanelPCC

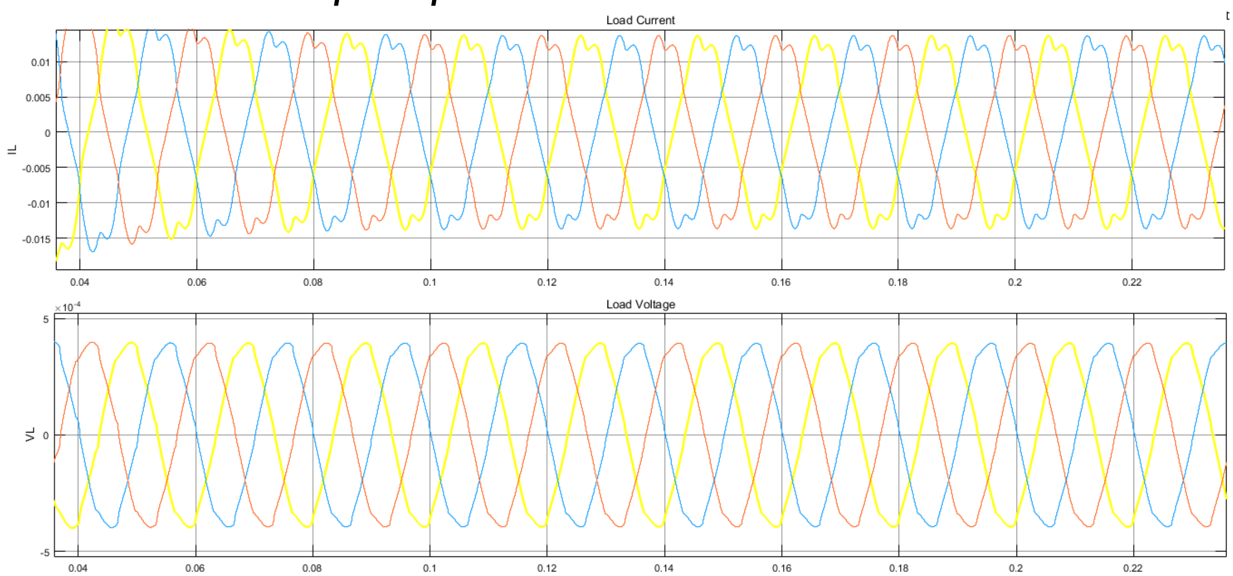


Figure 4.11:Load current and load voltage combined waveform for transformer#08distribution panel without DSTATCOM

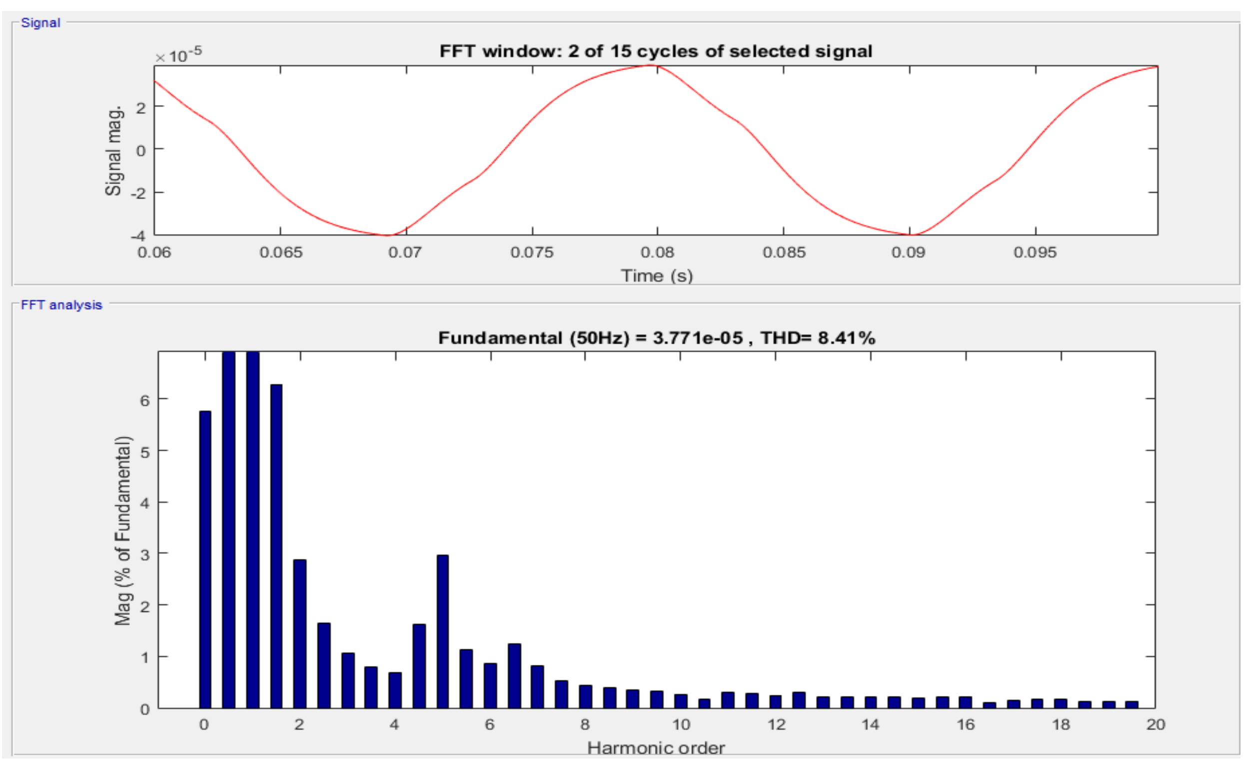


*Figure 4.12***:**Harmonic spectrum of load current at transformer#08 distribution board without DSTATCOM,THDIload=8.41%

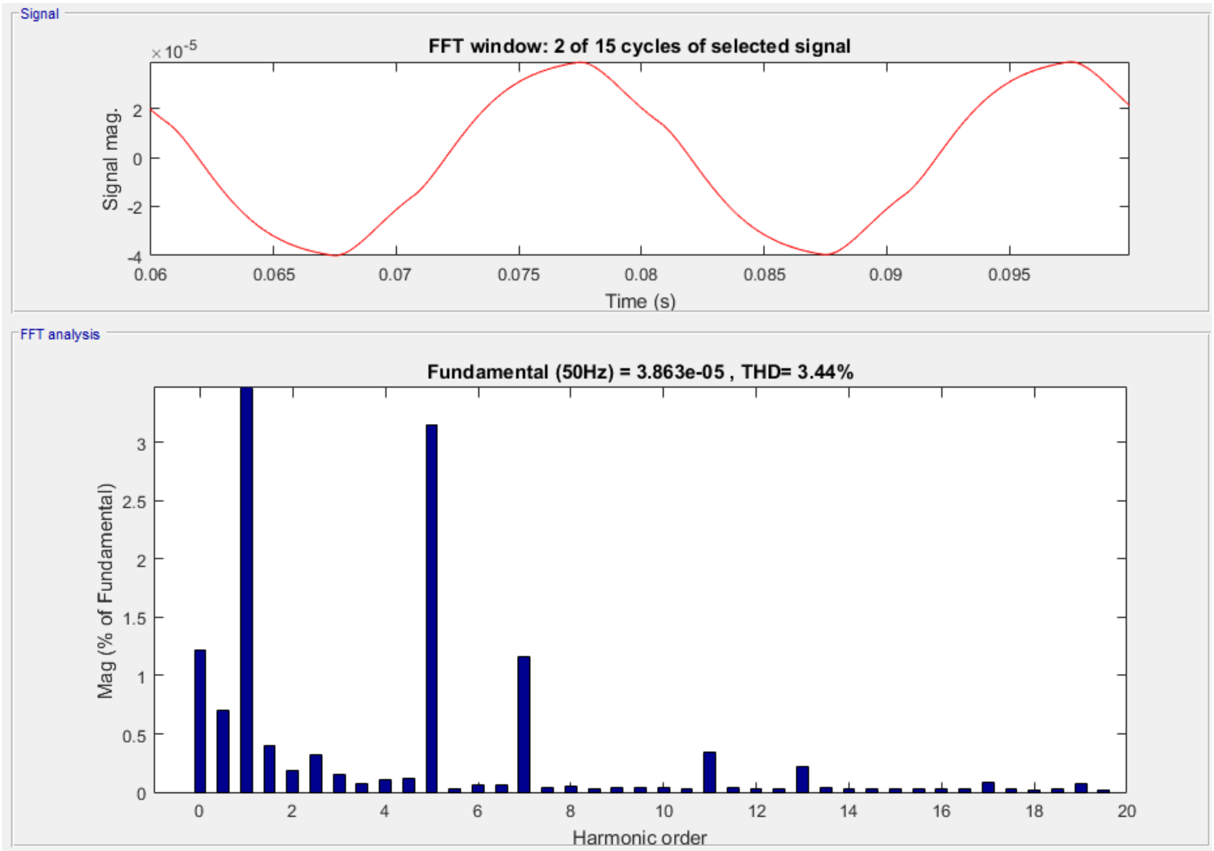


Figure 4.13: Harmonic spectrum of load current at transformer#08 power distribution board with DSTATCOM,THDIload=3.44%

From figure 4.13 it can be seen that the percentage of load current THD value is achieved through tuning PI and PID controllers gains by trial and error and the values of these controller gains at which THD of load current 3.44% foundkp=0.08 and ki=-0.05 for PI controller and kp=-15.6, ki=100 and kd=-0.505 for PLL's PID controller. More precise and optimum values of these controllers gain can be obtained by tuning them more and more. For this study as load current total harmonics distortion THD_{IL} found below considered standard limits, further tuning of these controlles is not important.

4.2.5 Simulation Result of Transformer#11 Distribution Panel PCC

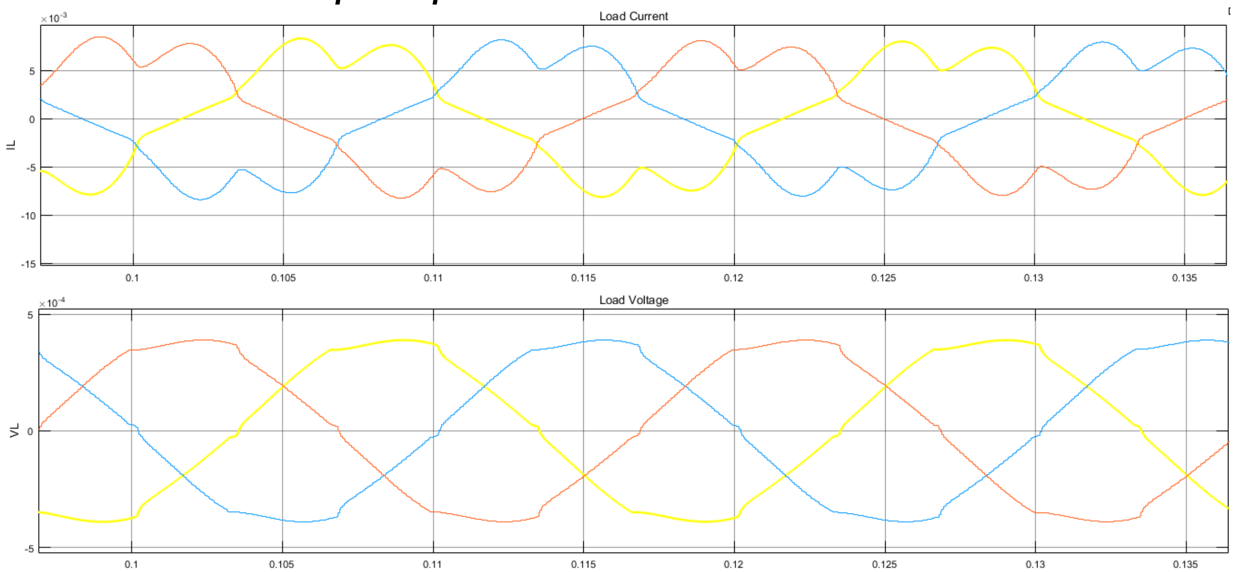


Figure 4.14:Load current and load voltage combined waveform for transformer#11 distribution panel without DSTATCOM

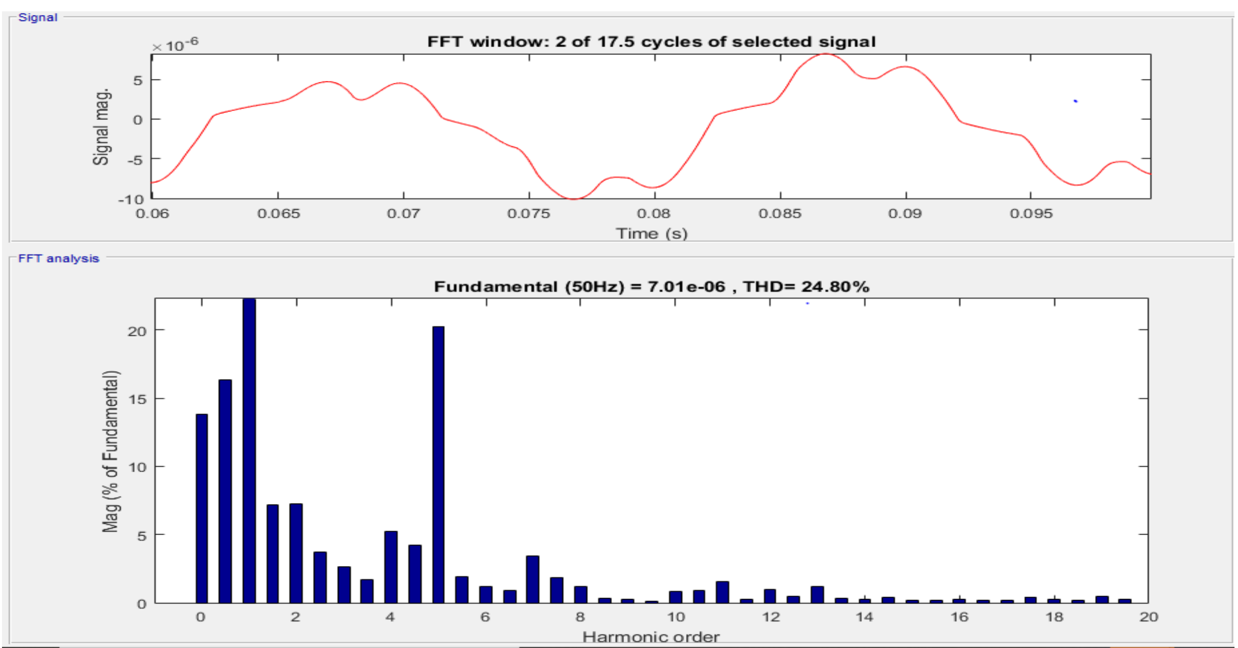


*Figure 4.15:*Harmonic spectrum of load current at transformer#11 distribution board without DSTATCOM,THDIload=24.80%

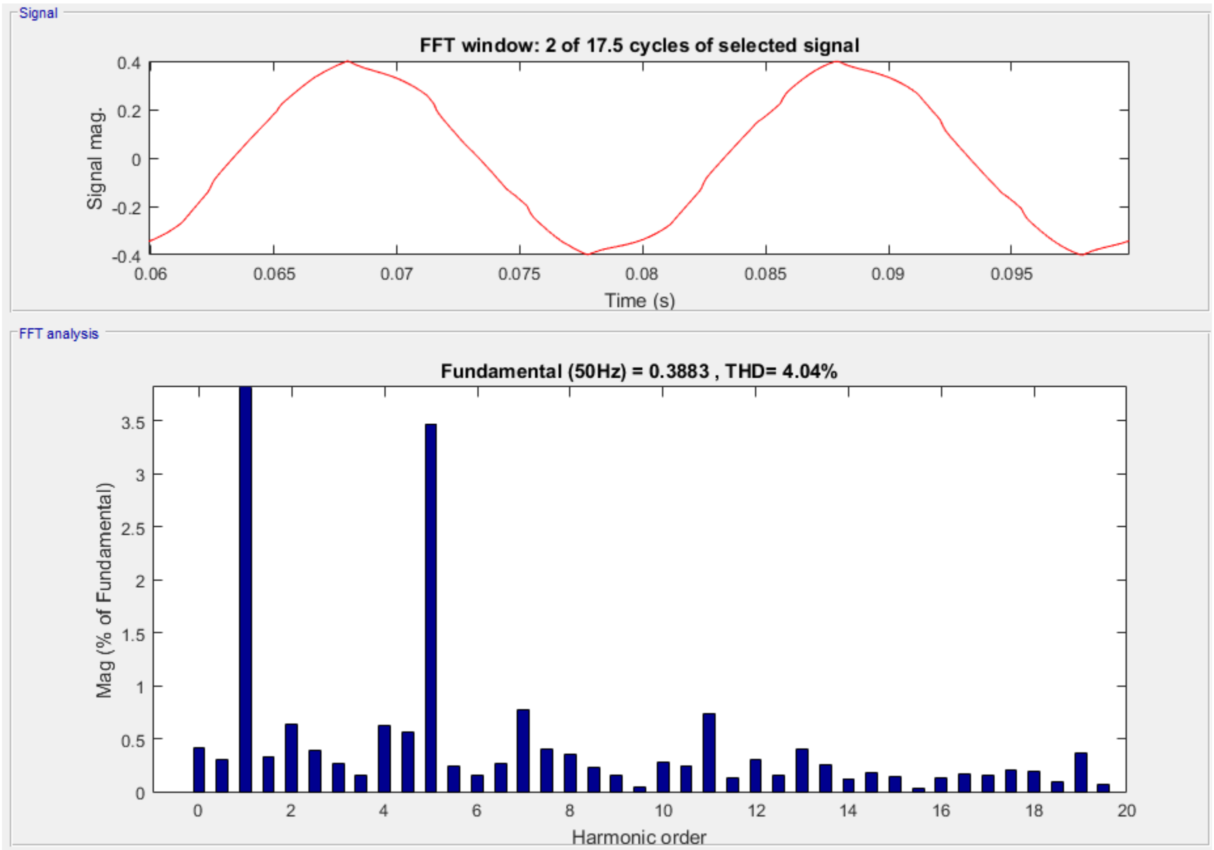


Figure 4.16: Harmonic spectrum of load current at transformer#11 distribution board with DSTATCOM,THDIload=4.04%

From Figure 4.16 it can be seen that the percentage of load current THD value is achieved through tuning PI and PID controllers gains by trial and error and the values of these controller gains at which THD of load current 4.04% found kp=ki=0.0008 for PI controller and kp=45, ki=70 and kd=1.75 for PLL's PID controller. More precise and optimum values of these controllers gain can be obtained by tuning them more and more. For this study as load current total harmonics distortion THD_{IL} found below considered standard limits, further tuning of these controlles is not important.

Table 4.1:Summary of Harmonics distortion analysis in comparison with standard(s).

Distribution Feeder	THDv(%)		TDD(%)		Ratio Isc/IL	Remark
	Actual	IEEE Std519-2014	Actual	IEEE Std519-1992 and IEEEStd 519-2014		
Trafo#1	1.53	8	4.62	5	12.41	Within limit
Trafo#2	2.01	8	13.58	5	1.30	Out of limit
Trafo#3	0.73	8	1.30	5	18.88	Within limit
Trafo#4	1.30	8	7.20	8	25.73	Within limit
Trafo#5	1.70	8	3.63	5	12.40	Within limit
Trafo#6	3.10	8	34.79	8	20.65	Out of limit
Trafo#7	1.52	8	10.26	5	2.56	Out of limit
Trafo#8	1.38	8	8.45	5	2.53	Out of limit
Trafo#10	1.50	8	3.57	8	24.32	Within limit
Trafo#11	1.20	8	24.8	8	34	Out of limit

4.3 Discussion of real-time data and simulation results

From monitored, recorded and tabulated real-time data (table 4.1) and simulation results shown in figure 4.1 through figure 4.16 current and voltage harmonic distortion was analyzed in depth. From those results it was observed that there is both harmonics current and voltage distortion both in each phase and the cumulatively. From selected power distribution panel namely transformer#2,6,7, 8 and 11 of distribution transformer designated as point of common coupling (PCC) results shows there is current harmonics distortion out of the stated IEC and IEEE standards limits.

From monitored, recorded and analyzed real-time taken by using HIOKI 3196 Power Quality Analyzer, it was observed that there is total current harmonics distortion of 8.16%,8.15% and 7.96% in phase A, phase B and phase Crespectively at transformer#02.Among distribution transformers power panel at which harmonics monitoring and recording have been made the highest individual harmonics currents distortion is 5^{th} order was found at transformer#06 power distribution panel and their value is 23.5%, 23.7% and 23.86% in phase A, phase B and phase C respectively. There is also total current harmonics distortion of 7th order found on this distribution transformer panel whose values identified as 8.89%, 8.7% and 8.85% in phase A, phase B and phase C respectively.There is also total harmonics current distortion (THD_I) exist having percentage magnitude of 25.2.%, 25.3% and 23.93% from phase A to phase C respectively. There is both total and individual harmonics current distortion identified at transformer#07 power distribution panel that are out of standard limits recommended in IEEE Std 519-1992 and IEEE Std 519-2014 practices and recommendations. The existed individual harmonics current distortion are 5th order 6.97% , 7.39% and 7.15% in phase A, phase B and phase C respectively and 7th order 5.04%, 4.92% and 5.12% in phase A, phase B and phase C respectively. There is also total harmonics current distortion (THD_I) exist having percentage magnitude of 8.7%, 9.1% and 8.93% from phase A to phase C respectively. It was identified that distribution transformer#08 is the transformer at which relatively the lowest total harmonics current distortion found compared to the other power distribution panel due the fact that there is relatively small size of variable drive (VFD) installed on this transformer's power panel. Theharmonics current distortion foundsome whatbelow the limits stated in the standards and have 4.67%, 4.14% and 3.93% in phase A, phase B and phase C respectively. But the total demand distortion at this distribution panel found 8.45%.

Transformer#11 which was recently repaired and installed for load minimization from other transformers is installed to feed 500kW VFD that drive Tandem B mill#3 in the replacement of steam mill turbine and boiler#3 induced drought fan motor. Real-time measurement taken from this transformer low tension panel shows that there is dominant 5th and 7th order individual phase harmonics current distortion that found out of IEEE Std 519-1992,IEEE Std 519-2014 and IEC 61000-3-4. The 5th order individual phase harmonicscurrent distortion found 10.5%, 11.7% and 11.2% for phase A, phase B and phase B respectively whereas the 7th order harmonics current distortion is 9.10%, 8.90% and 8.89% for phase A, phase B and phase C respectively.Beside to this there is also total harmonics current distortion in each phase and found 14.6%, 15.2% and 14.7% for phase A, phase B and phase C respectively.There noharmonic voltage distortion that exceed the stated standard limits found in any of transformers distribution panel at which measurement was taken. Real-time data measurement by using the instrument called HIOKI 3196 Power Quality Analyzer also show that there is harmonics current distortion flowing in neutral conductors of all transformers. To mitigate these harmonics current distortions whose values found out of the limits DSTATCOM which is among custom power devices (CPD) is selected and designed as well as simulated using MATLAB/SIMULINK model to show its effectiveness.

From the simulation carried out to show the capability of selected harmonics mitigation device shows that the total harmonics current distortion able toconsiderably reduced below the stated limits by tuning the DSTATCOM controller gains to relatively optimum values.Accordindgly as one can see from figure 4.4 it was abled to reduced total load current harmonics distortion found at transformer#2 PCC reduced from 13.58% to3.17%.

Figure 4.7 shows that the introduction of DSTATCOM able to reduce load current total harmonics distortion from 34.79% to 3.82% at transformer#06. Similarly the selected and designed harmonics distortion found reduced total load current harmonics distortion from 10.28% to 3.59%, 8.41% to 3.44% and from 24.80% to 4.04% for transformer#07, transformer#08 and transformer#11 respectively. This shows that selected custom power device for load current harmonics distortion mitigation has the capability to substially reduce current harmonics distortion much below the limits stated in (Hartmann et al., 1993) & (Halpin et al., 2014) standards.

5.CONCLUSIONS AND RECOMMENDATION

5.1 CONCLUSION

Real time data was sufficiently recorded at each point of common coupling (PCCs)of distribution transformer by using the device called HIOKI 3196 Power Quality Analyzer except from transformer#12 and then analyzed and tabulated in tables 3.5B through table 3.14B (Appendix B).The real time data measurement did not done on distribution transformer #12 as there is relatively small electrical load (not sufficient enough) on this transformer due tofactory fabrication workshop machines are almost idle during factory operation period and higher during off season factory overall maintenance time.The records and analysis show that there is 5^{th} and 7^{th} order harmonics current distortion found the dominant order of harmonics found on distribution transformer#2,6,7,8 and 11 PCCs are out of IEEE Std 519-1992,IEEE Std 519-2014 and IEC 61000-3-4 standards. There are also 11^{th} , 13^{th} and 17^{th} order harmonics cureent distortion but with smaller value compared to the dominant order harmonics current distortions. There is neither individual nor total harmonics voltage distortion that above the limits stated in IEEE Std 519-1992, IEEEStd519-2014,IEC61000-2-2 and IEC6100-3-4 standards found at transformer#1,3,4 and 5.From taken real-time data the highest individual and total harmonics voltage distortion found is 2.53% and 3.1% which is on distribution transformer#06 respectively. It was discovered that there is percentage of total harmonic load current distortion out of the stated limits at transformer #2,6,7,8 and 11 PCCs that nessisitatesmitigation of this deviations. The total harmonic load current distortion level is found 13.58%, 34.79%, 8.41%,10.28% and 24.80% at transformer#2,6,7,8 and#11 PCCs respectively. This figures show that the highest percentage of total harmonics current distortion (THDI/TDD) was found on distribution transformer#06 PCC. This is due to the fact that there is large size of variable frequency driven (VFD) load compared to other transformer loads that is responsible for generating harmonics current distortion.This does not mean that there are other sources of harmonics in the factory hence installed on this distribution transformer. Even though their level is different there is identified harmonics current and voltage distortion flowing through neutral conductors of all power distribution panels of transformers and the percentage of harmonics current flowing in neutral conductor is found relatively higher compared to the harmonics voltage distortion. MATLAB simulation results show in figure 4.5 to figure 4.16 shows that it is to reduce the distortion level installing DSTATCOM with SRF control theory.

Accordingly the modeled, designed and simulatedharmonics current distortion mitigation found reduced the total load current harmonics distortion from 13.58% to 3.17%,34.79% to 3.82%, 10.28% to 3.59%,8.41% to 3.44% and from 24.80% to 4.04% for transformer#02 ,transformer#06, transformer#07, transformer#08 and transformer#11 respectively. This implies the levelof reduction for this particular study is found from 65% to 89% of the total load current harmormicsdistortion.

Generally,among the ten distribution transformers PCCs five of them face harmonics current distortion exceeded the standard limits and the simulation results shows that DSTATCOM able to reduce the distortion below to the IEEE Std 519-1992 and IEEEStd 519-2014 standards.

It can be concluded that variable frequency drive (VFD) is found the mojor harmonics sources in Metahara Sugar Factory power distribution power panels.The other important issue is harmonics current flowing in neutral conductors which should be given attention.

5.2 RECOMMENDATION

The solution given for mitigation of load current harmonics distortion problem, DSTATCOM with SRF control theoryfor this particular factory power distribution network should be implemented for safe and reliable operation of electrical, electronics as well as mechanical equipments installed at those distribution transformers at which the level of identified harmonics current distortion found exceeded the recommendation and requirements stated in IEEE Std 519 and IEC61000-3-4standard. Even the installation of new variable frequency drives (VFDs) is increasing without considering the its effects. It is important that installation of additional VFDs should be considered its effect.

If installation of new VFDs is required it is possible to segregate the installation of variable frequency drive on different feeders to reduce its effect, I also recommend this.In the case of factory rehabilitation special attention should be given to power quality issues specifically harmonics problems based on this and additional study about power quality issues.Proper inspection for any loose connection and resizing (if required) and proper installation of neutral conductor that able to carry harmonics current in it that can reduce the probable cause of neutral conductor overloading and failure.

5.3 SUGGESSION FOR FUTURE WORK

The following suggestion for future work for is open researchers

- Indepth study of the effect of harmonics on distribution transformer is require as some transformers are being overheated and terminals some of them being detached
- Study of the effect of capacitor bank installed on transformer in amplification of harmonics to now resonance effect
- Power distribution system of the entire factory needs studyand redesigning as well as correction of power distribution system/installation (may needs investment)
- Harmonics analysis on VFD drive loads (electric motors) is required to know the shared effect of harmonics

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Appendix A :Collected and computed raw data

Table 3.1A: Data collected from metahara sugar factory, factory operation maintenance record log book

No	Failure category	UOM	Factory Operation campaign by year (GC)						Average	Remarks
			2016/17	2017/18	2018/19	2019/2020	2020/21	2021/22		
1	Failed motor stator coil	Pcs	15	33	45	35	20	15	27	Different size of equipment
2	Blown fuses	Pcs	300	200	250	170	200	180	230	
3	Relay tripping	numb	270	300	350	400	300	260	285	
4	Relay failure	Pcs	15	6	10	8	11	7	10	
5	Tripped CBs	Numb	6	7	9	8	7	5	7	
5	Failed CBs	Pcs	0	2	1	0	1	1	0.83	
6	Failed Transformer	Pcs	0	1	0	0	0	2	0.50	
7	Failed contactor	Pcs	15	16	10	12	8	6	11	
8	Failed power cables	Pcs	4	0	2	2	1	0	1.15	
9	Failed Capacitors	Pcs	3	2	2	0	0	0	1.5	
10	Failed VFDs	Pcs	3	4	3	0	0	1	1.83	

Table 3.2A: Collected actual load on each distribution transformer in the factory (case study)

S/N	Trafo	Total load (kw)	Average power factor and demand factor	Max current demand (IL)@ PCC in amps with standby load (A)	Total standby load (kw)	Total load without standby load in (kw) with demand factor	Max current demand (IL)@ PCC in amps without standby load with demand factor	Remarks
1	TR#1	632.8	0.80,0.60	1201.81	Nil	379.68	721.1	Done
2	TR#2	705	0.85,0.60	1260.16	33.5	671.5	1200.29	Done
3	TR#3	883	0.86,0.80	1560	344.5	706.4	1248	Done
4	TR#4	946.6	0.82,0.76	1753.94	257.8	719.42	1438.21	Done
5	TR#5	809.67	0.84,0.82	1518.71	424.07	663.93	1245.34	Done
6	TR#6	1047.8	0.86,0.60	1829.83	7.5	628.68	1110.68	Done
7	TR#7	872.64	0.68,0.35	1949.77	121.37	305.42	682.41	Done
8	TR#8	390.98	0.78,0.35	761.64	70.5	136.84	266.57	Done
9	TR#9	…….		----------	………	…..	………..	Fire accident on 25/1/22
10	TR#10	1079.82	0.88,0.63	1864.33	232	680.3	1174.51	Load transferred from TR#09
11	TR#11	632	0.87,0.60	1091.16	Nil	379.2	654.70	Load from TR#10 toTR#11
12	Diesel Tr#1&2 (TR#12)	436.49	0.85,0.85	780.21	Nil	371.02	663.5	400KVA each in parallel
13	TA cane knife	480	0.83,0.86	111.30	Nil	412.8	95.72	Three phase 3kv supply
14	TB cane knives	1080	0.83,0.72	250.42	Nil	776.6	180.07	Three phase 3kv supply
Tot		**8916.8**				**6831.79**		

Table 3.3A: Calculated and tabulated **Isc/IL** ratio and impedance for each transformer

Trans.No.	Trans.Ratings	%Ztrafo	Isc/IL Ratio	Rtr (Ohm)	Xtr (Ohm)	Xbranch	X=Xtr+X branch	Active power(kw)	Reactive power (kVAR)
Trafo#1	1000kVA	3.89	12.40	0.0778	j0.0129	j0.0553	j0.0682		
Trafo#2	1000kVA	3.90	1.30	0.0778	j0.0129	j0.0023	j0.0152	671.5	416.16
Trafo#3	1000kVA	5.37	18.88	8.475e-3	j1.4125e-3	j0.030e-3	j1.4425e-3		
Trafo#4	1000kVA	3.94	25.73	1.0364e-3	j6.218e-3	j0.575e-3	j6.793e-3		
Trafo#5	1000kVA	3.89	12.40	0.0778	j0.0129	j0.0833	j0.0962		
Trafo#6	1000kVA	4.91	20.65	0.0775	j1.2915e-3	j0.235e-3	j0.5265e-3	628.68	372.04
Trafo#7	1000kVA	4.01	2.53	0.0105	j0.0633	j0.0564	j0.1197	305.42	329.32
Trafo#8	1000kVA	4.01	2.53	0.0105	j0.0633	j0.0077	j0.071	136.84	109.78
Trafo#10	1000kVA	4.17	24.32	1.0969e-3	j6.58e-3	j3.053e-3	j9.633e-3		
Trafo#11	1000kVA	4.03	25.03	1.0969e-3	j6.448e-3	j2.700e-3	j9.148e-3	379.20	304.23
Trafo#12	(1000kVA	2.5	34	9.8054e-4	j5.8832e-3	j0.0503e-3	5.9335e-3		

Table 3.4A: Capacitor steps (capacitor banks) installed onto power distribution panels

No	Transformer Name	Installed capacitor bank in (KVAR)	Observed average power Factor at each PCC	Remark
1	Transformer # 1	137.5	0.80	
2	Transformer # 2	187.5	0.85	9 in number
3	Transformer # 3	225	0.86	
4	Transformer # 5	300	0.82	
5	Transformer # 6	200	0.84	10 in number
6	Transformer # 7	225	0.68	10 in number
7	Transformer # 8	225	0.78	10 in number
8	Normivak Panel	112.5	0.88	Literary '**Normivak'** is Holland name.

Table 3.5A: Summarized Variable Frequency Drive (VFD) driven load in number and capacity on different transformer

S/N	Trafo	No. of VFD units	Drive capacity (kw)	Capacity driven motor (Kw)	Connected load to the drive	pulse number
1	T2	1	200	180	• SA fan for boiler#4	6
2	T4	3	480	480	• BB mach#1-3	6
3	T6	8	415.1	368.70	• ID fan for boiler#4 • Boiler#1-3 screw bagasse feeder • OC filter drum drive#2	6
4	T7	6	725	540	• TB cane carriers (3) • TB cane table (2) • Feed water#03	12 and 6
5	T8	5	225	225	• TA cane carriers(3) • TA cane tables(2)	6
6	T10	2	320	320	• BB machines #4 and #5	6
7	T11	1	500	350	• TB mill#03 drive	12
Total capacity (kw):			2865.1	2463.7		

Appendix B: Recorded and computed Real-time data

Table 3.6B:Recorded and tabulated real time data (rms values) on distribution transformer#**01**

H.ord	Phase A				Phase B				Phase C				Neutral line			
	$\%V_{av}$	V_{av} (V)	$\%I_{av}$	I_{av} (A)	$\%V_{av}$	V_{av} (V)	$\%I_{av}$	I_{av} (A)	$\%V_{av}$	V_{av} (V)	$\%I_{av}$	I_{av} (V)	%vav	V_{av}	%I	I
1	100	220.2	100	720.8	100	220.5	100	725	100	222.3	100	733				
3	0.31	0.85	0.02	0.14	0.03	0.06	0.02	0.15	0.04	0.10	0.27	2				
5	0.85	1.37	0.78	5.60	0.88	1.94	0.16	1.16	0.88	1.95	1.5	11				
7	0.76	1.27	0.64	4.60	0.78	1.73	1.0	7.30	0.81	1.80	0.97	7.1				
11	0.89	1.16	0.58	4.20	0.92	2.03	0.73	5.30	0.92	2.04	0.57	4.2				
13	0.26	0.58	0.06	0.40	0.24	0.52	0.03	0.20	0.24	0.53	0.08	0.6				
15	0.02	0.04	0.06	0.30	0.02	0.05	0.06	0.30	0.02	0.05	0.06	0.2				
17	0.04	0.08	0.03	0.20	0.03	0.06	0.04	0.30	0.04	0.08	0.04	0.3				
19	0.01	0.03	0.04	0.03	0.03	0.06	0.06	0.40	0.02	0.05	0.03	0.2				
Tota	THDv=1.0%		THDI/TDD= 1.16/1.12%		THDv=1.5%		THDI/TDD=4.1/1.23%		THDv=1.53%		THDI/TDD=1.9/1.77%		THDv=8.5%		THDI=93%	

Table 3.7B: Recorded and tabulated real time data (rms values) on distribution transformer#02

H.ord	Phase A				Phase B				Phase C				Neutral line			
	%V_{av}	V_{av} (V)	%I_{av}	I_{av} (A)	%V_{av}	V_{av} (V)	%I_{av}	I_{av} (A)	%V_{av}	V_{av} (V)	%I_{av}	I_{av} (A)	%v	V	%I	I
1	100	221	100	510	100	220	100	527	100	221	100	521				
3	0.17	0.38	0.31	1.6	0.17	0.37	0.3	1.7	0.17	0.37	0.36	1.9				
5	1.47	3.25	6.6	34	1.47	3.23	6.6	35	0.88	1.95	6.6	34.2				
7	1.13	2.50	4.35	22.2	1.29	2.84	4.29	23	1.3	2.88	4.13	21.5				
11	0.52	1.14	1.2	6.1	0.88	1.93	1.14	6.6	0.77	1.71	1.25	6.5				
13	0.24	0.87	1.08	5.5	0.54	1.18	1.00	5.3	0.71	1.58	1.06	5.5				
15	0.33	0.73	0.99	0.53	0.10	0.22	0.06	0.3	0.02	0.04	0.05	0.25				
17	0.21	0.46	0.75	3.8	0.18	0.39	0.74	3.9	0.14	0.32	0.71	3.7				
19	0.19	0.42	0.94	4.8	0.23	0.51	0.89	4.7	0.23	0.50	0.79	4.1				
Tota	THDv=2.01%		THDI/TDD=8. 16/8.03%		THDv=2.2%		THDI/TDD=8. 15/8.01%		THDv=1.91%		THDI/TDD=7. 96/7.83%		THDv= 45%		THDI= 332%	

Table 3.8B: Recorded and tabulated real time data (rms values) on distribution transformer#03

H.ord	Phase A				Phase B				Phase C				Neutral line			
	$\%V_{av}$	V_{av} (V)	$\%I_{av}$	I_{av}(A)	$\%V_{av}$	$V_{av\ (V)}$	$\%I_{av}$	I_{av} (A)	$\%V_{av}$	$V_{av\ (V)}$	$\%I_{av}$	$I_{av\ (A)}$	%	V		%THDI4
1	100	222	100	504	100	224	100	533	100	223	100	515				
3	0.12	0.16	0.12	0.61	0.12	0.26	0.16	0.6	0.09	0.02	0.10	0.83				
5	0.55	1.00	0.31	1.55	0.48	1.07	0.36	1.9	0.64	1.43	0.31	1.95				
7	0.72	0.95	0.52	2.62	0.49	1.0	0.47	2.5	0.45	1.00	0.43	2.52				
11	0.55	0.73	0.29	1.46	0.31	0.70	0.30	1.6	0.51	1.13	0.24	1.45				
13	0.20	0.35	0.28	1.40	0.15	0.33	0.26	1.4	0.26	0.59	0.17	1.20				
15	0.13	0.19	0.26	1.31	0.05	0.12	0.23	1.2	0.02	0.04	0.15	0.75				
17	0.03	0.07	0.27	1.35	0.08	0.19	0.07	0.4	0.04	0.09	0.08	0.42				
19	0.06	0.14	0.06	0.30	0.14	0.31	0.08	0.3	0.03	0.07	0.04	0.20				
Tota	THDv=0.73%		THDI/TDD=0.82/0.81%		THDv=0.65%		THDI/TDD= 0.76/0.75%		THDv=0.55%		THDI/TDD= 0.75/0.0.74%		THDv= 32%		THDI= 121%	

Table 3.9B: Recorded and tabulated real time data (rms values) on distribution transformer#04

H.ord	Phase A				Phase B				Phase C				Neutral line			
	%Vav	V_{av} (V)	%I_{av}	I_{av} (A)	%Vav	V_{av} (V)	%I_{av}	I_{av}(A)	%V_{av}	V_{av} (A)	%I_{av}	I_{av} (A)	%v	V	%I	I
1	100	227	100	332	100	228	100	424	100	228	100	448				
3	0.04	0.09	0.90	3.0	0.05	0.1	0.90	3.8	0.02	0.04	1.05	4.7				
5	0.89	2.01	4.25	14.1	0.85	1.9	3.66	15.5	0.90	2.06	3.3	14.6				
7	0.68	1.54	2.92	9.7	0.72	1.6	2.12	9.0	0.70	1.60	1.99	8.9				
11	0.66	1.49	1.69	5.6	0.60	1.36	1.23	5.2	0.55	1.26	1.25	5.6				
13	0.29	0.65	0.48	1.6	0.24	0.55	0.50	2.1	0.15	0.35	0.25	1.1				
15	0.06	0.08	0.04	0.2	0.02	0.04	0.05	0.21	0.02	0.03	0.02	0.1				
17	0.02	0.05	0.15	0.5	0.03	0.06	0.10	0.42	0.03	0.07	0.09	0.4				
19	0.02	0.04	0.06	0.2	0.14	0.31	0.08	0.4	0.09	0.02	0.04	0.2				
Tota	THDv=1.3%		THDI/TDD=5.5/2.58%		THDv=1.2%		THDI/TDD=4.5/2.6%		THDv=1.07%		THDI/TDD=4.16/2.46%		THDv= 87%		THDI= 278%	

Table 3.10B: Recorded and tabulated real time data (rms values) on distribution transformer#05

H.ord	Phase A				Phase B				Phase C				Neutral line			
	%Vav	V_{av} (V)	$\%I_{av}$	I_{av} (A)	%Vav	V_{av} (V)	$\%I_{av}$	I_{av}(A)	$\%V_{av}$	V_{av} (A)	$\%I_{av}$	I_{av} (A)	%v	V	%I	I
1	100	223	100	425	100	226	100	399	100	226	100	436				
3	0.78	1.75	2.26	9.6	0.39	0.88	0.33	3.3	0.44	0.99	2.27	9.9				
5	0.92	2.06	0.96	4.1	0.29	0.65	0.33	1.2	0.62	1.4	0.71	3.1				
7	0.61	1.35	0.28	1.1	0.38	0.87	0.25	1.1	0.49	1.1	1.20	1.3				
11	0.94	2.1	0.26	2.1	0.49	1.11	0.30	1.0	0.97	2.19	0.60	2.6				
13	0.37	0.82	0.66	0.5	0.43	0.97	0.58	2.3	0.47	1.07	0.46	2.0				
15	0.15	0.34	0.28	1.2	0.03	0.06	0.08	1.3	0.11	0.25	0.21	0.9				
17	0.04	0.08	0.27	0.6	0.05	0.11	0.05	0.2	0.08	0.17	0.12	0.5				
19	0.02	0.04	0.02	0.4	0.04	0.10	0.08	0.3	0.03	0.06	0.07	0.3				
Tot	THDv=1.7%		THDI/TDD=2. 54/1.98%		THDv=0.9%		THDI/TDD= 0.98/0.84%		THDv=1.4 %		THDI/TDD=2. 5/2.05%		THDv= 24%		THDI= 35%	

Table 3.11B: Recorded and tabulated real time data (rms values) on distribution transformer#06

H.ord	Phase A				Phase B				Phase C				Neutral line			
	%Vav	V_{av} (V)	%I_{av}	I_{av} (A)	%Vav	V_{av} (V)	%I_{av}	I_{av}(A)	%V_{av}	V_{av} (A)	%I_{av}	I_{av} (A)	%v	V	%I	I
1	100	226.7	100	431	100	226.6	100	438	100	226.6	100	433				
3	0.06	0.14	1.73	7.47	0.1	0.23	1.9	8.4	0.06	0.13	0.45	1.94				
5	2.5	5.66	23.5	101.5	2.5	5.66	23.7	103.9	2.53	5.74	23.86	103.3				
7	0.54	1.23	8.89	38.3	1.67	3.77	8.7	38.1	1.7	3.8	8.85	38.33				
11	0.44	1.0	0.22	0.93	0.07	0.16	0.34	1.48	0.03	0.07	0.10	0.45				
13	0.43	0.98	0.02	0.15	0.03	0.06	0.23	1.1	0.02	0.05	0.07	0.31				
15	0.03	0.06	0.02	0.1	0.03	0.05	0.23	1.0	0.02	0.04	0.07	0.30				
17	0.43	0.97	0.28	1.22	0.23	0.52	0.18	0.78	0.36	0.81	2.15	0.21				
19	0.27	0.62	0.13	0.55	0.26	0.59	0.15	0.68	0.27	0.61	1.11	1.28				
Tota	THDv=2.66%		THDI/TDD= 25.2/21.54%		THDv=3.01%		THDI/TDD= 25.3/21.45%		THDv=3.1.%		THDI/TDD= 23.93/20.22%		THDv= 53%		THDI= 300%	

Table 3.12B: Recorded and tabulated real time data (rms values) on distribution transformer#07

H.ord	Phase A				Phase B				Phase C				Neutral line			
	%Vav	V_{av} (V)	$\%I_{av}$	I_{av} (A)	%Vav	V_{av} (V)	$\%I_{av}$	I_{av}(A)	$\%V_{av}$	V_{av} (A)	$\%I_{av}$	I_{av} (A)	%v	V	%I	I
1	100	225.5	100	331.6	100	225	100	343.7	100	226	100	343.9				
3	0.07	0.16	0.66	2.2	0.09	0.21	1.05	3.6	0.15	0.34	0.96	3.3				
5	1.07	2.42	6.97	23.1	1.11	2.5	7.39	25.4	1.12	2.52	7.15	24.6				
7	0.73	1.64	5.04	16.7	0.73	1.65	4.92	16.9	0.72	1.65	5.12	17.6				
11	0.45	1.01	1.18	3.9	0.41	0.93	1.28	4.4	0.53	1.20	1.02	3.5				
13	0.45	1.02	0.63	2.1	0.12	0.26	0.29	1.0	0.04	0.97	0.52	1.8				
15	0.02	0.05	0.15	0.50	0.03	0.07	0.26	0.90	0.04	0.09	0.23	0.80				
17	0.15	0.33	0.30	1.0	0.06	0.15	0.19	0.65	0.18	0.40	0.25	0.85				
19	0.17	0.34	0.10	0.32	0.02	0.05	0.17	0.6	0.15	0.33	0.02	0.07				
Tota	THDv=1.45%		THDI/TDD= 8.73/8.69%		THDv=1.4%		THDI/TDD= 9.1/9.03%		THDv=1.52%		THDI/TDD= 8.93/8.90%		THDv= 33.4%		THDI= 151.9%	

Table 3.13B: Recorded and tabulated real time data (rms values) on distribution transformer#08

H.ord	Phase A				Phase B				Phase C				Neutral line			
	%Vav	V_{av} (V)	$\%I_{av}$	I_{av} (A)	%Vav	V_{av} (V)	$\%I_{av}$	I_{av}(A)	$\%V_{av}$	V_{av} (A)	$\%I_{av}$	I_{av} (A)	%v	V	%I	I
1	100	226.6	100	393.8	100	226.5	100	406	100	227	100	396				
3	0.07	0.15	0.27	1.07	0.18	0.40	0.3	1.2	0.03	0.06	0.32	1.27				
5	0.91	2.07	3.69	14.53	0.91	2.05	3.18	12.9	0.93	2.12	3.06	12.1				
7	0.45	1.02	2.37	9.33	0.79	1.78	2.18	8.85	0.74	1.68	2.1	8.3				
9	0.04	0.09	0.07	0.28	0.22	0.50	0.06	0.24	0.03	0.07	0.08	0.33				
11	0.44	0.99	1.08	4.26	0.40	0.90	1.11	4.49	0.59	1.33	0.95	3.77				
13	0.40	0.90	0.35	1.37	0.35	0.80	0.38	1.56	0.36	0.81	0.32	1.26				
15	0.08	0.19	0.03	0.13	0.03	0.07	0.26	0.90	0.01	0.03	0.03	0.10				
17	0.14	0.32	0.24	0.96	0.26	0.60	0.26	1.05	0.06	0.13	0.21	0.83				
19	0.18	0.40	0.11	0.45	0.18	0.40	0.14	0.56	0.02	0.05	0.09	0.36				
Tota	THDv=1.19%		THDI/TDD= 4.674.55%		THDv=1.37%		THDI/TDD= 4.14/4.05%		THDv=1.38%		THDI/TDD= 3.93/3.9%		THDv= 42.1%		THDI= 225.15%	

Table 3.14B: Recorded and tabulated real time data (rms values) on distribution transformer#10

H.ord	Phase A				Phase B				Phase C				Neutral line			
	%Vav	V_{av} (V)	$\%I_{av}$	I_{av} (A)	%Vav	V_{av} (V)	$\%I_{av}$	I_{av}(A)	$\%V_{av}$	V_{av} (A)	$\%I_{av}$	I_{av} (A)	%v	V	%I	I
1	100	227	100	408	100	228	100	633	100	226	100	484				
3	0.04	0.10	0.76	3.11	0.05	0.12	0.47	2.95	0.24	0.54	0.66	3.18				
5	0.39	0.88	1.47	6.00	0.32	0.72	0.81	5.15	0.49	1.12	1.04	5.04				
7	0.27	0.62	0.82	3.34	0.25	0.57	0.70	4.42	0.23	0.51	1.00	4.86				
11	0.23	0.52	0.45	1.83	0.52	1.18	0.25	1.56	0.22	0.50	0.47	2.28				
13	0.18	0.41	0.29	1.17	0.35	0.80	0.13	0.80	0.19	0.42	0.30	1.44				
15	0.01	0.03	0.02	0.10	0.01	0.03	0.02	0.10	0.03	0.06	0.03	0.13				
17	0.02	0.04	0.09	0.36	0.03	0.07	0.06	0.40	0.03	0.07	0.03	0.14				
19	0.02	0.04	0.04	0.16	0.02	0.05	0.03	0.20	0.17	0.02	0.05	0.24				
Tota	THDv=0.50%		THDI/TDD=2.24/2.24%		TH Dv=0.8%		THDI/TDD=1.52/1.52%		THDv=1.5%		THDI/TDD=2.3/2.3%		THDv47.3%		THDI=98.1%	

Table 3.15B: Recorded and tabulated real time data (rms values) on distribution transformer#11

H.ord	Phase A				Phase B				Phase C				Neutral line			
	%Vav	V_{av} (V)	$\%I_{av}$	I_{av} (A)	%Vav	V_{av} (V)	$\%I_{av}$	I_{av}(A)	$\%V_{av}$	V_{av} (A)	$\%I_{av}$	I_{av} (A)	%v	V	%I	I
1	100	229.5	100	297	100	229	100	302	100	229.4	100	298				
3	0.07	0.15	0.65	1.94	0.05	0.11	0.39	1.18	0.04	0.21	0.35	1.04				
5	0.48	1.10	10.5	31.2	0.52	1.19	11.7	35.4	0.49	1.13	11.2	33.6				
7	0.66	1.51	9.1	27.1	0.63	1.44	8.90	26.9	0.62	1.42	8.89	26.5				
11	0.63	1.45	2.57	7.64	0.67	1.53	3.11	9.4	0.61	1.39	2.8	8.33				
13	0.28	0.64	1.14	3.38	0.31	0.71	1.36	4.12	0.31	0.70	1.32	3.93				
15	0.02	0.05	0.07	0.20	0.02	0.05	0.07	0.20	0.04	0.02	0.03	0.10				
17	0.19	0.43	1.00	2.98	0.17	0.40	1.40	4.24	0.20	0.47	0.58	1.73				
19	0.14	0.33	0.65	1.92	0.13	0.30	0.70	2.10	0.14	0.31	0.50	1.48				
Tota	THDv=1.13%		THDI/TDD= 14.6/13.65%		THDv=1.2%		THDI/TDD= 15.2/14.88%		THDv=1.1%		THDI/TDD= 14.7/14.37%		THDv= 27.6%		THDI= 54.7%	