Analysis and Mitigation of Power Quality Issues.

A Case Study: Assela Malt Factory.

Tamiru Bedada Sime

A Thesis Submitted to the Department of Electrical Power and Control Engineering

Collage of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirements for the Degree of Master's in Electrical Power and Control Engineering

(Power System Engineering)

Office of Graduate Studies

Adama Science and Technology University

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Adama, Ethiopia

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DECLARATION

I declare that this Thesis entitled **“Analysis and Mitigation of Power Quality Issues. A Case Study: Assela Malt Factory.”** is my original work and has not been submitted for the award of any academic degree in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Tamiru Bedada Sime	_________	_______________
Name of student	Signature	Date

RECOMMENDATION

I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled "**Analysis and Mitigation of Power Quality Issues. A Case Study: Assela Malt Factory**." prepared under my guidance by Tamiru Bedada Sime. Therefore, I recommend the submission to the department for further review and evaluation.

Dr. Kena Likassa	__________	20/06/25
Advisor	Signature	Date

APPROVAL PAGE OF MSc THESIS

I, here by certify that the recommendation and suggestions given by the thesis review committee are appropriately incorporated in to the final thesis entitled **"Analysis and Mitigation of Power Quality Issues. A Case Study: Assela Malt Factory."** by Tamiru Bedada Sime.

Dr. Kena Likassa	________	20/06/25
Advisor	Signature	Date

We, the undersigned, members of the Board of Reviewers of the thesis by Tamiru Bedada Sime have read and evaluated the thesis entitled "**Analysis and Mitigation of Power Quality Issues. A Case Study: Assela Malt Factory**." and examined the candidate during the open defense. This is, therefore, to certify that the thesis is accepted for Electrical Power and Control Engineering (Power System Engineering).

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Finally, approval and acceptance of the thesis is contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and college Graduate Committee (CGC).

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LIST OF ABBREVIATION

Abbreviation	Description
A	Ampere
AC	Alternative current
ASAI	Average system availability index
ATS	Automatic Transfer Switch
CAIDI	Customer average interruption duration index
DC	Direct Current
DLG	Double Line to Ground Fault
DSTATCOM	Distribution static compensator
DVR	Dynamic Voltage Restorer
DVR	Dynamic Voltage Restorer
EEP	Ethiopian Electric Power
EEU	Ethiopian Electric Utility
HRC	High Rupturing Capacity fuse
IEC	International Electro-Technical Commission
IEEE	Institute of Electrical and Electronics Engineers
IGBT	An Insulated-Gate Bipolar Transistor
KV	Kilo Volt
KVA	Kilo Volt Ampere
KW	Kilowatt
KWH	Kilowatt hour
LL	Line to Line Fault
LLL	Three Phase Line -Line - Line Fault
LLLG	Three Phase to Ground Fault (LLLG).
MVA	Mega Volt Ampere
PCC	Point of Common Coupling
PFC	Power Factor Controller
PIT	Process Immunity Time
PLC	Programmable Logic Controller
PLC	Programing Logic controller

PO	Political Optimization
PQ	Power Quality
PSO	particle swarm optimization
PU	per unit
RMS	root-mean-square
ROV	region of vulnerability
SAIDI	System average interruption duration index
SAIFI	System average interruption frequency index
SLG	Single Line to Ground Fault
SVC	static Var compensator
ASVC	static voltage compensator
TDD	Total Demand Distortion
THD	Total Harmonic Distortion
UPQC	unified power quality conditioner
UPS	Uninterruptible Power Supply
V	Voltage
VFD	Variable Frequency drive
VSC	Voltage Source Converter

ABSTRACT

The Assela Malt Factory and other local clients in Assela face serious power quality issues, including frequent power outages, voltage fluctuations, harmonic distortion, low power factor, and voltage imbalance. These issues lead to equipment damage, production interruptions, increased energy costs, and reduced system efficiency. Notably, problems like motor overheating, PLC card failures, and light bulb damage have been observed.

This thesis aims to evaluate these power quality challenges and propose a DSTATCOM-based solution using MATLAB/Simulink. The goal is to improve power factor, stabilize voltage, and mitigate harmonic currents. Implementing DSTATCOM will help the factory reduce reactive power charges, protect equipment, and enhance overall efficiency and system reliability.

The Assela substation, Ethiopian Electric Utility (EEU), and the company provided critical data showing poor power quality on the industrial feeder, including a low power factor of 0.77, frequent interruptions, and high harmonic distortions. Source voltage and current THD were 3.38% and 6.39%, respectively, with nonlinear load-induced current and voltage THD at 22.28% and 13.84%. Voltage unbalance averaged 2.2%, and fluctuations reached 9.09%.

After installing a DSTATCOM, THD values dropped significantly source current THD to 0.98% and load/source voltage THD to 1.55% preventing 12.1 kW in losses. Simulations in MATLAB/Simulink showed improved voltage levels and reduced current harmonics. The factory's monthly penalty due to poor power factor was about 3,175.28 birr, which was avoided by improving the power factor to 0.98 lagging. This also reduced system power losses by 38.26% (for two transformers operating parallel) and 37.92% (for one transformer working alone). A cost analysis of the DSTATCOM implementation was also conducted.

Key words : *Power quality, Power quality effects, DSTATCOM, Matlab/Simulink.*

CHAPTER ONE

INTRODUCTION OF POWER QUALITY

Modern society depends on electrical energy, which is the most common and efficient form of energy. How efficiently the end-user equipment functions are also significantly influenced by the quality and dependability of the electric power supplied. The majority of industrial and commercial loads need reliable, high-quality power.

In addition to availability, power quality refers to the waveform characteristics, frequency, and voltage magnitude of the power supply. A smooth sinusoidal waveform and stable, reasonable voltage and frequency levels are indicators of a good-quality electrical supply. But in reality, the power system is disturbed by malfunctions, certain equipment (in the home, office, and industry), and varying electrical consumption, which leads it to deviate from its usual behavior. If any of these occurs, the power quality is poor:

- If there are interruptions or outages in the supply.
- When the applied voltage is more than or lower than the allowed magnitude range.
- When the frequency of the power system is varying.
- Moreover, when there is a disturbance in the sinusoidal waveform of the supply's voltage and current.

Thus, power quality can be defined as the extent to which frequency, current, and voltage magnitude deviate from their nominal values. The shape of the waveform may also exhibit divergence. Another approach to define power quality is the extent to which the supplied power is compatible with the efficient operation of electrical equipment. IEEE Std 1159 - 2014 IEEE Recommendation for Electrical Power Quality Monitoring “The concept of powering and grounding sensitive equipment in a manner that is suitable for that equipment's operation" is the definition of power quality. Any power issue that presents as fluctuations in voltage, current, or frequency that result in the malfunction or loss of power of the client's equipment is considered a power quality issue. Poor power quality is a big problem for consumers in the commercial, industrial, and residential sectors. The most widely used worldwide standards for power quality in the industry were created by the Institute of Electrical and Electronics Engineers (IEEE) and the worldwide Electro-Technical Commission (IEC).

For example, several household devices and appliances may not work properly and may even sustain damage if the voltage is too high or too low. Low power quality can lead to early failure by producing malfunctioning or non-existent bulbs and electrical devices.

1.1 Back ground

On September 1st, 1984G.C. Asella Malt Factory was founded on the main road between Addis Ababa and Asella, close to the Kulumsa Agricultural Research Center. The Asella malt factory is situated in Kulumsa village, 8 km from Asella town, and 167 kilometers south of Addis Ababa. The Oromia Agricultural Cooperatives Federation Ltd. purchased the Assela Malt Factory in May 2018 as a result of the government's implementation of privatization plans. The facility was built with the intention of producing and supplying malt to the nation's current breweries (factory, 2016).

The Assela distribution substation provides two feeders that supply electricity to the Assela malt Factory. Two lines are used: a 15KV line for machines and utilities, and a 33KV line specifically for an electrical boiler and a 1600KVA diesel generator that acts as an automatic backup generator in the event that utility power is cut off. Three transformers for servicing machines and a transformer with a 7500KV capacity dedicated to electrical boilers make up the factory's power distribution system. Three transformers are used for servicing machinery; two are 800kVA and run in parallel, and the third transformer is 1250kVA. There is one 1600kVA diesel generator in the factory that is used for emergencies. But this thesis will focus on the 15KV line and machinery transformer only, 33KV is pure resistivity load I don’t concern it.

Power quality problems can have a substantial direct or indirect financial impact in the form of lost revenue from production delays, equipment damage, process interruptions, critical data loss, and raw material waste. Long-term power outages caused by poor power quality concerns have a negative impact on a variety of industries and businesses, including banking and pharmaceuticals. Voltage sag is causing several sensitive instruments to malfunction, which is impeding the procedure. Significant financial losses are suffered by the industrial sector as a result of it (Gangil, 2023).

The industrial sector in Ethiopia has expanded recently. But the power outage is still happening on a daily basis. Because of this, the utility and consumers alike only pay attention to power quality disruptions caused by interruptions, and quality of power is now only understood as the continuous supply of power.

The power quality of the electrical energy supplied to customers must be compatible with the operation of the equipment (M. Khalil Hammad, 2023). According to global customer surveys, complaints about related disturbances like harmonics, voltage sags, voltage swells, voltage fluctuations, voltage variations, flickers, etc. (Cebrian, April 5-8, 2021) (G. M. Bhutto, 2013) are occasionally on the rise. Modern customers use a large number of sensitive devices including power electronic (non-linear devices) that are extremely sensitive to power quality (PQ) disturbances in the supply power system.

The supply voltage variations become harmful to the end user equipment's' (Behera, 2020). On the other side, it was observed that the customer's loads often interact adversely with the power system components and alter the system's voltage.

Voltage swells are mainly caused by disconnected loads or switching large capacitors. Industrial equipment including motor drives, protection, and relays can be destroyed by voltage surges that result in overheating, tripping, or even other problems. For delicate loads, harmonic contamination has become an issue. Because the regulation of electronic equipment depends on either the peak value or the zero crossings of the supplied voltage, which are altered by harmonic distortion, electronic equipment is an extremely sensitive load to harmonics (Cebrian, April 5-8, 2021). When the voltages in the three phases of the system are not equal magnitude and phase shift, it is known as a voltage imbalance.

The customer's device receives non-sinusoidal current from the system when the supply voltage is changed, which may deviate from sinusoidal voltage circumstances. This may result in a variety of technical issues with the customer's devices, including excessive heating, malfunctions, premature device aging, etc. Additional losses and other issues are also brought on by the non-sinusoidal current in a number of system components (such as motors, cables, transformers, and electronics equipment). Customers impacted by poor power quality face significant financial costs (primarily to the businesses with process units). The issue may result in losses for producers and distribution utilities in terms of money.

The distribution power system in the industrial feeder is experiencing various power quality issues. The Assela Malt Factory is currently dealing with the following power quality issues as a result of obtaining its power from this power distribution system: low power factor 0.77–0.85 (lag), voltage variation, voltage imbalance, wave form distortion, primarily harmonic distortion, and frequent power outages.

Assela Malt Factory's and its other clients' production is negatively impacted by these power quality issues. Early equipment failure is caused by voltage drops; overvoltage damages electronics, burns lightbulbs, and happen power outages. Sensitive power electronic devices, such as power supplies and variable frequency drives, are damaged by voltage fluctuations.

Power quality is a critical aspect of electrical power supply that ensures the reliable and efficient operation of equipment and systems. By addressing power quality concerns proactively, stakeholders can enhance the resilience, performance, and sustainability of electrical infrastructure across various sectors.

This thesis is focused on the investigation and study of power quality problems and design of mitigation technique for the Assela Malt Factory.

1.2 Statement of the Problem

Many factors point to extremely poor electric power quality in the city of Assela's power distribution infrastructure. Power outages, voltage fluctuations, harmonic distortion, low power factor, voltage imbalance, and other issues are common among end users in commercial, residential, and industrial settings. According to what I have seen, the factory is dealing with poor power factor, under voltage, voltage variation, voltage imbalance, and power outages. The Assela Malt Factory's and the other clients' productivity is negatively impacted by these power quality issues.

The voltage drop is causes heating of the motors, early failure of equipment's for example two frequency convertor was failure recently due to power interruption, blackening of light bulbs, over voltage causes damage of electronic devices like Programmable Logic Controller (PLC) cards, burning of light bulbs, frequently power interruption and voltage fluctuation has result; semi-processed product, discontinuous in the flow of production, damage of sensitive power electronic devices. Low power factor is cause of the following unwanted effects in the factory; increases losses due to reactive load current, increases in kVA demand, Increases energy consumption, degrade voltage profile, reduce revenue since the factory pays extra money they are charged for the reactive power they consume, decrease the efficiency and performance of the factory.

Therefore, the objective of this thesis is to study and evaluate the power quality problems and designing the DSTATCOM as mitigation techniques in order to improve the power factor, to maintain the voltage stability of the system and also to eliminate the harmonic currents that is happening in the system due to non-linear loads. The thesis is going to use a simulation tool known as Matlab/Simulink for verification.

This has great significant to the factory by giving the following advantages: helps them to save the extra money they are charged for the reactive power they consume, to protect their equipment's from failure and useful lives of their equipment's, to increase efficiency, performance, Voltage stability of the system will be increased

1.3. Objectives

1.3.1. General Objective

The general objective of the thesis to study and evaluate the power quality problems and designing the DSTATCOM as mitigation techniques in order to improve the power quality issues.

1.3.2. Specific Objectives

- To investigate the power quality issues at Assela Malt factory these come from both the electric Utility and the consumer side.
- To determine the root cause and negative effects of the observed problems,
- Develop and simulate suitable mitigation strategies.
- Evaluate the effects based on designed simulating systems.
- Perform a cost-benefit analysis of the system

1.4. Scope of the work

This study primarily focuses on the Assela Malt Factory as a case study. It involves several key phases aimed at assessing and improving power quality within the plant. Initially, data was collected from both the Assela Malt Factory and the Assela substation to analyze existing power quality problems. The current need for power quality mitigation measures was then evaluated to determine necessary improvements. Major equipment within the plant was identified, and the industrial system was modeled using MATLAB software. Simulations were conducted under various scenarios and loading conditions to understand the plant's behavior. The resulting data from these simulations was thoroughly analyzed to identify viable solutions to the observed power quality issues. Finally, conclusions and recommendations were drawn based on the simulation outcomes.

The study did not include the implementation of hardware and did not take into account addressing other power quality issues that were not explicitly stated.

1.5. Significance of the Study

The results of this study are highly significant for both the Assela Malt Factory and the Ethiopian Electric Utility (EEU). For the Assela Malt Factory, this thesis provides valuable insights that can help reduce costs by minimizing the additional charges incurred due to reactive power consumption. It also contributes to the protection and extended lifespan of the factory’s equipment by improving power quality. Additionally, the study supports enhanced operational efficiency and overall performance of the plant.

For the EEU, the study offers benefits such as improved voltage profiles across the electrical power system and a reduction in voltage drops and power losses within the transmission and distribution networks. Furthermore, the reliability of the electric power system is expected to improve as a result of the proposed solutions and recommendations derived from the research.

1.6 Motivation of the study

The particular characteristics of the electrical supply that end users encounter under typical and consistent operating conditions are referred to as power quality. It includes a wide range of factors, including supply continuity, voltage, and current characteristics (magnitude, frequency, waveform shape, and balance).

In addition to its technical implications, power quality has significant economic ones. Damage to equipment caused by low power quality could be expensive.

Power quality problems such as voltage sag, voltage swell, harmonics, and interruptions are common in Assela industry area.

The purpose of this study is to use MATLAB simulation to analyze the power quality problems Assela malt factory, look into more effective mitigation techniques, and assess how well they function.

CHAPTER TWO

LITERATURE REVIEW

2.1. Literature Overview

Regarding the quality of electric power, both electric utilities and end users are growing more concerned. May of the studies and case studies have been conducted on the subject in various regions of the world. The breadth of this project has been covered in a large number of pertinent studies. Additionally, an analysis of the issue with power quality has been carried out by:

Juan Carlos Cebrian in 2021, write an article on a voltage dip, also known as sag, which is a brief period of time during which the supply voltage on one or more phases rapidly decreases to a value between 90% and 1% of the reference voltage, followed by a voltage recovery. Industrial consumers are interested in the disruptions or failures in manufacturing processes brought on by low-quality energy supplies, primarily because these occurrences result in large financial losses for the industry. The manufacturing chain may shut down entirely or partially as a result of certain equipment failing. The research of a supervisory system that can calculate a machine's process immunity time (PIT) is presented in this context by the paper. Each piece of equipment that contributes to the machine's operational control is evaluated for PIT values, supportability curves to voltage sags, and appropriate connections (serial, parallel, etc.) throughout the estimating phase. The findings demonstrate that the supervisory system can help planners make decisions that will lower operational expenses by serving as a helpful tool.

M.Veizaga, C. *et.al*. for ward degree conduct on ‘‘Using multivariate time series data, the sources of voltage sags in industrial power networks are classified.’’ The most common and significant interruptions to industrial power grids are voltage sags, which cause significant financial losses for industrial customers. The legal agreement between the energy provider and the industrial clients depends on the cause's identification and relative location. This study suggests a technique based on dynamic temporal warping and instantaneous symmetrical components to pinpoint the causes of voltage sags.

In the pre-processing step, the voltage and current waveforms are used to implement the Short-Time Fourier and Fortescue transforms. The sources of voltage sags are then found using a distance-based categorization technique. It uses a time-series signature with four dimensions as its features. Additionally, the categorization result is accompanied with a confidence index. With no prior collected data, the idea provides a simple implementation in industrial applications. One advantage is that it makes use of a reference database that is smaller and made up completely of synthetic data. The ability to generalize and the potential to provide an alert based on the confidence index are the primary benefits of the suggested approach. 100% classification accuracy was achieved using generated data with seven causes. Using field measurements from three distinct industrial locations that represent five classes, the technique achieves a classification F1-score more than 99%.

M. Khalil Hammad, et.al have used D-STATCOM to improve the PQ issue with the hybrid PV-wind system. In order to achieve this, political optimization (PO) and particle swarm optimization (PSO) are used to establish the ideal D-STATCOM controller parameters. A comparison with a static voltage compensator (SVC) is performed under various operating conditions, such as voltage malfunction, sag, swell, and harmonic distortion, in order to assess the system that is offered with D-STATCOM based on PSO and PO. Using comprehensive simulation data, the resilience and viability of the suggested technique for addressing these challenges are evaluated. With MATLAB/SIMULINK, the suggested system, D-STATCOM, and its controller are simulated. In addition to achieving a reduction in total harmonic distortion, the proposed D-STATCOM system can maintain the voltage at acceptable levels during voltage swell and raise it to acceptable levels during voltage sag.

Behera, C., et.al. have presented a new method for stochastically analyzing voltage sag data, which includes the study, representation, and vulnerability detection of the area. At any load site, voltage sag is a serious power quality issue that is mostly caused by short circuit defects. Because they produce immediate financial losses, their consequences are particularly evident in the industrial sector. Identifying the network nodes where voltage sag can occur is the first and most crucial step towards eliminating it completely or at least minimizing it. Thus, this article presents an innovative method for identifying the network's weak points, or locations where voltage dips more frequently. This novel approach is predicated on a stochastic normal probability distribution and correlation. An analytical method is employed to evaluate the voltage sag. The technique replicates the quantity, kind, and distribution of errors at random points in the system. Following the collection of voltage dip data, correlation and normal probability distribution ideas are applied to the analysis. The normal probability distribution represented the sag occurrence region, and the correlation notion provided the relationship between the sag frequency and other factors.

Research was conducted on power quality, which is a crucial component of electrical power. He improved power quality by using several types of electrical devices, which included reducing harmonics, current fluctuation, and voltage sags and dips. He employed several types of shunt compensating power electronics devices (such as D-STATCOM) to increase the quality of the power. D-STATCOM is used in various types of faults, such as Single Line to Ground Fault (SLG), Line to Line Fault (LL), Double Line to Ground Fault (DLG), Three Phase Fault (LLL), and Three Phase to Ground Fault (LLLG). D-STATCOM is typically connected at common coupling point (PCC) to overcome PQ type problems in power transmission lines. Because D-STATCOM has a relatively short operating time, it is the most effective shunt connected device. (Kumar, Performance of Custom Power Devices for Power Quality Improvement , 2017)

This study examines the electric power quality (PQ) of Ethiopian Electric Power (EEP) clients Walya-Steel Industries PLC (WSIPLC) and Ethio Plastic Share Company (EPSC). The two industries' PQ indicators are noted and examined. The investigation showed that while the power factor of the two companies' power systems is low, harmonic distortion is considerable in comparison to the matching IEEE suggested maximum allowable values. The remaining PQ indicators fall within the permitted range of values. Power electronic converters, which are used in both plants, are a major source of harmonic distortion, according to a simulation performed on the modeled power systems of the two companies. A capacitive filter has been created to mitigate low power factor and harmonic distortion based on the results of the simulation.

W. Edward Reid, Member, IEEE, (Reid, MAY/JUNE 2016) Power Quality Issues-Standards and Guidelines. The document provides an overview of the major concerns related to power quality by summarizing the relevant standards, areas where standards are being established, and essential factors.

Eklas Hossain, Mehmet Rida TÜR, et al (S. K. Goyal, 2020) The analysis and mitigation of power quality issues in distributed generation systems through the use of custom power devices is what they have completed. This essay addresses power-related problems for distribution generation systems that use wind and solar energy as sources of renewable energy. Power quality concerns, sources, criteria, and standards were thoroughly discussed. According to their analysis, voltage spikes and fluctuations are the next most serious power quality issues, followed by transients. In the paper power quality monitoring techniques have been employed for monitoring harmonics mainly, UPQC, STATCOM. The Statcom is most effective compare to the UPQC.

Semaegzer Sisay in 2022 at BDU, analyze the issues and find solutions for mitigating power quality problems in power distribution systems. This can be achieved by implementing power quality enhancement devices like D-STATCOM (distribution static compensator), unified power quality conditioner (UPQC), and Dynamic Voltage Restorer (DVR) for electric power systems, investigated only on the transmission line not on the industry plant.

2.2 Causes of power quality issue

Power quality issues can arise from different sources, including faults in the power grid, equipment malfunctions, or internal factors within industries. These issues can result in undesirable variations in voltage levels, such as sags, swells, or interruptions, which can disrupt the normal operation of electrical devices and systems.

Harmonic distortion is another aspect of power quality that can occur due to the presence of non-linear loads, such as electronic equipment or variable speed drives. Harmonics are unwanted frequencies that can distort the sinusoidal waveform of the voltage or current, leading to increased energy losses, equipment overheating, and interference with other electrical systems.

To address power quality issues, utility companies play a crucial role in monitoring and maintaining a stable power supply. They invest in infrastructure upgrades, implement monitoring systems, and take measures to minimize disruptions and voltage fluctuations (Gangil, 2023).

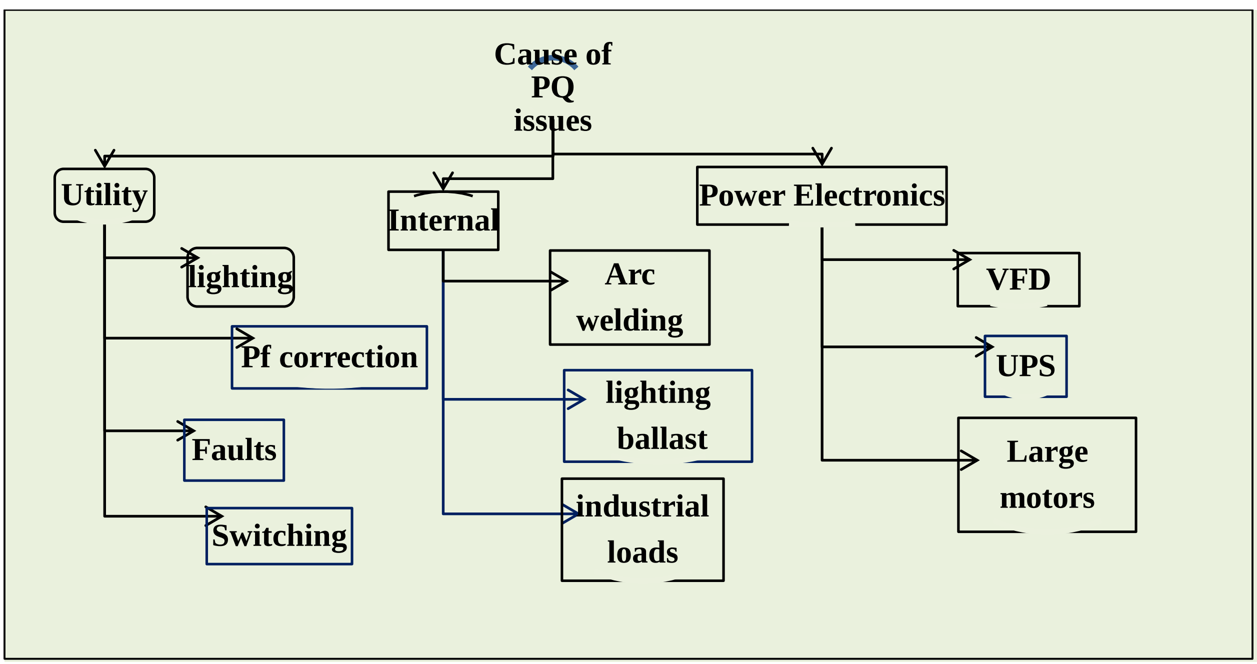


Figure 2:1 Cause of Power quality

Power quality is essential to ensure the reliable and efficient operation of electrical devices and systems. It requires collaboration between utility companies, industries, and the application of power electronics to monitor, manage, and improve the quality of electrical power supply.

2.3 Classification of Power Quality Problems

Several power quality issues commonly occur during the operation of a current power system. Any kind of inadequacy in the ideal sinusoidal waveforms that correspond to either voltage, current, or both is the cause of all these power quality issues. Increased use of power electronic devices, which have intrinsic nonlinear switching characteristics, is the primary cause of the majority of these power quality issues. A brief description of some of the most notable issues with power quality is provided below:

A. Transients

Undesirable, temporary variations in the power system's voltage and/or current signals are known as transients. The power system experiences transients for a variety of reasons. These include lightning strikes, inadequate or loose connections, abrupt load changes, and arcing between the switch contacts. These transients can be divided into two groups. These categories are impulsive and oscillatory.

i. Impulsive Transient

An unexpected, non-power frequency shift in the steady-state voltage, current, or both is known as an impulsive transient. Typically, impulsive transients are identified by their spectral content as well as their rise and decay times. The most common cause of impulsive transients is lightning strikes. An impulsive transient created by lightning strikes may be caused by a direct hit on a power line or by magnetic induction on adjoining lines (Std I. S., 1995).

ii. Oscillatory Transient

Rapid polarity shifts are a characteristic of an oscillatory transient, which is an unanticipated, non-power frequency disruption in the steady-state condition of current, voltage, or both. It is comprised of a rapidly shifting polarity voltage or current waveform that is characterized by its magnitude, duration, and spectral content. Oscillatory transients, which fall into one of three frequency ranges high, medium, or low. High-frequency transients usually last in the microsecond range and have a predominant frequency component higher than 500 kHz. The predominant frequency component of medium-frequency transients’ ranges from 5 kHz to 500 kHz, and their durations are measured in tens of microseconds. Low-frequency transients last between 0.3 and 50 milliseconds and have a predominant frequency component below 5kHz. Each transient type's etiology is frequently associated with a certain frequency range.

B. Short-Duration Voltage Variation

For less than a minute, it is the root mean square (rms) voltage changes at power frequencies. Short-term voltage fluctuations caused by fault circumstances, the energization of big loads requiring high beginning currents, or sporadic weak connections in power system wiring. The defect may result in either transient voltage swells or sags or a total loss of voltage interruptions, depending on the fault location and system conditions.

i. Voltage Sag/dip

A brief decrease in voltage magnitude is known as voltage sag. Voltage sag is defined in IEEE Standard 1159 [9] as a decrease in RMS voltage of 0.1 p.u. to 0.9 p.u. during intervals of approximately half-cycles to one minute. The most common causes of voltage sags are starting large motors, energizing heavy loads and short circuit defects in the system. Induction motors in electric machines, for example, will draw seven to ten times their full load current when they first start. The voltage across the system will decrease as a result of this trailing current (Std I. S., 1995).

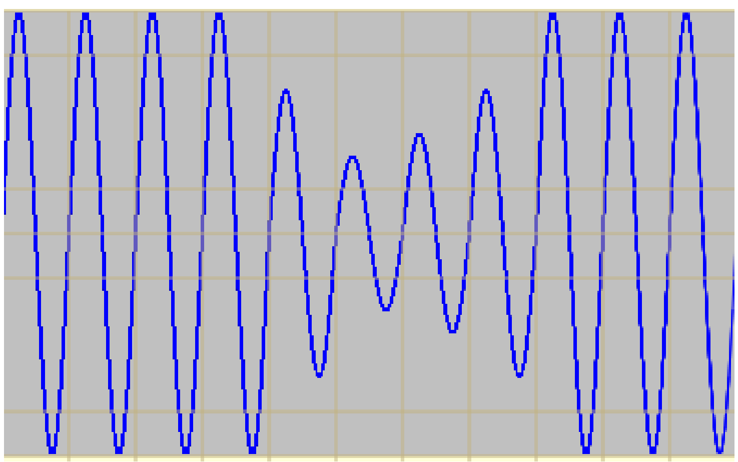


Figure 2:2 Instantaneous Voltage sag

ii. Voltage Swell

Voltage swell is the term used to describe an unexpected rise in voltage magnitude above the usual tolerance value. A surge in RMS voltage between 110% and 180% of nominal at the power frequency is referred to as a swell for durations between half a cycle and a minute (Shaik, 2016). Swelling may result from the momentary increase in voltage on the unfailed phases. The distribution system swells when a high load is turned off, a single line ground fault is transferred to an unfaulty feeder, or a huge capacitor bank is turned on.

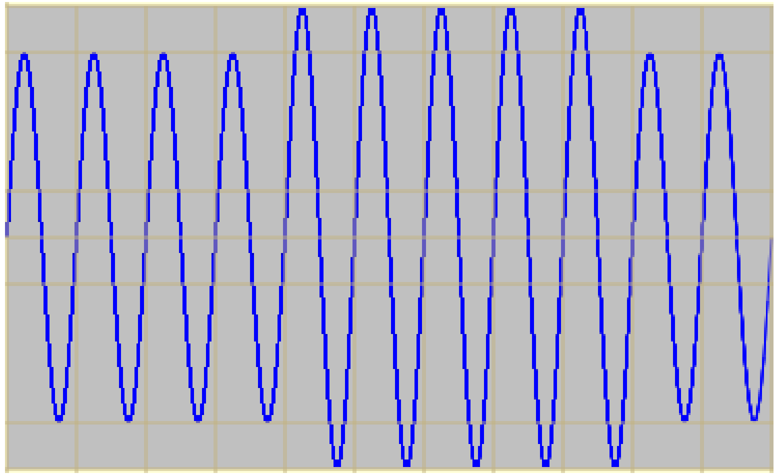


Figure 2:3 Instantaneous voltage swells

iii. Interruption

An interruption occurs when the supply voltage or load current is lowered to less than 10 percent (0.1 p.u.) of nominal for a duration of no more than one minute (Shaik, 2016). Interruptions are caused by equipment, power system, and control failures. The duration of the interruptions is used to quantify them because the size is always less than 10% of the typical amount.

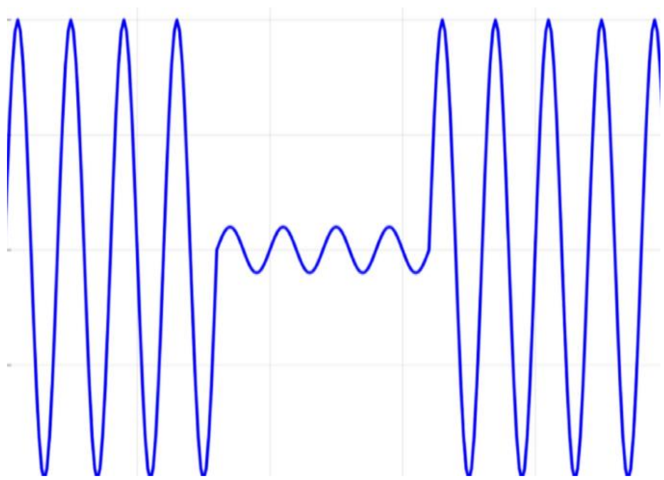


Figure 2:4 Short-interruption

C. Long-Duration Variation

Long-duration variations consider root-mean-square (RMS) deviations at power frequencies for periods greater than one. Long duration variations are typically not the consequence of system problems, although they can be brought on by system switching procedures and changes in the system's load. Depending on the cause, the long-duration variation could be an under voltage, overvoltage, or prolonged interruption.

i. **Overvoltage**

A rise in the root mean square of the ac voltage that is more than 110% of the nominal value at the power frequency for more than a minute is referred to as an overvoltage. Poor voltage management, incorrect tap setup of transformers, and disconnecting large loads can all result in an overvoltage. Overvoltage may cause insulation flashover of the utility devices and hardware failure in the apparatus as a result of overheating.

ii. **Under voltage**

For more than a minute, it is defined as a drop in the root mean square of the ac voltage to less than 90% of the nominal value at the power frequency (S. K. Goyal, 2020). Turning off the capacitor bank, turning on a load, or overloading the circuit can all result in under voltage. The primary cause of under voltage is an excessive amount of impedance between the load that needs to be supplied and the power system supply. As a result of the weak power system, the terminal voltage falls too low under high load. System failure, equipment malfunction, and reduced equipment efficiency are all potential outcomes of this voltage droop.

iii. Sustained Interruption

A persistent interruption occurs when the supply voltage remains at zero or falls to less than 10% of the nominal value for more than a minute. Sometimes permanent in nature, voltage disruptions lasting longer than a minute require human intervention to restore the system. Human mistake, control issues, protective device malfunctions, and problems in the power system network can all cause interruptions. Power will be totally cut off for a while until the issue is fixed if there is a persistent disruption.

We employ reliability indices, which can be computed in the following ways, to monitor and evaluate the behavior of power failures and the severity of issues.

We must first take into account the following points:

Ci - Number of interruptions from customers

Rd - Duration of interruption.

C_T - total amount of customer disruptions during a specified period.

Ri - Number of interruption within given time.

SAIFI: System average interruption frequency index indicates how frequently, during a predetermined amount of time, the typical consumer encounters a prolonged interruption. The following distribution reliability indices are defined by IEEE Standard 1366-2003, IEEE Guide for

Electric Power Distribution Reliability Indicators. (J.Duncan Glover, 2012) . It is the ratio of total customer interruptions to total number of customer served.

$$SAIFI = \sum_i \frac{c_i x R_i}{c_T} \qquad (2.1)$$

SAIDI: The system average interruption the duration index displays the average customer's total interruption duration during a specified time period (J. Duncan Glover, 2012). It is generally quantified in customer minutes or customer hours of interruption.

$$SAIDI = \sum_i \frac{c_i x R_{id}}{c_T} \qquad (2.2)$$

CAIDI: The average time needed to restore service is represented by the customer average interruption duration index (J. Duncan Glover, 2012).

$$CAIDI = \frac{\sum_i c_i x R_i}{\sum_i c_i} \qquad (2.3)$$

ASAI: According to J. Duncan Glover (2012), the customer average interruption duration index shows the typical amount of time needed to restore service.

$$ASAI = \frac{H_{ca}}{H_{cd}} x100\% \qquad (2.4)$$

Whereas:

Hca - Customer hour’s service availability.

H cd - Customer hour’s service demand.

D. Voltage Unbalance

When a three-phase system's voltages are not the same magnitude and/or the phase variances between phases are not precisely 120 degrees, this is known as voltage unbalance. One can determine the degree of voltage imbalance by calculating the ratio of the negative- (or zero-) sequence component to the positive-sequence component, or by dividing the highest deviation from the average of three-phase voltages by the average of three-phase voltages. Unbalanced single-phase loading in a three-phase system, an open circuit on the distribution system primary, an uneven or unbalanced utility supply, and unequal line impedances are the main causes of voltage unbalance in power distribution systems (Shaik, 2016). Unbalanced voltage reduces the longevity and degrades the performance of three-phase equipment. Phase current becomes unbalanced due to voltage imbalances at the motor stator terminals; these unbalanced currents result in increased vibrations and mechanical strains, higher losses, and motor overheating, all of which shorten the life of the winding insulation.

Voltage unbalance express as

$$Voltage\ unbalance\ ratio(\%) = \frac{Maximum\ Voltage\ devation}{Average\ Voltage}\ x100\% \quad (2.5)$$

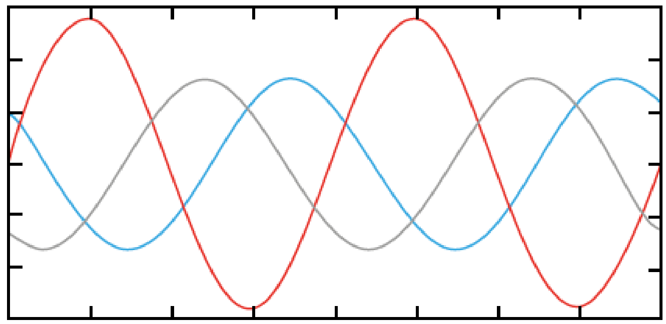


Figure 2:5 Voltage unbalance

E. Waveform Distortion

The key indicator of the steady-state deviation of the voltage and/or current waveform from an ideal sine wave of power frequency is the spectral content of the deviance. Harmonics, interharmonics, dc offset, noise, and notching are the five main causes of waveform distortion (Shaik, 2016).

i. Harmonics

Sinusoidal voltages or currents having frequencies that are integer multiples of the fundamental frequency, also referred to as the design frequency of the supply system, usually 50 or 60 Hz, are called harmonics. The sum of the fundamental frequency and harmonics can be used to deconstruct periodically warped waveforms. The nonlinear characteristics of devices and loads on the power system lead to harmonic distortion. The full harmonic spectrum, which comprises the magnitudes and phase angles of each distinct harmonic component, is used to characterize the levels of harmonic distortion. To determine the effective value of harmonic distortion, it is also common practice to use a single metric, total harmonic distortion (THD).

Total Harmonic Distortion (THD) and Total Demand Distortion (TDD) are the two most widely used indices for determining a waveform's harmonic content. The effective value of a distorted waveform's harmonic components in relation to the fundamental is measured by the THD. Either voltage or current can be used to calculate this index:

$$TDH_V = \sqrt{\sum_{n=2}^{N} {V_n^2}/{V_1}} \quad (2.6)$$

$$TDH_I = \sqrt{\sum_{n=2}^{N} {I_n^2}/{I_1}} \quad (2.7)$$

Where V_1 and I_1 are represent the fundamental rms voltage and current respectively

V_n and I_n are represent the n^{th} harmonics amplitude RMS voltage and current respectively where n= 2, 3, …

ii. Inter harmonics

Inter harmonics are voltages or currents with frequency components that are not integer multiples of the frequency at which the supply system is intended to function (such as 50 or 60 Hz). They may manifest as a wideband spectrum or as distinct frequencies. Networks of all voltage classes contain interharmonics. Induction furnaces, arcing devices, cyclo converters, and static frequency converters are the primary causes of interharmonic waveform distortion. Inter-harmonics is another term for power line carrier signals. Much study has been done on this topic up to this point. The causes and consequences of interharmonic distortion are now better understood. Usually the consequence of frequency conversion, it fluctuates with load and is frequently not consistent.

Because the fluctuating inter-harmonic frequency coincides with the system's natural frequencies, such inter-harmonic currents have the potential to cause very serious resonances in the power system. They have been demonstrated to alter power-line-carrier signaling and cause visual flicker in computer display devices, fluorescent lighting, and other arc lighting.

iii. DC offset

DC offset is the phrase used to describe the existence of a DC voltage or current in an AC power system. A geomagnetic disturbance or the asymmetry of electronic power converters may be the cause of this. For instance, diodes used in incandescent light bulb life extenders may lower the RMS voltage sent to the lightbulb by half-wave rectification. Because it biases transformer cores to saturate during normal operation, direct current in ac networks can be harmful. Additional heating and transformer life loss result from this. Grounding electrodes and other connectors may also erode electrolytically as a result of direct current.

iv. Notching

When current is commutated from one phase to another during the regular operation of power electronic devices, a periodic voltage disturbance known as notching occurs. The harmonic spectrum of the impacted voltage can be used to characterize notching because it happens continually. It is typically handled as a particular instance, though. Notching-related frequency components can be rather high and may be difficult to identify using measurement tools typically employed for harmonic analysis.

v. Noise

Unwanted electrical signals having a broadband spectral content below 200 kHz that are present on neutral conductors or signal lines, or superimposed on the power system voltage or current in phase conductors, are referred to as noise. Power electronic devices, control circuits, arcing equipment, loads with solid-state rectifiers, and switching power supply can all contribute to noise in power systems. Inadequate grounding that does not transfer noise away from the power system frequently makes noise issues worse. Any undesired distortion of the power signal that does not fall under the categories of harmonic distortion or transients is essentially referred to as noise. Electronic gadgets like programmable controllers and microcomputers are disrupted by noise. Filters, isolation transformers, and line conditioners can all help to lessen the issue.

F. Voltage Fluctuation

Random variations in the voltage envelope with magnitudes ranging from 0.9 to 1.1 PU are referred to as voltage fluctuation. Higher-power loads that require current that fluctuates rapidly and continuously can result in voltage fluctuations (Eklas Hossain, 2018). The term "flicker" refers to the way that voltage variations affect lamps, making them appear to flicker to the naked eye. While voltage flicker is measured in terms of human eye sensitivity, the RMS magnitude of a flickering signal is expressed as a percentage of the fundamental. A light bulb may flicker if the frequencies are between 6 and 8 Hz and the magnitudes are as low as 0.5 percent. One frequent cause of voltage fluctuations in utility transmission and distribution networks is the arc furnace (Farhoodnea, 2014).

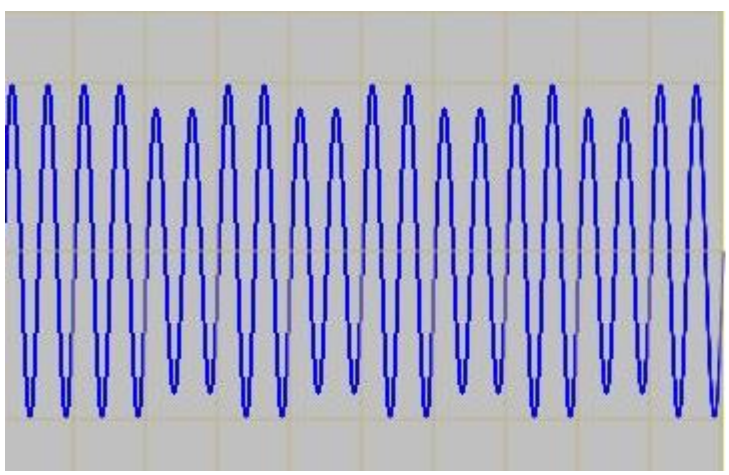


Figure 2:6 Voltage fluctuation

G. Power Frequency Variations

Power frequency variations are any change in the fundamental frequency of the power system from its nominal value, which is typically 50 or 60 Hz. The rotational speed of the generators that supply the system is linked to the power system frequency. As the dynamic balance between generation and load shifts, frequency variations take place. The parameters of the load and how responsive the generating control system is to changes in the load dictate the frequency deviation's size and duration (Eklas Hossain, 2018). Changes in frequency may cause a significant generation source to shut off, a major load to be disconnected, or a power transmission system to fail.

In response to sudden changes in load, frequency-sensitive equipment may not be able to adapt within the limited bandwidth needed. Possible results include device damage, system failures, and data loss (T. Ghanbari, 2018).

Literature review summary

There is no combination solution research for the power quality study in industrial systems; instead, the majority researcher concentrates on the solution of individual problems, such as low voltage study, voltage sag, harmonics, and distribution network study. In order to improve power factor, maintain system voltage stability, reduce harmonic distortion, lower reactive power consumption of the loads from the source, and mitigate related power quality issues found in the factory, we concentrated on evaluating the power quality issues found in the industrial plant Aseela malt factory and designing a mitigation device, or DSTATCOM.

CHAPTER THREE

ANALYSIS OF POWER QUALITY ISSUES AND MODELING OF THE SYSTEM IN THE INDUSTRY

3.1 Introduction

We concentrated on data collecting, analysis and modeling of the system depend on the mathematical modeling we calculate the original system electrical parameters and represent the one-line diagram of the factory. The mitigation device or DSTATCOM mathematical and matlab modeling representation is also discussed in this chapter. The control system of the DSTATCOM mathematical representation and Matlab Simulink modeling is also done.

We evaluate the outcomes of data analysis to industry standards like IEEE, IEC, and others. Following analysis, the mitigation tool has been created. Figure 3.1 below indicates the factory's one-line diagram. The factory features have a backup generator and a service transformer. Electrical characteristics of the transformer 1250KVA, 15KV/0.38KV, 50Hz, and 5.26% impedance and two transformers are operating parallel and each of them have 800KVA, 15KV/0.38KV, 50Hz, and 4.73% impedance.

The standby generator specification is power factor = 0.8, 400V, 2309.5A, 50Hz, and 1600kVA. There are three product section areas in the factory. These include the following: a machine tower section with a 550 kVA capacity and a 0.81 power factor; a steeping, germination and old kiln section with an 850 kVA capacity and a 0.79 power factor and new kiln and utility section with 686kVA capacity and a 0.8 power factor.

The electrical system of Assela Malt Factory is fed from Assela substation which is located 4.9km from the factory. The substation is connected to the national grid network of Ethiopia through Adami tulu line. Assela substation has one 132KV incoming lines from Awash, and one outgoing line to Adami Tulu. There are one 132KV incoming line from Awash and one outgoing line to Adami Tulu at the Assela substation. Two autotransformers are now installed in the Asella substation: a 132±12.5% /15KV/33KV, 25MVA, %Z=18, Wye-Delta stationary step-down transformer, and a 132±12.5% /33KV, 25MVA, %Z=18, Wye-Delta stationary step-down. There are twelve lines of feeders in total, nine of which are 15kv and three of which are 33kv. Through two step-down transformers, the portable step-down transformers are providing electricity to numerous commercial, industrial, and industrial clients, mostly in Asella city.

Furthermore, this substation serves other customers located within and along the way to neighboring cities such as Sagure, Eteya, Kersa, and Bekoji. Only the Asella malt production and the Chilalo Food Complex use one of the nine 15KV primary distribution feeder lines on the stationary step-down transformers, which is designated as an industry feeder. A further 33kv dedicated line at the Asalla Malt Factory is used only for boiling water. The impact of 15KV lines on power quality and their numerous industrial applications were the main topics of this thesis.

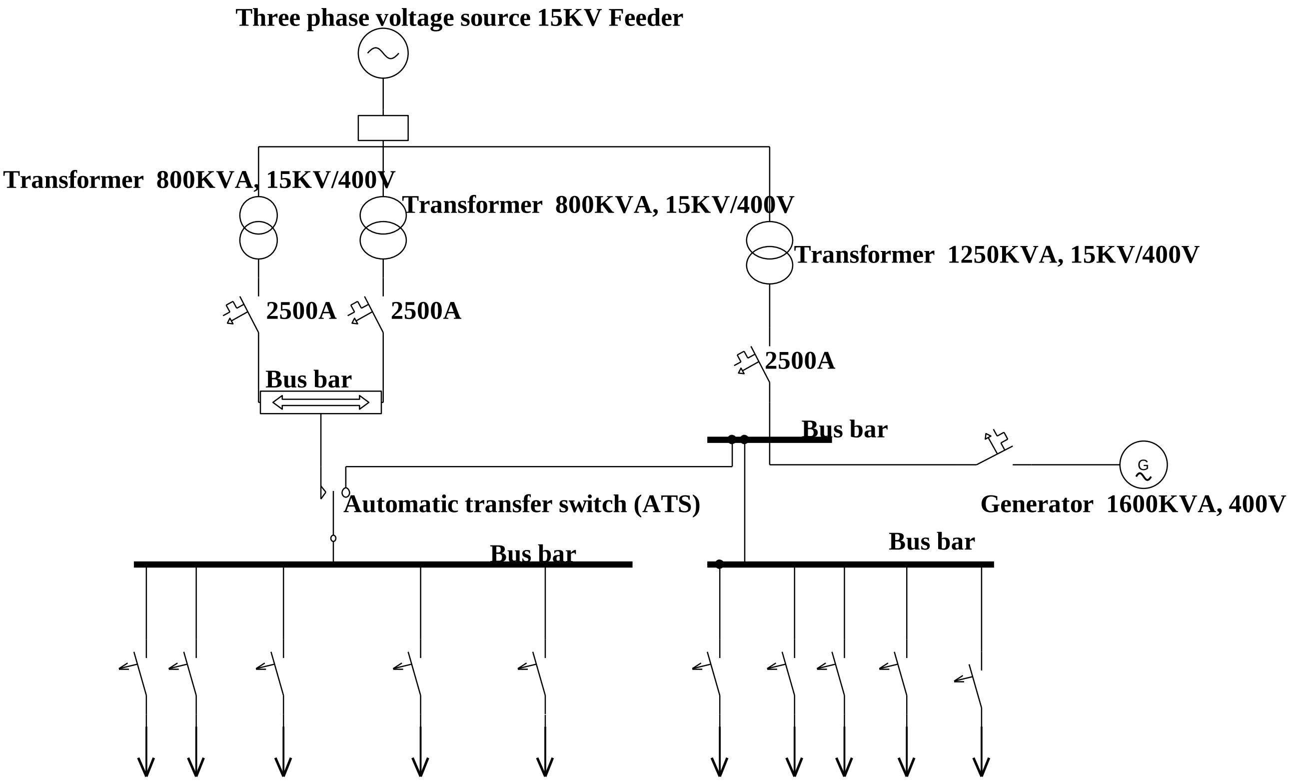


Figure 3:1 single line power distribution block diagram of factory

Table 3-1 The factory using transformers data

Two transformer are working parallel	The other transformer
Manufacture: Mechelen/Belgian Connection: star – delta Rating power: 2x800KVA Primary voltage/current: 15KV/30.8A Secondary voltage/Current:400V/1155A	Manufacture: Hyderabad/India Connection: star – delta Rating power: 1250KVA Primary voltage/current: 15KV/48.11A Secondary voltage/current: 400V/1804.2A

Figure 3:2 Assela Malt Factory power house

3.2 Data gathered at Full Load from the Transformer

3.2.1 Analysis of Long-Duration Voltage Variation Data

The RMS voltage variation is presented in the table below. The data is collected over an interval of a month at various times during the factory's working hours. The average values for each case are then computed. For line voltage, the nominal value is 380V, and according to the transformer's voltage specification established in the industry, the phase to phase voltage is 380V.

Table 3-2 Long-term average hourly changes in voltage data from the secondary sides of the two parallel operating transformer while it is fully loaded.

Measuring time	L1 –L2 (RMS value)	Voltage Variation (%)	L1 –L3 (RMS value)	Voltage Variation (%)	L2 –L3 (RMS value)	Voltage Variation (%)
8:00 am	380	5	372	7	379	5.25
8:30 am	379	5.25	373	6.75	378	5.5
9:00 am	383	4.25	381	4.75	369	7.75
9:30 am	378	5.5	380	5	370	7.5
10:00 am	375	6.25	368	8	374	6.5
10:30 am	378	5.5	366	8.5	376	6
11:00 am	369	7.75	373	6.75	374	6.5
11:30 am	374	6.5	365	8.75	373	6.75
12:00 pm	378	5.5	368	8	375	6.25
12:30 pm	373	6.75	364	9	372	7
1:00 pm	371	7.25	369	7.75	370	7.5
1:30 pm	376	6	368	8	379	5.25
2:00 pm	377	5.75	370	7.5	377	5.75
3:30 pm	377	5.75	371	7.25	379	5.25
4:00 pm	381	4.75	371	7.25	383	4.25
4:30 pm	389	2.75	373	6.75	387	3.25
5:00 pm	393	1.75	371	7.25	392	2
5:30 pm	391	2.25	375	6.25	392	2
6:00 pm	392	2	374	6.5	394	1.5

$$\text{Voltage Variation }(\%) = \frac{Desired\ value - actual\ value}{desired\ value} * 100\% \qquad (3.1)$$

In this project, voltage variations more than 9% are not recorded. The accompanying table indicates the RMS voltage variation; under voltage occurs at various times. The voltage variation is not caused by the factory operating at full load. The daily voltage variance is caused by problems with the EEU's supply system. Under voltage occurs the motor windings and other components of the machinery are stressed because greater current must be drawn to compensate for the reduced voltage. This can lead to overheating, decreased performance, increased energy consumption, and even early failure factory equipment.

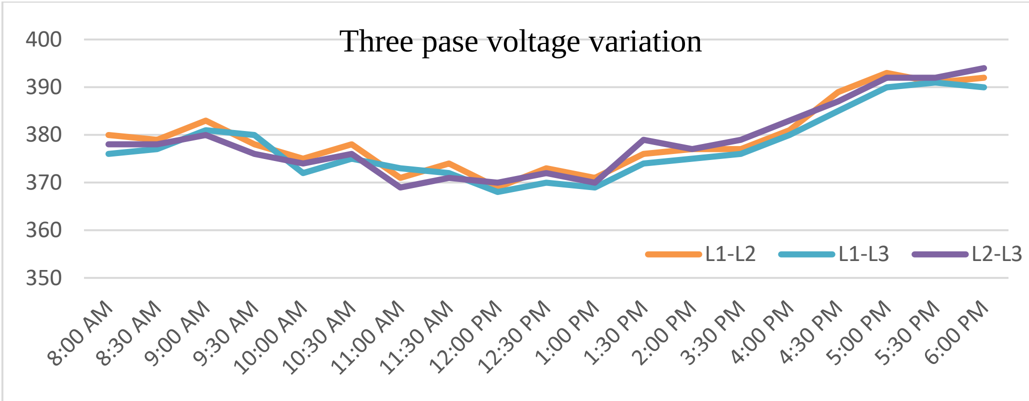


Figure 3:3 Long-term average hourly changes in voltage data from the secondary sides of the two parallel operating transformer while it is fully loaded.

information about the variations in Transformer 1 and Transformer 2 current on the secondary sides at full load.

Table 3-3 Current variation data from the transformer secondary sides at full loads.

Measuring time	Frequency	Current (I1) RMS	Current (I2) RMS	Current (I3) RMS
8:00 am	50	588	463.8	498
8:30 am	49.5	582	467.4	490.8
9:00 am	49.5	594	459	492
9:30 am	50	580.2	442.8	493.8
10:00 am	50.5	552	418.8	516.6
10:30 am	50	554.4	419.4	513.6
11:00 am	50	551.4	420.6	508.8
11:30 am	50.5	557.4	417.6	507
12:00 pm	49.5	534	429	438
12:30 pm	50.5	531.6	422.4	456
1:00 pm	49.5	54594	420	444
1:30 pm	49.5	585.6	433.2	450
2:00 pm	49.5	588	437.4	468.6
3:30 pm	50	582	441.6	470.4
4:00 pm	50	594	444	477.6
4:30 pm	50	557.4	417.6	507
5:00 pm	50.5	534	429	438
5:30 pm	50	531.6	422.4	456
6:00 pm	50	54594	420	444

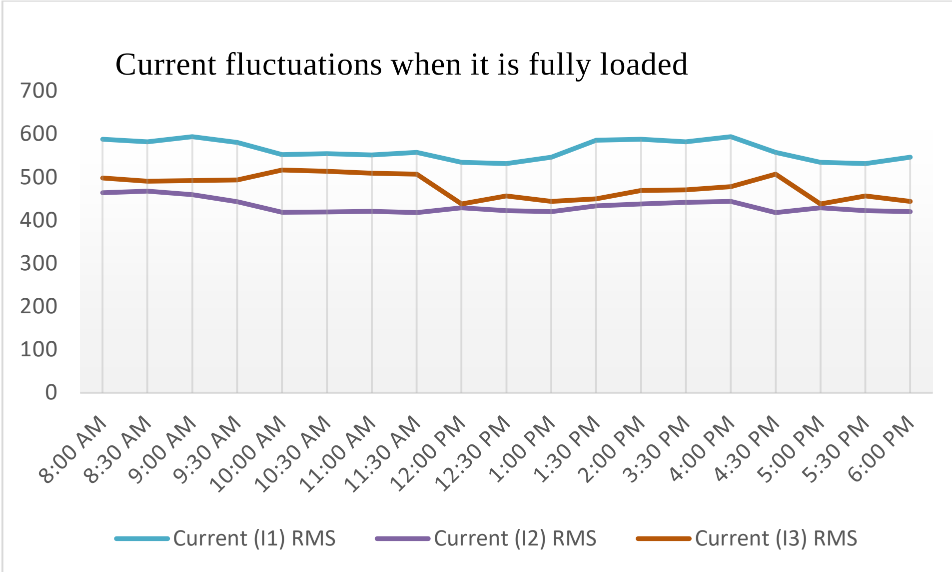


Figure 3:4 Current variation data from the transformer secondary sides at full loads.

Transformers 1 and 2 power the majority of the production equipment in the plant. However, the main loads attached to the transformer 3 are cooling plant loads, utility loads, and new kiln loads. The factory has one standby 1600KVA diesel generator is connected to the emergency main distribution board (MDB-EM) via an ATS (Automatic Transfer Switch).

The Factory plant is an innovative manufacturing facility that is sensitive to even the smallest variation in the power quality provided. Using energy-efficient and technologically advanced machinery. It also has a tendency to distort the supplied pure sine wave. The following categories apply to the factory's items.

- ✓ AC and DC motors
- ✓ VFD (Variable Frequency drive)
- ✓ UPS (Uninterrupted power supply)
- ✓ Programing Logic controller (PLC)
- ✓ Furnace
- ✓ Fluorescent lamps
- ✓ cooling system (compressor)
- ✓ Welding machines
- ✓ Office equipment (computers, printers, …)

The AC induction motors and VFDs are the two most common types of loads in the plant. The distribution network is connected to around 50 VFDs (variable frequency drives) with power ratings ranging from 2.5 Kw to 250KW. The distribution of these VFDs on each distribution transformer is presented on Table 3.4. Because transformers T1 and T2 have a greater installed capacity and total number of VFDs attached to them, there is a greater chance that these two transformers may exhibit higher levels of harmonic distortion.

In addition to the induction motors controlled by these VFD, there are a lot of AC induction motors installed in the factory which controlled by Direct on line (DOL), Star-Delta, and soft starter starting methods.

Table 3-4 Number and capacity of VFD on each transformer.

Transformer	Total number of VFDs (variables frequency drive)	Total estimated power capacity of VFDs
T1 & T2 are operating parallel	48	585.5 Kw
T3	2	255.5KW

The Automatic Power Factor Controller (PFC) units on Transformer 1 and 2 boards track the instantaneous power factor (cos φ) and make adjustments when it drops below 0.72 by gradually adding capacitors of varying sizes to the network. The types and patterns of the loads connected to each CMDB determine the pre-designed capacitor stages. Anti-resonance harmonic filters (reactors) are connected in series with each power factor correcting capacitor to detune the system and prevent resonance phenomena, but it not enough for correcting power correction.

Experience indicates that the self-resonant frequency of the resonant circuit, which is created by the power factor correction capacitors and the feeding transformer, is normally between 250 and 500 Hz, or in the range of the fifth and seventh harmonics, as mentioned in the PFC manufacturer product profile (Pandey, 2014). The self-resonant frequency of such detuned systems is scaled below the lowest line harmonic. In order for the detuned PFC system to be solely inductive as perceived by harmonics above this frequency, the anti-resonant reactors that have been put in series with the capacitors are intended to lower the self-resonance frequency to fr=189Hz. Reactive power is corrected by the detuned system's exclusively capacitive behavior at the 50 Hz line frequency.

3.3 Power Quality Related Problems in the Factory

The factory's weekly and monthly maintenance performance reports are analyzed to look for electrical issues that may have arisen due to power quality disruptions. The issues with power quality and dependability that occurred at the factory during the past three years are listed below.

- ✓ Several problems occurred in the control panel unit, such as the failure of the HRC fuses that connect the capacitors to the bus bar, contactors, and the power factor correction capacitor. Furthermore, the control panel boards have faced fire incidents more than three times as a result of these issues.
- ✓ A lot of fluorescent lamps and ballasts failing at abnormal rate.
- ✓ Frequent burnouts of some electric motors that are running at their full rated capacity, such as water pump motors, compressor motors, CO2 exhaust fan motors, steeping discharge motors, and grain cooler compressor motors, and etc.
- ✓ Some electrical components, such as VFDs (variable frequency drives), various panel elements, such as contactors, power switches, safety switches, PLC cards, power converters, and different types of fuses, are fail.
- ✓ Conductors and terminal connectors may overheat and burn out.
- ✓ PLC data corruption and loss on control boards.
- ✓ According to the monthly energy consumption statistics in the appendix B, the factory's overall power factor has become lower than below 0.81 since it paid 76,206.72 Birr two years ago.

3.3.1 Voltage Unbalance Data Analysis

In a three-phase system, voltage unbalance, happens when the three-phase voltages deviate from the ideal 120° separation and equal magnitudes by vary in amplitude or phase angle.

The main causes of voltage imbalance in factory are reduced motor efficiency, overheated machinery, higher energy consumption, and more voltage fluctuations. This is a result of an inductive device's current imbalance. The machines may experience torque pulsations, increased vibration, higher mechanical stress, increased losses, and motor overheating as a result of current imbalance. These results indicate degrading in winding insulation life. The system has harmonics as a result of current imbalance. When the motor is operated with an unbalanced voltage, it becomes hot. As a result, the temperature rises, and it ca be calculated as follow. (Kumar, Performance of Custom Power Devices for Power Quality Improvement , 2017):

$$\text{Additional temperature rise} = 2*(\%\text{voltage unbalance})^2 \quad (3.2)$$

From our measurement and calculation of voltage unbalance tabulated in table 3.4 the average voltage unbalance is 1.766%. Therefore, the additional temperature rise $= 2 * 1.766^2$ =6.23°C. Winding insulation life is reduced by one-half for each 10°C increase in operating temperature (Kumar, Performance of Custom Power Devices for Power Quality Improvement, 2017). The data for the analysis of the voltage unbalance are measured from the transformer secondary sides at full loads

Table 3-5 Voltage unbalance data from the transformer secondary sides at full loads.

Measuring time	L1 –L2 in volt (RMS value)	L1 –L3 in volt (RMS value)	L2 –L3 in volt(RMS value)	Average value in volt	Voltage unbalance (%)
8:00 am	380	372	379	377.00	1.33
8:30 am	379	373	378	376.67	0.97
9:00 am	383	381	369	377.67	2.30
9:30 am	378	380	370	376.00	1.60
10:00 am	375	368	374	372.33	1.16
10:30 am	378	366	376	373.33	1.96
11:00 am	369	373	374	372.00	0.81
11:30 am	374	365	373	370.67	1.53
12:00 pm	378	368	375	373.67	1.52
12:30 pm	373	364	372	369.67	1.53
1:00 pm	371	369	370	370.00	0.27
1:30 pm	376	368	379	374.33	1.69
2:00 pm	377	370	377	374.67	1.25
3:30 pm	377	371	379	375.67	1.24
4:00 pm	381	371	383	378.33	1.94
4:30 pm	389	373	387	383.00	2.61
5:00 pm	393	371	392	385.33	**3.72**
5:30 pm	391	375	392	386.00	2.85
6:00 pm	392	374	394	386.67	3.28

$$\text{Voltage unbalance (\%)} = \frac{\text{Average Value} - \text{Minimum Value}}{\text{Average Value}} * 100\% \quad (3.3)$$

The transformer measures power factor, reactive power, and real power.

Table 3-6 Transformer-measured statistics on real power, reactive power, and power factor.

Month	Active power(kWh)	Reactive Power (kVAR)	Power factor	Paid bill in birr
January, 2025	155,070	112,268.74	0.81	477,030.77
December, 2024	51,030	38,272.50	0.8	150,327.96
November, 2024	189,585	152,100.52	0.78	544,149.98
October, 2024	315,675	244,990.51	0.79	760,689.34
September, 2024	278,460	208,845.00	0.8	505,965.76
August, 2024	322,470	258,711.69	0.78	501,612.39
July, 2024	316,935	262,621.35	0.77	488,798.53
June, 2024	329,580	238,611.80	0.81	517,464.24
May, 2024	300,690	209,882.91	0.82	470,901.37
April, 2024	298,485	200,583.14	0.83	487,612.96
March,2024	406,890	315,781.07	0.79	621,805.50
February,2024	309,555	208,022.22	0.83	495,033.07

In the table 3.6 real power, reactive power, and power factor readings from the factory's transformer's energy meter at various operating hours are recorded. According to data obtained on the transformer's energy meter, the supply power is consuming a significant amount of reactive power, which will raise the feeder's reactive power burden. The reactive power compensating devices in this work must be constructed to decrease the feeder's excessive reactive power consumption. We found that the average power factor is low, at about 0.8, based on the transformer measured data. As a result, the Ethiopian Electric Utility (EEU) has received additional payment from the factory for the charging of reactive electricity from the supply.

In average, the factory pays 3,175.28 Birrs each month for the power factor penalty. To use the power efficiently, avoid paying more, and lower the reactive power consumption from the source power, the power factor must be adjusted to acceptable values by building a suitable mitigation device. By employing mitigation devices to compensate for the reactive power of the loads, the system's active power consumption rises, improving system efficiency and reducing power loss from reactive currents.

3.3.2. Power Frequency Data Analysis

The power frequency measurement has taken from automatic transfer switch (ATS) panel the results are illustrated in the and as shows in table 3.7.

Table 3-7 Power frequency variation from the factory meter.

Measuring time	Current frequency (Hz)	Deviation from Fundamental frequency (%)
8:00 am	50	0
8:30 am	49.5	-1
9:00 am	49.5	-1
9:30 am	50	0
10:00 am	50.5	1
10:30 am	50	0
11:00 am	50	0
11:30 am	50.5	1
12:00 pm	49.5	-1
12:30 pm	50.5	1
1:00 pm	49.5	-1
1:30 pm	49.5	-1
2:00 pm	49.5	-1
3:30 pm	50	0
4:00 pm	50	0
4:30 pm	49.5	-1
5:00 pm	50.5	1
5:30 pm	50	0
6:00 pm	50	0

The frequency reading is taken throughout various industrial working hours. Individual frequency drops range from -1.00% to 1.00%, while the average frequency deviation is 0.158%, or a 0.158% drop from the fundamental values of 50 Hz. This drop in frequency may be the result of overloading the systems or system loading, which occurs when the production is operating at full capacity. We noticed that the frequency fluctuated between 49.5 Hz and 50.5 Hz.

The maximum percentage variance is 1.00%. These results were compared to the IEEE limit, which is a ±1% deviation from the nominal value in a 50Hz system with frequency ranges of 49.5Hz to 50.5Hz. According to the factory's recorded data, the power frequency variation does not exceed the standards' upper limit.

3.3.3 Wave Form Distortion Data Analysis

3.3.3.1 Harmonic Distortion Data Analysis

IEEE 519-2014 defined limitations on harmonic currents and voltages at the point of common coupling (PCC), also known as the point of metering (standard, IEEE 519-2014), and recommended techniques and procedures for harmonic control in electrical power systems.

IEEE 519 Standard for Current Harmonics: General Distribution Systems, ≤ 69 KV:

The current harmonic distortion limitations for odd harmonics are shown in the following table 3.8; even harmonics are restricted to 25% of the odd harmonic limits (James K. Phipps and et al). The distortion limitations for all power production equipment are $I_{SC}/I_L<20$. The maximum short circuit current at the "PCC" coupling point is known as I_{SC}. The highest load current at fundamental frequency at PCC is denoted by I_L. Total Demand Distortion (THD adjusted by I_L) is known as TDD. The current harmonic distortion limits apply to limits of harmonics that loads should draw from the utility at the PCC. Note that the harmonic limits differ based on the ISC/IL rating, where ISC is the maximum short circuit current at the PCC, and IL is the maximum demand load current at the PCC (James K. Phipps and et al).

Table 3-8 Current Distortion Limits for Harmonics (James K. Phipps and et al).

I_{SC}/I_L	H<7	7<H<13	13<H<17
<50	2.2	1.6	1.1
50-100	2.9	5.2	1.6
100-1000	12	8	2.2
>1000	18	12	6

Whereas:

H - Harmonics order.

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

I_L - Maximum demand loads current (fundamental frequency component) at the point of common coupling. It can be calculated as the average of the maximum monthly demand currents for the previous 12 months or it may have to be estimated. All power generation equipment applications are limited to these values of current distortion regardless of the actual short circuit ratio I_{SC}/I_L.

$$I_L = \frac{P}{\sqrt{3} \text{ x PF x KV}} \qquad (3.4)$$

$$Isc = \frac{V_{2o}}{\sqrt{3} * Z_T} \qquad (3.5)$$

For the 1250KVA transformer the transformer impendance is 5.26% while the two transformer operating parallel impedance is 4.73%

So Isc= $\frac{380V}{\sqrt{3}*0.0526\Omega}$ = 4170.97A Total current = 2,408.11A per phase current

Short circuit ration $I_{SC}/I_L = \frac{2408.11A}{1804.2A}$ = 1.33 and,

Isc= $\frac{380V}{\sqrt{3}*0.0473\Omega}$ = 4638.33A Total current = 2,678A per phase current

Short circuit ration $I_{SC}/I_L = \frac{2678A}{1155A}$ = 2.32A

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

Isc - Short circuit current of the transformer.

%Z - Percentage transformer impedance.

P - Load demand.

PF - Power Factor.

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

$$TDD = \frac{\sqrt{\sum_{h=2}^{hmax} I_h^2}}{I_L} \qquad (3.6)$$

Whereas:

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

h - Harmonic order.

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

IEEE-519-2014 is the IEEE standard for voltage harmonics. Limits of Voltage Distortion: The power quality is subject to the limits of voltage harmonic distortion. For example, IEEE 519 specifies limits of 3% harmonic distortion for a single frequency component and 5% for total harmonic distortion for systems with voltages lower than 69 KV.

Table 3-9 Voltage Distortion Limits for Harmonics (standard, IEEE 519-2014)

Voltage Level (kV)	THD Limit (%)	Single Harmonic (%)
< 69 kV	5.0	3.0
69–161 kV	2.5	1.5
> 161 kV	1.5	1.0

We use the measured total load demand, transformer impedance value of 5.26%, and the two transformers working in parallel impedance of 4.73% from the transformer nameplate, and line-to-line voltage to determine the harmonic limits. Equation (3.4) yielded load currents of 1804.5A and 1155A, respectively. Equation (3.5) yields a short circuit current of 2408.11A and 2678A of the transformer impedance value of 5.26%, and the two transformers working in parallel impedance of 4.73%, respectively.

Then, the I_{SC}/I_L short circuit ratios are 1.33 and 2.32, of the transformer impedance value of 5.26%, and the two transformers working in parallel impedance of 4.73% respectively. The IEEE 519-2014 standard states that for harmonics of order less than eleventh, the Current Distortion Limits for Harmonics of the factory is must be less than 4% and the TDDI must be less than 5% (standard, IEEE 519-2014). However, the data shows that the harmonic current distortion is greater than the standard range. The main consequences of harmonics in factories or plants are:

- Overheating: Transformers, motors, and other equipment may overheat due to harmonics, reducing their lifespan and raising maintenance expenses.
- Premature Failure: Electrical equipment may be stressed by harmonics, which could lead to the premature breakdown of parts like insulation and capacitors.
- Problems with the motor: Harmonic currents have the ability to cause currents to flow through the rotor, which can result in pulsating torque, rotor heating, and decreased motor efficiency.
- Problems with transformers: Harmonics can cause overheating and possible damage by increasing iron and copper losses in transformers.
- Capacitor Issues: Due to their heightened sensitivity to harmonic voltage and current, capacitors may overheat and malfunction.
- Higher Energy Losses: Harmonics cause conductors, transformers, and other equipment to lose more power, which raises energy costs.

- More Maintenance Costs: Equipment failures and damage associated to harmonics result in greater maintenance and repair expenses.
- Oversized Equipment: In order to offset the increased losses and stresses caused by harmonics, equipment may need to be oversized, which raises the initial expenses.
- Reduced Power Factor: Harmonics can cause a system's total power factor to drop, which further reduces efficiency and may result in increased energy expenses.

As a result, harmonics have the combined effect of making the transformer heat up more and producing noise. These contribute to the inappropriate use of electricity. After that, the system needs to be free of harmonics.

The sources of harmonics in the factory:

The main sources of harmonic in the factory are the following:

- Non-linear loads such as VFDs and computer,
- Three-phase power converters,
- AC drives,
- Arcing devices like arc furnace.
- Inadequate wiring installation plan

Most of the loads in the factory are squirrel cage induction motors. These motors are controlled by adjustable speed drive called Variable frequency driver and soft starter to control their speed.

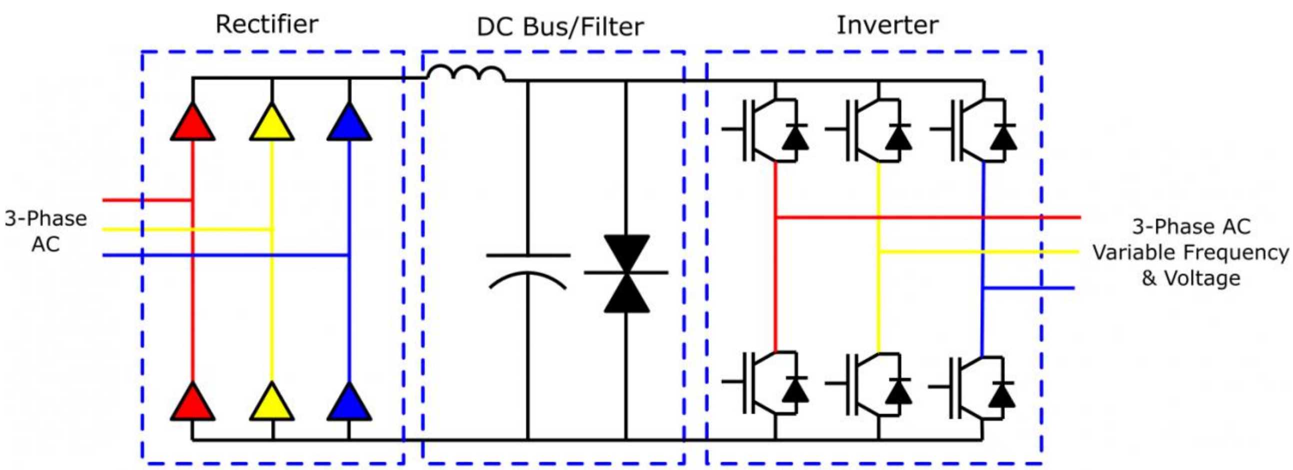


Figure 3:5 circuit diagram of three –phase VFD

The harmonics spectrum is related to the number of torque pulsations of the nonlinear loads, which is why the waveforms change irregularly in the nonlinear loads. Currents in the waveforms change incorrectly for different speed and torque values of the motors operation. The harmonics distortion in these devices is random or not constant.

Assessment results:

All things considered, the analysis of all the data collected throughout the Assela Malt Factory investigate period shows a number of unexpected disruptions, such as: -

Power outages The results show that the factory has serious problems with electrical power interruptions. The primary reasons for interruptions in Assela City's distribution networks are overloading, malfunctions, and operational problems. To overcome this, the plant has been using a 1600KVA standby generator. This thesis study has not proposed any other ways to mitigate this problem.

Long duration Voltage variation (under voltage)

According to the investigation, the transformer's secondary side, or supplying terminal, is where voltage variation occurs. Under voltage occurs most of the time. Variations in load have no effect on the RMS voltage variation. The factory's full load operation has not been the source of the under voltage that occurs at different times (for example, in the morning, midday, or early afternoon). The distribution feeder fault, system overload, and inadequate substation voltage regulation are the primary reasons. Under voltage in industrial plants causes motors to halt and run inefficiently.

Therefore, in order to improve the factory's voltage profile, this issue needs to be fixed. This has the benefit of increasing industrial production and ensuring that every motor operates safely.

Voltage unbalance

Voltage unbalance occurs when the three phase voltages' phase angle discrepancy or voltage magnitude differs from one another. Incorrect load distribution in the power supply phases and the supply transformer's relative distance from the plant's load center are the main causes of voltage imbalance in the factory. Motors and transformers may overheat and lose efficiency due to voltage imbalance. This is a result of an inductive device's current imbalance.

To distribute the load uniformly across all phases, this imbalance can be fixed. When the unbalance is remedied by equally distributing the single phase loads in the system, we can see that the neutral currents caused by the imbalance are zero in the simulation outputs.

Low power factor

We were able to determine the true power for each phase, reactive power, and power factor readings from the reading values. According to the transformer measured data, the average power factor is 0.78, which is far below the EEU norm. Unwanted effects of this low power factor include raising loss through an increase in reactive current, raising the demand for electricity through an increase in reactive power consumption, and other effects on the system, including the industry. The Ethiopian Electric Utility (EEU) has been compensated by the manufacturer for charging reactive electricity from the supply as a result. Therefore, in order to use electrical power efficiently and avoid paying more, the power factor needs to be adjusted to the proper values.

Harmonic distortion

The industry's electrical machinery is negatively impacted by harmonics. For instance, iron and copper are lost at harmonic frequencies in transformers and induction motors, which results in an increase in heat. Current harmonics produce copper loss, and voltage harmonics cause iron loss. The factory's efficiency declines as a result of these issues. As a result, the system needs to reduce harmonics as much as possible. The following mitigation strategies are recommended:

- ✓ Install Distribution static compensator (DSTATCOM).
- ✓ Install of static var compensator (SVC).
- ✓ Install Dynamic Voltage Restorer (DVR) at medium voltage side.
- ✓ Using Uninterruptible Power Supply (UPS). In order to isolate and fed all sensitive
- ✓ and critical loads.

The performance of each device is studied in the following table: 3.10.

Table 3-10 power quality mitigation techniques with their performance levels.

Mitigation technique	Problems that are mitigated	Performance levels
DSTATCOM	Poor power factor voltage profile increment, harmonics elimination	Satisfactory
UPS	Emergency power shortage	Acceptable
SVC	Flickers and unsymmetrical loads	Satisfactory
DVR	Voltage sag and swells	Acceptable

The solution of power quality problems, DSTATCOM provides to mitigate poor power factor and voltage and current harmonics. It also works for voltage profile increment and reactive power compensation. Emergency power shortage can be handled by using UPS which is mainly used for electronic and telecommunication devices. SVC is used to mitigate flickers and unsymmetrical loads. To solve voltage sag/swell problems, DVR can be a potential choice.

Among all these devices we select DSTATCOM based on the following reasons:

DSTATCOM is very well known and can provide cost effective solution for the following points:

- ✓ Compensation of reactive power.
- ✓ To increase the voltage profile.
- ✓ To upgrade power factor to acceptable values in the system.
- ✓ To eliminate harmonic distortion in the system.

3.4. DSTATCOM

It is a compensating device based on power electronic technology to be used in the distribution line; it is essentially a controlled current injecting device connected in shunt with the distribution line. As shown in Figure 3.6 below, DSTATCOM is a shunt connected solid state device that is installed at the point of common coupling of the loads in order to control the load side disturbances. It can exchange reactive and real power with the distribution line; the magnitude of the DSTATCOM voltage can be controlled to control the reactive power and real power in the distribution line (Piyushkumar M. Saradva, 2016). It provides reactive power compensation in ac networks.

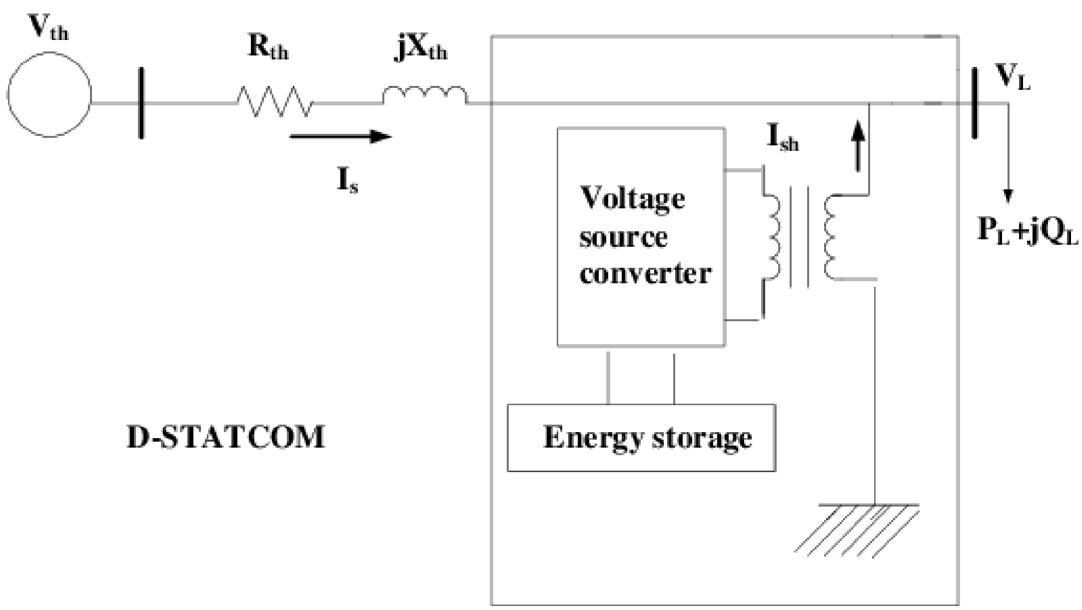


Figure 3:6 Basic Structure of DSTATCOM (Eklas Hossain, 2018).

At the distribution level, a DSTATCOM serves the following functions: Regulating voltage and correcting power factor. To give reactive power to the system, eliminate any harmonic distortions of the voltage in order to lessen imbalance or distortions in the supply voltage or source current (Eklas Hossain, 2018).

3.4.1 Basic Configuration of DSTATCOM

For properly working, the DSTATCOM has different parameters, or components. The main components of DSTATCOM are the following (Eklas Hossain, 2018):

- Voltage Source Converter
- Energy Storage Device
- LC Passive Filter
- Coupling Transformer
- Control Block

Voltage Source Converter: AVSC uses the DC voltage across the storage device to produce a three-phase AC output voltage wave. The output voltage's magnitude and phase angle are controlled to generate the leading or lagging reactive power required for compensation. VSCs can be three-phase, three-wire, or three-phase, four-wire. There is the option of a two-level or three-level converter.
Energy Storage Device: A shunt connection is made between a DC source and a DC capacitor. This storage device can be charged using a battery source or recharged using a converter. Its main responsibility is to supply energy to VSC over a DC link so that the injected voltage can be generated.
LCL Passive Filter: The type of system and the presence of harmonics at the inverter output dictate which LCL filter is best. The LC filter eliminates the harmonics and matches the output impedance of the inverter.

Coupling Transformer: A coupling transformer connects the output voltage of the voltage source converter to the AC system. The reactance of the coupling transformer connects these voltages to the AC system.

Control Block: The primary duties of the control block are fault detection, system voltage sag and swell detection, voltage computation, trigger pulse production for the sinusoidal PWM-based DC-AC converter, and closing the trigger pulses after the event is over.

The control blocks also manage external devices like banks of capacitors that are mechanically switched.

Location of DSTATCOM: As seen in figure 3.7, DSTATCOM is connected to the distribution bus at the point of common coupling. When required by the loads, the distribution STATCOM is connected between the source bus and the load bus to interchange reactive and actual power.

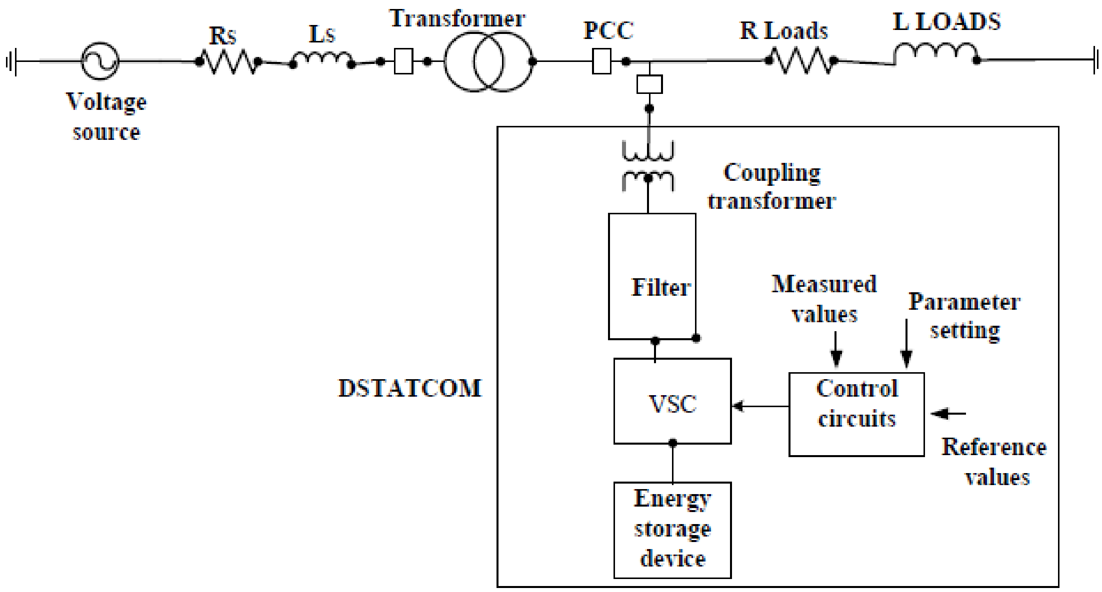


Figure 3:7 Design of DSTATCOM to the system (Eklas Hossain, 2018)

3.4.2 Operation Principle of DSTATCOM

A Distribution Static Compensator (DSTATCOM) is a shunt-connected reactive power compensation device used in power distribution networks. It improves power quality by lowering harmonics, regulating power factor, and controlling voltage. The basic principle of DSTATCOM operation is the generation or absorption of reactive power through a voltage source inverter (VSI). The necessary energy storage is provided by a DC link capacitor, which also supports the VSI. A coupling transformer connects it to the electricity system (EIA, 2023).

A DSTATCOM procedure is depicted in a single line diagram in Figure 3.8.

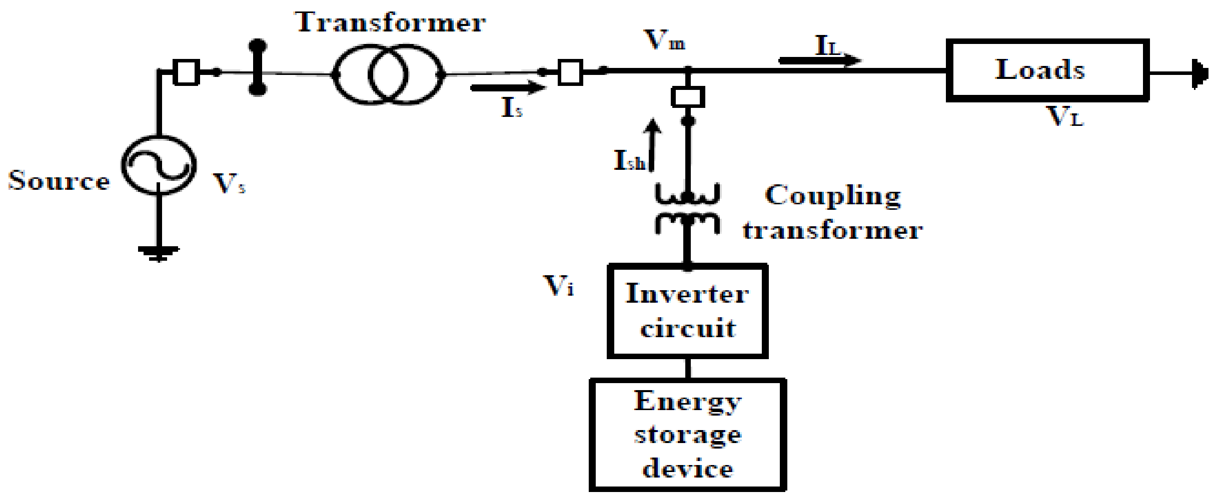


Figure 3:8 Basic Operation principles of DSTATCOM (Eklas Hossain, 2018).

The DC voltage is converted into a set of three-phase ac output voltages by the IGBT-based VSC. These voltages are in phase and connected to the AC system via the coupling transformer's reactance. The DSTATCOM output voltages' phase and magnitude are appropriately changed in order to effectively regulate the active and reactive power exchange between the DSTATCOM and the ac system.

Exchange of Reactive Power The reactive power exchange between the DSTATCOM and the AC system is controlled by the variable amplitude of the DSTATCOM output voltage. The DSTATCOM's reactive power is determined by (Beaty):

$$Q = \frac{(Vi - Vs)xVs}{X} \qquad (3.7)$$

Where,

Q is the reactive power.

Vi is the magnitude of DSTATCOM output voltage.

Vs is the magnitude of system voltage.

X is the equivalent impedance between DSTATCOM and the system.

Reactive power exchange between DSTATCOM and AC system based on the figure 3.8 is explained through the following cases:

Case I: Reactive current is a zero and reactive power is neither generated nor absorbed by the DSTATCOM if the output voltage (Vi) and the AC system voltage (Vs) are equal.

Case II: When the system voltage comes in below the nominal values, the DSTATCOM output voltage rises above the amplitude of the AC system voltage. The lagging current then flows from the DSTATCOM to the AC system via the transformer reactance, which causes the device to produce capacitive reactive power. such that the nominal values of the system voltage are reached.

Case III: The leading current flows from the AC system to the DSTATCOM and the device generates inductive reactive power if the system voltage is higher than the nominal values and the DSTATCOM output voltage amplitude is reduced to a level lower than that of the AC system. in order for the system voltage magnitudes to return to their initial values.

Exchange of Active Power: Because more switching devices are being used, the DC capacitor is necessary to provide actual power to the switches. In the case of direct voltage control, actual power exchange is necessary to maintain a constant capacitor voltage.

3.5. Mathematical Modeling of the System

Three phase source modeling: consider the ac power grid in the steady state. This power gird contains passive elements resistor, inductor and capacitor (R, L, C), and the sinusoidal current and voltage sources. The supply source voltage is 15000V at the terminal of the industrial feeder in the substation for the 132kV/15kV step down transformer secondary side. The power delivered to the loads through the industrial feeder of the system is 12.5MVA [load report data of the EEU documents]. The source resistance and inductance can be calculated by using the following expressions (A. A. Imam, 2020).

$$R_s = \frac{V^2}{S*10} \tag{3.8}$$

$$R_s = \frac{15000^2}{12.5*10^6*10} = 0.18\Omega$$

$$L_s = \frac{V^2}{2\pi Sf} = \frac{15000^2}{2*3.14*12.5*10^6*50} = 0.057H$$

Therefore, the source resistance and inductance are 0.18Ω and 0.057H respectively with the system frequency of 50Hz.

Three phase transformer modeling: distribution transformer modeling: the power rating of the distribution transformer is 1250kVA and two 800kVA parallel operating transformer. The primary side voltage of the transformer is 15000V and the secondary side is 380V phase –to- phase voltage in the system and 220V phase –to- ground and 5.26% and 4.73% impedance 1250kVA and 800kVA transformer respectively.

Transformer impedance is computed as follows: To meet industry requirements, we want to use the transformer model to determine the winding's resistance and inductance per unit (P.u.). The calculation is based on the transformer's rated power. system fundamental frequency F_{sys} and the nominal voltage V_n in Vrms for each winding. The following is a description of the resistance and inductance per unit (Behera, 2020):

For distribution transformer is 1250kVA

$$Z_{base} = R_{base} = X_{base} = \frac{V_n^2}{S_{rated}} = \frac{(15000V)^2}{1250{,}000VA} = 180\Omega$$

$L_{base} = \frac{X_{base}}{2\pi F_n} = \frac{180\Omega}{2*3.14*50Hz} = 0.57H$, and

For distribution transformer is two 800kVA parallel operating transformer

$$Z_{base} = R_{base} = X_{base} = \frac{V_n^2}{S_{rated}} = \frac{(15000V)^2}{800{,}000VA} = 281.25\Omega \qquad (3.9)$$

$$L_{base} = \frac{X_{base}}{2\pi F_n} = \frac{140.625\Omega}{2*3.14*50Hz} = 0.896H$$

Source impedance values in the winding one $R_s = 0.18\Omega$ & $L_s = 0.057H$ based on these compute the resistance and inductance in p.u for the transformer windings.

$$R_{1250kVA} = \frac{0.18\Omega}{180\Omega} = 0.001pu \text{ and } L_{1250KVA} = \frac{0.057H}{0.57H} = 0.01pu$$

$$R_{800kVA} = \frac{0.18\Omega}{281.25\Omega} = 6.4*10^{-4}pu \text{ and } L_{800KVA} = \frac{0.057H}{0.896H} = 0.063pu$$

Modeling of the 50-meter distance between the transformer and the load terminal: the supply voltage is 220V phase to neutral and 380V line to line, and the distance between the transformer and the load terminal is approximately 50 meters. Line length belongs to the short transmission line category when categorized as transmission lines based on line length and voltage magnitude is taken into account. (Cebrian, April 5-8, 2021)

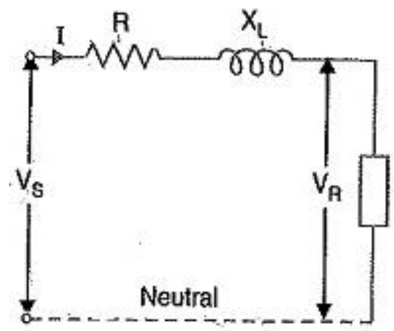


Figure 3:9 The feeder line between the transformer and the load terminal is represented by a short transmission line.

The following expression provides the transformer's secondary voltage expression (Eklas Hossain, 2018):

$$V_s = V_R + IR\cos\emptyset + IX\cos\emptyset \quad (3.10)$$

The voltage regulation is given by: $\%V_R = \frac{V_S - V_R}{V_R}$ *100% (3.11)

The 5% figure is a respectable average estimate worldwide, while power loss during transmission and distribution might vary depending on variables like distance, technology, and infrastructure quality (EIA, 2023).

Power lose:

$$P_{losses} = 3I^2R \quad (3.12)$$

Where

Vs = output voltage transformer

V_R = load voltage

I = load current

R = resistance in each conductors

X_L = reactance

∅ = power factor of the system

The total load two operating of the transformers is 1450KVA and the total load current all transformer is 2203A and the power factor of the system is 0.77 and consider 5% of total power loss in the lines. Total power loss due to the resistance of the lines, can be calculated

$P_{losses} = 3I^2R \ = \ 0.05 * 1116kW^2 * 0.77 *= 36.4KW$ and,

The total load of the transformers is 686KVA and the phase current all transformer is 512A and the power factor of the system is 0.78. Total power loss due to the resistance of the lines, can be calculated

$$P_{losses} = 3I^2R \ = \ 0.05 * 263kW^2 * 0.78 = 26.75KW$$

From the above equation R = 0.05Ω*0.05/km and 0.054Ω*0.05/km of the two identical transformers which operate parallel and single transformer which operate alone respectively.

Electrical loads: There are several loads in the manufacturing, each with an individual function. According to our investigations at the factory, there are single phase motors like pumping, three phase squirrel induction motors, servomotor and wound motor, and nonlinear loads like VFD. computers, fluorescent lights.

Based on the factory-specified installed transformer capacity, the system's maximum electrical load power demand 1450KVA on the two parallel transformer and 685.9KVA on the other transformer. Since the system's total apparent power is the sum of its active and reactive power, the load power factor, when this power is calculated as active and reactive power, is between 0. 77.

$$S^2 = P^2 + Q^2 \quad (3.13)$$

$$P= S cos\theta \quad (3.14)$$

$$Q= S cos\theta \quad (3.15)$$

So, total real and reactive power of the system, of the two transformer is P = 1116.5kW *and* Q =925.22$kVAr$. and the other transformer is P = 528.14kW *and* Q =437.63$kVAr$

Nonlinear loads represented by three phase diode rectifier connected to a resistive and

inductive loads. Nonlinear three phase loads: P =263.5kW *and* $Q \approx 220kVAr$.

3.6 DSTATCOM Mathematical Modeling

Another aspect of power quality that D-STATCOM enhances is long-term voltage adjustment. Due to the energy storage system's low capacity, this device can't give active power to the system for an extended period of time because it is employed under steady-state conditions. Consequently, the load flow program has a good D-STATCOM model. Furthermore, D-STATCOM determines and analyzes analytically and mathematically the direction and rating of reactive power that must be replaced for voltage compensation in the goal value of 1p.u. using phasor diagram method (Gyugyi, 2000). After considering the effect of DSTATCOM on voltage improvement at other nodes, the best location for D-STATCOM to mitigate under voltage problems in the distribution network is determined. Load flow is an essential technique for the analysis, planning, and operation of any power system in steady-state conditions.

3.6.1 Basic Structure of DSTATCOM

A DSTATCOM consists of:

- DC - link capacitor
- Coupling transformer
- Voltage Source Inverter (VSI)

a) Design of DC Link capacitor

The purpose of the DC link capacitor is to keep the DC connection voltage constant. The DC link voltage of the DSTATCOM is maintained at a constant magnitude or level due to the appropriate switching of the IGBT device of the voltage source converter. The voltage output of the DSTATCOM is produced by the VSC using the DC link capacitor. The speed of the controller responses and the harmonic distortion of the voltage produced by the DSTATCOM are directly impacted by the DC link capacitor. If the size of the capacitor is small, the controller will respond rapidly even though the output has a lot of ripples and harmonic distortion. The output voltage will increase if the DC connection capacitor is very large (Piyushkumar M. Saradva, 2016.).

Therefore, a PI controller is employed to regulate the DC link voltage. Careful tuning of the PI controller parameters is essential to ensure system stability. Based on the analysis above, the selection of the capacitor voltage and its corresponding capacitance values is determined using the relevant equations.

$$V_{dcref} = \frac{2\sqrt{2}\,V_r}{\sqrt{3}\,m_a} = \frac{2\sqrt{2}*380V}{\sqrt{3}*1} = 620.55V \qquad (3.16)$$

$C_{dc} = \frac{S*\tau*2}{{V_{dc}}^2} = \frac{1450*10^3*0.004*2}{(620.55V)^2} = 0.0301 farad$ for the 1450 kVA load of two transformers and

$C_{dc} = \frac{S*\tau*2}{{V_{dc}}^2} = \frac{685.9*10^3*0.004*2}{(620.55V)^2} = 0.01425 farad$ for the 685.9 kVA load of transformers

Where V_{dcref} is the reference capacitor voltage,

V_{L-L} Line to line load voltage with value of 380V,

m_a is the modulation index with value of 1,

S is the system's power rate, which is 1450KVA and 685.9KVA for two transformer operating parallel and one working alone transformer respectively,

C_{dc} is the DC capacitor value, and

τ is the system's time constant, which is 4ms.

Reference The estimated 700V DC-link voltage comes from the rectified DC voltage from the supply system, which is kept in the capacitor. It is estimated that the DC-link capacitor has a value of 59200µF and 28100µF for 1600KVA and 1250KVA transformer system respectively.

b) Coupling transformer

LCL filters' inductors must be designed in accordance with the standard, which states that the voltage drop across them cannot be greater than 10% of the grid phase voltage (Prabir Ranjan Kasari, November 5-8, 2017.).

$$\omega L_g * I_n < 10\% \frac{U_n}{\sqrt{3}} \quad (3.17)$$

Where,

L_g *is* grid-side *inductance*

ω is natural frequency, 314.16rad/sec.

I_n is Current per phases.

U_n is phase to ground voltage.

For 1600KVA system,

$$I_n = \frac{S_n}{\sqrt{3}U_n} = \frac{1600000VA}{\sqrt{3}*380V} = 2430.94A \quad (3.18)$$

$$\omega L_g * I_n < 10\% \frac{380V}{\sqrt{3}} = 21.94V$$

$$L_g < \frac{21.94V}{\omega * I_n} = \frac{21.94V}{2 * 3.14 * 50 * 2430.94A} \approx 0.0287mH$$

Maximum inductor size is $L_g < 0.0287mH$

Let choose L_{total} = 0.025mH

The two side inductance values are selected when the power loss of the system is less than 10%. The converter side and grid side inductors are connected by a few constants, and in this thesis, we used a ratio of 0.1pu for the inductors while accounting for power loss. Such as $L_g = \alpha * L_c$, $\alpha < 1$, where, $\alpha = 0.1.$ so, $L_c = 22.5\mu H$ and $L_g = 2.25\mu H$

For 1250KVA system

$$I_n = \frac{S_n}{\sqrt{3}U_n} = \frac{1250000VA}{\sqrt{3} * 380V} = 1899A$$

$$\omega L_g * I_n < 10\% \frac{380V}{\sqrt{3}} = 21.94V$$

$$L_g < \frac{21.94V}{\omega * I_n} = \frac{21.94V}{2 * 3.14 * 50 * 1899A} \approx 36.8\mu H$$

Maximum inductor size is $L_g < 36.8\mu H$

Let choose $L_{total} = 35\mu H$

Also we used a ratio of 0.1pu for the inductors while accounting for power loss. Such as $L_g = \alpha * L_c$, $\alpha < 1$, where, $\alpha = 0.1$. so, $L_c = 31.5\mu H$ and $L_g = 3.15\mu H$

For better efficiency of DSTATCOM, reactive power absorbed by the capacitor filter must be less than 5% of rated capacity of the system power and *Filter cutoff 1.2 kHz* is recommend,

(Gyugyi, 2000).

For 1600KVA transformer designing of capacitor filter size the Switching frequency is 3 kHz, Phase voltage: 220 V and nominal current 2430.94A

Choose resonance frequency(f_r) well below switching frequency (3 kHz), Now compute for capacitance

$$f_r = \frac{1}{2\pi} \sqrt{\frac{L_{total}}{L_c \, L_g C_f}} \qquad (3.19)$$

$$C_f = (\frac{1}{2\pi f_r})^2 \frac{L_c L_g}{L_{total}} = (\frac{1}{2 * 3.14 * 1200Hz})^2 \frac{2.5 * 10^{-6} * 22.5 * 10^{-6}}{25 * 10^{-6}}$$

$$C_f = 3.96\mu F$$

the filter capacitor, which is linked to the inverter's output sides, has a value of 3.96μFarad.

To control LCL resonance damping resistor is computed

$$R_d = \frac{1}{3\omega_r C_f} = \frac{1}{3 * 2 * 3.14 * 1200 * 3.96 * 10^{-6}} = 0.111\Omega$$

For 1250KVA transformer designing of capacitor filter size the Switching frequency is 3 kHz, Phase voltage: 220 V and nominal current 1899A

Choose resonance frequency(f_r) well below switching frequency (3 kHz), Now compute for capacitance

$$f_r = \frac{1}{2\pi} \sqrt{\frac{L_{total}}{L_c \, L_g C_f}}$$

$$C_f = (\frac{1}{2\pi f_r})^2 \frac{L_c L_g}{L_{total}} = (\frac{1}{2 * 3.14 * 1200Hz})^2 \frac{3.5 * 10^{-6} * 31.5 * 10^{-6}}{35 * 10^{-6}}$$

$$C_f = 5.544\mu F$$

the filter capacitor, which is linked to the inverter's output sides, has a value of 12.94µFarad.

To control LCL resonance damping resistor is computed

$$R_d = \frac{1}{3\omega_r C_f} = \frac{1}{3 * 2 * 3.14 * 1200 * 12.94 * 10^{-6}} = 0.798\Omega$$

Coupling transformer: A 700V/380V coupling transformer which ensures makes coupling between the VSC inverter and the ac system.

Reactive Power determination: The variable amplitude of the DSTATCOM output voltage regulates the reactive power exchange between the DSTATCOM and the AC system. Based on the supplied DC voltage, the supply system's AC voltage, and the total impedance between the AC system and the DSTATCOM, the DSTATCOM determines the total reactive power compensation. The reactive power supply of the DSTATCOM is established by:

$$Q = \frac{(V_i - V_s)V_s}{X} \quad (3.20)$$

Where,

Q is the reactive power.

V_i is the magnitude of DSTATCOM output voltage.

V_s is the magnitude of system voltage.

X is the equivalent impedance between DSTATCOM and the system.

c) Design of voltage source converters

The mathematical modeling of the voltage source converter (VSC) system in the dq-reference frame serves as the foundation for the control approach. A regulated voltage source for the AC side, as seen in figure 3.10 (a) below, and a current source for the DC side, as seen in figure 3.10 (b) below, can be used to illustrate the voltage source converter. Thus, the following analogous circuit can be used to depict the converter and grid interaction (Eklas Hossain, 2018).

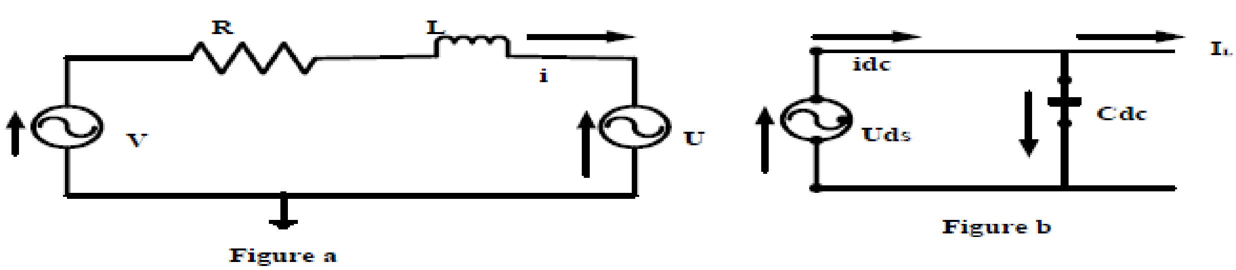


Figure 3:10 VSC design equivalent circuit

When Kirchhoff's voltage low is put across the reactor and the resistor, the following formula holds true.

$$L\frac{di_{abc}}{dt} = V_{abc} - U_{abc} - Ri_{abc} \quad (3.21)$$

Where,

R - Reactor resistance

L - Reactor inductance

V_{abc} - AC voltage in abc reference frame.

U_{abc} - Converter AC side output voltage in abc reference frame.

I_{abc} - AC current through the reactor in abc reference frame.

The time-varying three phase values are then converted to vectors in a two coordinate (α, β) system using the coordinate transformation method called Clark transformation.

$$\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = \frac{2}{3}.\begin{bmatrix} 1 & \cos\frac{2\pi}{3} & \cos\frac{4\pi}{3} \\ 0 & \sin\frac{2\pi}{3} & \sin\frac{4\pi}{3} \end{bmatrix}\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \quad (3.22)$$

This Clark transformation offers the advantage of dimension order reduction. Consequently,

$$L\frac{di_{\alpha\beta}}{dt} = V_{\alpha\beta} - U_{\alpha\beta} - Ri_{\alpha\beta} \quad (3.23)$$

The following park transformation is used to further convert the electrical quantities from the (α, β) stationary coordinate system quantities to rotational dq-reference frame equivalent numbers using the transformation angle from the system phase measurement at the Phase-Locked Loop (PLL).

$$\begin{bmatrix} x_d \\ x_q \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{bmatrix}\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} \quad (3.24)$$

This equation is change to

$$L\frac{di_{dq}}{dt} = V_{dq} - U_{dq} - (R + j\omega L)i_{dq} \quad (3.25)$$

Where,

$L\frac{di_{dq}}{dt}$ = rate of change of the d-q current scaled in the inductance

V_{dq}= voltage applied to the system

U_{dq}=Back electromotive force (EMF) An internal voltage that produced by the mutual magnetic flux in the transformer.

$(R + j\omega L)i_{dq}$=losses and additional voltage drop

Ri_{dq}= pure resistive voltage drop

$j\omega Li_{dq}$= voltage drop caused by being in a rotating frame and The electrical angular frequency (rad/s) is denoted by ω. This speed voltage term illustrates how the rotation of the reference frame introduces cross coupling between the quantities of the two axis. The following is the outcome of analyzing equation (3.25) into its constituent elements.

$$L\frac{di_d}{dt} = V_d - U_d - (R + j\omega L)i_d \quad (3.26)$$

$$L\frac{di_q}{dt} = V_q - U_q - (R + j\omega L)i_q \quad (3.27)$$

These formulas illustrate the connection between the input currents and converter voltages in the dq-reference frame. Conversely, applying Kirchhoff's current low at the DC side node in figure 3.10 above to the converter's DC side is represented as follows:

$$I_{cap} = C_{dc}\frac{dU_{dc}}{dt} = i_{dc} - i_L \quad (3.28)$$

Where,

I_{cap} is current flowing into the DC capacitor

I_L is the DC current through the DC connection,

Idc is current coming from the DC side.

Cdc the value of DC Capacitance capacitor and

Udc is DC-link voltage

If more current enters the capacitor than exits ($i_{dc} > i_L$), the capacitor charges; if more current is drawn than supplied ($i_{dc} < i_L$).

Complete the mathematical modeling of VSC using equations (3.26), (3.27) and 3.28. In order to achieve the goal of employing dq quantities to manage active and reactive power, it is now required to discuss the power relations in the dq-reference frame. The total of the instantaneous powers generated by each phase of a three-phase system is its instantaneous power. Thus:

$$P(t) = V_a(t)i_a(t) + V_b(t)i_b(t) + V_c(t)i_c(t) \quad (3.29)$$

The following power equation can be obtained by expressing the currents and voltages in a two-phase (α, β) stationary system.

$$P(t) = \frac{3}{2}\left(V_\alpha i_\alpha + V_\beta i_\beta\right) + 3V_0 i_0 \quad (3.30)$$

There is no link between the coordinate system and the active power. In the dq-reference frame, it may therefore be written as follows:

$$P(t) = \frac{3}{2}\left(V_d i_d + V_q i_q\right) + 3V_0 i_0 \quad (3.31)$$

The zero components are equal to zero in a balanced state. P will therefore have the form.

$$P(t) = \frac{3}{2}\left(V_d i_d + V_q i_q\right) \qquad (3.32)$$

Conversely, the apparent power can be used to compute the reactive power as follows:

$$S(t) = \frac{3}{2}Ui^* = (t) + jq(t) \qquad (3.33)$$

Reactive power is represented by the imaginary component of this equation. Therefore,

$$q(t) = Im\left(\frac{3}{2}Ui^*\right) = \frac{3}{2}\left(V_q i_d - V_d i_q\right) \qquad (3.34)$$

The following significant relationship results from synchronizing the d axis voltage with the system voltage.

$$V_d = V \text{ and } V_q = 0 \qquad (3.35)$$

The power equations then turn into:

$$P = \frac{3}{2}V_d i_d \text{ and } q = -\frac{3}{2}V_d i_q \qquad (3.36)$$

Reactive power depends on the q-axis current, whereas active power depends on the d-axis current, according to equation (3.36). As a result, active and reactive powers are separated, and id and iq can be individually controlled. However, the DC side's power equation is as follows:

$$P_{dc} = V_{dc} i_{dc} \qquad (3.37)$$

The inner portion of the cascaded control approach is known as the current controller loop. For the control system to be stable, it must be incredibly quick in comparison to the external controllers. It receives dq converted currents from transducers and current reference values from the outer controllers. The general configuration of the inner current control loop is as follows.

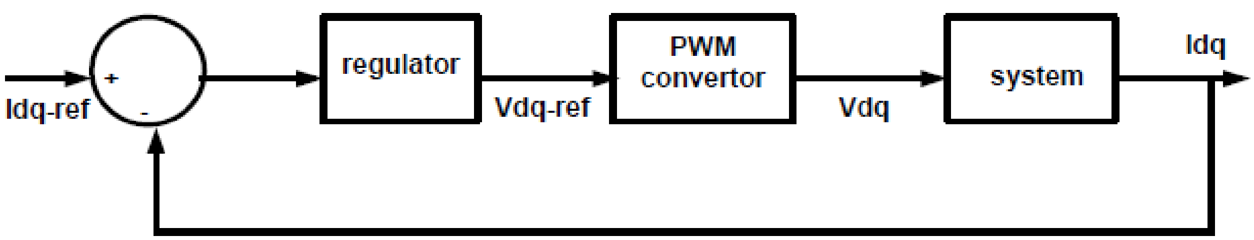


Figure 3:11 The Control Loop for Internal Current.

Two PI regulators for the d and q axis currents each make up the inner current control loop. These controllers turn the comparison's erroneous current into a voltage signal that the PWM generator uses to switch the converter.

PI regulator: Proportional and integral controller is the term that PI stands for. A PI controller is enough to get the steady state error signal down to zero because of the DC vectors created by the dq-transformation. The following equation represents the PI regulator:

$$K_p(1 + \frac{1}{sT_i}) \quad (3.38)$$

where Ti is the integral time constant and Kp is the proportional gain. The PWM converter receives the voltage order from the regulator. Therefore, the regulator's output is from the inner current control loop in figure 3.12.

$$\left(i_{dq}{}^{ref}(s) - i_{dq}\right)\left(K_p\left(1 + \frac{1}{sT_i}\right)\right) = U_{dq}{}^{ref}(s) \quad (3.39)$$

PWM converter: A first-order equation approximates the converter. As seen in Figure 3.12 above, it generates an output voltage that is the converter side voltage.

$$u_{dq}{}^{ref}\left(\frac{1}{(1+T_a s)}\right) = u_{dq} \quad (3.40)$$

Where $T_a = \frac{T_{switch}}{2} = \frac{3.333 * 10^{-4}}{2} = 1.67 \; * 10^{-4} sec$

A converter switching frequency of 3kHz is selected in our design case. resulting in Ta = 0.00033s. With time delay Ta, this approximation thus demonstrates that the converter is a perfect power transformer. It is excepted that the switching frequency in PWM will be significantly higher than the system frequency.

System transfer equation: It is clear from equation (3.27) that a cross coupling term jωLidq is present in the dq representation of the AC side of the converter system. This word is seen as a disturbance for each axis from a control perspective.

$$T_a = {}^{T_{switch}}/_{2}$$

Compensation terms Vd and ωliq are fed forward on the d-axis controller, whilst Vq and ωLid are fed forward on the q-axis controller, in order to remove the cross coupling (disturbances). Now that the decoupling compensation terms have been applied, the converter input from the controller is:

$$u_d{}^{ref} = -(i_d{}^{ref} - i_d)(K_p\left(1 + \frac{1}{sT_i}\right)) + \omega L i_q + v_d$$

$$u_q{}^{ref} = -(i_q{}^{ref} - i_q)(K_p\left(1 + \frac{1}{sT_i}\right)) + \omega L i_d + v_q \quad (3.41)$$

so, the output of the converter is:

$$(-(i_d{}^{ref}(s) - i_d)(K_p\left(1 + \frac{1}{sT_i}\right)) + j\omega L i_q + v_d)(\frac{1}{1 + T_a s}) = u_d(s)$$

$$(-(i_q{}^{ref}(s) - i_q)(K_p\left(1 + \frac{1}{sT_i}\right)) + j\omega L i_d + v_q)(\frac{1}{1+T_a s}) = u_q(s) \qquad (3.42)$$

Since the converter is thought to be an ideal transformer, its input is solely affected by a time delay. With the exception of time delay, we can therefore presume that the converter's input and output are identical. The following happens in the time domain when equation (3.27) is substituted for equation (3.42).

$$u_d = L\frac{di_d}{dt} + Ri_d \text{ and } u_q = L\frac{di_q}{dt} + Ri_q \qquad (3.43)$$

Since the cross coupling terms are removed, as shown in equation (3.43), the d and q component currents can be independently controlled. The following is the result of the Laplace transformation of equation (3.44):

$$i_{dq} = \frac{1}{R+Ls} * u_{dq}(s) \qquad (3.44)$$

Therefore, the system transfer equation will become:

$$G(s) = \frac{1}{R} * \frac{1}{1+s\tau} \qquad (3.45)$$

τ defines as the reactor time constant, $\tau = \frac{L}{R}$

Equation (3.45) indicates that the system is of first order and that the two equations are independent of each other.

Tuning the current controller: A variety of methods can be used to tune the controller. The goal of tuning is to maximize plant performance and obtain quick system responsiveness.

The controller can be tuned in a number of ways. Optimizing plant output and getting a fast response from the system are the two main objectives of tuning.

Here, the VSC controllers are tuned using the same technique as the fundamental electrical derivatives. As a result, the controllers move faster in the direction of the inner loop. The optimum modulus criterion is used to tune the inner loop. When there is one dominant time constant and one minor time constant in the controlled system, this technique is used. To get a conventional transfer function, the controller zero cancels the dominating pole. The other parameters are then obtained by equating the absolute value (modulus) of this transfer function to 1 from the unity gain criterion. It was selected since it is easy to use and responds quickly when tracking the reference value.

$$G_{ol} = K_p(\frac{1+sT_i}{sT_i})(\frac{1}{1+sT_a})(\frac{1}{R+sL}) \quad (3.46)$$

And simplifying that gives: $G_{ol} = K_p(\frac{1+sT_i}{sT_i(1+sT_a)(R+sL)}$ (3.47)

In this case, the controller's zero is positioned above the system's dominating pole. Ti is therefore equivalent to the reactor time constant, Ʈ. the reactor values L=25µH, R=0.111Ω and L= 35µH, 0.798Ω of the two parallel operating transformer and single transformer respectively that are computed under the fitter design specifications:

$T_i = \tau = \frac{L}{R} = \frac{0.025mH}{0.111} = 2.25sec$ for 1600KVA transformer and $T_i = \tau = \frac{L}{R} = \frac{0.035mH}{0.798}$ = 4sec for 1250KVA transformer

Pole zero cancellation occurs as a result. The dominant pole is cancelled by the controller's zero. As a result, the following second order close loop transfer function is resulted in:

$$G_{ol} = \frac{K_p}{T_iT_aR} * \frac{1+sT_i}{s^2+\frac{s}{T_a}+\frac{K_p}{RT_iT_a}} \quad (3.48)$$

In order to get optimal performance across shoot and rise time, ζ the damping constant of the second order equation must be 0.707 is standard. Therefore, using equation (3.48), we can obtain,

$$\omega_n = \sqrt{\frac{K_p}{T_iT_aR}} \quad (3.49)$$

The result enables us to calculate as follows: $\xi = \frac{1}{2}\sqrt{\frac{T_iR}{K_pT_a}}$ (3.50)

Solving for Kp and replace the values

$$K_p = \frac{T_iR}{4\xi^2T_a} \approx \frac{2.25sec * 0.111\Omega}{4 * 0.707^2 * 1.67 * 10^{-4}sec} = 748 \; for \; 1600kVA$$

$$K_p = \frac{T_iR}{4\xi^2T_a} \approx \frac{4sec * 0.798\Omega}{4 * 0.707^2 * 1.67 * 10^{-4}sec} = 956 \; for \; 1250kVA$$

DC-voltage controller: Regulating the power exchange between the two sides of the converter requires DC voltage management. Using the converter current as a control variable, the DC voltage control is intended to maintain the DC voltage at a predetermined level. The active power entering the converter is equal to the active power exiting the converter, assuming that the converter is loss-less. The DC power equation (3.37) and the active power equation (3.36) are then equivalent to:

$$\frac{3}{2}V_di_d = V_{dc}I_{dc} \quad (3.51)$$

I_{dc} may answer the given equation (3.28) as follows:

$$I_{dc} = I_L + C_{dc}\frac{dU_{dc}}{dt} \qquad (3.52)$$

Equation (3.52), when substituted in equation (3.51), provides the relationship between the d-axis current and the DC voltage:

$$\frac{3}{2}V_d i_d = V_{dc}.(I_L + C_{dc}\frac{dU_{dc}}{dt}) \qquad (3.53)$$

The following expression is obtained by applying Laplace transformation and solving for Udc:

$$U_{dc} = \frac{1}{Cs}(\frac{3}{2}.\frac{V_d i_d}{V_{dc}} - i_L) \qquad (3.54)$$

Here, the compensation period, which has been implemented to mitigate the impact of the disruption from i_L, Before the converter, the value $\frac{3}{2}.\frac{V_d}{V_{dc}}\, i_L$ might be added. The first-order equation approximates the inner current loop. Adjusting the DC voltage controller: Symmetrical optimal tuning is used to adjust the DC controller. The following are the results of tuning the voltage controller's parameters using a symmetrical optimal technique. The time constant proportional:

$$T_i = \alpha^2 T_{eq}$$

Between 1/Ti and cross over frequency and 1/Teq and cross over frequency, α is the symmetrical distance. The range of acceptable values for α is 2 to 4. The following formula is used to determine the equivalent time delay caused by the current control loop:

$$T_{eq} = 2T_a = 3.33 * 10^{-4} sec$$

Consequently, 0.000208 seconds is the proportional time constant requiring α = 2.5. To determine the proportionate gain, use the following formulas: Vd = 380V, C = 59200μF, and V_{dc} = 700V for 1600KVA two transformer and Vd = 380V, C = 59200μF, and V_{dc} = 700V for 1250KVA transforme.

$$K_p = \frac{2}{3}.\frac{V_{dc}C}{V_d \alpha T_{eq}} = \frac{2}{3} * \frac{700V * 59200\mu F}{380V * 2.5 * 3.33 * 10^{-4} sec} = 9$$

$$K_p = \frac{2}{3}.\frac{V_{dc}C}{V_d \alpha T_{eq}} = \frac{2}{3} * \frac{700V * 28100\mu F}{380V * 2.5 * 3.33 * 10^{-4} sec} = 4$$

AC-voltage controller: PI controllers are essentially AC voltage controllers. Monitoring or managing the reactive power exchange between the converter and the PCC is the primary duty of the AC voltage controller. Trial and error is used to determine the value of the controller parameters until Matlab/Simulink software produces the best results. Ti 0.5 and KP = 65 are chosen based on this trial.

Tables 3.11 and 3.12 below provide summaries of the original system's and the DSTATCOM's total system parameters based on the mathematical analysis.

Table 3-11 The parameters of the designed system of the factory.

System quantities	**System parameters**	**Parameters values of the two identical transformer system**	**Parameters values of the single transformer system**
Source	Source voltage(V_L)	15000	15000
	Power capacity	1450000	685900
	Source resistance	0.18Ω	
	Source inductance	0.057H	
	System frequency	50Hz	
Service transformer	Primary voltage	15000	15000
	KVA rating	16000	1250
	Secondary voltage	380V	380V
	Resistance in p.u	$6.4*10^{-4}$	0.001
	Inductance in pu	0.063	0.01
Electrical loads	General load	1600KVA	
	Nonlinear loads	263.5KW	

Table 3-12 The parameters of the designed DSTATCOM.

DSATCOM Parameters	**Parameters values of the two identical transformer system**	**Parameters values of the single transformer system**
VSC rating	182.86KVAR	117.26KVAR
DC link voltage	700V	700V
DC link Capacitor	59200μF	28100μF
Switching frequency	3KHz	3KHz
LCL filter	Lg=2.5μH, Lc= 22.5μH, C_{inv} & C_{damp} = 3.96μF and Rd = 0.111Ω	Lg=3.5μH, Lc= 31.5μH, C_{inv} & C_{damp} = 5.54μF and Rd = 0.798Ω
DC PI controller	Parameter value	
Proportional gain	9	4
Integral time constant	0.000208	0.00028
AC voltage controller	Parameter value	
Proportional controller	65	55
Integral time constant	0.5sec	0.5sec
Current controller	Parameter value	
Proportional controller	748	956
Integral time constant	2.25sec	4sec

3.7. System Modeling with Matlab/Simulink

The mathematical analysis or computations performed in the preceding sections serve as the foundation for the Matlab/Simulink representation of each system and the system as a whole. This section uses Matlab/Simulink software to simulate the entire system, the factory's original systems, and the DSTATCOM configuration and control systems based on the requirements.

3.7.1. DSTATCOM Modeling with Simulink

The DSTATCOM that was created is based on the equations given in section 3.6. The simplicity of building and simulating electrical models with the Simscape library's blocks is the reason for choosing Simulink. The general Matlab DSTATCOM configuration is shown in Figure 3.12 below. It contains the main parts of the DSTATCOM. They are used as energy storage devices and include control units, coupling transformers, VSCs, LCL filters, and DC-link capacitors.

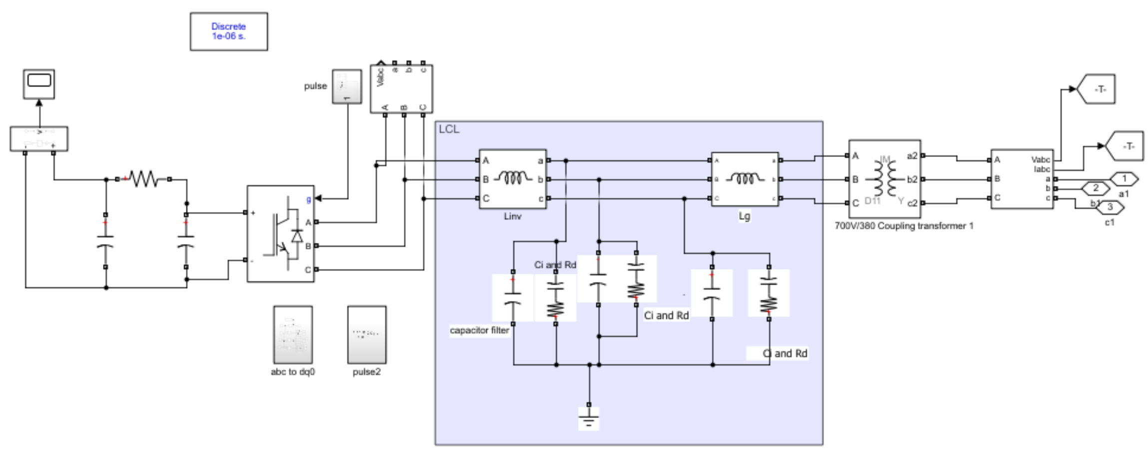


Figure 3:12 DSTATCOM configuration with Matlab.

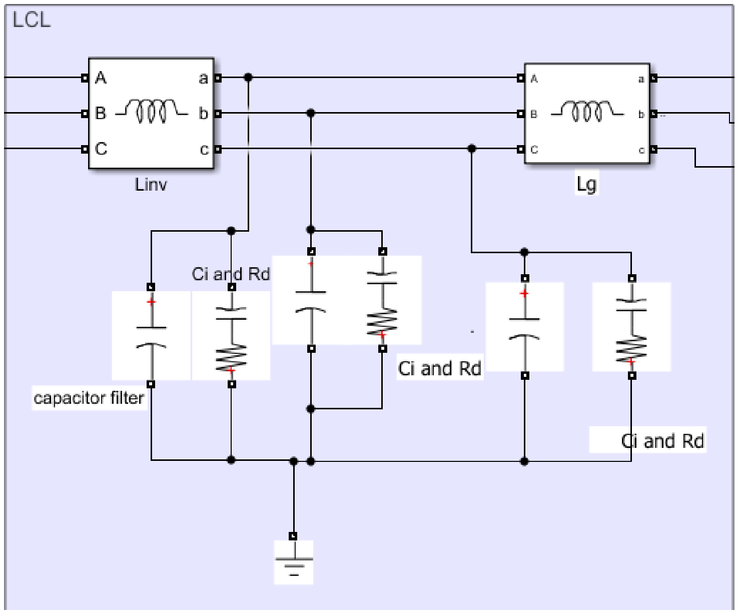


Figure 3:13 Matlab-based LCL filter design.

Source voltage, dc voltage, and source currents are produced following the measurement of the source voltages and their filtering through a second-order low pass filter. The process utilized to complete this work is depicted in Figure 3.14 below. A voltage The resistance is linked in series with the capacitor to remove harmonics from the waveforms created by the VSC, and the source converter is connected to the bus via damping inductance to reduce output voltage oscillation.

A power electronics device called a voltage source converter can provide sinusoidal voltage with the necessary phase angle, frequency, and magnitude. Because the inverter system's DC bus contains rectified voltage, the 59200µF capacitor and 2810µF for the parallel operating and single transformer respectively has the ability to store energy from the DC source. As a result, the capacitor serves as the inverter's DC voltage source. The point of common coupling, or PCC, is where reactive power is generated or absorbed by the device and the system.

Because of its smaller size and lower switching losses, the IGBT is typically used as the switching device at the distribution voltage level. It is necessary to produce the necessary number of pulses for the VSC operation control system. The DSTATCOM's whole operation is controlled by the control system.

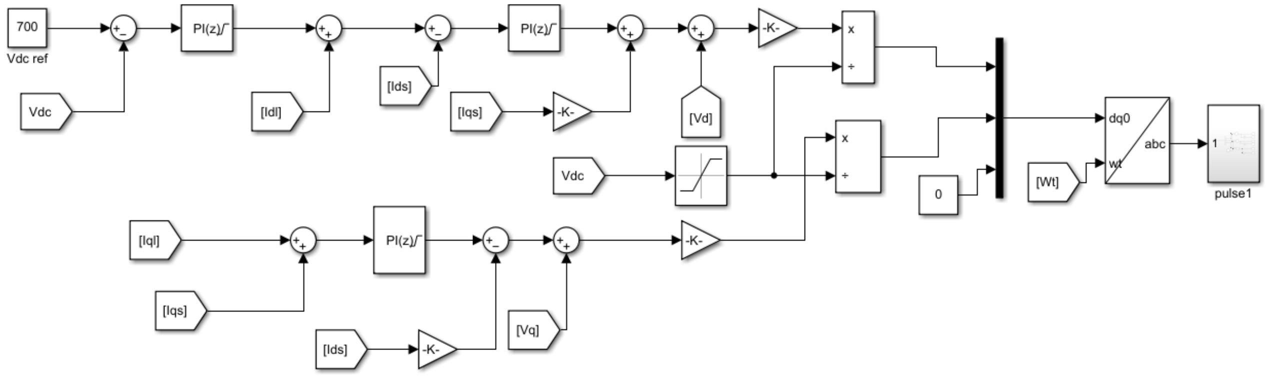


Figure 3:14 Control System Block Diagram of DSTATCOM.

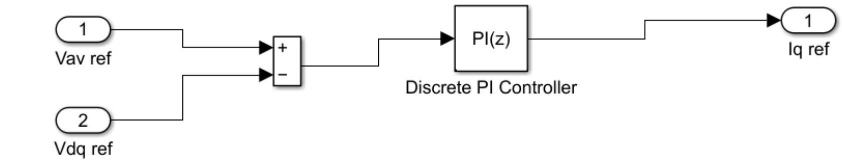
The following subsystems function are the control system

a) **Phase-locked loops (PLLs)**: are synchronized with the fundamental of the transformer primary voltages or with the input three-phase primary voltage, Vabc. The direct-axis and quadrature-axis components of the AC three-phase voltage and currents (shown as Vd, Vq or Id, Iq on the diagram) are calculated using the PLL's output.

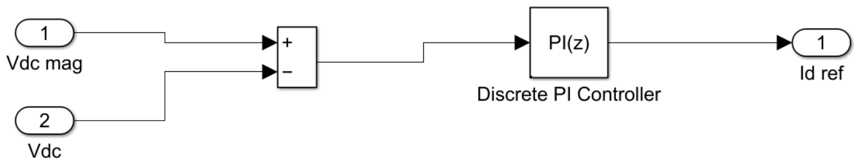
(b) Measurement Systems: DC voltage is measured and regulated using a DC voltage regulator. The system also measures the *d*- and *q*-axis components of AC voltages and currents for control purposes. The **Vmeas** and **Imeas** blocks perform this function by applying an **abc–dq transformation**, which converts three-phase signals into their corresponding *d*- and *q*-axis components.

c) AC voltage regulator and a DC voltage regulator: The reference current I_{qref}, which is the output of the AC voltage regulator and is displayed in figure 3.15 below, is current in quadrature with voltage, which regulates the flow of reactive power. The reference value specified in the control system dialog box is maintained by the PI controller as the primary voltage. The reference current Idref, which is current in phase with voltage and regulates active power flow, is the output of the DC voltage regulator. The DC link voltage is maintained at its nominal value (Vdc = 700V) using a DC voltage controller.

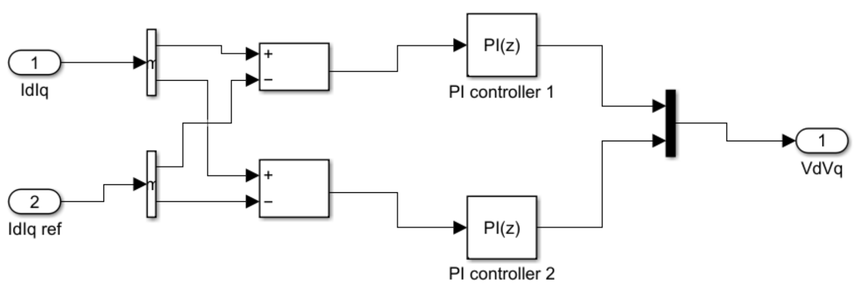
IV) Current regulator: This loop, which is depicted in figure 3.15 below, is composed of two proportional-integral (PI) controllers that regulate the d-axis and q-axis currents. The Idref and Iqref reference currents, which are produced by the DC voltage regulator and the AC voltage regulator, respectively, in voltage control mode, are used by the current regulator to control the magnitude and phase of the voltage produced by the PWM converter (Vd Vq). The PWM voltages are created by converting the Vd and Vq voltages into the phase voltages Va, Vb, and Vc.



a) Ac voltage regulator



b) DC voltage regulator



a) Current regulator

Figure 3:15 Configurations of AC and DC voltage and current regulators.

The following elements make up the DSTATCOM:

Voltage source PWM inverter: The dc voltage is inverted to the ac voltage. The equivalent voltage source averaged over one cycle of the switching frequency (3kHz) represents the PWM in the ac side. The inverter's harmonics can be eliminated because this frequency is high enough. As a result, the system does not exhibit any harmonics. The current source that charges the dc capacitor on the dc side represents the PWM. The loss in the VSC is negligible so that the instantaneous power at the ac side is equal to the instantaneous power on the dc side, ($V_aI_a+V_bI_b+V_cI_c = V_{dc}I_{dc}$). From this we can calculate the DC current I_{DC} on the system.

LCL filters connected: The inverter output is where the LCL filters are linked. To reduce the harmonic produced in the VSC's AC side, resistances are connected in series with capacitors. The oscillation of the voltage's output wave form on the AC side of the VSC is dampened by the inductor.

3.7.2. Modeling of the overall system

The three-phase source is a model of a wye neutral transformer with a source of external impedance having a 50 Hz system frequency, a 0.18 Ω source resistance, a 0.057H source inductance, and a 15000V base voltage phase to phase.

Three-phase transformer: the transformer is a 15000V/380V step-down transformer and two parallel operating transformer are made by Mechelen/Belgain and the other transformer is made by Hyderabad/India. The two transformers are 1600KVA and the other is 1250KVA power rating, and the system frequency is 50Hz. The magnetizing resistance and inductance for two identical transformers are 1587.3pu and the other transformer is 1000pu, whereas the resistance and inductance Pu are $6.3*10^{-4}$ and 0.06 respectively and the other transformer resistance and inductance Pu are 0.001 and 0.01 respectively. The primary connection type is delta, while the secondary connection type is wye neutral.

Length modeling: R = 0.08*0.06Ω/km, inductance is 0.005H and 0.0045H for the identical transformer and for other single transformer correspondingly, and the distance between loads and the transformer secondary side is 50 meters.

Load modeling: Three specific types of loads are included in the load bus models. These are clarified in the ways listed below.

Three phase parallel loads: which are made up of resistive and inductive loads, are a representation of three phase general loads. The nominal phase-to-phase voltage is 380V, the system frequency is 50Hz, and the resistive and inductive total loads for two identical transformers is P = 1116.5kW and Q =925.22kVAr. and the other transformer = 528.14kW and Q =437.63kVA respectively.

Nonlinear loads: illustrated with a three-phase diode rectifier coupled to both inductive and resistive loads. There are 220kVAr of inductive loads and 236.5 kW of resistive loads. The nominal phase to phase voltage is 380V, and phase to neutral 220V for nonlinear single phase and the system frequency is 50Hz.

DSTATCOM modeling: Between the source bus and the load bus is DSTATCOM modeling. The common coupling point (PCC) is where the DSTATCOM and load bus are connected. Reactive power is exchanged between the DSTATCOM and the original system at this moment (PCC).

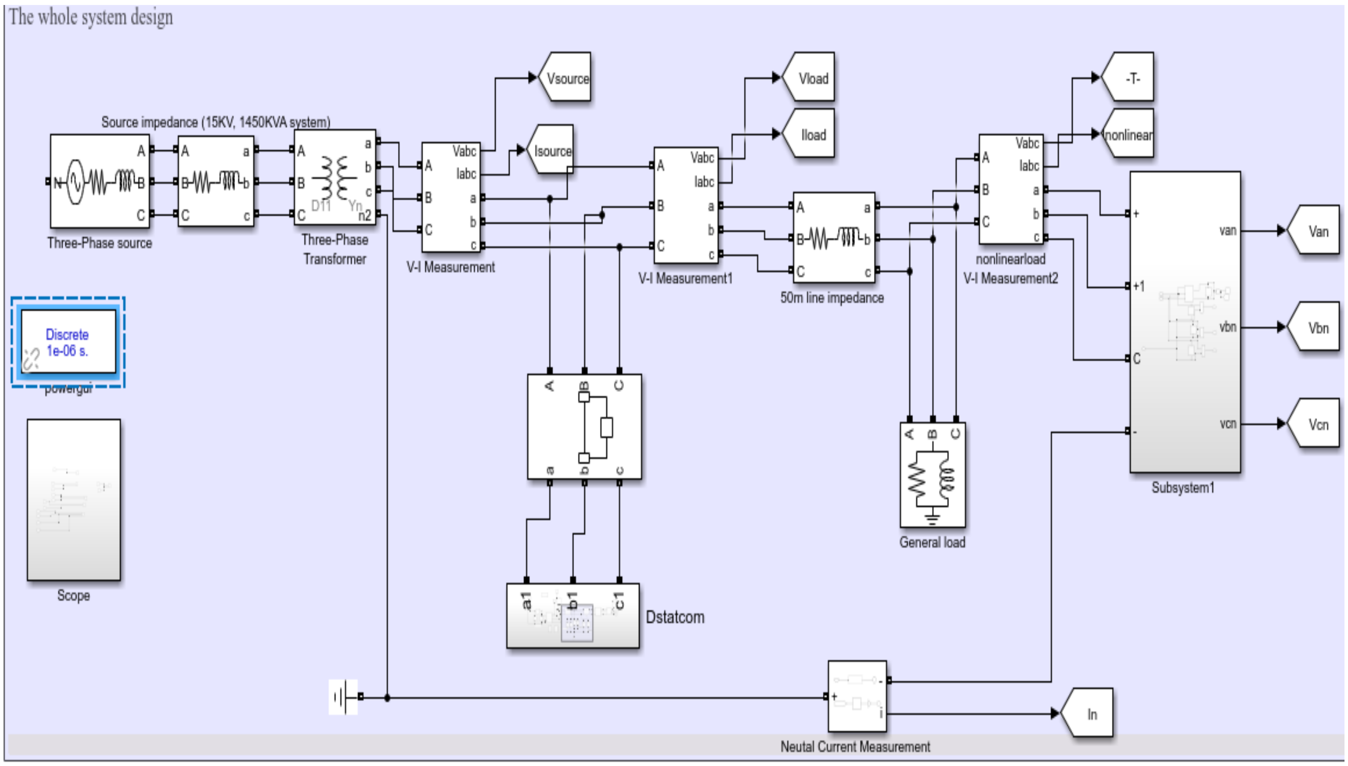


Figure 3:16 the whole system design

CHAPTER FOUR

ANALYSIS AND RESULTS

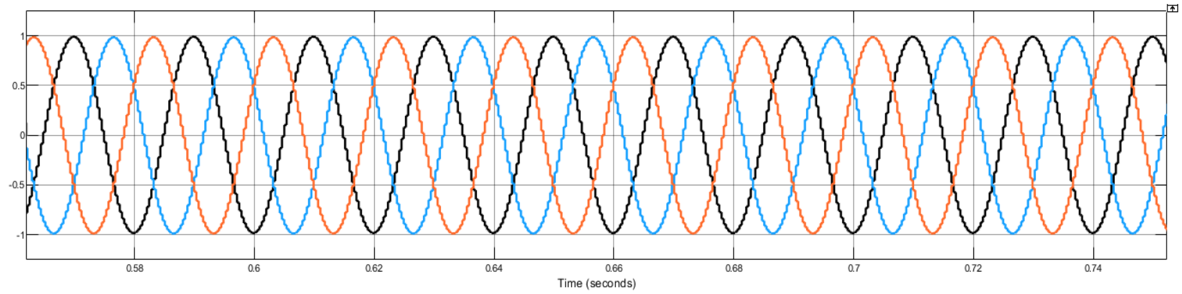
4.1. Introduction

The simulation results from the Matlab/Simulink model completed in Chapter three are covered in this chapter. There are two stages to the simulation for both parallel operating and single transformer. In the first stage, DSTATCOM is without connected. The results are recorded, and we discuss them based on the findings. Next, by installing or connecting the DSTATCOM to the modeling system, we can simulate the system and see how the DSTATCOM affects the system's power quality improvement in comparison to the outcomes we got without it.

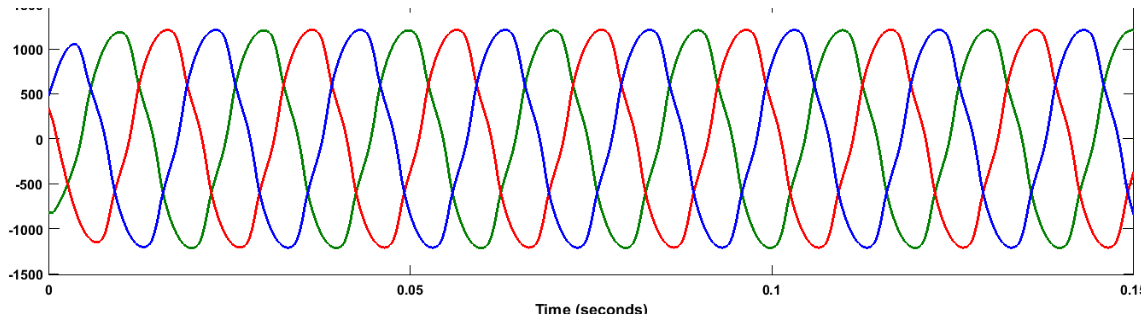
4.2. System Simulation Results without DSTATCOM

For determining the system's initial power quality, the system is simulated without the DSTATCOM configuration. Figure 4.1 below illustrates the source voltage and current along with the impacts of the system disturbance. Given the various components in the system, the voltage profile in figure 4.1 below shows a voltage p.u. value of less than 1, such as 0.9 p.u and were 0.9p.u. for the two identical transformer which operate parallel and single transformer respectively, . Because of the system's inductive and nonlinear loads, there is a significant reactive power consumption among them. The nonlinear loads cause distortion in the source voltage and current signals. The loads' required voltage and current are shown in Figure 4.2 below.

The source voltage profile and the load voltage profile are comparable. We found that the load voltages per unit values were 0.9p.u. and 0.9 p.u for the two identical transformer which operate parallel and single transformer respectively, which is less than 1. This is because nonlinear loads and other types of loads use a lot of reactive power. The nonlinear loads also caused distortion in the signals of the load voltages and currents. Because of the reduced voltage profile and the wave distortion of the voltage and currents, the heat of various equipment, including transformers, increases during operation. Elevating the temperature of the machines results in a decrease their efficiency, shortage of lifespan, and overall system productivity. For this reason, when low voltage occurs in the system, ATS usually shut down the EEU line and start stand by generator. The voltage profile and wave shapes need to be corrected in order to clear these issues.

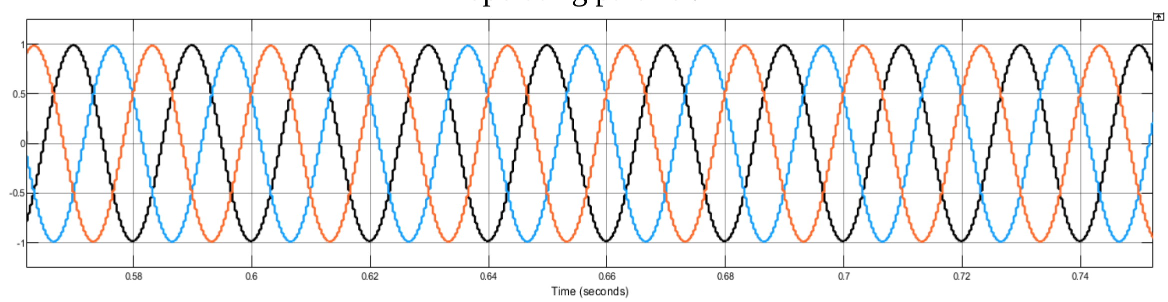


a) Voltage source without DSTATCOM

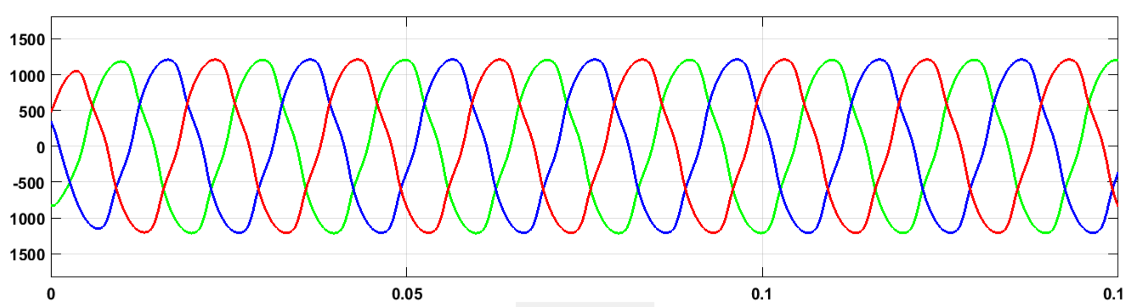


b) Current source without DSTATCOM

Figure 4:1 voltages and currents Source without DSTATCOM for two identical transformer operating parallel.

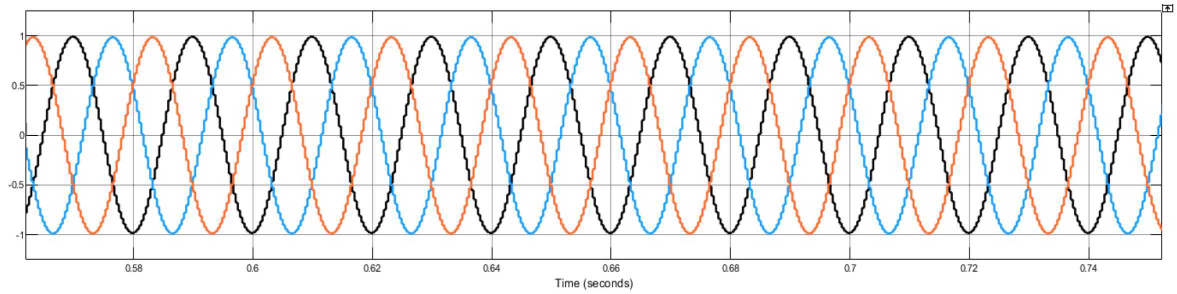


a) Load voltage without DSTATCOM

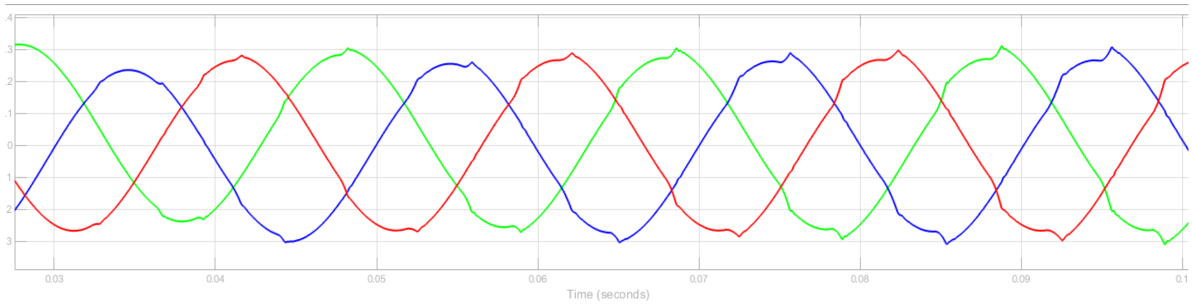


b) Load current without DSTATCOM

Figure 4:2 General load voltages and currents without DSTATCOM for two identical transformer operating parallel.

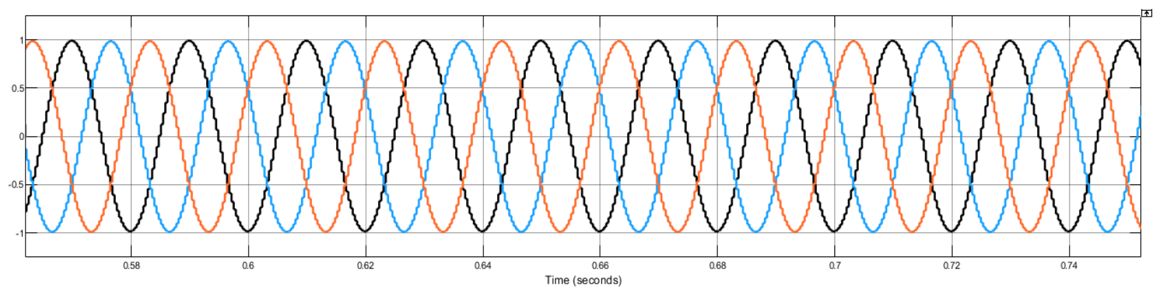


a) Voltage source without DSTATCOM

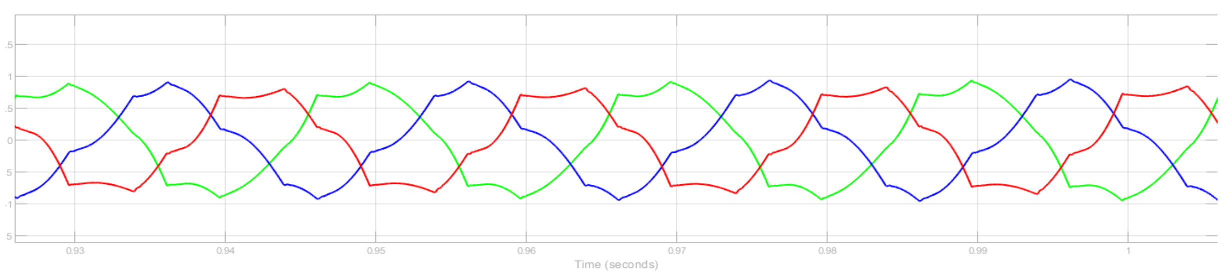


b) Current source without DSTATCOM

Figure 4:3 voltages and currents Source without DSTATCOM for single transformer



a) Voltage load without DSTATCOM



b) Current load without DSTATCOM

Figure 4:4 voltages and currents Source without DSTATCOM for single transformer

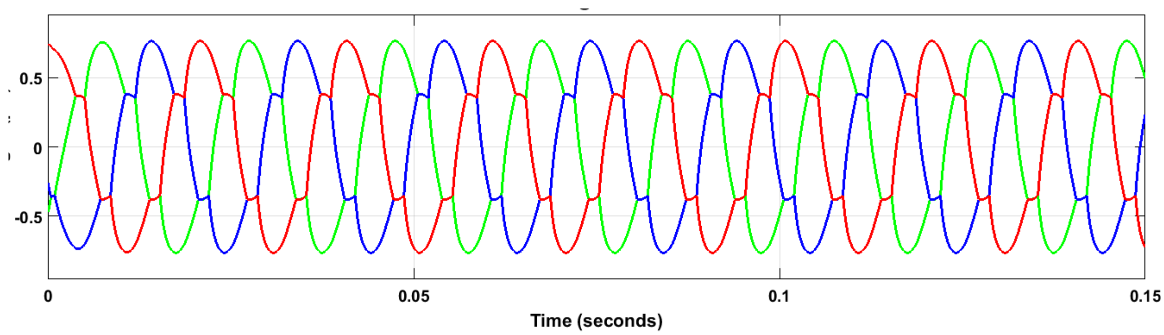
Because nonlinear loads have significantly more waveform distortion than linear loads, their voltage and current waveforms are different from those of general loads, as seen in figure 4.5 below. The rectified qualities of nonlinear loads lead to distortion of their waveforms. Most of the factory's loads are driven by squirrel cage induction motors.

The Variable frequency driver (VFD) is controlling the speed of those induction motors by varying the frequency of the system. like computers, and fluorescent lights, are examples of nonlinear loads in the system. The nonlinear loads in the factory are the cause of the wave distortions or harmonics in the voltage and currents throughout the system.

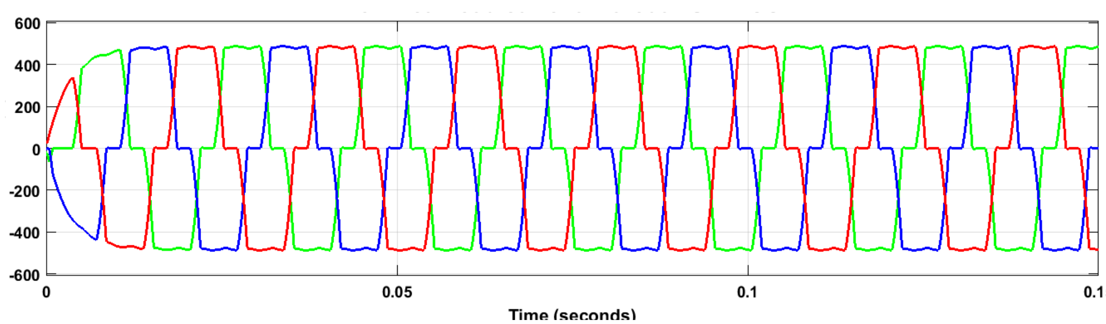
Figure 4.5 below shows how the voltages and currents of the nonlinear loads respond in terms of their wave shapes. The following are the main impacts of harmonics in factories:

- Many of motors overheat when there is power loss at harmonic frequencies.
- Harmonics increase power losses on transformers.
- Reduces the power factor in the system.

Consequently, harmonics have the dual effect of increasing the transformer's temperature and creating noise. These are some of the factors that lead to improper electricity use. Therefore, it makes sense to lower the harmonic magnitudes of the system.

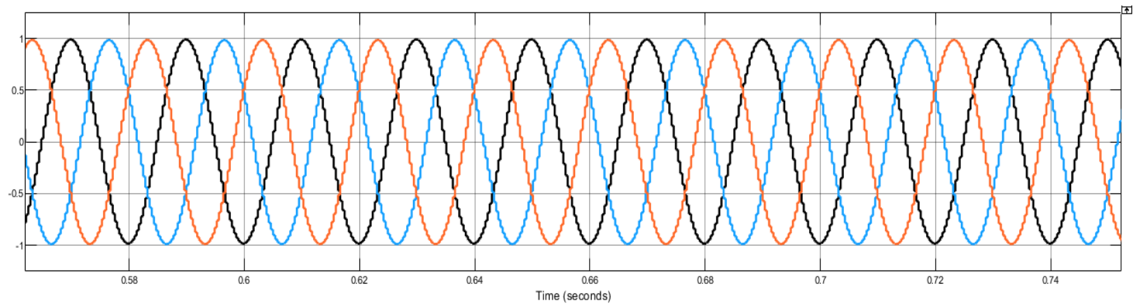


a) Voltage of nonlinear load without DSTATCOM

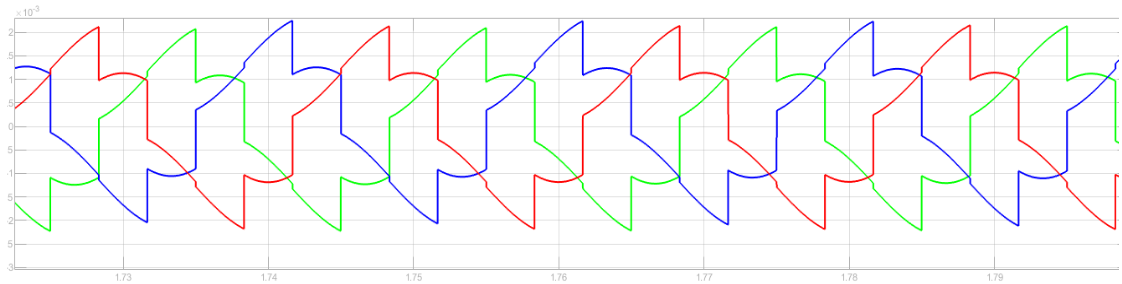


b) Current of nonlinear load without DSTATCOM

Figure 4:5 Voltage and current of nonlinear load without DSTATCOM for two identical transformer operating parallel.



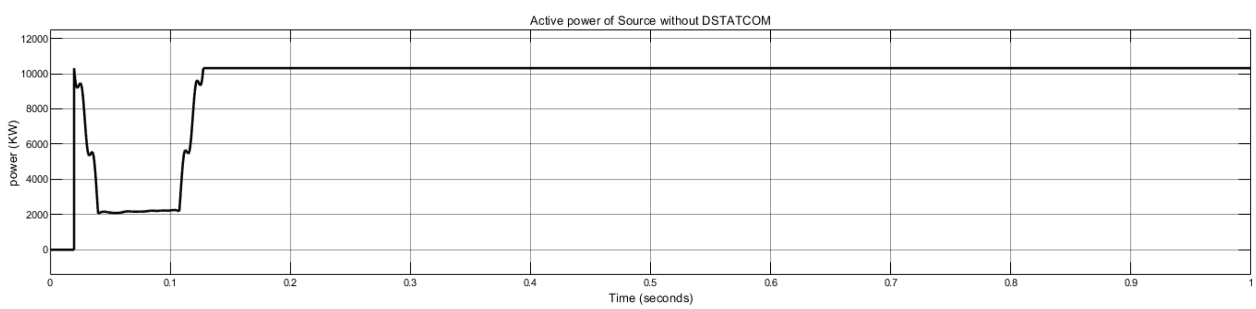
a) Voltage of nonlinear load without DSTATCOM



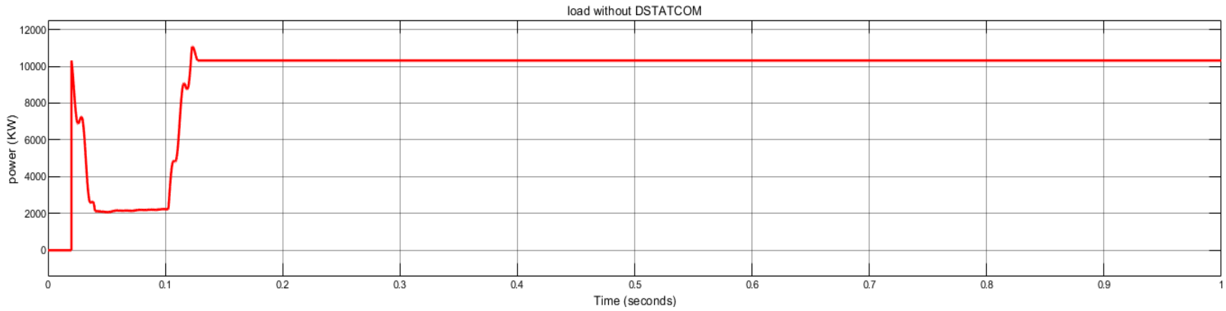
b) Current of nonlinear load without DSTATCOM

Figure 4:6 Voltage and current of nonlinear load without DSTATCOM of single transformer

The source, loads, and dstatcom's active and reactive power are displayed in Figures 4.7, 4.8, 4.9 and 4.10 below, respectively. It is seen that the total load power is equal to the complete power supply and that the dstatcom active power is quite low. The overall supply power real power is 1116.5kW and reactive power is 925.22kVAr for two identical transformers which operate parallel and power real power is 528.14kW and reactive power is 437.63kVAr for single transformer. The reactive power consumption is high, as seen in Figure 4.8 and 4.10 below. Reactive power consumption is caused by nonlinear and inductive loads in the system.

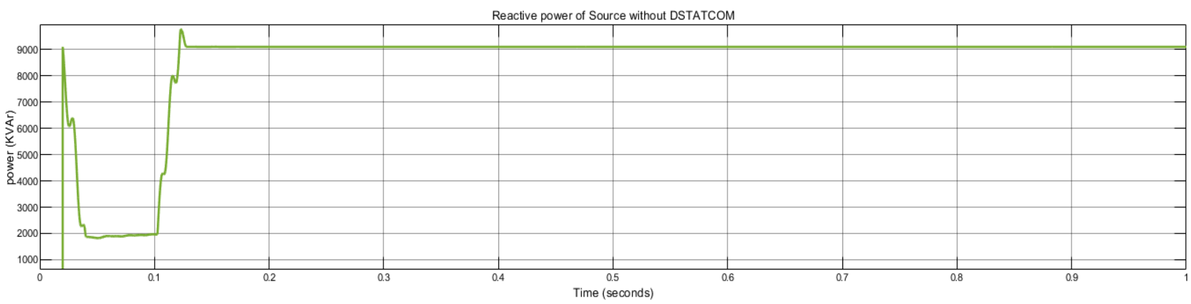


a) Active power of source without of DSTATCOM for two identical transformers which operate parallel

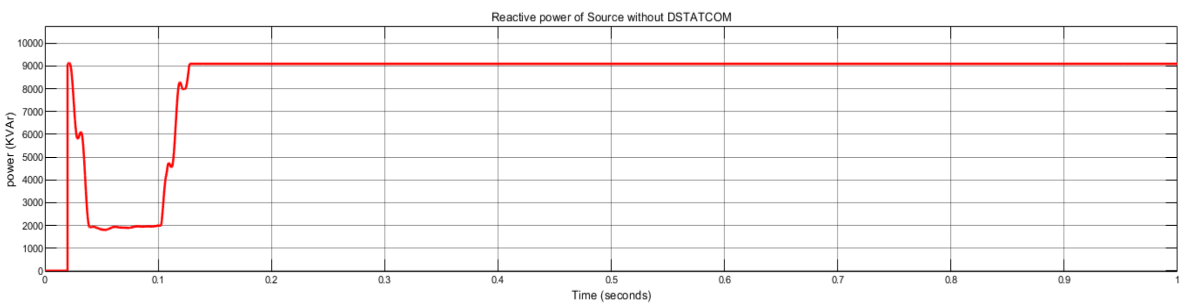


b) Active power of load without of DSTATCOM for two identical transformers which operate parallel

Figure 4:7 Active power of the system without the DSTATCOM.

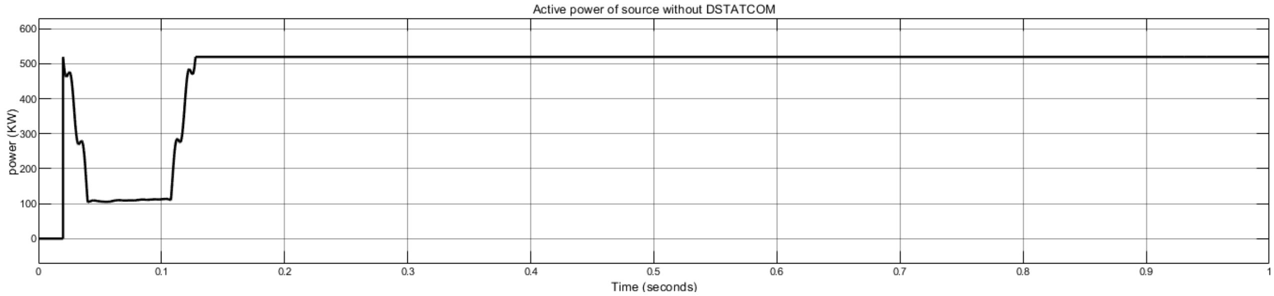


a) Reactive power of source without of DSTATCOM for two identical transformers which operate parallel

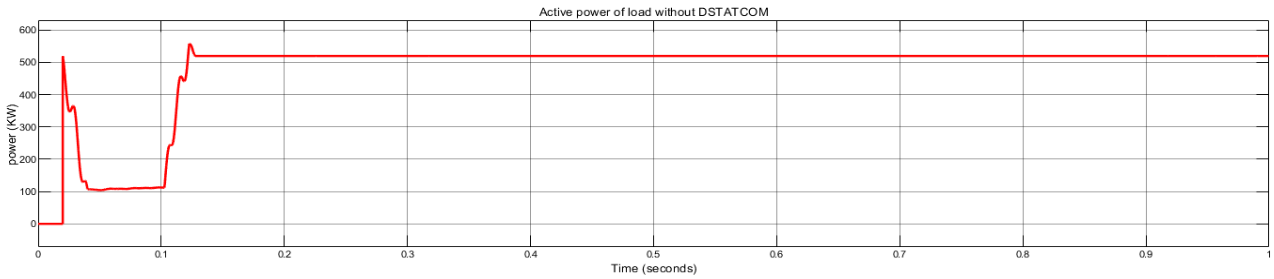


b) Reactive power of load without of DSTATCOM for two identical transformers which operate parallel

Figure 4:8 reactive power of the system without the DSTATCOM.

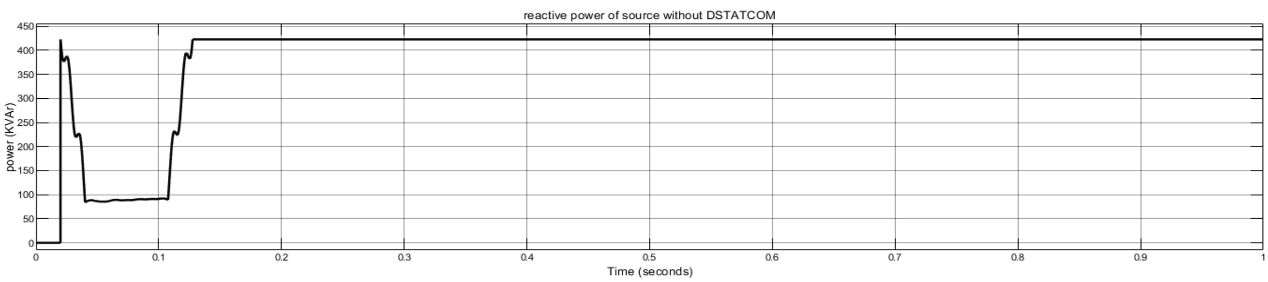


a) Active power of source without of DSTATCOM for single transformer

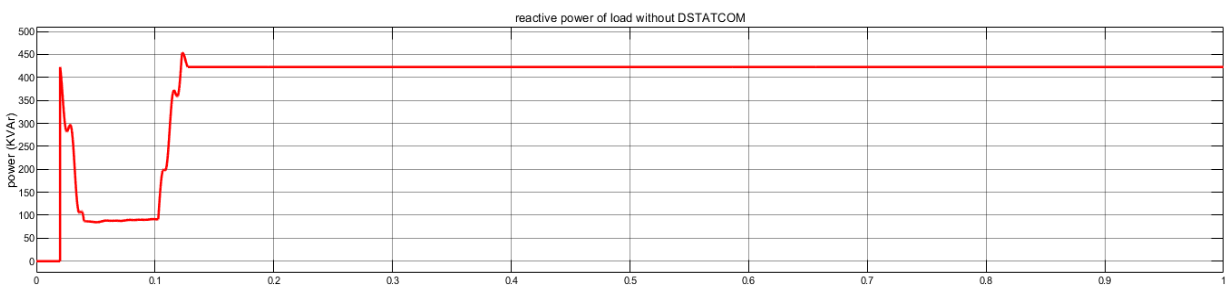


b) Active power of load without of DSTATCOM for single transformer

Figure 4:9 Active power of the source system without the DSTATCOM.



a) Reactive power of source without of DSTATCOM for single transformer



b) Reactive power of load without of DSTATCOM for single transformer

Figure 4:10 Reactive power of the load system without the DSTATCOM.

When we observe a power system without the DSTATCOM, the system is fluctuation at the beginning of a simulation or operation, it is typically produced by natural transients in the power system as it approaches steady state.

Total harmonic distortion of the system: The harmonics generated by the nonlinear loads are seen in the source currents and voltages. The THD for the source voltages, source currents, and load currents is determined using the FFT tool in the powergui Simulink block. Figures 4.11, 4.12, and 4.13 below display the findings, accordingly.

The source and load voltage THDs are the same, at 3.38%, before the DSTATCOM is connected to the system. The measured THD of the load current, which is 6.39%, explains why the THD of the source currents is the same, as shown in figure 4.12 below.

The system with a fractional frequency component detects the THD due to the interharmonic and noise signals. Interharmonic refers to the intermodulation of the fundamental and harmonic components of the system with any other frequency component. The first is the formation of components in the sidebands and harmonics of the supply voltage frequency as a result of changes in their phase angles and/or magnitudes. They are caused by sudden changes in the current passing through equipment and systems, which can also cause voltage swings.

Disturbances are caused by loads operating in a temporary state, either continuously or temporarily. These interruptions, which are primarily unstable, depend on load fluctuations that are normal for the equipment and procedures in use. They become visible when the number of loads rises. These loads include power electronics converters, induction motors, and other devices that do not pulse in time with the fundamental power system frequency. Because of the DC component brought about by the power electronic converters and the characteristics of the loads, the system contains zero order harmonics.

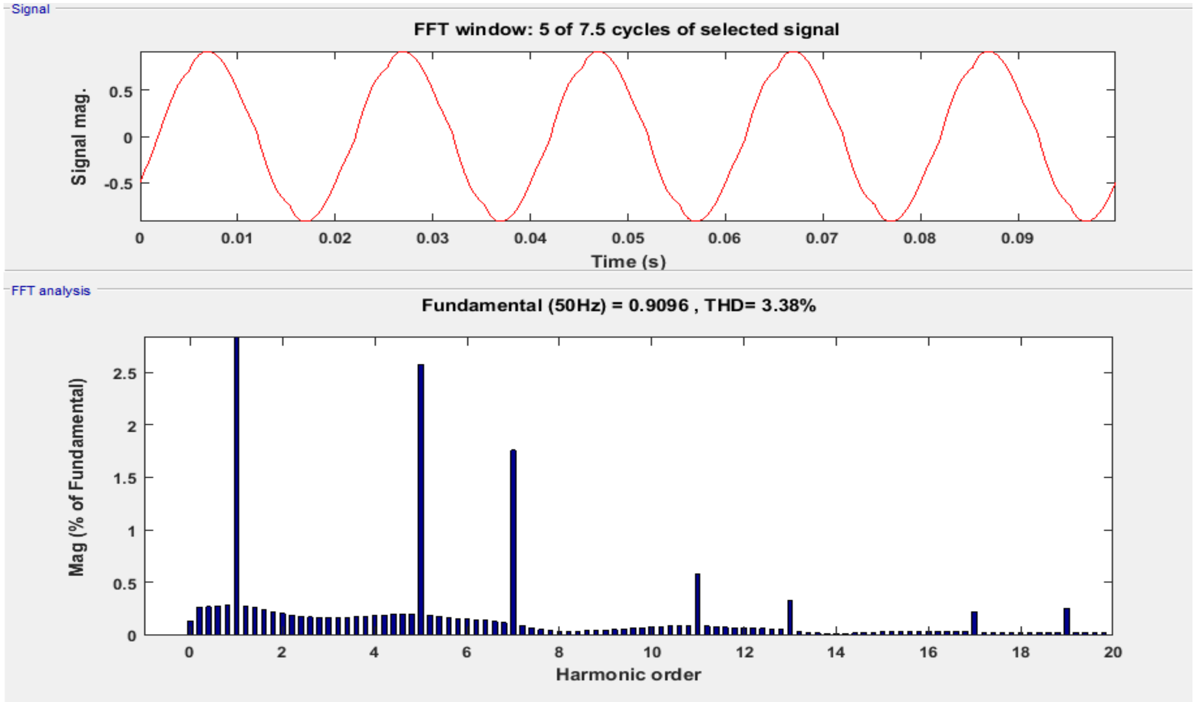


Figure 4:11 THD of source voltages without the DSTATCOM.

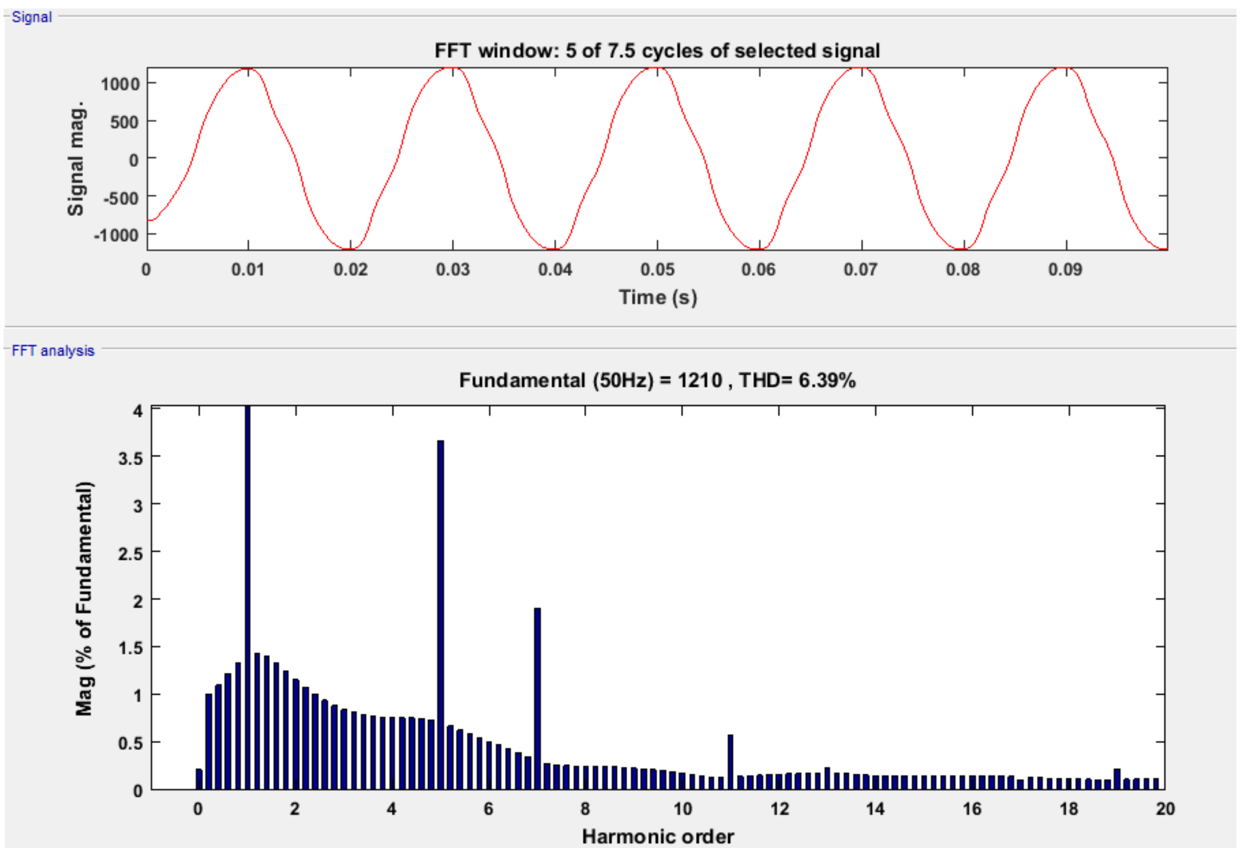


Figure 4:12 THD of source currents without the DSTATCOM.

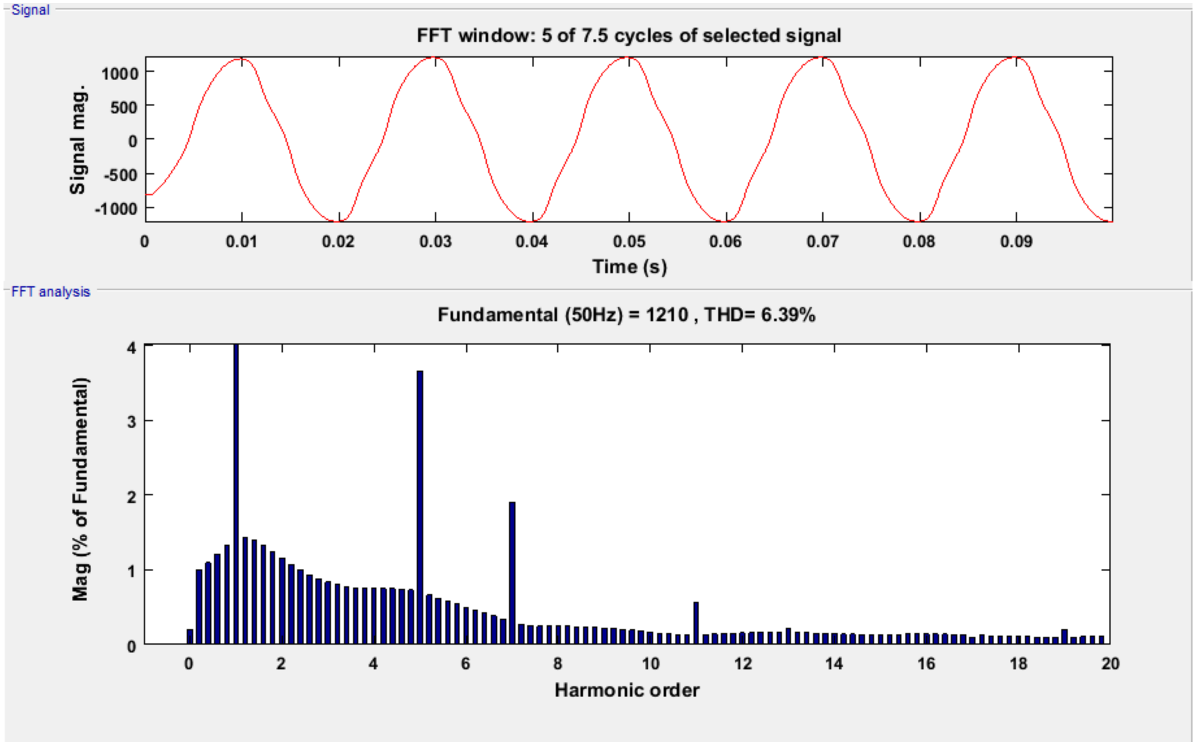


Figure 4:13 THD of load currents without the DSTATCOM.

The results of figures 4.14 and 4.15 below show that the harmonic distortions in the nonlinear loads have higher voltage and current THD contents than the typical loads. This is due to the nonlinearity features of the loads. THD for voltage is 13.84%, whereas THD for current is The THD is 22.28%, as seen in Figures 4.14 and 4.15 below.

THD of load currents without the DSTATCOM.

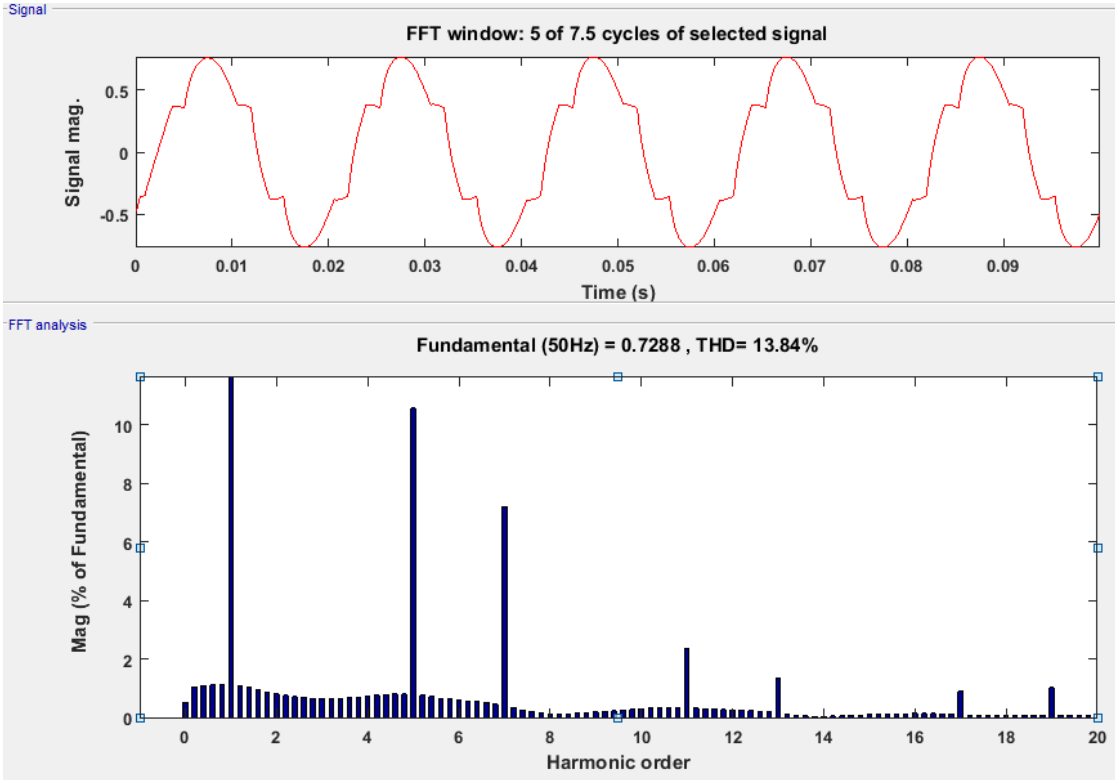


Figure 4:14 THD of nonlinear load voltage without the DSTATCOM.

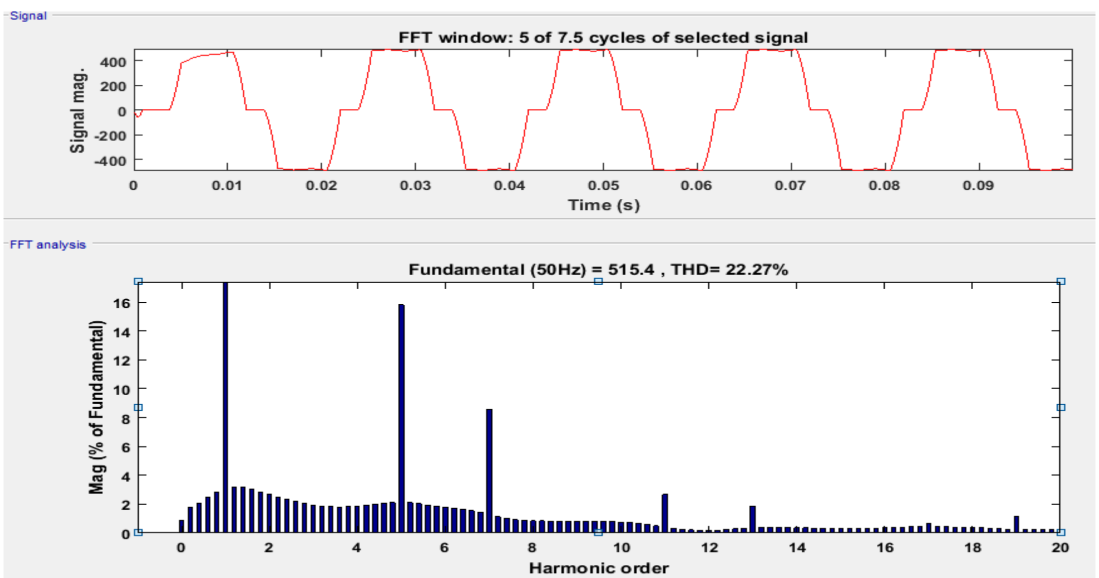


Figure 4:15 THD of nonlinear load currents without the DSTATCOM.

4.3. System Simulation Results with DSTATCOM

We analyzed the following outcomes after connecting the DSTATCOM to the system and executing the simulation. The figures below redraw the distortion wave for voltages and currents to show how the DSTATCOM can either improve or reduce the system's current power quality issues. The simulation output is displayed in figure 4.16 below, and the dc voltage needed across the DC-link capacitor is determined and set at 700 V.

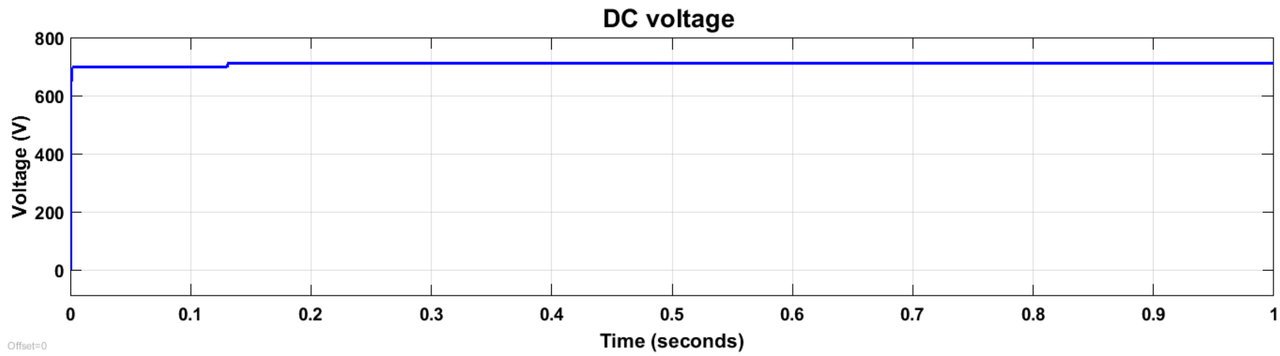


Figure 4:16 The dc voltage required across the DC-link capacitor.

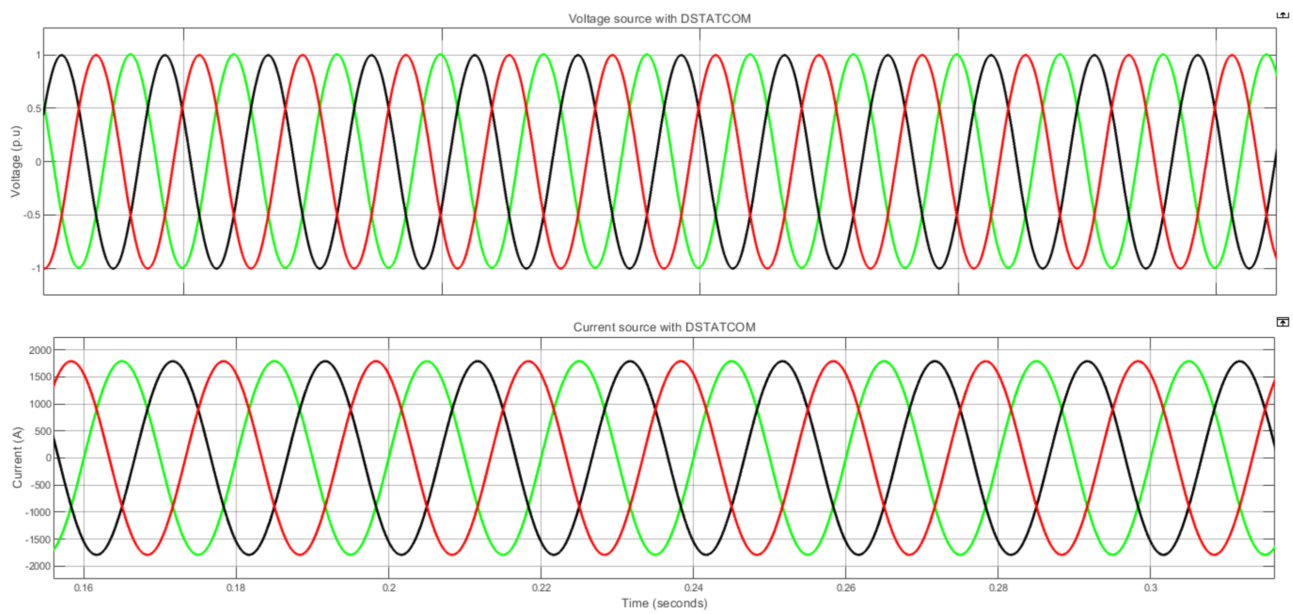


Figure 4:17 source voltages and currents with DSTATCOM.

The source voltage waveforms are more sinusoidal than the original system voltage waveforms, as seen in figure 4.17 above. Its voltage profile is rising to 0.9805 p.u. values, which is nearly equivalent to the system's basic values expressed in terms of units like 1 p.u. Compared to the initial numbers we acquired from the simulation without the DSTATCOM, the source currents' wave shape becomes more sinusoidal.

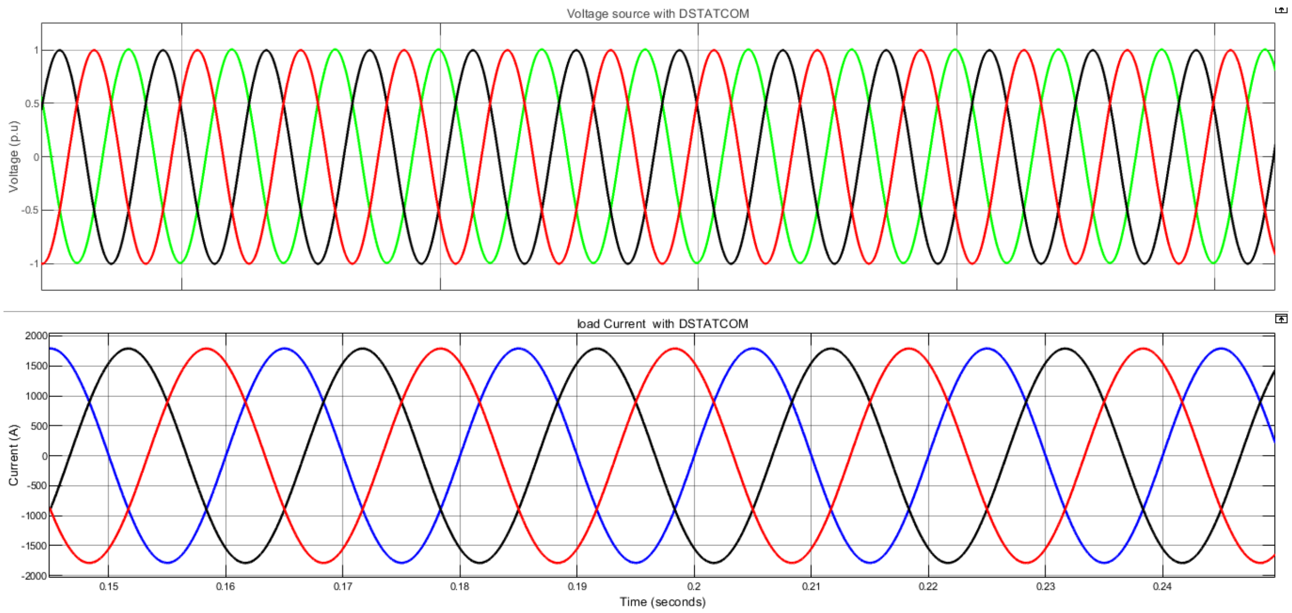
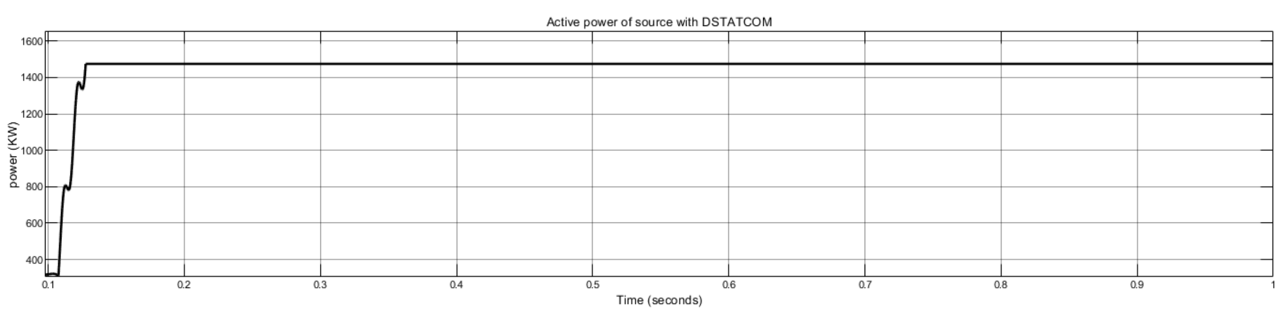


Figure 4:18 load voltages and currents with DSTATCOM.

The source voltages and source current profiles are enhanced because the DSTATCOM provides reactive power to the system when needed. As a result, the source voltages are more sinusoidal than they would be in the absence of the DSTATCOM connection, and the current wave shapes remain unaltered despite load bus disturbances. The active power of the two identical transformers and single transformer of the system with DSTATCOM installed are shown in figures 4.19 and 4.20 below, respectively.

Active power of the system after installation of DSTATCOM:



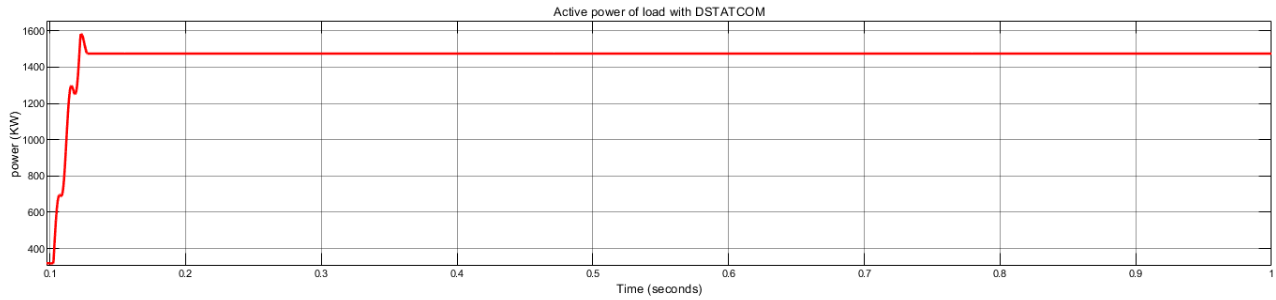


Figure 4:19 Active power of the system with DSTATCOM for two identical transformers which operate parallel.

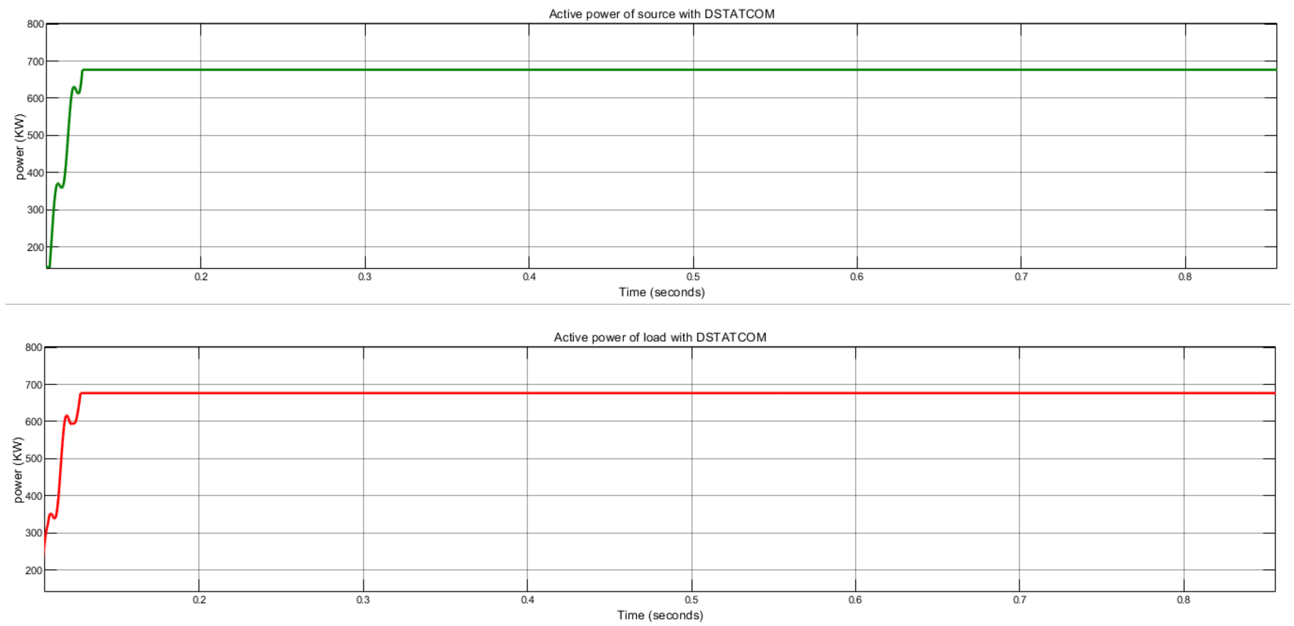


Figure 4:20 Active power of the system with DSTATCOM for single transformers

Figure 4.19 and 4.20 above shows that the source power has been slightly raised to 1421.7kW, and 672.5kW the active power of the load is nearly equal to that of the source respectively. The active power difference between the source bus and the load bus is caused by power loss in the DSTATCOM and filters.

Reactive power of the system with DSTATCOM: The reactive power of the two identical transformers and single transformer of the system with DSTATCOM installed are shown in figures 4.21 and 4.22 below, respectively.

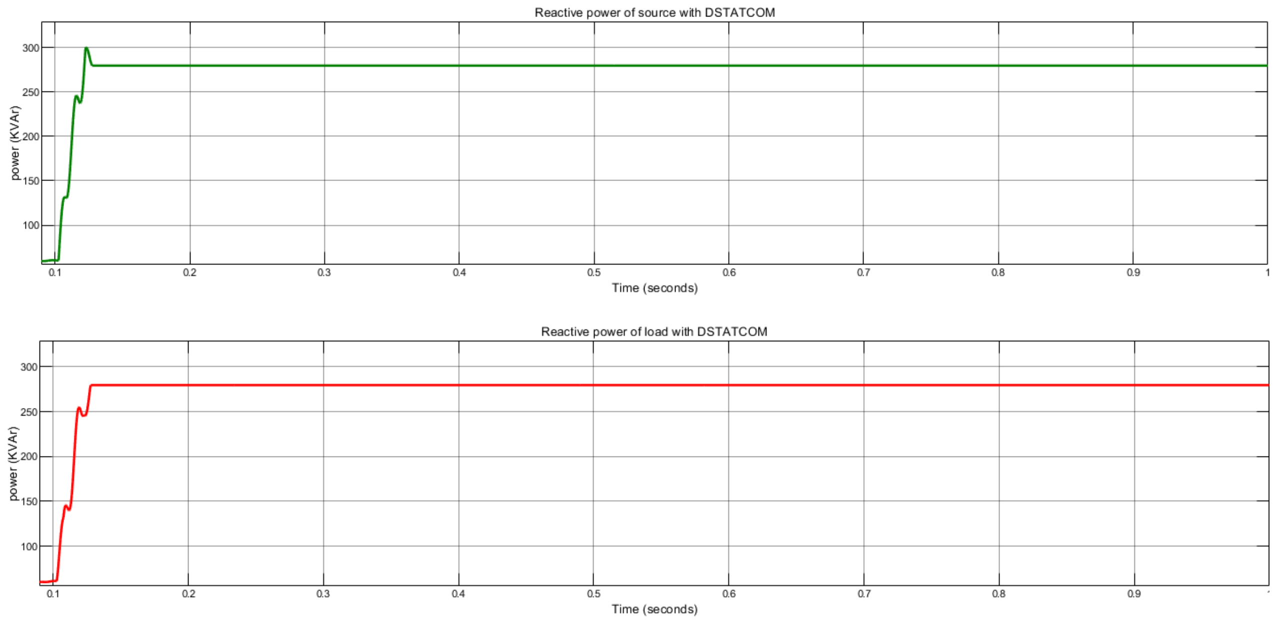


Figure 4:21 Reactive power of the system with DSTATCOM for two identical transformers which operate parallel.

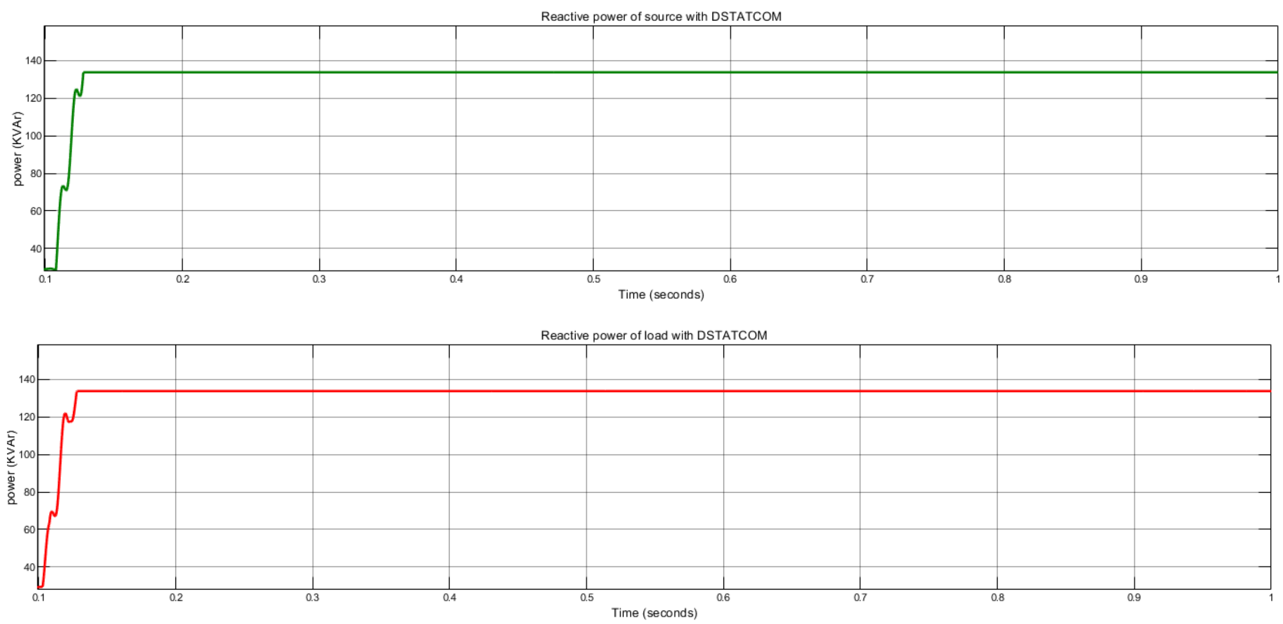


Figure 4:22 Reactive power of the system with DSTATCOM for single transformer

As we can see from Figure 4.21 and figure 4.22 above, the DSTATCOM nearly offsets the reactive power generation source. 925.22kVAr and 220kVAr is the reactive power consumption of the load of the two identical and single transformer respectively. The DSTATCOM provides almost all of the reactive power needed for this load, with a total reactive power supply of 925.22kVAr and 220kVAr. For each transformer. In contrast, the source bus's reactive power supply is reduced to just

284.86kVAr and 134.75 kVAr. As it approaches unity, the source bus's power factor is raised from 0.7125 to 0.9805 lagging. We can see that the source bus's reactive power consumption has decreased to 284.86kVAr and 134.75 kVAr in figure 4.21 and figure 4.22 above respectively.

Because of this, the manufacturer can avoid the penalty zone by using the utility's reactive electricity and avoiding additional costs, such as savings. By increasing the source's power factor, the system's efficiency rises because low power factor waste is removed, and the voltage profile and stability are also improved.

Analysis of the THD of the system after installation of DSTATCOM.

This THD is shown in Figures 4.23, 4.24, and 4.25 for the source voltages, source currents, and load currents, respectively, with the DSTATCOM. As seen in figure 4.23 below, the source voltage's THD is lowered to 1.55%, but the load voltage's THD remains the same. to the THD of the source voltage. It is found that the supply current's THD level is 0.98%. This indicates that the harmonics in the load current may be compensated for by the suggested DSTATCOM, and as a result, they are absent from the source current. As anticipated, the THD level of the load current is nearly constant, at 7.09%.

Figures 4.24 and 4.25 below show the source and load currents' THD values. High power loss occurs in the DSTATCOM configuration and the LCL filters in order to remove the THD of the source current. To reduce the system's power loss, we experiment with various filter parameter, switching frequency, and sample time combinations.

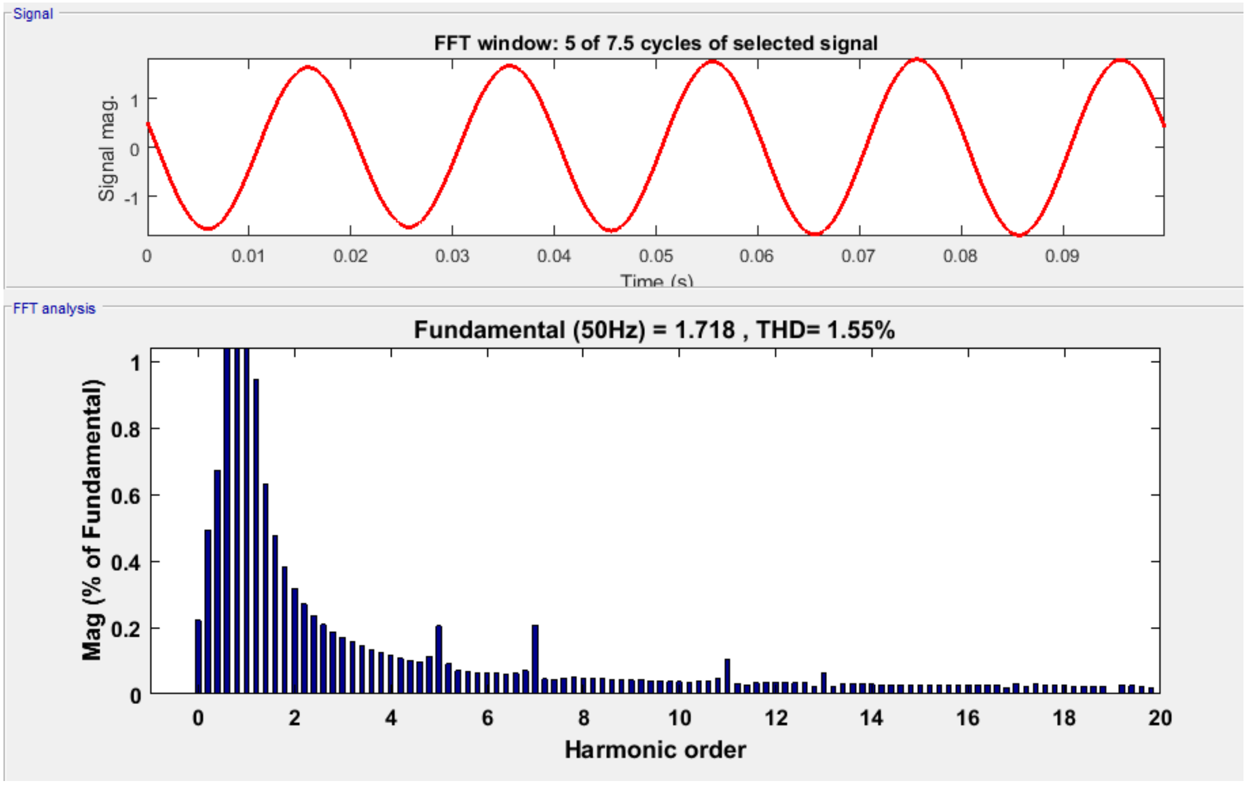


Figure 4:23 The THD of the source voltage with DSTATCOM.

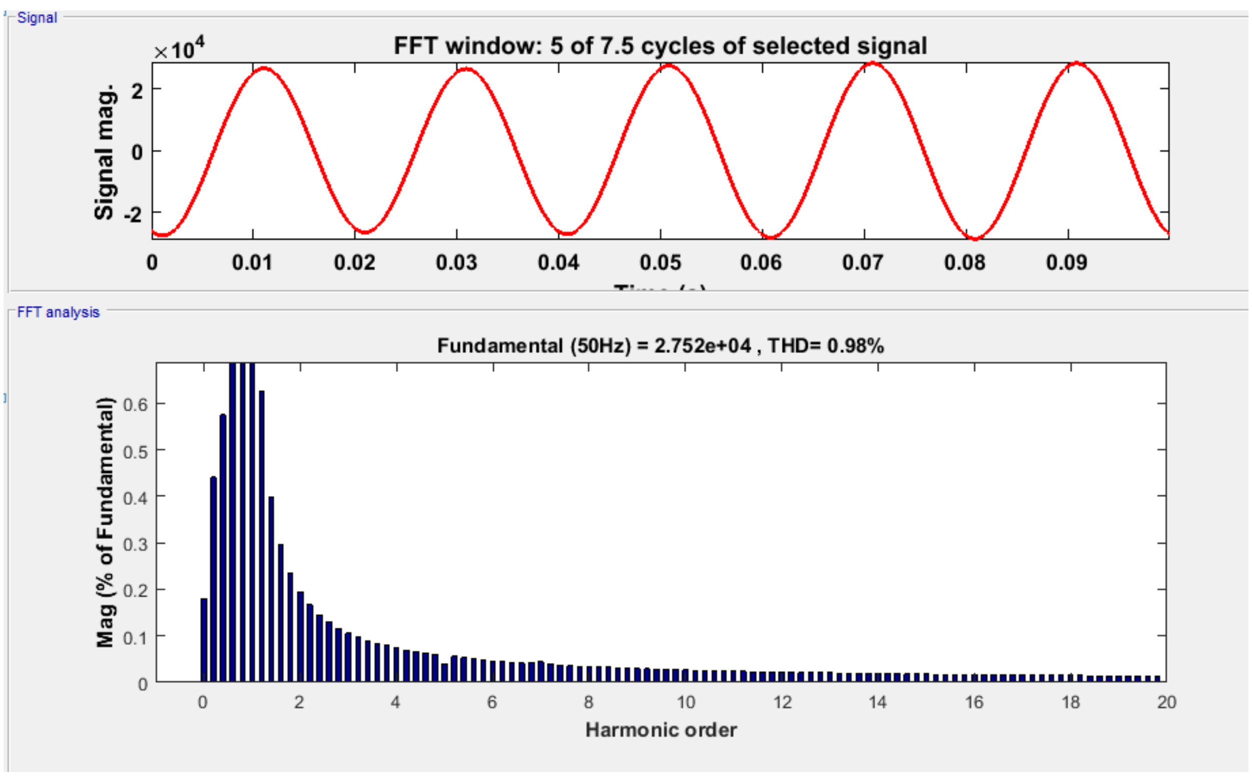


Figure 4:24 The THD of the source currents with DSTATCOM.

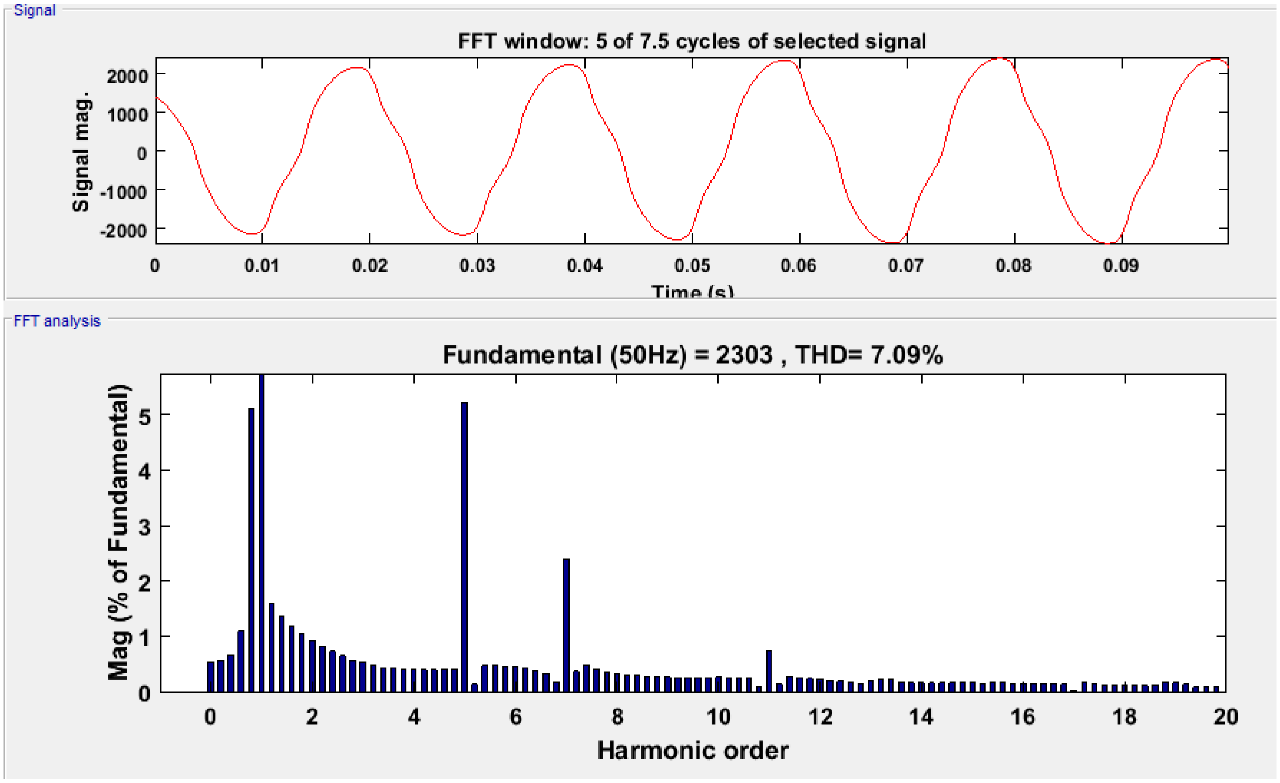


Figure 4:25 The THD of the load currents with DSTATCOM.

Figure 4.26 below illustrates the voltage THD of the nonlinear loads, which is 11.87% and nearly constant. Nonlinear loads now have a THD of 23.86%. The outcome is displayed in figure 5.26 below. Because of the mitigation mechanism, the THD of the nonlinear loads has no effect on the source voltage and source current waveforms.

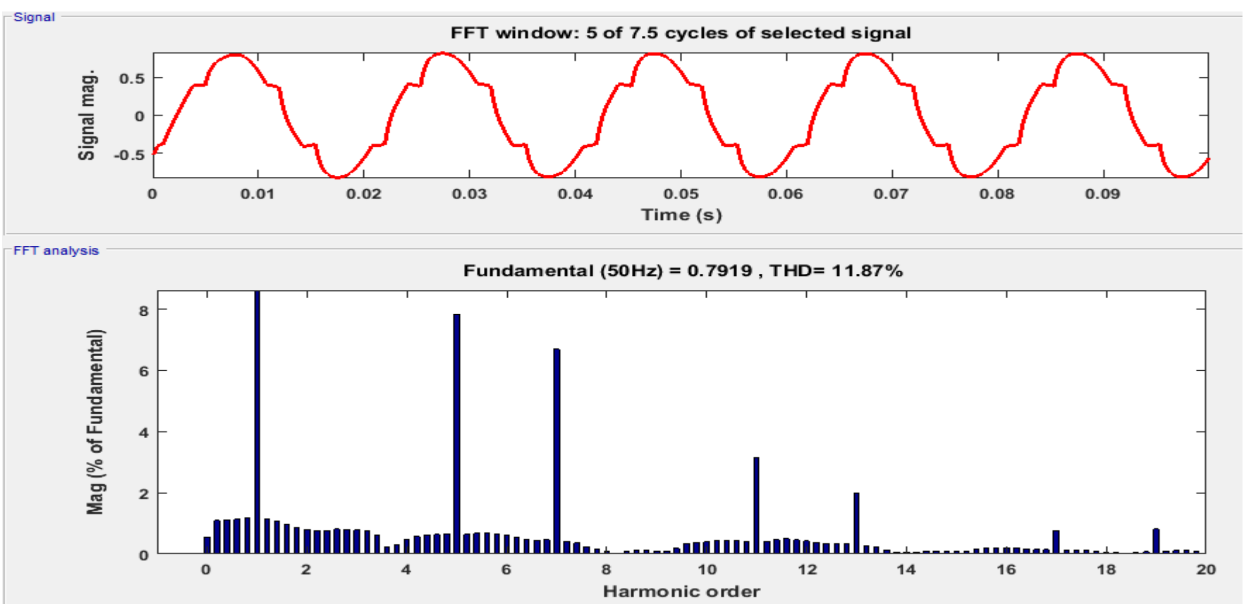


Figure 4:26 The THD of the nonlinear load voltages with DSTATCOM.

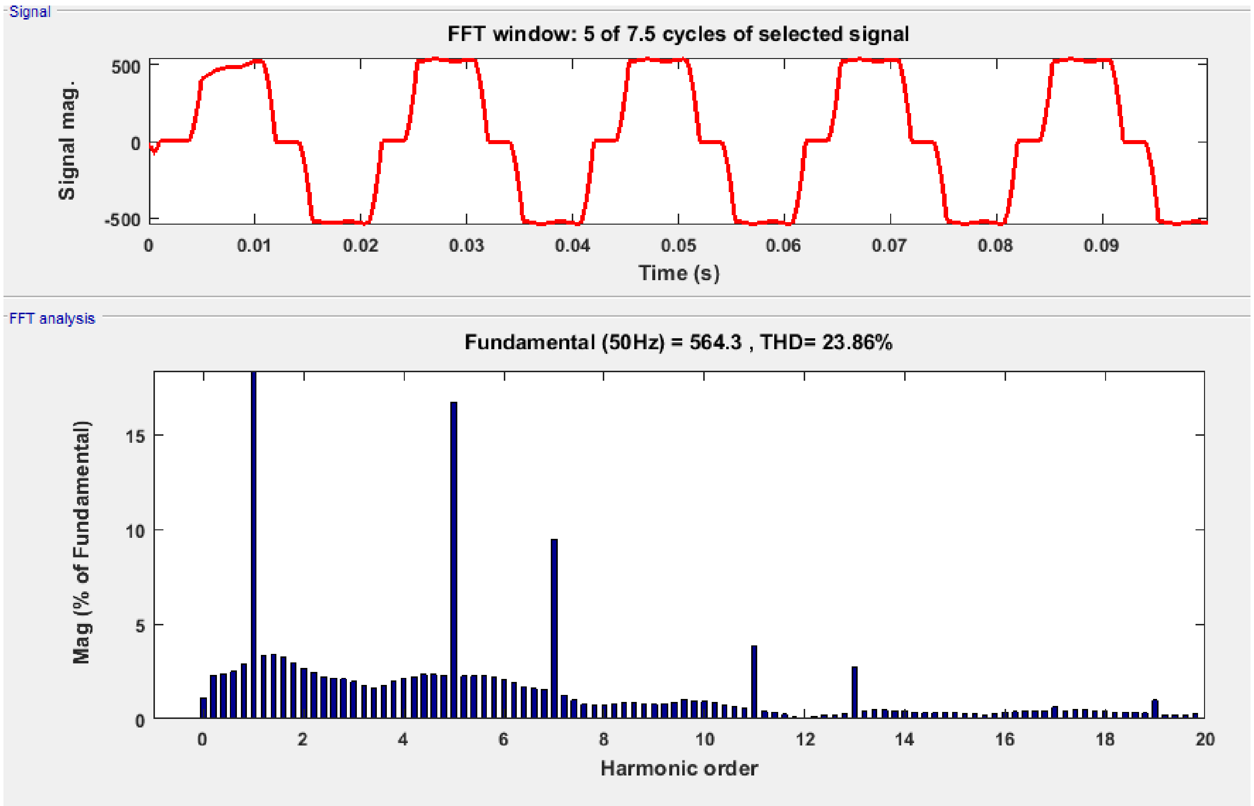


Figure 4:27 The THD of the nonlinear load currents with DSTATCOM.

From the above simulation results we analysis the following points:

- ✓ After the DSTATCOM is installed, the waveforms of the source and load voltages become more sinusoidal.
- ✓ With a mitigation system, the source current waveform becomes more sinusoidal.
- ✓ Both load current and voltage THDs fall within the range of the IEEE 1159-2019 standards.
- ✓ Reactive power compensation of loads minimizes the source reactive power generation and increases the system's power factor to unity since the DSTATCOM almost provides the load's reactive power consumption.
- ✓ The DSTATCOM and LCL filters have reduced active power loss.

4.4. Loss Minimization in Power Distribution System of the Factory

The system's harmonic voltage is eliminated and placed within an acceptable range thanks to the LCL filters' design for harmonic reduction. Source voltage and current have original system harmonic components of 3.38% and 6.39%, respectively. We saw from the data that the LCL filters reduced the harmonics of the source and load voltages to 1.55%. The source and load currents have corresponding THDs of 0.98% and 7.09%.

According to the transformer rating, the load voltage was 380VL-L or 220Vn, the load current was 1272A, and the source voltage THD was 3.38% and the source current THD was 6.39% before the DSTATCOM connection. Therefore, the harmonic current and voltage of the system can be obtained using the following formulas:

$$\%THD_v = \frac{V_H}{V_N} * 100, \text{ e.i } \quad V_H = \frac{\%THD_V * V_n}{100} = \frac{3.38\% * 220v}{100} = 7.436V$$

$$\%THD_I = \frac{I_H}{I_L} * 100, \text{ e.i } \quad I_H = \frac{\%THD_I * I_L}{100} = \frac{6.39\% * 1272A}{100} = 81.28A$$

After DSTATCOM and an LCL filter are installed in the system, the harmonic voltage and current can be calculated as follows:

$$\%THD_v = \frac{V_H}{V_N} * 100, \text{ e.i } \quad V_H = \frac{\%THD_V * V_n}{100} = \frac{1.55\% * 220v}{100} = 3.4V$$

$$\%THD_I = \frac{I_H}{I_L} * 100, \text{ e.i } \quad I_H = \frac{\%THD_I * I_L}{100} = \frac{7.09\% * 1272A}{100} = 90.18A$$

decrease in loss as a result of the service transformers obtaining the filtered harmonic voltages from the loads:

$$P_{save} = 3 * \frac{V^2{}_H}{R_{line}} length = 3 * \frac{(7.43 - 3.4)^2}{0.05} * 0.05 = 12.1kw$$

Consequently, 12.1kW of power was saved in this instance as a result of voltage harmonic elimination. There is no need to specifically compute the harmonic power loss resulting from these values because the THD of the existing harmonics remains within the accepted standard ranges. Thus, the system will save a total of 12.1kW of power as a result of the harmonics being eliminated.

Power factor correction-induced loss reduction: The following formula is used to express the apparent power in the three-phase system. (C.Dungan, 2004)

$$S = \sqrt{3}.V.I = P + jQ$$

The following expression defines the system's power loss:

$$P_{lose} = 3I^2 * R_{line}$$

From the current equation

$$P_{lose} = \mathrm{I}^2 R = R(\frac{P^2 - Q^2}{V^2})$$

R = 0.05Ω/km and 0.05km and R 0.54Ω/km and 0.05km are the lengths of the factory power distribution lines, which go from the service transformer to the loads. The following formula can be used to determine power loss. It is possible to calculate the power loss in the factory.

$$I_L = \frac{P}{\sqrt{3}\,V_{line} * PF} = \frac{1116 * 1000}{\sqrt{3} * 380 * 0.77} = 2203A$$

$$P_{lose} = 3 * R * I^2{}_L = 3 * 2203A^2 * 0.05 * 0.05\Omega/km = 36.4kw$$

$\Delta P_{lose} = P_1\left[1 - \frac{cos\varphi_1{}^2}{cos\varphi_2{}^2}\right] = 36.4kW\left(1 - \frac{0.77^2}{0.98^2}\right) = 13.92kW$ for two identical transformers, and

$$I_L = \frac{P}{\sqrt{3}\,V_{line} * PF} = \frac{263 * 1000}{\sqrt{3} * 380 * 0.78} = 512A$$

$$P_{lose} = 3 * R * I^2{}_L = 3 * 512A^2 * 0.54 * 0.05\Omega/km = 21.23kw$$

$\Delta P_{lose} = P_1\left[1 - \frac{cos\varphi_1{}^2}{cos\varphi_2{}^2}\right] = 21.23kW\left(1 - \frac{0.77^2}{0.98^2}\right) = 7.78kW$ for single transformer

Whereas;

P1-power loss before power factor is correction

Cosϕ1- power factor before power factor correction

Cosϕ2- power factor after power factor correction

The system's DSTATCOM harmonic elimination and power factor correction are carried out consecutively. Before rectification, the system's power factor was Cosϕ1 = 0.77 and 0.78 for the two identical transformers and single transformer respectively; after correction, it was Cosϕ2 = 0.98 for both systems.

The following formula can be used to determine the percentage of power loss reduction following power factor correction to 0.98:

$\%loss\ of\ reduction = 100.\left(1 - \frac{0.77^2}{0.98^2}\right) = 38.26\%$ for two identical transformers which operate parallel , and $\%loss\ of\ reduction = 100.\left(1 - \frac{0.78^2}{0.98^2}\right) = 37.92\%$ for single transformer which operate alone.

Evaluation of the cost of the mitigating device: Energy users who draw energy with a monthly average power factor below 0.9 are subject to penalties under the tariff scheme used by the Ethiopian electric company. If the customer's power factor drops between 0.7 and 0.9, the Ethiopian utility authority requires them to pay for the reactive power they use from the supply system. The supply line will be cut off or the utility will require the consumer to change their power factor to acceptable levels if their reactive power requirements are too high, such as if their power factor is less than 0.7.

If the customer's power factor is greater than 0.9, the EEU is not paid for reactive power use. The Assela factory has been paying the power factor penalty because of the power factor is low on each month 3175.28birr. The cost of the yearly payment was approximately 38,103.36 birr.

The type of device utilized and the problems found determine the cost. The DSTATCOM is the best choice for enhancing power quality when compared to the other devices on the following list, and its cost is reasonable considering its purpose.

For these reasons, we have chosen DSTATCOM for our scenario in order to reduce the system's power quality issues.

Total cost of energy per year: The amount of energy in money equals 105996kWh *1.4565birr/kWh = 154,383.17 Birr, and the total energy lost in the plant as a result of harmonic voltages is 12.1kW *8760h = 105996kWh. The annual total amount paid for the power factor penalty is 38,103.36 Birr. The total cost due to power quality is 192,486.53 Birr/year.

4.5. Results Discussion

The main issues identified and the mitigation device designed are emphasized in the results of this thesis work. We investigated the several Assela malt factor power quality issues in this paper, including low power factor, system voltage volatility, power supply interruption, and waveform distortion of the system's currents and voltages.

We investigated the root cause of these power quality issues as well as how they affect the industrial system's productivity and manufacturing economics. As an emergency generator, the factory uses a 1600kVA diesel generator. According to our investigation, the main issues in the factory are the excessive reactive power consumption from the supply power and the harmonic distortions.

The system's source voltage and current have a total harmonic distortion of 3.38% and 6.39%, respectively. Current harmonic distortion from nonlinear loads is 22.28%, whereas total harmonic distortion from nonlinear loads is 13.84% for voltage. After DSTATCOM installation, the source current THD is 0.98% and the total harmonic distortion (THD) of the load voltage and source voltage is decreased to 1.55%. The system's harmonic reduction can prevent 12.1kW of loss. The Ethiopian Electric Utility standard, PF > 0.98, is exceeded by the factory's low power factor of 0.77 lagging.

The factory pays a power factor penalty of about 3175.28birr each month as a result of the low power factor. The power factor of the supply power has increased to 0.98 lagging after DSTATCOM was installed at the system's common coupling point (PCC). Power factor improvement is crucial since it lowers the system's power loss by 38.26% for two identical transformer systems and 37.92% for a single transformer. The mitigating device's cost has been examined. The annual cost resulting from poor power quality is 192,486.53 Birr per a year.

CHAPTER FIVE

5. CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK

5.1. Conclusions

The different power quality problems at the Assela Malt factory, including waveform distortion of currents and voltage imbalance, low power factor, system voltage variation, and power supply interruption, were investigated in this thesis work using direct measured and recorded data. After analyzing the root cause of these power quality issues and their implications on the industrial system's productivity or manufacturing economics, we designed the planned mitigation device.

According to our study, the supply power is using a significant amount of reactive power, as indicated by the working power factor of 0.77, which is below the Ethiopian Electric Utility standard of PF > 0.9. The factory pays a monthly power factor penalty of about 3175.28birr as a result of its poor power factor. The data analysis shows that the overall harmonic distortion of the system's source voltage and current is 3.38% and 6.39%, respectively. Current harmonic distortion from nonlinear loads is 22.28%, compared to 13.84% for voltage harmonic distortion. The average voltage unbalance, corresponding to our analysis of the voltage data collected during our fieldwork, was 2.75%, while voltage variances might exceed 9%.

After DSTATCOM installation, the source current THD is lowered to 0.98% and the total harmonic distortion (THD) of the load voltage and source voltage is decreased to 1.55%. The system's harmonic reduction can prevent 12.1kW of loss. The power factor of the supply power increased to 0.98 lagging after DSTATCOM was installed at the system's common coupling point (PCC). Power factor upgrades are essential because they lower the system's power loss by 38.26% for two identical transformer systems and 37.92% for a single transformer. However, after the mitigating device is installed the factory loses 192,486.53 Birr annually, according to our cost study.

5.2. Recommendations

From this thesis work, the following recommendations are given.

- Due to several power issues that affect the entire socioeconomic activity of the community, Ethiopian Electric Power and Ethiopian Electric Utility must put a lot of effort into addressing power quality disturbances on the power distribution system.
- The factories ought to investigate the state of their supply system's power quality as well as how their equipment reacts to issues with power quality.
- The Ethiopian electric utility should put a lot of effort into raising society's awareness of power quality issues and determining how society can contribute to improvements in power quality in the relevant areas, as end users are not very aware of these issues or how they affect electric equipment.

5.3. Recommendations for Future Work

This paper concentrates on how DSTATCOM affects power quality problems in industrial facilities; however, it suggests that future studies use both DVR and DSTATCOM and compare the results. Future research should focus on lowering power losses in the systems, especially in the resistive elements and LCL filters used to eliminate total voltage and current harmonics in the system. This is because LCL filters used to eliminate total harmonics in the source current have a high power loss.

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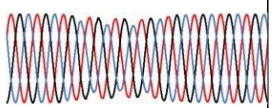
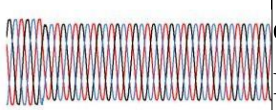
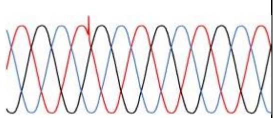
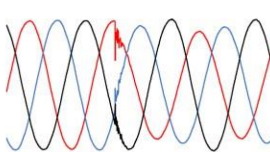
Appendix

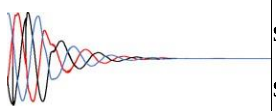
Appendix A Table: power quality indices (IEEE 1159-2019) with possible causes and consequences.

Voltage Sag/Under voltage A voltage sag occurs when the RMS voltage decreases between 10% to 90% of the nominal voltage for a time greater than 0.5 cycles (8ms), and less or equal to 1 minute. An under voltage is a decrease in rms voltage less than 90% for a duration longer than 1 min. Typical values are between 80% and 90%.			
Description	**Waveform**	**Consequences**	**Possible causes**
Sag		Unplanned production stoppages. Malfunction of PLC’s, VFD’s failures. Nuisance tripping. Increase maintenance cost. Electronic card failures. Data loss. Compressor failure. Failure of refrigeration systems.	Faults in the network caused by weather, animals across terminals, traffic accidents. Load switching upstream. Startup of large loads or transformer energization.
Under voltage		Production stoppages, equipment stoppages. Reduce life of equipment. Electronic board damage.	Utility reduced voltage. Load switching on or overloaded circuits can also result in a under voltage.
Voltage Swell/Overvoltage An overvoltage is a rms increase in ac voltage greater than 110% of the nominal voltage for a duration longer than 1 min. Typical values are 110% to 120%. A swell is an increase in rms voltage above 110% for durations from 0.5 cycle to 1 min. Typical values are 110% to 120%.			
Description	**Waveform**	**Consequences**	**Possible causes**
Swell		Nuisance tripping. Reduce life of equipment. System stoppages.	Faults in the network but less common than sags. Single line ground faults, resulting in a temporary voltage rise on the

			upfaulted phases. Switching of large loads, load shedding or switching on a capacitor bank.
Overvoltage		Reduced life of equipment. System stoppages. Breakdown of insulation over time. Increase maintenance cost.	Utility capacitors left online during lower load conditions. Switching off large loads. Switching on a capacitor bank. Poor system voltage regulation. Incorrect tap settings on a transformer can results in overvoltage.
Transient Impulse - a sudden, change from the nominal condition of voltage, current or both, that is primarily either positive or negative. Sometimes called notching. Oscillatory - a sudden, nonpower frequency change in the steady state condition of the voltage, current or both, that included both positive and negative polarity values.			
Description	**Waveform**	**Consequences**	**Possible causes**
Impulse Transient		Loss of data. Electronic component damage like computers, instruments, and control devices. System stoppages.	Utility fault clearing. Lightning strikes. Can excite resonance in the system and produce oscillatory transients. Line switching of heavy loads, operation of vacuum circuit breakers, welding equipment, poor grounding, SCR rectifier.
Oscillatory Transient		VFD, DC link overvoltage tripping. Reduce equipment life, Shorten the life of input diodes on drives. Timing errors on electronic circuits. Could produce multiple zero crossings.	Capacitive switching upstream to adjust the line voltage for differences in day and night load (shunt capacitors). Transformer energization.

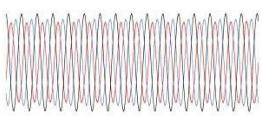
Voltage Interruption

Momentary Interruption - A type of RMS voltage variation where the complete loss of voltage on one or more phase conductors for a time between 0.5 cycles and 3 seconds. Sustained Interruption - The complete loss of voltage on one or more phase conductors for a time greater than 1 minute.

Description	Waveform	Consequences	Possible causes
Interruptions		Loss of production, system stoppages, loss of data, damage shutdown, VFD stoppages. Compressor failure. Failure of refrigeration systems.	Recloser operation, Switching, utility faults, breaker tripping, equipment, or electronic failures.

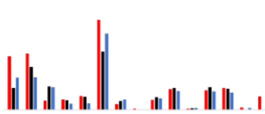
Voltage Unbalance

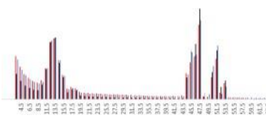
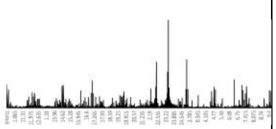
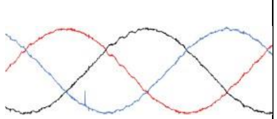
Voltage unbalance in a three-phase system is defined as the ratio of the magnitude of the negative sequence component to the magnitude of the positive sequence component, expressed as a percentage.

Description	Waveform	Consequences	Possible causes
Voltage Unbalance		Reduce life on induction motors. VFD drive failure. Derating of a motor. Stator and rotor copper losses. Increase maintenance cost. Bearing degradation. Compressor failure. Failure of refrigeration systems.	Uneven distribution of loads in buildings between phases, Faulty rectifiers.

Waveform Distortion

Waveform distortion is defined as a steady-state deviation from an ideal power frequency sinusoid principally characterized by the spectral content of the deviation.

Description	Waveform	Consequences	Possible causes
Harmonics		Transformers overheated, system stoppages. Capacitor failures. Nuisance tripping. Increase heat in conductors and motor windings. Heat and fire risk in the neutral	Non-linear loads like rectifiers, switching power supplies, computers, CFL, VFD's injects current harmonics into the system.

		conductor. Faster bearing degradation.	
Interharmonics		Affect power line carrier signaling, induce visual flicker in display devices. Induce background noise in sensors, RF, scanning equipment. Communication interference. Heating. Common mode Noise.	The main sources are pulse-width modulated inverters, static frequency converters, cycloconverters, induction furnaces, and arcing devices. Power line carrier signals can also be considered as Interharmonics.
Notching		Can cause frequency or timing errors on electronic circuits. Produce additional zero crossings. Case gating errors on SCR-based systems.	Three-phase converters that produce continuous dc. Interaction by large VFD drives. System resonance cause ringing. Windfarm resonance cause by significant capacitance in the system.
Noise		Noise disturbs electronic devices such as microcomputers and programmable controllers. Data loss.	Caused by power electronic devices, control circuits, arcing equipment, loads with solid- state rectifiers, and switching power supplies. Noise problems are often exacerbated by improper grounding.
Flicker		Human discomfort, health issues. Productivity loss. Injuries.	Arc furnaces are the most common cause. Ball mills in cement and mining. Car Shredders and Rock Crushers

Appendix B: Table 1: Real Power, Reactive Power and Power factor data measurement on transformer.

Appendix B Table 1: Real power, reactive power and power factor data measured on transformer.

Month	Active power(kWh)	Reactive Power (kVAr)	Power factor	Paid in birr
January, 2025	155,070	112,268.74	0.81	477,030.77
December, 2024	51,030	38,272.50	0.8	150,327.96
November, 2024	189,585	152,100.52	0.78	544,149.98
October, 2024	315,675	244,990.51	0.79	760,689.34
September, 2024	278,460	208,845.00	0.8	505,965.76
August, 2024	322,470	258,711.69	0.78	501,612.39
July, 2024	316,935	262,621.35	0.77	488,798.53
June, 2024	329,580	238,611.80	0.81	517,464.24
May, 2024	300,690	209,882.91	0.82	470,901.37
April, 2024	298,485	200,583.14	0.83	487,612.96
March,2024	406,890	315,781.07	0.79	621,805.50
February,2024	309,555	208,022.22	0.83	495033.07
January, 2024	197,280	122,263.16	0.85	354,541.35
December, 2023	149,760	100,639.33	0.83	249,441.05
November, 2023	208,350	156,262.50	0.8	323,838.82
October, 2023	225,225	163,060.09	0.81	337,729.76
September, 2023	232,695	106,018.97	0.91	353,347.165
August, 2023	246,600	191,382.46	0.79	366,616.17
July, 2023	201,060	156,039.57	0.79	307,506.65
June, 2023	214,740	155,469.08	0.81	324,889.18
May, 2023	192,555	134,404.22	0.82	303,601.14
April, 2023	200,205	144,945.92	0.81	307,359.25
March,2023	181,260	117,082.39	0.84	289,415.92
February,2023	160,605	99,534.04	0.85	266,454.84
January, 2024	83,655	56,216.50	0.83	169,064.28

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Hojii Gaggeessaa Qajeelchaa
Oomishaa fi Teekniikaa

Appendix B Table 2 Long-term average hourly changes in voltage data from the secondary sides of two parallel operating transformer at full load

Appendix B Table 2 Long-term average hourly changes in voltage data from the secondary sides of the two parallel operating transformer while it is fully loaded.

Measuring time	L1 –L2 (RMS value)	Voltage Variation (%)	L1 –L3 (RMS value)	Voltage Variation (%)	L2 –L3 (RMS value)	Voltage Variation (%)
8:00 am	380	5	372	7	379	5.25
8:30 am	379	5.25	373	6.75	378	5.5
9:00 am	383	4.25	381	4.75	369	7.75
9:30 am	378	5.5	380	5	370	7.5
10:00 am	375	6.25	368	8	374	6.5
10:30 am	378	5.5	366	8.5	376	6
11:00 am	369	7.75	373	6.75	374	6.5
11:30 am	374	6.5	365	8.75	373	6.75
12:00 pm	378	5.5	368	8	375	6.25
12:30 pm	373	6.75	364	9	372	7
1:00 pm	371	7.25	369	7.75	370	7.5
1:30 pm	376	6	368	8	379	5.25
2:00 pm	377	5.75	370	7.5	377	5.75
3:30 pm	377	5.75	371	7.25	379	5.25
4:00 pm	381	4.75	371	7.25	383	4.25
4:30 pm	389	2.75	373	6.75	387	3.25
5:00 pm	393	1.75	371	7.25	392	2
5:30 pm	391	2.25	375	6.25	392	2
6:00 pm	392	2	374	6.5	394	1.5

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Appendix B Table 3 current variation data from the transformer secondary

Appendix B Table 3 Current variation data from the transformer secondary sides at full loads.

Measuring time	Frequency	Current (I1) RMS	Current (I2) RMS	Current (I3) RMS
8:00 am	50	588	463.8	498
8:30 am	49.5	582	467.4	490.8
9:00 am	49.5	594	459	492
9:30 am	50	580.2	442.8	493.8
10:00 am	50.5	552	418.8	516.6
10:30 am	50	554.4	419.4	513.6
11:00 am	50	551.4	420.6	508.8
11:30 am	50.5	557.4	417.6	507
12:00 pm	49.5	534	429	438
12:30 pm	50.5	531.6	422.4	456
1:00 pm	49.5	54594	420	444
1:30 pm	49.5	585.6	433.2	450
2:00 pm	49.5	588	437.4	468.6
3:30 pm	50	582	441.6	470.4
4:00 pm	50	594	444	477.6
4:30 pm	50	557.4	417.6	507
5:00 pm	50.5	534	429	438
5:30 pm	50	531.6	422.4	456
6:00 pm	50	54594	420	444

Misgaanaawu Abdiisaa
Hojii Gaggeessaa Qajeelchaa
Oomishaa fi Teekniikaa

Appendix C Table: Ethiopian electric utility (EEU) electricity tariff,

Dec, 2021 up to August, 2024				
Flat Rate	1.193birr/kwh			
Demand Charge rate	147.54birr/kwh			
Service Charge	54birr			
Since 2024/2025				
	September	October –December	January-march	April –June
Flat Rate	1.39	1.61	1.83	2.05
Demand Charge rate	188.8063	215.9126	243.019	
Service Charge	55.19	56.38	58.75	59.94

Appendix D Table: for yearly total interruptions occur in the industrial feeder

Feeder	Operational		Non operational		Unsold Energy (KWH)	Yearly total		Year
	Frequency	Duration	Frequency	Duration		Frequency	Duration	
Industry	189	82:32	75	63:28	155,706.01	264	146:00	2023
Industry	205	145:40	147	123:24	612,936.68	352	270:04	2024
Industry	52	2:37	46	4:32	2600	98	7:19	February and January 2025

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Adama Science & Technology University

1888 Adama, Ethiopia. Phone: 0221100002 Fax: +251-022-1-110-480 Email: depce.soeec@astu.edu.et

To: Ethiopian Electric Power
Addis Ababa, Ethiopia

21/5/2017
704

Date: 28/01/2025
Ref.: EPCE/01/0011/25
Head, Electrical Power and Control Engineering Department
Addisu Safo Bosera

Subject: Request for Cooperation

The student mentioned below is currently studying his MSc in our department and he is doing MSc research on "**Analysis and Mitigation of Power Quality Problems.**" Thus, to do his research he needs some data's, documents and information from your office. Hence, we kindly request your good office to cooperate and give them the necessary data, support and information which are used for the intended purpose only.

The lists of students are:

1. Tamiru Bedada….. PGE/28290/15

22/05/17

With kind regards

Addisu Safo Bosera
Addisu Safo Bosera
Head, Electrical Power and Control Engineering Department

School of Electrical Engineering and Computing
Electrical Power and Control Engineering Department

CC//

- EPCE Dep't