Identification and Mitigation of Power Quality Problem Using Unified Power Quality Conditioner (Case of Wonji Showa Sugar Factory)

Mudin Gena Hawas

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

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Power System Engineering

Office of Graduate Studies
Adama Science and Technology University

September, 2024
Adama, Ethiopia

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Advisor: Dr. C S Reddy

Co-advisor: Dr. Tafese Asrat

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DECLARATION

I, hereby declare that this master thesis entitled "**Identification and Mitigation of Power Quality Problem Using Unified Power Quality Conditioner (Case of Wonji Showa Sugar Factory)**" is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Mudin Gena Hawas	________________	________________
Name of student	Signature	Date

RECOMMENDATION OF ADVISOR

We, the advisors of this thesis, hereby certify that we have read the revised version of the thesis entitled" **Identification and Mitigation of Power Quality Problem Using Unified Power Quality Conditioner (Case of Wonji Showa Sugar Factory)** " prepared under our guidance by **Mudin Gena** submitted in partial fulfillment of the requirements for the degree of Masters of Science in Power System Engineering. Therefore, we recommend the submission of revised version of the thesis to the department following the applicable procedures.

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Co-advisor	Signature	Date

APPROVAL PAGE

We, the advisors of the thesis entitled "**Identification and Mitigation of Power Quality Problem Using Unified Power Quality Conditioner (Case of Wonji Showa Sugar Factory)**" and developed by **Mudin Gena**, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Dr. C S Reddy	____________	____________
Major Advisor	Signature	Date
Dr. Tafese Asrat	____________	____________
Co-advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by **Mudin Gena** have read and evaluated the thesis entitled "**Identification and Mitigation of Power Quality Problem Using Unified Power Quality Conditioner (Case of Wonji Showa Sugar Factory)**" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Power Systems Engineering.

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Final 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 School Graduate Committee (SGC).

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TABLE OF CONTENTS

CONTENTS **PAGE**

LIST OF FIGURES

FIGURES **PAGE**

LIST OF TABLES

TABLES **PAGE**

LIST OF ACRONYMS AND ABBREVIATIONS

AC	Alternating Current
AEP	American Electric Power
APF	Active Power Filter
ASD	Adjustable Speed Drive
BESS	Battery Energy Storage System
CPD	Custom Power Device
CT	Current Transformer
DC	Direct Current
DVR	Direct Voltage Restorer
DSTATCOM	Distribution Static Synchronous Compensator
EEP	Ethiopia Electric Power
EPRI	Electric Power Research Institute
ETAP	Electrical Transient & Analysis Program
ETB	Ethiopian Birr
FACTS	Flexible AC Transmission System
HV	High Voltage
IEC	International Electro-Technical Commission
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated-gate bipolar transistor
KVA	Kilo Volt Ampere
KW	Kilo Watt
MCC	Motor Control Center
MV	Medium Voltage
MW	Mega Watt
PC	Personel Computer

PCC	Point of ommon Coupling
PHF	Passive Harmonic Filter
PI	Proportional Integral
PLC	Programmable Logic control
PQ	Power Quality
RMS	Root Mean Square
SCR	Silicon Controlled Rectifier
SEAPF	Series Active Power Filter
SHAPF	Shunt Active Power Filter
S&PGP	Steam and Power Generation Plant
SPWM	Sinusoidal Pulse Width Modulation
SRF	Synchronous Reference Frame
TCD	Tonic cube per day
TDD	Total Demand Distortion
THD	Total Harmonic Distortion
UPQC	Unified Power Quality Conditioner
UPS	Uninterruptable Power Supply
VSC	Voltage Source Converter
VSD	Variable speed Drive
WSF	Wonji Sugar Factory
WSSF	Wonji Showa Sugar Factory

ABSTRACT

Electrical energy is the most easily utilized type of energy, and demand for it has significantly expanded as a result of technological advancements. A power quality problem is the issue resulting in frequency, voltage, or current variations that cause utility or end-user equipment to malfunction or fail to operate. Severe power quality issues, such as an excessive neutral current, harmonic currents, supply voltage imbalances, harmonic voltage flicker, voltage sags, voltage swells, surges, notches, and spikes are currently affecting power distribution networks. Because of a variety of causes, several industries were disturbed by the issue of poor power quality.Therefore, it would be beneficial to investigate and mitigate the problem that affects the quality of power in the distribution network. In this thesis, identification of voltage sag and harmonics as power quality problems and proposing the proper mitigation technique in Wonji Showa Sugar Factory (WSSF) at the Steam and Power Generation Plant (S&PGP) distribution network was presented. The Powerlogic PM800 device is used for the measurement of harmonic distortion level. The measured current and voltage harmonic distortion data at the distribution board is compared with Institute of Electrical and Electronics Engineers (IEEE) standards, and the obtained data showed that the current harmonic distortion level is above the standard limit and the voltage harmonic distortion level is below the IEEE standard limit. During the collection of data, the voltage sag was also found in the distribution network of S&PGP. In order to mitigate the problem found in the distribution network, Synchronous Reference Frame (SRF) theory based Unified Power Quality Conditioner (UPQC) was proposed. The effectiveness of the suggested mitigation strategy was evaluated by modeling the distribution network of the plant with and without SRF theory based UPQC as the proposed control technique using MATLAB/Simulink. As a result of load current harmonics, the source current Total Harmonic Distortion (THD) percentage was 20.19%, 20.11%, and 19.88% for phases 1, phase 2, and phase 3, respectively, and because a fault occurs in the distribution network, a load voltage drops to 0.8 p.u. With the addition of the SRF theory based UPQC, the load voltage became 1 p.u., and the %THD_I decreased to 4.10%, 4.58%, and 5.55% for phase 1, phase 2, and phase 3, respectively. The simulation results show that voltage sag issues and current harmonics that occur in the distribution network have been reduced to below the IEEE standard limit with UPQC devices connected to the distribution network.

Key Words: *Harmonics, MATLAB/Simulink, Power quality, SRF theory, THD, Voltage sag*

CHAPTER ONE

INTRODUCTION

1.1 Background of the study

Power quality is the measurement, evaluation, and enhancement of current or voltage to sustain a waveform that is sinusoidal at rated voltage as well as frequency within a specific power system (Masoum & Fuchs, 2015). The quality of electrical energy at the consumer's end is determined by power quality (PQ). It is a group of electrical characteristics that enable equipment to operate as designed without experiencing significant drops in performance or durability. Due to the addition of numerous multiple delicate power electronics devices, control equipment, and energy from renewable sources to the distribution network, the need for power has expanded significantly during the past few decades**.** The main causes of non-sinusoidal currents include numerous network faults, switching capacitor banks, the existence of nonlinear loads like PLCs, fluorescent lamps, and ASD. Furthermore, load voltage is also distorted as a result of the flow of distorted currents, which leads to issues with power quality (Sharma et al., 2018). A wide range of external as well as internal factors also influence the amount and quality of power that is delivered. In developing nations like Ethiopia, there are issues with power supply in terms of availability and quality.

The assessment and mitigation approaches for power quality must have concentrated on industry sectors that use sensitive loads, as power quality issues vary depending on the site. Non-linear loads include power supplies with a switch mode, which are used in both commercial and industrial computers and microprocessors; variable speed drives (VSD) used in process control; arcing devices like welders and arc furnaces; SCRs used in air conditioners; and essentially any electrical device that draws current in pulses (Masoum & Fuchs, 2015).

Electric utilities, educational institutions, industries, and research facilities are currently worried about the electricity's quality. This is primarily due to the fact that modern load equipment is more sensitive to changes in power quality, power systems are using more harmonic-generating devices, end users are more aware of power quality issues, a single fault in an interconnected power system can have severe consequences, and giving high attention to optimizing efficiency and system performance is given top priority.

It has also been attempted to reduce harmonics through the application of passive filters. These filters, however, are appropriate for specific load circumstances and can be used to selectively eliminate harmonics. Resonances can occasionally arise as a result of unwanted interactions between passive filters and other loads. Thus, APFs were presented as the best solution to mitigate these kinds of issues. These APFs are categorized as series APFs (SEAPFs) and shunt APFs (SHAPFs) (Jauhari et al., 2020). SHAPF is one of the best tools for reducing issues related to the current. All voltage-related issues are mitigated by SEAPF. In order to get the appropriate pure sinusoidal waveform of the load voltage, the SEAPF stops source-side voltage disturbances from accessing the load side (Sai Kumar et al., 2023). On the other hand, the SHAPF connected in parallel across the load restricts the current-related problems to the load side, resulting in a source current that is only sinusoidal (Sai Kumar et al., 2023).

To enhance power quality, compensating devices such as active filters, dynamic voltage restorers, and uninterruptible power supplies are suggested. However, because they are limited to solving one or two power quality issues, it is difficult to mitigate a lot of issues at the same time. However, unified power quality conditioners (UPQCs) can concurrently achieve a number of goals, including keeping the bus's voltage sinusoidal to which they are connected, mitigating voltage swells, removing harmonics from source currents, mitigating voltage sags, load balancing, and improving power quality (Sarker & Goswami, 2016). Thus, UPQC is combination of the SEAPFs and SHAPFs that use a common DC link to be connected back to back. UPQC is typically implemented in distribution systems near to PCCs. The primary goal of UPQC is to mitigate the power quality related problem.

In this thesis, the power quality problem, at the S&PGP of WSSF distribution network was identified and a proper mitigation of the problem using SRF theory based UPQC has been presented.

1.2 Statement of the Problem

The primary purpose of the power system is to give its customers an optimal level of quality and economical and sufficient electrical supply. There are so many power outages that make government organizations, non-governmental organizations, residences, business centers, and other electric power users have difficulty in achieving their objectives. The existence of the harmonics and voltage sag in the S&PGP of WSSF is what inspired me to work on this thesis. The plant of the factory power system experienced voltage sags and current harmonics because of a short circuit fault and non-linear loads, respectively. The non-linear load at the distribution network includes fluorescent lamps, adjustable speed drives, and different computers. These voltage sags and injected harmonics impose a risk to end users and the utility. The voltage and harmonic disturbance are examined, along with their basic causes and effects. This investigation identified harmonics and voltag sag in the distribution network and suggested suitable mitigation techniques, thereby increasing industrial profitability and power quality.

In general, the plant is facing a lot of problems as a result of these power quality disruptions, such as significant ASD failure, frequent electric motor and fluorescent bulb burnouts, software corruption, and a number of fire incidents in the distribution network.

1.3 Objective of the Study

1.3.1 General Objective

The main objective of this research is to focus on identifying electrical power quality issues, in WSSF at the S&PGP distribution network, and suggesting UPQC as appropriate solutions.

1.3.2 Specific Objectives

The specific objectives of this study are:

- ✓ To measure the harmonic distortion by Powerlogic PM800, read the level of voltage sag from the display, compare the level of the disturbance with IEEE standards, and then identify the cause and major impact of the identified problem.
- ✓ To design and simulate the SRF theory based UPQC as suggested mitigation technique using MATLAB/Simulink and compare performance of the system's with and without a mitigating device and made comparison with IEEE standard.
- ✓ Evaluate the cost effectiveness of UPQC.

1.4 Significance of the Study

Power quality problems, have been covered in this research effort, and their mitigation strategies are simulated to make the significant evident. The benefits of UPQC as a mitigating device for power quality issues have also been examined. The industry uses the suggested solutions to safeguard its equipment against power quality problem. The distribution network of the plant uses this mitigation device in order to improve the equipment's performance and efficiency, save money lost due to production losses, and protect sensitive electronic equipment from damage. The study might also serve as a guide for future scholars working in related fields.

1.5 Scope of the Study

Due to financial and time constraints, it is unlikely to cover every section of factory that experiences poor power quality. Instead, the study is restricted to the steam and power generation plant (S&PGP) of WSSF, concentrating on identifying and resolving power quality issues. The study begins with research into power quality issues and how they affect the electrical system's power quality. After problems have been recognized, the study simply concentrates on the issues in order to provide remedies. This study uses MATLAB/Simulink to simulate the distribution network with SRF theory based UPQC for pwer quality problem minimization on personal computers.

1.6 Limitation of the Study

This study was limited to mathematical design and the system simulation using MATLAB/Simulink with the aim of demonstrating how the system's components interact. The system's real deployment is difficult due to the high expense needed.

1.7 Thesis Orginazation

There are five chapters in this thesis, and each chapter has an important impact on presenting the research.

Chapter 1: Introduction: This chapter starts with a background study on the role of UPQC in power quality improvement. It then defines the objective of the thesis, emphasizes its importance and scope, and describes the limitations of the study.

Chapter 2: Literatures Review: This chapter discusses various types of power quality issues, examines current developments in power quality enhancement, and discusses UPQC and other power quality problem mitigation devices. This chapter additionally addresses power quality standards. Finally, this chapter ends with a description of related work on the enhancement of power quality.

Chapter 3: Materials and Methods: This chapter includes methods of data collection, data analysis, design of the study area distribution network, and design of UPQC with the control algorithm used.

Chapter 4: Results and Discussions: This chapter analyzes the performance of the system's with and without a mitigating device and makes comparisons with IEEE standards.

Chapter 5: Conclusions, Recommendations, and Future Works: This section of the chapter presents the conclusion drawn from the results of the investigation, followed by suggestions made to the factory and further research that has to be done.

CHAPTER TWO

LITERATURES REVIEW

2.1 Introduction

Recently, residential building enterprises, and companies have been increasingly concerned about power quality. The grid system does not have control over the current that a customer requests; it only has control over the voltage quality. Electric power quality monitoring has grown in significance, because it helps in identifying issues with the factory's electrical machinery and electric distribution network. Good power quality monitoring helps to avoid future issues that might lead to damage to machinery or early aging of electrical components including wiring cables, transformers, and circuit breakers.

Power quality can be defined differently by the utility, the end-user of electricity, or the manufacturer of the load apparatus. It might be defined by a utility as simply reliability. On the other hand, a load equipment manufacturer describes power quality as the aspects of the power source that allow the apparatus to function as intended. According to the end user's perspective, a power quality issue is any change in electrical current, voltage, or frequency that results in the customer equipment malfunctioning or deteriorating (Singh, 2013). IEEE 1159 standard defines power quality as "energizing and grounding equipment that is sensitive in a way that is appropriate for the operation of that equipment (IEEE, 2014).

2.2 Power Quality Problem in Distributin System

Power quality issues are any fluctuation in frequency, voltage as well as curreent that result in the customer apparatus malfunction or failing. Power quality is a serious concern, because digital and modern control equipment is sensitive to distortion and degradation in power quality. The power must be delivered to the customer at a frequency of 50 Hz in a pure sinusoidal waveform with no problems with power quality.

Power quality issues are separated into two groups (Andrei et al., 2017). The first one is transient issues and the second one is steady-state issues. Transient issues including daynamic load dynamic situation, voltage sag, voltage imbalance, and voltage swell and steady-state issues include current and voltage harmonics. Voltage, current, and frequency are examples of quantities that can be used to make the second classification of power quality issues. For the current, they involve involve harmonic currents, unbalanced currents, excessive neutral current, and the reactive power portion of current and similarly for the voltage comprise voltage disto rtions, flicker, notches, noise, sag, swell, unbalance, under voltage, and overvoltage (Kazmierkowski, 2015). This section discusses on the common power quality issues that found in the distribution network.

2.2.1 Short Duration Voltage Variation

A short duration interruption continues for less than a minute, whereas a long duration interruption lasts more than a minute. Short-duration variations in voltage may be caused by load switching, insufficient connections, and faults.

The short-duration disruptions categorized as interruption, sag and swell.

I. Voltage Sag

Voltage sags are the decreases in the rms supply voltage that caused by current fault for a short duration of time less than a minute as shown in Figure 2.1. The most common cause of overcurrent's that lead to voltage dip are transformer energizing, motor starting, and faults. sag is the decrease in voltage at the power frequency from 0.5 cycles to a minute. Voltage sags are typically linked to system malfunctions, but they can also result from the energization of high loads, such as the supply of huge inductive loads in industry or the occasional starting of large motors (Jacob et al., 2019).

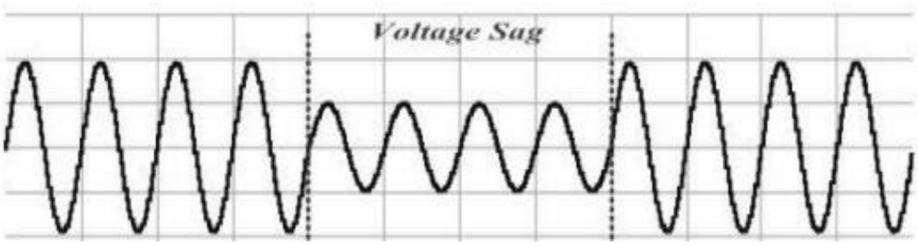


Figure 2.1: Waveform of voltage sag (Abas et al., 2020)

Main Cause of Voltage Sag

Voltage sags due to faults: It can be caused by faults in the transmission or distribution system (of which more than 70% are weather-related, including lightning and other events), or by switching loads that have high initial starting currnt requirements, like motors as well as large DC power supplies (Hossain et al., 2020). The operation of a power plant may be seriously impacted by voltage drop that is brought by fault.

Voltage sags caused by motor starting: Since the induction motors are the balanced three phase loads, the voltage drop that is brought by starting of the motor is symmetrical, resulting in almost the same inrush current being drawn by each phase (Kumar et al., 2022).

II. Voltage Swell

It is described as the increase in rms rise in ac voltage from its fundamental value, such as a shift in voltage from 10% to 80% over the period of a half-cycle to a minute as shown in Figure 2.2. The primary causes include excessive load start/stop cycles, inadequately sized power supplies, and poorly controlled transformers. Data loss, equipment malfunction or damage from extremely high voltage levels, lighting, screen burnout, insulation failure, electrical equipment to overheat are among the consequences (Abas et al., 2020). The location of the fault, system impedance, and grounding all affect how severe the voltage surge is during a fault condition.

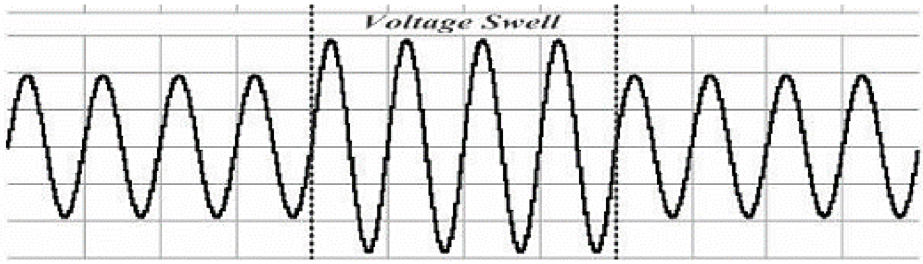


Figure 2.2: Waveform of voltage swell (Abas et al., 2020)

III. Interruption

It occurs when the load current or source voltage drops to less than 10% for a maximum of one minute. Power system problems, control issues, and equipment failures can all lead to interruption (Jacob et al., 2019). As shown in Figure 2.3, the interruption reveals that the current or voltage is approach to zero for a duration less than zero. Due to the fact that thevoltage magnitude is consistently lower than 10% of nominal, the interruptions are quantified by their time duration.

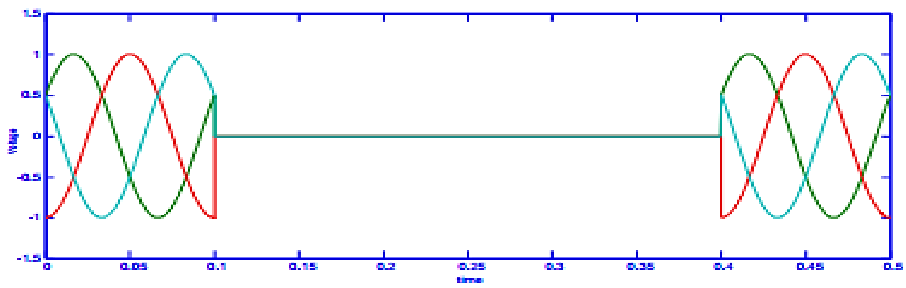


Figure 2.3: Graph of interruption (Pal et al., 2019)

2.2.2 Long Duration Voltage Variation

It is defined as voltage variations that occur at power frequencies and last longer than a minute. Under voltage, over voltage and sustained interruptions are examples of long-duration variations. They are brought on by changes in the system's load and switching operations of the system.

I. Under Voltage

It occurs when the rms ac voltage drops to less than 90% for longer than one minute at the power frequency. An under voltage may result from a load turning on or capacitor bank turning off upto the system's voltage control components can restore the voltage to within tolerances. Under voltages can also arise from circuits that are overloaded (Andrei et al., 2017).

II. Over Voltage

It is an increase in the rms ac voltage of more than 110% for a time longer than a minute at the power frequency. The most common cause of overvoltage's are load switching, such as turning off a heavy load or turning on a capacitors bank. Improper tap settings on the transformers can also result in overvoltages in the system (Yang et al., 2015).

III. Sustained Interruptions

A sustained interruption occurs, if the supply voltage is zero for a duration of time more than one minute (Andrei et al., 2017).

2.2.3 Transient

It is an undesired event that occurs momentarily and that disappear when an perating situation change from seady state to another. Impulsive and oscillatory are the two types into which transients can be divided. The major impacts of transients are the running of motor at a high temperature, equipment failure brought on by deterioration in the motor winding's insulation ,an increase in the motor's losses and its operating temperature, a degradation of the protective devices' contacting surfaces, an increase in hysteresis losses, and a reduction in transformer.

I. Impulsive Transient

It is a quick, unidirectional, non-power frequency alteration in voltage, current, or both in the steady-state condition; these changes are often either positive or negative. The main cause of this problem is lightning. For impulsive transient the schematic diagram that show the waveform is shown in Figure 2.4.

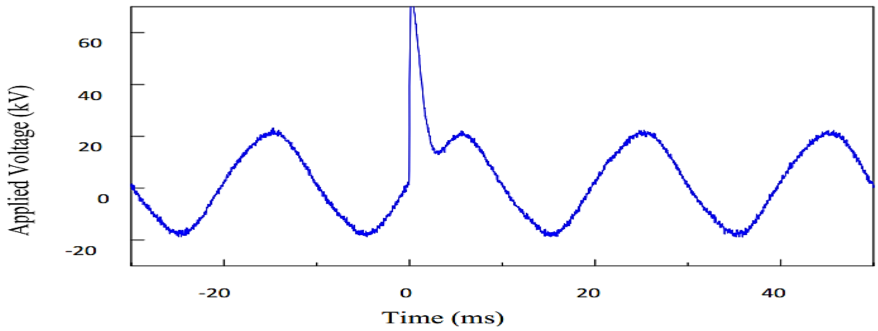


Figure 2.4: Schematic diagram of impulse transient

II. Oscillatory Transient

It is a sudden non-power frequency changes in the steady-state voltage, current, or both conditions, involving polarity value of both positive and negative as shown in Figure 2.5. Oscillatory transients cause system lock-up, equipment failure, annoying adjustable-speed drive tripping, data loss, and corruption

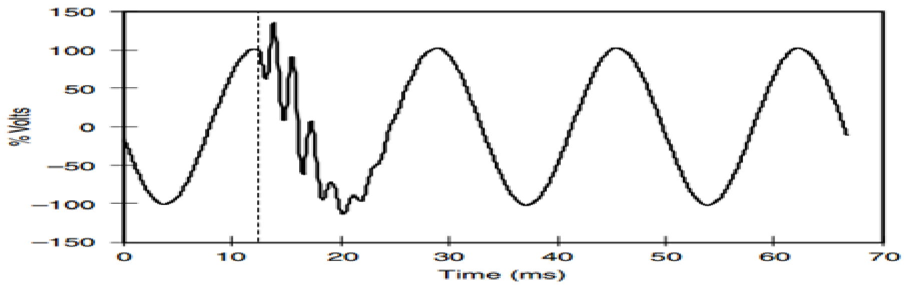


Figure 2.5: Graph of oscillatory transient (Andrei et al., 2017)

2.2.4 Voltage Unbalance

It is defined as the the maximum divergence from three-phase voltages or currents that are averaged divided by the three-phase averaged currents or voltages and which is expressed in percentage terms (Bajo et al., 2015). A three-phase motor's life is shortened and its performance decreased by voltage imbalance. Phase current imbalance results from voltage imbalance at the motor stator terminals and results in out of proportion to the voltage imbalance. Shorter winding insulation life is caused by imbalanced currents, which also increase losses, mechanical strains, vibrations, and motor overheating. The waveform that show the voltage unbalance disturbance is shown in Figure 2.6.

$$\%Voltage\ unbalance\ ratio = \frac{Maximum\ voltage\ deviation}{Average\ voltage} * 100 \tag{2.1}$$

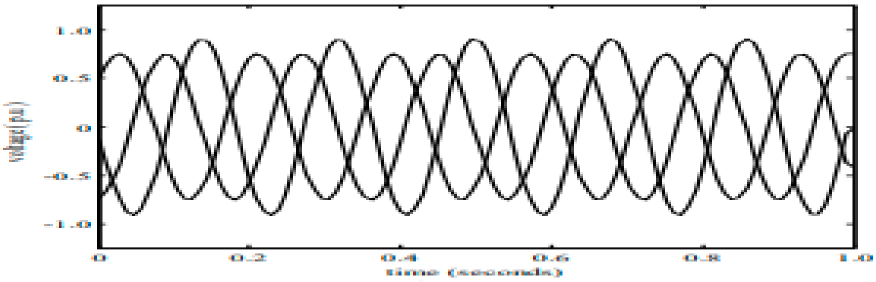


Figure 2.6**:** Voltage unbalance (Singh, 2013)

2.2.5 Voltage Flicker

Flicker is the perception of varying brightness, that arises during the frequency of perceived change falls between a few hertz and the fusion frequency of pictures as shown in Figure 2.7. The human eye perceives flicker as the fast on/off feeling of incandescent and fluorescent bulbs. Electric arc furnaces, welders, quickly cycling loads, and big ASDs with insufficient DC-link filtering on poor distribution systems are some of the sources of flicker. Light bulbs and television screens that flicker at high frequencies can cause eye strain and headaches, that can be harmful to people's health. Additionally, flicker shortens the lifespan of lamps and other electrical devices.

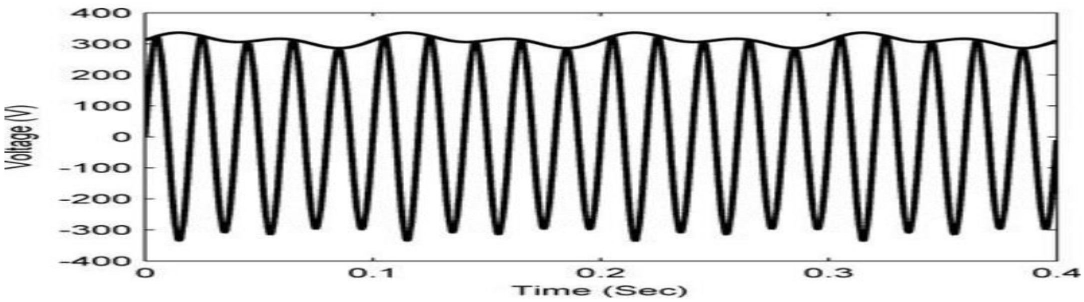


Figure 2.7: Schematic diagram of voltage flicker (Ravi & Ravi, 2016)

2.2.6 Waveform Distortion

Waveform distortion is the term used to describe any deviation from the sinusoidal sine wave in the voltage and current waveform power supply's (Gullapelli & Hadpe, 2020). Waveform distortion can be categorized into five types. These are noise, DC offset, notching, inter-harmonics, and harmonics.

I. Harmonics

It is one of the numerous power quality issues that is more common than others, because of the increase in the usage of the power electronic apparatus. Harmonics is the waveform portions that are multiples of the fundamental frequency, which is often 60 Hz or 50 Hz**.** It's waveform is shown in Figure 2.8**.** Both voltage and current exhibit harmonics, with current harmonics occurring more frequently. Due to the non-linear loads and the switching required, current is drawn in pulses that occasionally have sharp rise or decrease of edges. Total harmonic distortion (THD), which is the ratio of the RMS of components of the harmonic to the RMS of the component of the fundamental, is typically used to quantify and characterize harmonics. The total harmonic distortion of current and voltage shown in equation 2.2 and 2.3, respectively (Darussalam et al., 2020):

$$THD_I = \frac{\sqrt{I_2^2+I_3^2+I_4^2 \ldots +I_n^2}}{I_1^2} \tag{2.2}$$

$$THD_V = \frac{\sqrt{V_2^2+I_3^2+V_4^2 \ldots +V_n^2}}{V_1^2} \tag{2.3}$$

Where, V_n and I_n are the RMS magnitude of harmonic voltage component and harmonic current component respectively, where n=2……. ∞ and V_1 and I_1 are the RMS voltage and current magnitude of the basic component respectively.

When working with light loads, the THD result might be misleading as the basic component's magnitude is small and the harmonic component's magnitude could be significantly greater, resulting in a high percentage of THD. When taking the system as a whole into consideration, this distortion may be negligible. Accordingly, total demand distortion is utilized to prevent this ambiguity. The ratio is calculated with respect to the system's rated current, as provided by I_R, rather than the fundamental component (Sanjan et al., 2020).

$$TDD_I = \frac{\sqrt{I_2^2+I_3^2+I_4^2 \ldots +I_n^2}}{I_R^2} \tag{2.4}$$

The following are some major damage that harmonics cause to the power system (Persson, 2014):

- ✓ Increase in losses and heating
- ✓ A shorter service life as a result of the power system's components deteriorating more quickly.
- ✓ Interference with other devices and communication networks.
- ✓ Malfunction or failure of capacitor banks and safety mechanisms

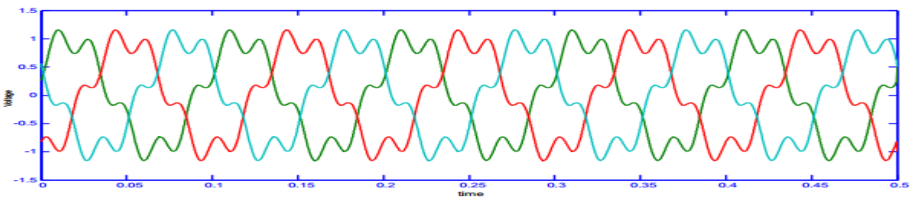


Figure 2.8: Harmonic distortion waveform (Pal et al., 2019)

II. Inter-harmonics

Inter-harmonics are voltages as well as currents whose frequency components aren't integer multiply of the frequency (like 50 or 60 Hz) where the power supply system is intended to operate. They may manifest as a wideband spectrum or as discrete frequencies. Inter-harmonic waveform distortion is mostly caused by arcing devices, cyclo-converters, induction furnaces, and static frequency converters (Andrei et al., 2017). Variations in the inter-harmonics frequency may cause significant resonances with the system's fundamental frequencies. Power-line-carrier signaling is impacted by inter-harmonics, which also cause visual flicker in computer displays and other arc lighting sources (Jacob et al., 2019).

III. DC Offset

The term "DC offset" refers to the presence of a DC current as well as DC voltage in the AC power system as shown in Figure 2.9. The geometric disturbance of electronic power converter is one of the cause for the occurrence of DC offset.

The Consequences of the DC-offset is as follows:

- ✓ The transformer core may become saturated, leading to more heating and a reduction in transformer life.
- ✓ Grounding electrodes and other connectors may also erode by electrolysis due to direct current.

Figure 2.9: DC offset (Hoffmann et al., 2021)

IV. Notching

When the phase of the current is changed during the regular operation of power electronic devices, a periodic voltage disturbance known as notching results as shown in Figure 2.10.

An illustration of voltage notching coming from a three-phase inverter that generates uninterrupted DC current is provided in the figure that follows. when the current switches from a particular phase to another,ntches appear. A brief short circuit across two phases, occurs during this time , bringing the electrical voltage as close to zero as the system impedances will allow.

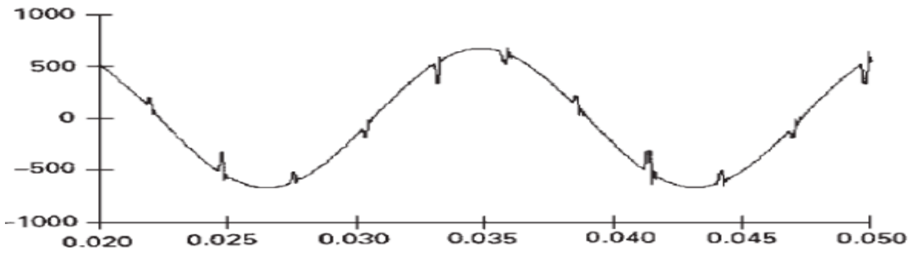


Figure 2.10: Voltage notching (Jacob et al., 2019)

V. Noise

Noise is defined as an undesired signal overlaying on power system signal lines that has a wideband spectral content of less than 200 kHz Figure 2.11. Electronic equipment, arcing devices equipment isolation transformers, solid-state rectifiers, control circuits, switching power supplies, power-electronics devices and line conditioners are the reasons for the cause of noise. These kinds of power quality probem are lessened by the usage of filters.

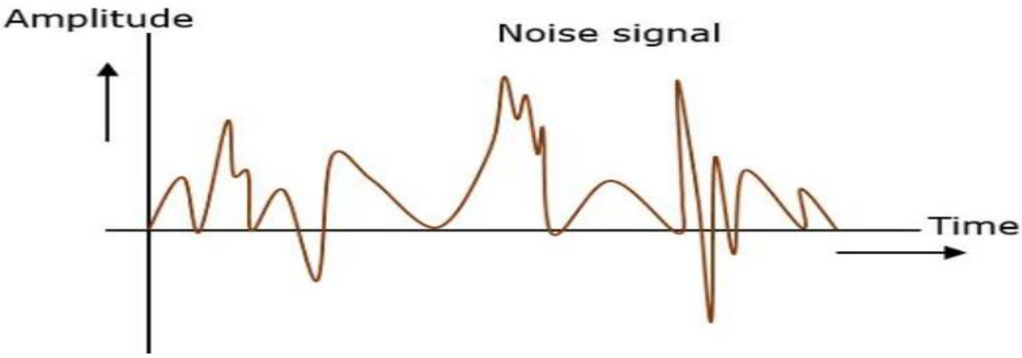


Figure 2.11: Noise (Gullapelli & Hadpe, 2020)

2.2.7 Power Frequency Variation

Power frequency fluctuations are described as the basic frequency of the electrical system deviation from its nominal magnitude, which is 50 and 60 Hz as shown Figure 2.12. Frequency changes can be brought on by huge-scale load disconnections, large-scale generation sources falling down, or failures in the bulk power transmission system.

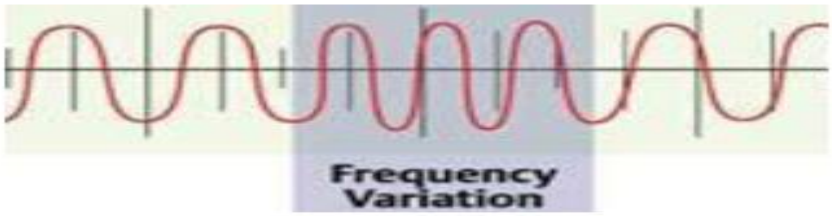


Figure 2.12: Power frequency variation (Gullapelli & Hadpe, 2020)

The Table 2.1 shows the of list of power quality problem, subclass of power quality disturbance, it's cause and effects.

Table 2.1: List of power quality problem with its cause and effect (Sanjan et al., 2020)

Problem type	**Sub-type**	**Cause**	**Effects**
Short duration Voltage variation	Voltage swell	Capacitor switching, huge load switching	Data loss, screen burnout, bright light, malfunction sensitive equipment
	Voltage sag	Due to faults, due to transformer energizing and due to motor starting	Fail to operate of sensitive equipment, poor lighting, screen shrinkage, device failure, and loss of memory, errors in data
	Interruption	Defect of equipment and temporary faults	Damage to protective equipment
Long duration voltage variation	Over voltage	Energizing a capacitors bank, turning off a huge load	Increase of loss and damage to equipment
	Under voltage	Capacitor bank turning off or turning on load	
	Sustained interruption	Faults	
Transient	Impulsive	Lightning strikes	Power system resonance and data loss

	Oscillatory	Capacitor switching and load switching	Equipment malfunction and system lock-up
Voltage unbalance		Unequal load distribution across each phase	Increase losses, mechanical strains, vibrations, and motor overheating.
Voltage flicker		Variation of the load	Malfunction of the protective device
Power frequency variation		Disconnection of huge block of load, bulk power transmission faults	Damage to the generator and other device
Wave form distortion	Harmonics	Non-linear load	Saturation in the transformer, harm to sensitive equipment, accelerated deterioration of equipment, electromagnetic interference, increased losses and audible noise
	Notching	Arc welders, light dimmers, variable speed drive etc.	
	Inter-harmonics	Non-linear load	
	Noise	Improper grounding, electromagnetic interferences.	
	DC-offset	Power supplies, faulty rectifier.	

2.3 Power Quality Standard

Organizations of all throughout the world have established a number of international standards that define or suggest limits for issues associated to power quality. In order to detect harmonics in the supply system, two categories of international standards are typically recommended (Saggu & Singh, 2016). One is from the IEC and the other is from IEEE. International Electro technical (IEC) standards are primarily targeted at small customers, while Institute of Electrical and Electronics Engineers (IEEE) standards are primarily intended for large industrial consumers.

Power quality standards prevent utility and consumer equipment from malfunctioning when the frequency, current, and voltage diverge from specified norms. Moreover, power quality standards help utilities and consumers to distinguish between acceptable and undesired service levels. IEEE standards and definitions will be primarily utilized in this study, due to their widespread use in fields of study and their high degree of clarity in characterizing each of the significant electrical phenomena that comprise power quality.

2.3.1 IEEE Standards

IEEE-519 is not a list of restrictions, but rather a collection of recommendations. It provides the TDD measurement at the PCC, with its magnitudes determined by the system's rated current. The IEEE Std 519-2014 current and voltage harmonics distortion limit is shown in Table 2.2 and Table 2.3, respectively.

There are different IEEE standards that related to power quality problem. Some them are:

- ✓ IEEE Std 519-2014: Requirements and recommendations for power systems' harmonic cntrol.
- ✓ IEEE Std 1159-2009: Suggested method of action for managing power quality. The consequences of low power quality on utility and customer devices, measurements of electromagnetic phenomena, AC power system control over electric power quality, and descriptions of power quality terms are presented.
- ✓ IEEE Std 1159-2003: Recommendations for sending data about the quality of power.

Table 2.2:The current distortion limits for systems rated from 120 V to 69 KV (IEEE, 2014)

Maximum harmonic current distortion in percent of I_L						
Individual harmonic rder (odd harmonics)						
I_{SC}/I_L	3≤h<11	11≤h<17	17≤h<23	23≤h<35	35≤h<50	TDD
<20	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Where, I_{SC} = maximum short-circuit current at PCC and I_L = maximum demand load current at the PCC's (basic frequency component) under typical load conditions of operation.

Table 2.3 : Voltage distortion limits(IEEE, 2014)

Bus voltage V at PCC	**Individual harmonic (%)**	**Ttal harmonic distortion THD(%)**
V≤1.0kV	5.0	8.0
1kV<V≤69kV	3.0	5.0
69kV<V≤161kV	1.5	2.5
169kV<V	1.0	1.5

2.4 Effects of PQ Problems on Sugar Industries

Sugar industry is the main agriculture industry in Ethiopia. Every season in our country a million of sugar cane is produced for sugar production purpose. The plant in the sugar factory used electrical power from Ethiopia electric power, diesel and steam power from the boiling of the water using bagasse.The plant at the sugar factory use different types f electrical motor. This motor,s speed has to be controlled. During the control speed of the motor at the factory, the adjustable speed drive was used. The harmonics current from ASD result increase in reactive power, overheating of the equipment, damage of the capacitor bank and high consumption energy (Aramwanid & Boonyaroonate, 2015).

Problems with electric power quality can have severe consequences. These impacts usually translate into negative environmental impact, depreciation of fixed assets, increase in operating expenses, safety hazards, downtime, loss of productivity in the business world, overheating of the motors, effect cause to mechanical failure, the cost needed for additional service and the cost needed for maintenance, decrease in power factor, and reduced equipment lifetime. The effects of low power quality might cause deliveries to be delayed and damage the image of a company. The sugar plant facing many challenges due to nonlinear device used for the control of the motor. This nonlinear device lead to harmonics ,unwanted disturbance in voltage and current, increase of the loss in the system (Aramwanid & Boonyaroonate, 2015).

The power quality problem affects different component of the sugar industries. These are:

Effect on motor and process device :The malfunction of the device that used for processing the operation, fail to operate of the motor, overheating and decrement in the efficiency of the system are the effect of power quality issues on electrical motor (More et al., 2014).

Effect on variable speed drives: ASD is a significant portion of the commercial and industrial three-phase electrical load. Adjustable speed drives (ASDs) transform a fixed supply frequency into a variable frequency motor driving voltage via an electrical converter. They are widely utilized in processing of operation, material handling, and manufacturing operations. When there is a sag, the electrical system's energy supply is decreased and may be less than what the process needs, which can lead to a loss of control. Motor-controlled processes seldom run in isolation, therefore this may lead to an uncoordinated shutdown and a lack of synchronization with other process components (Muhamad et al., 2007).

When voltage sags are used with variable speed drives, the following issues arise:

- ✓ The motor cannot receive enough voltage (loss of torque, slowdown)
- ✓ The control circuits that connected to the network unable to operate
- ✓ Overcurrent occurs when voltage recovers (recharging the drive filter capacitor)
- ✓ Overcurrent and unbalanced current occur when voltage sags on a single phase
- ✓ DC drives acting as inverters lose control (regenerative braking)

Relays, Circuit breakers and AC Contactors: Relays and contactors are designed to function in a several coil voltage and contact specification ranges(Aramwanid & Boonyaroonate, 2015). Power-electronics devices like IGBTs have largely replaced the contactor function in most places these days. Conversely, PLCs that use digital logic have replaced control relay functions. Line-voltage sags and interruptions affect devices, whether they are solid state or electromagnetic.

Effect on personal computers: This device is intended to be used for many general tasks, including computing. The disturbance of the voltage affects the PC at the industries by creating software problems that lead to interruption, blocking of the working system, and failure to respond to any command from the keyword.

Effect on used energy: Energy will be wasted during the restart stage if a manufacturing process is interrupted. The energy used up until that time is lost if product damage results from a process stoppage or malfunction brought on by an outside force.

Effect on equipment life span: Many systems facing disruptions that is visible and hidden have seen a reduction in equipment lifespan. Even in systems with transient suppressors, high energy, quick rise time transients have the potential to completely destroy circuit boards or to degrade systems over time to just delay burnout. Phase imbalance and harmonic distortion can work together to overstress transformers and motors, reducing their usable lives.

Effect on transformer: In a transformer, the existance of harmonic current raises the losses related with the core, copper, and stray flux. Voltage harmonics mostly effect no load loss; however, this loss only slightly increases as a function of harmonics. A transformer's load losses have an opposite relationship with the square of the load current and rapidly increase at high harmonic frequencies (Stein, 2002).

2.5 Mitigation Techniques for Power Quality Problems

Two methods exist to mitigate issues related with power quality (Singh, 2013). The two techniques that are used are line conditioning and load conditioning. Load conditioning helps to guarantee that the machinery is less vulnerable to fluctuations in power. Providing continuous sinusoidal voltage with constant amplitude and frequency as well as balanced currents at the main AC is the primary goal of electric utilities for their customers. In order to avoid disturbance due to non linear load in electric distribution network the protective device is needed.

Major power quality (PQ) issues such as large reactive power, loads that are not balanced, voltage sag, transient ,over voltage, interruption ,harmonics, and excessive neutral current impact today's AC distribution networks. As a result, these power quality issues need to be eliminated for the industry to function effectively. In order to address and manage power quality issues, several solutions have been proposed.

2.5.1 Custom Power Devices (CPDs)

The idea behind custom power device is to use the power electronics controller devices into the power distribution system in order to meet sensitive consumers' demands for a certain quality of power (Desale et al., 2014). Compared to traditional capacitor and inductor banks, which are often larger, more prone to loss, less reliable, and have poorer control and lower efficiency, CPD have a number of advantages (Vaughan, 2017). Most of them are offered commercially, and they operate effectively at medium-distribution levels. Network reconfiguration and compensatory CPDs are the two categories of CPDs. There are three types of custom power device as shown in Figure 2.13.

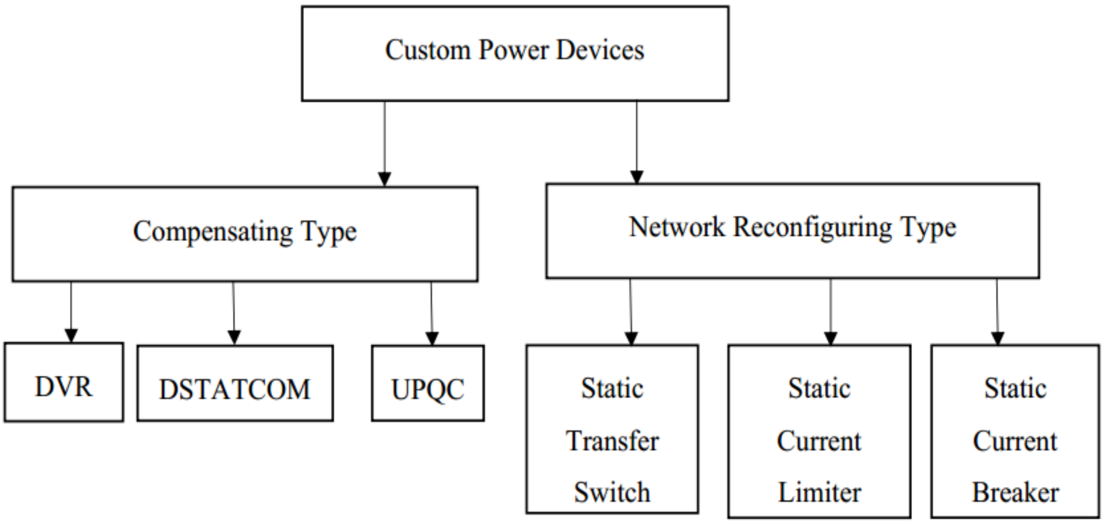


Figure 2.13: Custom power device (Desale et al., 2014)

A) Network Reconfiguring Type CPD

These devices, which are based on GTOs or thyristors, are typically employed for rapid current limiting and breaking. The main specialized power devices for network reconfiguration are the solid state breaker, uninterruptible power supply, static transfer switch, and static current limiter.

B) Compensating type CPD

The compensatory custom power devices are used for power factor optimization, active filtering, and voltage regulation (sag/swell). Three categories of custom power devices are DSTATCOM, DVR, and UPQC (Desale et al., 2014).

a) DVR

DVR is a seriesly connected device that, preserves the load voltage from the supply voltage quality issues such as, imbalance, sag/swell, surges, and spikes (Kumar et al., 2022). The DVR connect in series with distribution line to compensate the disturbed voltage as shown Figure 2.14. In order to to return load voltage to its reference value, the DVR adds a compensated voltage between the supply and the consumer load.

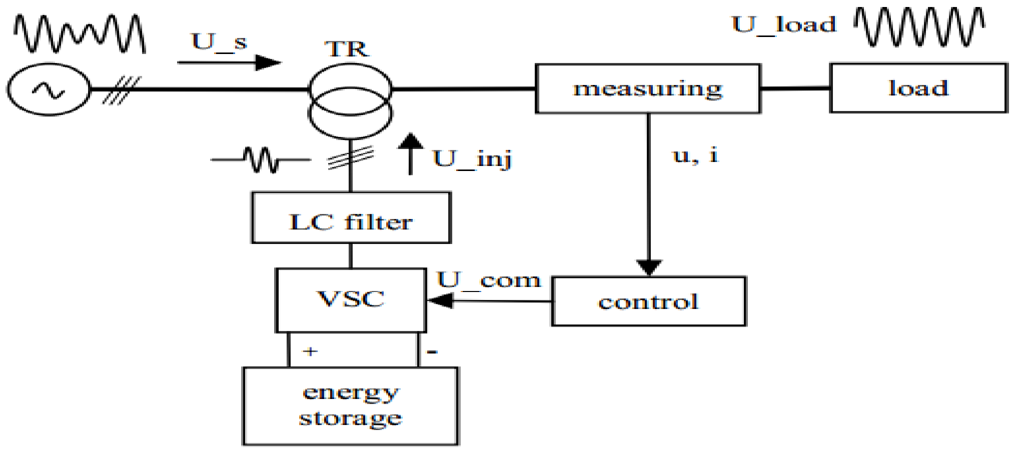


Figure 2.14: Schematic diagram of DVR

The DVR is made up of various components. The following are among the components of DVR:

Injection Transformer: The high voltage windings on the injection transformers allow the DVR to be connected to the distribution network. They convert and connect the VSI-generated injected compensatory voltages to the supply voltage that is coming in.

Voltage Source Converter (VSC): The device uses a PWM inverter that makes use of IGBT switches. IGBT switches are frequently utilized in circuits with series connections. The three-terminal power semiconductor known as an insulated gate bipolar transistor, or IGBT, is renowned for its quick switching and excellent efficiency (Engineering & Engineering, 2016)s.

Energy storage device/ Control system: The the of an energy storage device has a significant influence on the system's ability to compensate for large voltage sags. Examples of energy storage devices include flywheels, super-capacitors, DC capacitors, and batteries.

Passive Filters: At the DVR's high voltage side, passive filters are positioned to filter harmonics. In order to avoid phase angle shift, which could interfere with the control algorithm, these filters are positioned on the inverter’s high voltage side.

b) DSTATCOM

The DSTATCOM is a shunt device that is placed parallel to the consumer load and offers reactive power compensation, balance of loads, neutral current compensation, and harmonic mitigation as shown in Figure 2.15 (Kazmierkowski, 2015).

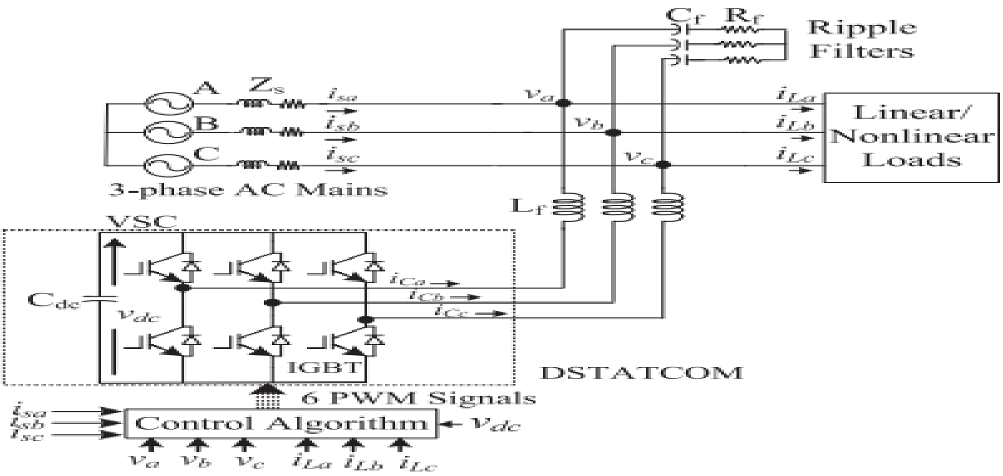


Figure 2.15: Schematic diagram of DSTATCOM

c) UPQC

The importance of UPQC is due to its capacity simultaneously to mitigate issues with voltage and current quality, such as harmonics, flickers, swells, interruptions, and voltage sags throughout a distribution network. The fundamental components of a UPQC are a parallel and a series voltage source inverter paired back-to-back through a shared DC connection, and normally connected at the point of common coupling of a distribution system. Series converters are effective at reducing PQ issues related to voltage, while shunt converters are better at reducing PQ issues related to current. As seen in Fgure 2.16, the series inverter is linked in series with the line of service connecting the load and the source, while the shunt inverter is connected in parallel (Kota & Vinnakoti, 2018)**.**

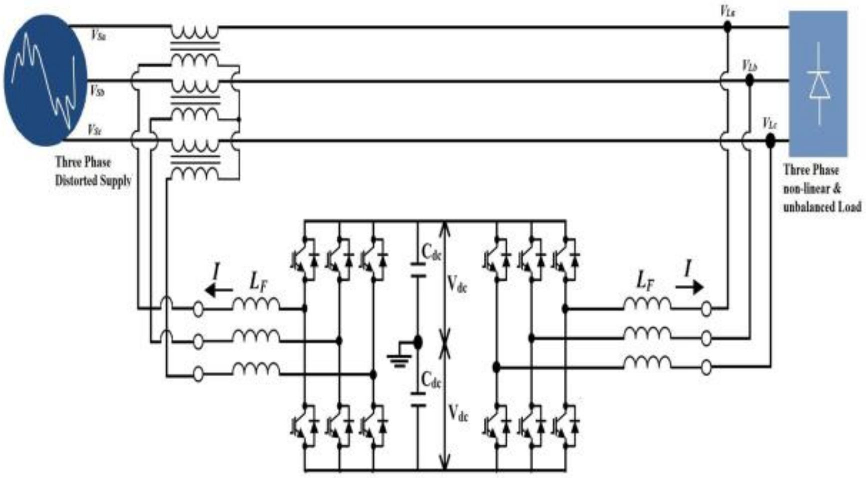


Figure 2.16: Basic structure of UPQC

To mitigate the power quality problems associated with current and voltage, the DSTATCOM and DVR of the UPQC are independently controlled. There are numerous methods to categorize UPQCs (Qasim et al., 2024):

- ✓ Supply-based (two-wire UPQC, three-wire UPQC and four-wire UPQCs).
- ✓ Converter-based (VSC- based and CSC-based UPQCs).
- ✓ Topology-based (left shunt UPQCs and right shunt UPQCs).
- ✓ Classification based on method of control (UPQC-P, UPQC-Q, and UPQC-S).

To obtain the pulses needed by UPQC inverter, an appropriate control mechanism must be employed. Some of the techniques mentioned are space vector modulation, deadbeat control, hysteresis control, and sinusoidal pulse width modulation (SPWM)(Heenkenda et al., 2023). Using series and shunt inverters, a traditional UPQC model was developed and simulated to examine the structure of and how it affects the load and the system waveforms.

UPQC consists of two IGBT-based VSCs, one shunt and a series connected via a shared DC bus. Low-pass and high-pass passive filters, series and shunt transformers, DC capacitors, and converters are essential parts of a UPQC. The following are the UPQC main parts:

Series APF: Is typically connected in series to the distribution network via a transformer. This inverter is employed to compensate for issues brought on by voltage imbalance and distortion (Sai Kumar et al., 2023). In order to provide precisely balance and regulated voltage at the load, the series APF injects a compensating voltage. The principles of hysteresis controller is employed by comparing voltage of the reference with actual voltage in order to generate pulse.

Shunt APF: Is often linked to the network in parallel when there is a transmission line. To mitigate the harmonic distortion caused by current shunt APF is employed. The shunt APF is employed to maintain the fully sinusoidal and distortion free source current because nonlinear introduce harmonics at the load current (Jeraldine Viji & Aruldoss Albert Victoire, 2014). In order to ensure that the source current is entirely sinusoidal and free of distortion, shunt APF injects compensatory current. Through the use hysteresis controller, the shunt APF is controlled by comparing the reference current generated with actual current.

Series transformer: Joins the distribution networks to series inverters. Choosing the right turn ratio is often the first step towards lowering a series inverter's voltage and current rating.

A common DC link: A DC link source, which is typically an energy-storing component like a capacitor or inductor, is linked between two inverters. A capacitor DC link is utilized to maintain a steady DC bus voltage (Bhosale et al., 2018).

LC filter: Reduces high-frequency switching fluctuation on the voltage produced by the inverter.

Shunt coupling inductor: Is used to interconnection of the shunt inverter to the distribution network. Additionally, it aids in the current wave shape's smoothing.

Controller of series and Shunt APF: Integrated controller with the series and shunt APF is used to provide the compensating voltage reference and compensating current reference.

Ripple filter: Is Connected to the UPQC's load terminal. It is used to filter out the high frequency component of pulse voltage from the voltage source converter of the DSTATCOM of the UPQC.

2.6 Review of Related Works

Due to the increase need for electricty through out the world, delivering high-quality electricity has emerged as the top priority for both power providers and consumers. An attempt has been made to enhance the power quality. According to the findings of several scholars, the power quality has become major concern in the last few years, particularly with the introduction of more advanced equipment for automated distribution systems in the electrical utility. A brief description of the literature on power quality problem mitigation and enhancing of the power quality shown as follows:

(Park et al., 2021) focus on the application of passive harmonic filter to reduce harmonics in the power of a steel mill. This case study focuses on addressing the issue of harmonics, which are unwanted frequencies and voltage distortion that can occur in electrical systems due to the presence of nonlinear loads. Despite the fact that these filters were easy to construct, the electric power system's quality and performance would be limited by their tendency to induce resonance and incorrect amplification of current harmonics. In the study one LC branch can only adjust for a particular frequency harmonic, therefore it needs to install too many filtering branches.

(Bellapukonda Sravani, B Kavyasanthoshi and D Ravi Kishore, 2021) investigate power quality problem improvement using DSTATCOM. This study uses instantaneous power theory (PQ theory) based DSTATCOM to control and compensate for power quality issues, primarily focusing on voltage regulation and reactive power compensation. The PQ theory-based DSTATCOM is a widely utilized technology to enhance distribution power quality. The DSTATCOM is effective for specific conditions but may require additional devices for comprehensive power quality improvement.

(Molla et al., 2024) involves addressing issues like voltage sags, swells, and flickers that can affect industrial processes using ultra-capacitor-based DVR. This study uses an ultracapacitor in combination with a DVR to deliver high power quickly, which is crucial for mitigating short-term voltage sags. The ultra-capacitor is generally smaller and lighter compared to other energy storage devices like batteries. The study has some limited functionality if a broader range of power quality problems needs to be addressed.

(Sanjan et al., 2020) aim to address the issue of power quality in domestic environments by proposing the utilization of harmonic filters. The paper likely begins by highlighting the significance of power quality in domestic loads. It also discusses the adverse effects of poor power quality, such as harmonics and power factor issues, on electrical appliances and equipment. The authors emphasize the need for effective solutions to enhance power quality in domestic environments and aim to address the issue of power quality in domestic environments by proposing the utilization of harmonic filters.

(Islam et al., 2021) use a capacitor bank and BESS to improve the distribution network's power quality. The load-reactive power demand has been compensated by the capacitor banks. It is the simplest and, in certain cases, the most successful method of adjusting for load-reactive power consumption. This study has a number of significant drawbacks, including fixed compensation, the possibility for resonance conditions to occur with neighboring loads, transient switching, bulky size, and the aging effect.

(Al-Gahtani et al., 2022) investigate the importance of power quality and the adverse effects of voltage sags and swells on electrical equipment and overall system stability. In this paper, DVRs are introduced as effective devices for compensating voltage disturbances. It presents a valuable contribution to improving power quality under severe sag and swell conditions. The proposed technique provides several benefits, including fast response times, robustness against severe voltage disturbances, and improved power quality in the distribution system. The DVR proposed by this study mitigates only voltage related power quality problems.

2.7 Literatures Review Summary

Most of the works mentioned in the literature review of this study focus on mitigating power quality-related problems using DVR, DSTATCOM, passive filters, capacitor banks, and others. However, the custom power devices like DSTATCOM and DVR mitigate either current-related or voltage-related power quality issues. The study that uses DSTATCOM has limitations in dynamically adjusting to varying power quality issues because the device is limited to mitigating only current-related power quality problems. The passive filter mentioned in the literature review of this study has some limitations, like resonance and incorrect amplification of current harmonics; it can only adjust for a particular frequency harmonic; therefore, it has to install too many filtering branches. The passive harmonic filter deals with steady-state harmonic distortion. However, power systems frequently encounter dynamic events, including load variations, switching operations, and failures, which can impact harmonic levels. The UPQC can function in both steady-state and dynamic conditions. These gaps motivate this study to use SRF theory based UPQC to mitigate power quality problems. UPQC is more capable of daynamic adjustments due to its comprehensive control strategy, enhancing reliability under varying conditions. This study uses SRF theory based UPQC for power problem mitigation. Due to its versatility and capability of handling a wide range of disturbances with a single device, it is better to use the UPQC for improving power quality problems.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Methodology

The study's methodology starts with identifying the problem and doing thorough literature studies of related books, papers, and websites. The main problem that needs to be addressed is power quality problems. The main focus of this study is the insertion of the mitigating device called UPQC into WSSF at the S&PGP distribution network for the purpose of mitigating power quality issues. A review of literature on power quality mitigation is the first step in this study. After reviewing different books and articles on mitigation of power quality problems, relevant information is gathered from the WSSF at S&PGP distribution network. Measurements and records from the equipment's nameplate and display are used to get the required data. Analysis of the collected data, design of the distribution network, and design of the compensating device are done in this thesis work. MATLAB/Simulink is used for this study. Simulation takes place with and without UPQC as a mitigating device and depends on SRF theory as a control algorithm.

Generally, to achieve the objective of this research, the methodology flow chart of the thesis is shown in Figure 3.1.

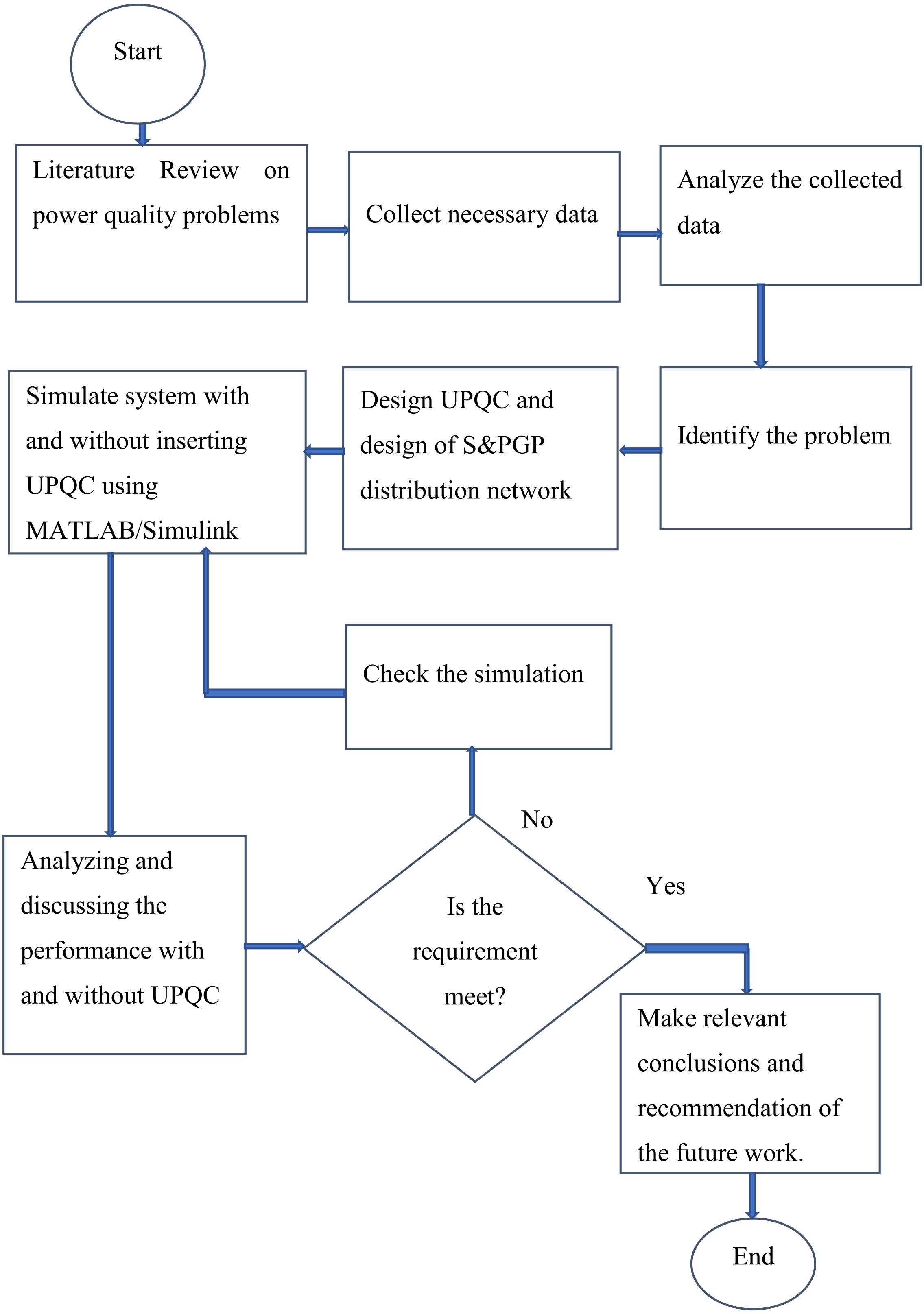


Figure 3.1: Methodology flow chart of the thesis

3.2 Material or Software Tool of the Study

The following material was needed in order to prepare this thesis:

- ✓ Microsoft Word 2016: research materials can be written, formatted, and organized using this word processing tool.
- ✓ Math-type: this tool is used to format and easily incorporate mathematical equations into the document of the study.
- ✓ Mendeley: an application for monitoring references that helps with bibliography creation, citation organization, and research literature management.
- ✓ MATLAB/Simulink software: Modeling and simulation of the distribution network with and without UPQC is performed using this software.
- ✓ Electrical Transient & Analysis Program (ETAP): This study utilizes the ETAP software to draw a single line diagram of the electrical distribution system.

3.3 Description of Study Area

This section focus on the background of WSSF, section of the factory and the distribution network of the factory.

3.3.1 Background of WSSF

Since 1954 E.C., when a Dutch business established WSF with crushing 1400 tons of cane per day (TCD), Ethiopia's sugar industry has grown significantly. The first sugar factory in Ethiopia was WSSF. 1962 brought the construction of the Shoa Sugar Factory, which had a 1600 TCD crushing rate, eight years after WSF was founded. They are called by the name WSSF and are all managed by the same management and it's overview is shown Figure 3.2. The two oldest plants, however, are currently closed, and as a result, a new factory has been built in Dodota, some 21 kilometers from Wonji Subcity. The factory has a rated crushing capacity of 6250 TCD. The facility is situated at an elevation of 1540 meters above sea level in the Oromia region's Rift Valley, approximately 149 kilometers southeast of Addis Ababa.

Figure 3.2: Study area of WSSF

3.3.2 Unit Operation at WSSF

The factory has two sector. The plantation and its operations. The factory operations process the sugarcane to yield sugar and the plantation sector is focused on growing sugar cane. The factory has five typical plants which are:

- ✓ Steam and power generation plant
- ✓ Boiling plant
- ✓ Clarification plant
- ✓ Milling plant
- ✓ Water treatment plant, and awash pump station

The WSSF cogeneration plant comprises two diesel generators with a capacity of 625 KVA and 1250 KVA in addition to one 31.25 MW steam turbine-powered generator. Its single-line diagram is displayed in Figure 3.3. The cogeneration unit is linked in parallel to the national grid of EEPCO through a switchyard that was constructed on the site. It contains a 30/38 MVA power transformer, with the primary winding 132KV with a delta connection and the secondary winding 11KV with a star connection.

3.3.3 WSSF Electric Power Distribution Network

The distrbution network of WSSF is shown in Figure 3.3 and under each section of the plant there are different loads.

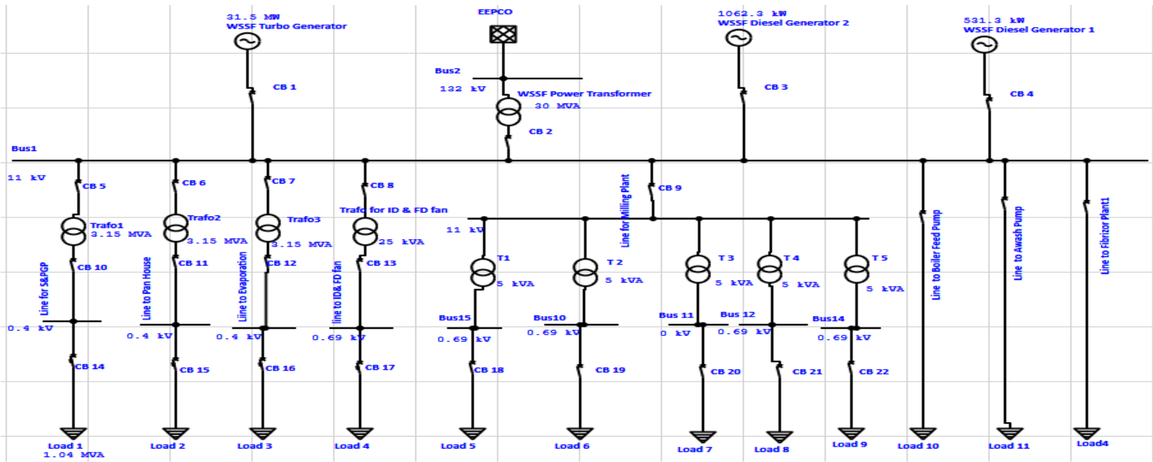


Figure 3.3: Single line diagram of WSSF electric power distribution network

In Figure 3.3 above, the load 1 belongs to the S&PGP and the other load mentioned is belongs to the other plant of the WSSF.

3.3.4 Steam and Power Generation Plant (S&PGP) of WSSF Electric Power Distribution Network

The distrbution network of (S&PGP) of WSSF is shown in Figure 3.4. In this distribution network of the plant, there different loads such as, Cooling tower, Auxilary for boiler 1, Water treatment MCC, boiler 1 ESP, Bagasse handle MCC, Main socket, MCC 2 Common Auxilary, Work shop and other loads.

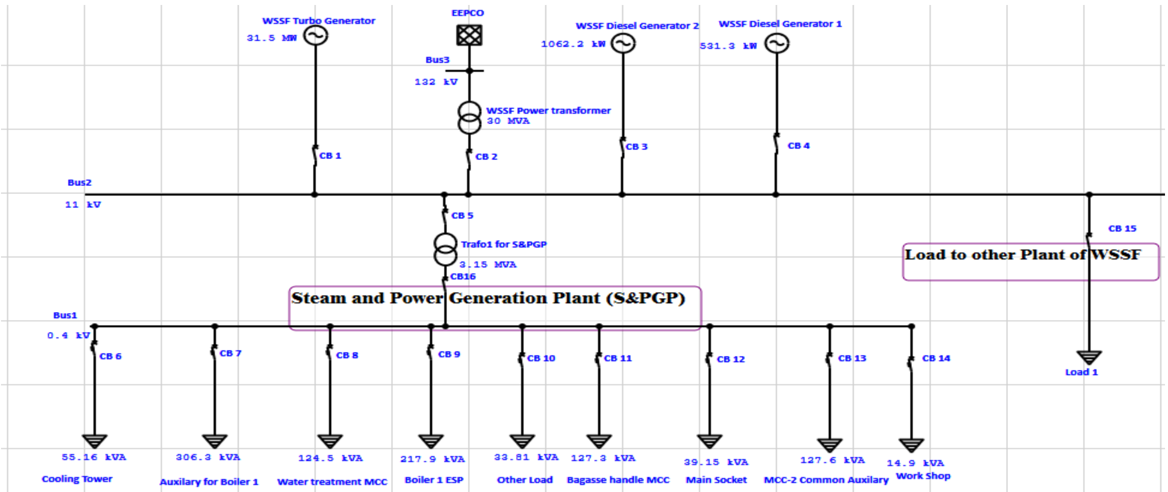


Figure 3.4: Single line diagram of S&PGP distribution network

The S&PGP shown in Figure 3.4 take 11KV and step down to 0.4KV voltage and it distributes the this three phase voltage to the load conneted to the distribution board. The load 1 shown in Figure 3.4 belongs to other plant of the WSSFs.

3.4 Method of Data Collection

The data used for this study is collected during the full operation of the factroy. Power quality measurements are needed in order to identify the issue related to power quality and determine whether the results comply with the IEEE 519-2014 standard. The data collected in this study includes energy consumption of the factory by interviews and other sources, voltage sag from display by recording, and current and voltage harmonics measured by a powerlogic PM800. The data acquired is analyzed and compared with IEEE 519-2014 standard. Once the issue is identified, a device known as a unified power quality conditioner is used to reduce the disturbance that was arising in the S&PGP electric power distribution network.

3.4.1 Measuring Device

Monitoring was carried out using powerlogic PM800 as shown in Figure 3.5. This meter offer a simple, reliable solution for kWh metering, KVar reading, voltage and current harmonics measuring and other specialty applications.

The measuring device have the following drawback:

- ✓ They don't display the taken measurement value's waveform.
- ✓ The device is not capable of logging or storing data. The immediate measured values must therefore be manually recorded at various times.
- ✓ The device is notun appropriate for quickly changing the sites of measurements. That means, it is fixed to the distribution network at some point.

Figure 3.5: Powerlogic PM800

3.4.2 Measuring Location

The IEEE 1159-2014 standard advises mounting the monitor on the secondary of the distribution transformer if the goal of the monitoring is to look into a facility's overall quality. For this study, the measurements were taken at the transformer secondary low voltage.

3.5 Data Collection

The data needed for this study is mentioned in the below sub-section and in the appendices of this document.

3.5.1 Harmonic Data Collection at S&PGP Distribution Network

To describe the system's harmonic cause and its effect, the harmonic distortion level is measured using Powerlogic PM800. It is also suggested that the measurement take place at the PCC for a different time. The collected harmonic data at the distribution board of the plant distribution network must be examined in order to use a UPQC as a mitigation device for the S&PGP distribution network that suffers from power quality issues. Appendix B contains the data on harmonic distortion observed at S&PGP.

3.5.2 Voltage Sag Data at S&PGP Distribution Network

The whole voltage sag issue data is collected by manually recording data from the display at various times. The manually collected voltage sag data was shown in Appendix C.

3.6 Design of S&PGP Distribution Network

The stage at which electricity is transferred from a transmission line to a particular customer is known as electric power distribution. To carry out the factory analysis, it is necessary to model the distribution network components, such as the load installed in each transformer and distribution transformer. The estimations and calculations used to model various distribution network components are discussed in the below section.

3.6.1 Distribution Transformer Modelling

The transformer that completes the last stage of voltage conversion in the distribution grid is known as a distribution transformer. Without a distribution transformer, the utility would not be able to provide customers with energy. It is the costliest and most important piece of machinery in the network that distributes electricity. This transformer step down 11kV voltage from the feeder to the 400V industrial voltage that is frequently utilized. The kVA rating, X/R ratio, percentage impedance, and the voltage are the transformers' specifications. Leakage reactance and series resistances are also used for modeling of the transformers. As is the case in most power system analyses, core losses, shunt admittances, and magnetizing current are ignored. The impedance of the distribution transformer was calculated from the percentage transformer as shown in equation (3.1).

$$Z_{tr} = \frac{\%Z \times (KV)^2 \times 10}{KVA} \tag{3.1}$$

Where, Ztr, %Z, KVA, and KV are impedance of transforme, percentage impedance, power rating and three phase voltage, respectively.

The 3150 KVA has been chosen as the base KVA. The transformers X/R ratio is typically not listed on the name plate. It can be computed using the transformer's full load and no load loss data, or it can be requested from the manufacturer. Furthermore, the standard value of the X/R ratio for various transformer ratings is provided according to IEEE 141-1993 standard. Since the transformer nameplate of our transformer does not specify no load or full load losses. Therefore, for this investigation, the the standard values is obtained from IEEE Std 141-1993 are used. The graph indicates that the 3150KVA transformers X/R ratios are approximately 9 (IEEE Industry Applications Society. & Power Systems Engineering Committee., 2010). The Table 3.1 shows the data on the distribution transformer that are used at Steam and Power Generation Plant of the study area.

Table 3.1:The data given on distribution transformer at S&PGP

Parameters for service transformer	Values
Power rating	3150kVA
Voltage(in kV)	11(HV), 0.4 (LV)
Current(A)	165.33(HV),4546.63(LV
System frequency	50Hz
Percentage Impedance	6.5434
Vector Group	Dyn11

By using the equation (3.1), the impedance of transformer becomes,

$$Z_{tr} = \frac{6.5434 \times (0.4)^2 \times 10}{3150} = 3.3236 * 10^{-3}\ \Omega$$

Using X/R and the impedance of transformer (Z_{tr}), the secondary side of the transformer's resistance and reactance values are determined. From X/R ratio of 9 and the relation $Z = \sqrt{R^2 + X^2}$ the values of resistance of transformer $R_{tr} = 0.367 * 10^{-3}\Omega$ and the reactance of the transformer $X_{tr} = 3.30327 * 10^{-3}\Omega$.

3.6.2 Loads Connected to S&PGP Distribution Network

The electrical load connected to the distribution board the S&PGP distributin network is a power consuming part of the circuit. he active power used by the load is computed from the factory document. The apparent power is also calculated by the equation (3.2).

$$S = \frac{P}{pf} \tag{3.2}$$

Where, P, pf, and S are real power consumed, power factor and apparent power, respectively.

The average power factor that is recorded at different times during the test is used to determine the actual power factor. Table 3.2 displays the average power factor for the transformer's distribution board as measured at various times.

Table 3.2: Readings of the power factor at various times.

Date	Power factor reading at main distribution board of S&PGP
29/1/2024	0.760
31/1/2024	0.754
2/2/2024	0.758
5/2/2024	0.764
7/2/2024	0.766
12/2/2024	0.770
Average power factor	0.762

Using the average power factor of Table 3.2 and the loads linked to the distribution board of the S&PGP of WSSF on Appendix A with a total active power of 792.482 KW, the apparent power is obtained as

$$S = \frac{792.482}{0.762} = 1040.003KVA$$

The loads' reactive power was calculated as,

$$Q = \sqrt{S^2 - P^2} \tag{3.3}$$

Where, Q, S and P are reactive power, apparent power, and real power respectively.

$$Q = \sqrt{1040.003^2 - 792.482^2}KVar = 673.482KVar$$

In the S&PGP section of the factory, there are different types of loads. The loads connected to the distribution networks are three-phase linear loads, three-phase non-linear loads (like the three-phase motor connected to the ASD), and single-phase non-linear loads (like the computer and fluorescent lamp).

3.6.3 Three Phase Modeling of the Source

The steady state ac power grid consists of passive elements such as resistors, inductors, and capacitors, as well as sinusoidal current and voltage sources. At the substation's industrial feeder terminal, the supply source voltage for the secondary side of the 132 kV/11 kV step-down transformer is 11 kV. According to the load report data from the WSSF document at the 11KV feeder, the system's distribution board delivers 4607.2849 kVA of electricity to the loads. The following formulas can be used to compute the source resistance and inductance (Andrei et al., 2017).

$$R_s = \frac{V^2}{S*10} = \frac{(11000)^2}{(4607.2849*10^3)*10} = 2.6262\Omega \tag{3.4}$$

$$L_s = \frac{V^2}{S*\omega} = \frac{(11000)^2}{4607.2849*10^3*2*\pi*50} = 83.596mH \tag{3.5}$$

Thus, with a system frequency of 50Hz, the source resistance and inductance are 2.6262Ω and 83.596mH, respectively.

Data Analysis

3.7.1 Voltage Sag Analysis

A voltage sag occurs when the rms voltage as well as current at the power frequency drops to between 0.1 and 0.9 p.u for periods ranging from 0.5 cycle to 1 minute. The measurement conducted at the step down transformer PCC, at which the power is supplied to the load. On the third day of the weak, at 09:08:10, during the measurement, there was a voltage sag on phases 1, phase 2, and phase 3 and the value of the voltage decreased to 195 volts, 196.4 volts, and 194 volts, respectively, for 150 milliseconds. The measurement result at the last was shown that the voltage sag was about 15.159% during third day. The factory's activity was disrupted at this point. The duration of voltage distortion was occurred for 150ms that runs from 0.1ms to 0.25ms for the third day.

3.7.1.1 Cause of the Voltage Sag at S&PGP Distribution Network

The short circuit fault in the factory distribution system is the main cause of the voltage sag issue. This short circuit fault is identified when the distribution network's breakers trip in an attempt to isolate the fault. The section head informed me, based on the results of the recorded problem that, the short circuit occurred in the factory due to mechanical damage, poor wiring by technicians, and insulation failure of the winding, which led to a voltage sag issue.

3.7.1.2 Effect of Voltage Sag on the S&PGP Distribution Network

The voltage sag can lead to the disruption of the equipment that is used for manufacturing purposes; due to this, the equipment fails to operate at reduced voltage. The factory must also account for the time required to clean up and restart the process. Industrial materials that are susceptible to voltage sag issues include PLCs, variable-speed drives, and various control systems. The response of S&PGP to the voltage sag happens includes the following: malfunction of sensor, production shut down that lasts for hours or even days, significant financial losses, reduction in efficiency of motor, and even burn of the motor. In order to mitigate this problem, the appropriate mitigating device called UPQC is suggested. A UPQC can accomplish multiple goals at once, including removing harmonics from source currents, preserving voltage during system voltage sags and swells, and sustaining a voltage that is sinusoidal at the bus to which it is linked (Sarker & Goswami, 2016).

3.7.2 Harmonic Analaysis

Harmonic is a sinusoidal periodic wave or quantity with a frequency that is an integral multiple of the fundamental frequency—typically 50 or 60 Hz (Park et al., 2021). The nonlinear features of the loads and devices on the power system at S&PGP cause harmonic distortion. Both voltage and current harmonics are referred to as harmonics. Nonlinear electronic loads produce current harmonics, which in turn cause harmonic voltages.

Harmonic distortion can be caused by loads like electric arc furnaces, discharged lighting (such as fluorescent lamps), and adjustable speed drives (like those found in fans, blowers, pumps, and process drives).

The following section discusses several different procedures that can be used to evaluate and assess a system for harmonic distortion:

- ✓ Measure the level of harmonic distortion for particular installations to describe the system's harmonic sources. It is recommended that such measurements be conducted at the PCC for some days in order to record all cyclical load variations.
- ✓ Analyze the measured levels of distortion compared to the chosen standard limit. Various standards may need certain extra system parameters besides the measurement data. For instance, determining a system's short circuit current to maximum fundamental load current ratio I_{SC}/I_L is necessary in order to apply the current distortion limitations on the IEEE 519-2014 standard.
- ✓ Mitigation actions are required if the system measurement is outside the ranges suggested by the chosen standards. The UPQC is selected as the best mitigation strategy that suits the system under evaluation.
- ✓ After the chosen mitigation approach has been applied, reevaluate the system.

The S&PGP distribution network's harmonic distortion level is evaluated using the general procedure outlined above. The upcoming subtopics and chapters include a detailed presentation of every step taken for this particular investigation.

3.7.2.1 Calculation of Short Circuit Current to Average Load Demand Current Ratio

The IEEE 519-2014 standard is the most widely used industry standard for electric power system harmonics (Darussalam et al., 2020). The standard states that a facility's current draw has an impact on how many harmonics it can introduce into the utility's electrical distribution system. This section calculates the short circuit current to the maximum fundamental load current ratio to determine the maximum TDD limit for the transformer.

The following formula can be used to express the three-phase short circuit current:

$$I_{sc} = \frac{I_{FL}*100}{\%X_{SC}} = \frac{I_{FL}*100}{\%X_{tr}} \tag{3.6}$$

Where, I_{sc}, %Xtr, and I_{FL} are short circuit fault current, percentage reactance of the transformer, and full load current, respectively.

Percentage reactance can be expressed as follows:

$$\%X_{tr} = \frac{I_{FL}X_{tr}}{V_{ph}} * 100 \tag{3.7}$$

The full load current is given by:

$$I_{FL} = \frac{KVA}{\sqrt{3}(KV)} \tag{3.8}$$

$$I_{FL} = \frac{3150}{(0.4)\sqrt{3}} = 4546.633A$$

From the equation (3.7) and value of reactance of transformer $X_{tr} = 3.303272 m\Omega$, the expression for percentage reactance is follows:

$$\%X = \frac{KVA * Xtr}{10(KV)^2} = \frac{3150 * 0.003303272}{10(0.4)^2} = 6.5033$$

Then, the short circuit current become:

$$I_{sc} = \frac{I_{FL} * 100}{\%X_{tr}} = \frac{4546.633 * 100}{6.5033} = 69912.70585A$$

To get the average demand current, we must know the load's average active demand power. The factory's monthly energy usage, which is listed in Appendix D, is used to calculate this power. Utilities use this report for billing purposes. Take note that the average active demand power is calculated between February 2023 and January 2024.

$$P_D = \frac{Sum\ of\ maximum\ power\ demand\ \ for\ 12\ months\ from\ (February\ 2023-January\ 2024)}{12} \tag{3.9}$$

$$P_D = \frac{(7857+7782+7310+1360+1206+1386+778+681+334+2335+2878+8528)KW}{12} = 3536.25kW$$

The average demand current is obtained as:

$$I_L = \frac{P_D}{pf*\sqrt{3}*KV} \tag{3.10}$$

Where, pf and P_D are power factor and load average active power demand respectively.

The overall WSSF power factor is given by:

$$pf = cos[\ tan^{-1}(\frac{total\ KVarh}{total\ KWh})] \tag{3.11}$$

Then, the WSSF power factor is:

$$pf = cos\left[tan^{-1}\left(\frac{11834697.195}{14168994}\right)\right] = 0.767$$

After power factor was calculated we can calculate the average load demand current of the overall factory as:

$$I_L = \frac{P_D}{pf * \sqrt{3} * KV} = \frac{3536.25KW}{0.76749 * \sqrt{3} * 0.4KV} = 6650.043A$$

The average load share of the industrial distribution transformer is used to calculate the average demand current of each distribution transformer. We can compute the percentage load share of the transformer required for our study by dividing its energy consumption by the overall energy consumption of the factory. The average load demand current for the transformer at S&PGP, is $I_L = 1501.01A$, because the percentage load share of this transformer is 22.57%. As a result, the steam and power generation plant's transformer's short circuit ratio becomes;

$$\frac{I_{SC}}{I_L} = \frac{69912.70585A}{1501.01A} = 46.57$$

For the distribution network of S&PGP, which is under study, the following standard limitations have been established based on the standards of Tables 2.2 and 2.3:

- ✓ The maximum permissible current TDD level of 8% was used for the distribution board since the ratio of short circuit current to the maximum fundamental load current was 46.57, which is between $20 < I_{SC}/I_L < 50$.
- ✓ Maximum permissible voltage THD level of 8% will be used for the distribution board of S&PGP, and because the bus voltage at PCC is less than 1KV, the individual harmonic component has a maximum percentage of 5%.

3.7.2.2 Comparison of Harmonic Distortion Level with IEEE Standard

The evaluation and interpretation of the measurement outcomes are presented in this section. To make sure it is accepted, the harmonic distortion level is also checked with regard to IEEE Std 519-2014 standards as shown in Table 3.3.

The suggested voltage and current distortion limitations by IEEE Std 519-2014 are shown in Tables 2.2 and 2.3. The values are given as percentages of the maximum demand current (I_L) and the rated power frequency voltage (V_r). In the previous section the average load demand current at transformer of S&PGP is computed. To determine the total demand distortion using the measured values, the value must be transferred to CT's primary side. For example, with a CT's ratio of 2000/1A at S&PGP distribution network and I_L at CT's secondary of 1501.01A, the I_L at the primary become 0.75A. The values of each individual voltages harmonic in percentage of the nominal power frequency voltage, Vr, and each individual current harmonics in percentage of the maximum demand current, I_L, are able to be obtained using the following formulas.

$$\%I_h = \frac{I_h}{I_L} * 100 \quad 3.12$$

$$\%V_h = \frac{V_h}{V_L} * 100 \quad 3.13$$

Where, I_L is the maximum demand current value, $\%I_h$ is the individual current harmonic level expressed as a percent I_L, V_r is the rated power frequency voltage, and $\%V_h$ is the individual voltage harmonic value in percent of V_r.

Using equation 3.12, the $\%I_h$ for each harmonic order are, $\%I_3$ =5.28, $\%I_5$ =17.98, $\%I_7$ =16.77, $\%I_9$ =4.14, $\%I_{11}$ =3.08 and $\%I_{13}$ =2.64 and $\%V_h$ for each harmonic order are, $\%V_3$ =0.03, $\%V_5$ =2.51, $\%V_7$ =1.04, $\%V_9$ =0.08, and $\%V_{11}$ =0.09, $\%V_{13}$ =0.23.

Total demand distortion (TDD) for an average demand current of 0.75A can be computed using equation (2.3). TDD was calculated from data obtained on 22/02/2024, when the THD_I was at its maximum as follows:

$$TDD = \frac{\sqrt{(3.96)^2+(13.49)^2+(12.58)^2+(3.13)^2+(2.31)^2+(1.98)^2}}{0.75} = 25.75$$

Table 3.3: The Comparisons of harmonic values at distribution board with the relevant IEEE 519-2014 standard.

Harmonic order	Voltage harmonic level (%V)	IEEE 519-2014 standard	Current harmonic level (%I)	IEEE 519-2014 standard
3rd	0.03	5	5.28	7
5th	2.51	5	17.98	7
7th	1.04	5	16.77	7
9th	0.08	5	4.17	7
11th	0.09	5	3.08	3.5
13th	0.23	5	2.64	3.5
THD/TDD	2.72	8	25.75	8

The analysis of the collected data demonstrates that, the percentage of total voltage harmonic distortion (THD_V) reaches its highest value of 2.72%. THD_V obtained is within the IEEE standard voltage harmonic distortion limit of 8% and all individual voltage harmonic values are also below the IEEE standard permitted value of 5%. On the other hand, the harmonic data analysis indicates that the TDD obtained is 25.75%, which is above the standard limit of 8% set by IEEE. Additionally, the individual 5^{th} and 7th order harmonic currents are likewise beyond the IEEE standard limits as demonstrated in Table 3.3.

Generally, the analysis of harmonics shows that, it is necessary to install the mitigating device for current harmonics to meet IEEE standard value.

3.7 Design of Unified Power Quality Conditioner (UPQC)

UPQC serves to do DVR and D-STATCOM tasks. Two VSCs linked by the common DC bus to make up UPQC. When it comes to a distribution feeder, one of the VSCs is linked in series, and the other is linked in shunt (Jaya Raju & Ramesh Babu, 2013). While designing the UPQC, the following crucial parameters need to be taken into account: switching frequency, series inductance, shunt capacitor, shunt inductance and DC link voltage and capacitor. The required parameter for the design of the UPQC is shown in Table 3.4. The SHAPF and SEAPF designs are part of the the three-phase, three-wire UPQC's design (Kazmierkowski, 2015).

Table 3.4: Required parameters for designing the UPQC

No	Parameter required	It's values
1	Three phase line Voltage	400V
2	DC bus recovered time, t	3ms
3	Phase voltage	230.94V
4	Variation of energy during dynamics (k1)	10%
5	Overloading factor (α)	1.2
6	Modulation index (m)	1
7	Current Ripple ($I_{cr;pp}$)	15%
8	Switching frequency (fs)	10kHz

3.8.1 Design Shunt Active Power Filter of UPQC

A ripple filter, voltage source converter and shunt inductors are all component of the SHAPF of the UPQC. The VSC design includes the voltage of the DC bus level, DC capacitance, and IGBT rating that are used in VSCs (Kazmierkowski, 2015).

a. DC Capacitor Voltage

The lowest DC bus voltage of the SHAPF of UPQC should be more than twice the distribution system's peak phase voltage. By computation, the DC bus voltage is shown to be:

$$V_{DC} = \frac{2\sqrt{2}}{\sqrt{3}m} V_{LL} \tag{3.14}$$

Where, V_{LL} is the shunt active filter AC lines output voltage and m is the modulation index, which is regarded as 1. For a V_{LL} of 400V, V_{DC} is thus obtained to be 653.197V, and it is chosen to be 700 V.

b. DC Bus Capacitor

The amount of the DC capacitor (C_{DC}) of the shunt active power filter of UPQC is determined by the instantaneous energies available for it during transients.

$$\frac{1}{2} C_{DC}(V_{DC}^2 - V_{DC1}^2) = k_1 3V(aI)t \tag{3.15}$$

Where, a is the overloading factor, I is the phase current, V_{DC1} is the DC bus's minimum voltage level, V_{DC} is the nominal DC voltage equal to the reference DC voltage, V is the phase's voltage, and t is the time that the DC bus voltage needs to be recovered.

Considering V_{DC1}=653.197V, t=3ms, a=1.2, I = 1143.85A and V=230.94V and k_1=10% then the equation 3.15 becomes:

$$\frac{1}{2} C_{DC}(700^2 - 653.197^2) = 3 * 0.1 * 230.94V * 1.2 * 1143.85A * 3 * 10^{-3}s$$

Then, C_{DC} =9009.22μF and the selected C_{DC} is $9500\mu F$

c. AC Inductor for the Phase Leg of the VSC

A VSC's AC inductance (Lf) is derived from its DC bus voltage (V_{DC}), switching frequency (fs), and current ripple (Icr;pp). It is determined as:

$$L_f = \frac{\sqrt{3} m V_{DC}}{12 a f_s I_{cr,pp}} \tag{3.16}$$

Where, $I_{cr;pp}$ is percentage of ripple current, fs is switching frequency, a is the overloading factor, and m is the modulation index.

For this design 15% ripple current is taken. The ripple current used in the design is the percentage of the supplied current in the shunt inductor. When, fs = 10kHz, m = 1,$V_{DC} = 700V$, $I_{cr;pp}$ =15%, and a = 1.2 are taken into account, then from equation 3.16, L_f is found to be 0.0491mH.

d. The solid-state switches' voltage and current ratings:

Under dynamic situations, the voltage rating (V_{sw}) of the device can be computed as (Kazmierkowski, 2015):

$$V_{sw} = V_{DC} + V_d \tag{3.17}$$

Where, V_d describes 10% overshoot in DC link voltage in the condition of under dynamic. The switch has a voltage rating of 770 V according to calculations. The VSC's current rating is calculated as:

$$I_{sw} = 1.25(I_{cr,pp} + I_{peak}) \tag{3.18}$$

Where, $I_{cr,pp} = 15\% * I_{ph} = 15\% * 1143.85A = 171.57A$ and $I_{peak} = \sqrt{2} * 1143.85 = 1617.65A$

From the equation (3.18) the switch's current rating is determined to be 2236.52A. The current and voltage ratings of IGBT switches can be calculated using the aforementioned formulas. The switch's current rating is determined to be 2236.52A. Therefore, an IGBT solid-state switch with the rating of 770 V and 2236.52A is chosen for the VSC.

e. Ripple Filter

To remove noise from the PCC's voltage, a high-pass first-order filter adjusted at half the frequency of switching is utilized.When compared to the fundamental time period (T), the filter's time constant should be very short, R_fC_f << T/10, with Rf and Cf stand for the ripples filter's resistance and the capacitance, respectively. With the harmonic voltage at the frequency of 10 kHz and a low impedance of 10.41 Ω, the capacitor of ripple filter is built with C_f = 5.5 µF. The capacitor (C_f) is linked in series with a 10Ω series resistance (R_f). The ripple filter draws very little fundamental frequency current since the impedance at fundamental frequency is found to be 637 Ω, which is appropriately large.

3.8.2 Design Series Active Power Filter of UPQC

The design of the SEAPF of UPQC include the VSC, injection transformers, ripple filters, and interfacing inductors.

a. Design of an Injection Transformer

The VSC of a SEAPF is linked in series with the supply via an injection transformer. The value of voltage to be injected and the VSC's DC bus voltage decide the transformer's voltage rating (Kazmierkowski, 2015). To compensate for 25% change in voltage, the voltage that has to be injected is determined as:

$$V_{SEAPF} = XV_s \tag{3.19}$$

Where, V_S is the supply phase voltage and X is the percentage of voltage sag.

During voltage sag investigation at S&PGP, the single phase voltage drops to nearly 195V. On the other hand, this voltage might be lowered more than this percentage decrease. Therefore, if there is a 25% voltage variation, the voltage that SEAPF needs to inject in order to make up for this voltage difference in the system is:

$$V_{SEAPF} = 0.25 * 230.94V = 57.74\,V$$

The injection transformer's turns ratio for the SEAPF of UPQC is calculated using the equation (3.20). The SEAPF requires 57.74V in each phase in order to compensate the disturbance arise in each phase phase.

$$K_{SEAPF} = \frac{V_{VSC}}{V_{SEAPF}} \tag{3.20}$$

From the equation (3.20), the injection transformer's maximum turn ratio value is 3.99 ≈ 4.

The rating of the VA of injection transformer is:

$$S_{SEAPF} = 3 * V_{SEAPF} * I_{SEAPF(under\ sag)} \tag{3.21}$$

Where, S_{SEAPF}, $I_{SEAPF\ (under\ sag)}$, and V_{SEAPF} are VA rating of injection transformer, current rating and injected voltage respectively.

$$S_{SEAPF} = 3V_{SEAPF} * \frac{P}{3(V_s - XV_s)} = 3 * 57.74 \frac{792.482kW}{3(230.94V - .25 * 230.94V)}$$
$$= 264.184KVA$$

b. Interfacing Inductors of the SEAPF

The real power of the load determines the current flowing through the injection transformer's secondary side. During an electrical voltage swell, current supplied is at its lowest. The supply current's lowest value is:

$$I_{SEAPF(under\ swell)} = \frac{P}{3(1+X)V_S} \tag{3.22}$$

From equation (3.22) the supply current with lowest value is:

$$I_{SEAPF(under\ swell)} = \frac{792.482kw}{3(1+0.25)230.94} = 915.08\text{A}$$

With a 15% supply current ripple taken into account, the SEAPF's filter inductance value is as follows:

$$L_{SEAPF} = \frac{m\frac{\sqrt{3}}{2}V_{DC}K_{SEAPF}}{6af_S\Delta I_{SEAPF}} \tag{3.23}$$

From the equation 3.23), the interfacing inductor of SEAPF of the UPQC is calculated as:

$$L_{SEAPF} = \frac{1 * \frac{\sqrt{3}}{2} * 700 * 4}{6 * 1.2 * 10 * 10^3 * 0.15 * 915.08} = 0.2454mH$$

c. Design of Voltage Rating of Series VSC

SEAPF devices have the same voltage rating as SHAPF devices, because they share a common DC link.

d. Current Ratings of a Three-Leg VSC of the SEAPF

The maximum current in the SEAPF of UPQC device is

$$I_f = \frac{P}{\sqrt{3} * V_{LL}} \tag{3.24}$$

$$I_f = \frac{792.482kw}{\sqrt{3} * 400V} = 1144A$$

e. Design of VA Rating of UPQC

Total KVA rating of the UPQC depend the KVA rating of series APF and shunt APF of the UPQC. It is given as (Jauhari et al., 2020);

$$S_{UPQC} = S_{SEAPF} + S_{SHAPF} \tag{3.25}$$

In order to solve equation (3.25), first the KVA rating of shunt APF of the UPQC is obtained as follow;

$$S_{SHAPF} = V_{SHAPF} * I_{SHAPF} \quad 3.26$$

Where V_{SHAPF} = 400V,which is the same as AC load, as it is connected to the load and the current rating is calculated by equation (3.27)

$$I_{SHAPF} = \sqrt{{I_{SHAPFA}}^2 + {I_{SHAPFR}}^2} \quad 3.27$$

I_{SHAPFR} is the reactive current at the load and it is given as;

$$I_{SHAPFR} = I_L\sqrt{1 - pf^2}=1501A\sqrt{1 - 0.762^2} = 972.02A$$

I_{SHAPFA} is active power component of shunt APF of UPQC current and it is calculated as;

$$I_{SHAPFA} = (V_s X)I_S/V_S = 230 * 0.25 * 1501.01A/230 = 375.25A$$

Depending on the I_{SHAPFR} and $I_{SHAPFA,}$ current rating of the shunt APF of the UPQC at equation (3.27) obtained as;

$$I_{SHAPF} = \sqrt{375.25^2 + 972.02^2} = 1347.2A$$

From the obtained result at equation (3.27), the eqution (3.26) is found as;

$$S_{SHAPF} = 400V * 1347.2A = 538.9KVA$$

Using KVA rating of series APF at equation (3.21) and KVA rating of shunt APF at equation (3.26), the KVA rating of the UPQC becomes;

$$S_{UPQC} = 264.184KVA + 538.9KVA = 803.06KVA$$

3.8 Control of UPQC

This section accomplishes the MATLAB/Simulink modeling for the control of the UPQC in order to mitigate the disturbance that occur in the distribution network of S&PGP. UPQC use the SRF theory as proposed control algorithm to compensates voltage sag and mitigates harmonics.

3.9.1 Synchronous Reference Frame (SRF) Theory

Any balanced three-phase system's voltage as well as current signals, contain only positive sequence components; in contrast, non-linear and unbalanced systems have positive, negative as well as, zero sequence components (Jeraldine Viji & Aruldoss Albert Victoire, 2014). The coordinates for positive, zero, and negative components are determined from SRF theory based control and are shown as the direct axis (d-axis), zero axis (0-axis),and quadrature axis (q-axis), respectively. For this study the control of series as well as shunt of UPQC, the transformation of three-phase to two phase,that means (a-b-c) to (d-q-0) and the inveverse transformations are carried out.

3.9.1.1 Control of the SHAPF of the UPQC

The SHAPF of the UPQC is controlled using the SRF theory-based control algorithm. The goals of SHAPF of UPQC are to enhance the supply current's power quality and to support both the SEAPF and the SHAPF shared DC bus by absorbing active power. Figure 3.6 shows a modelling of the control algorithm of SHAPF of the UPQC control scheme. This method separates the essential positive as well as, negative sequence components of instantaneous currents, by transforming the load currents from the reference frame that is stationary to the dq synchronous reference frame (Mortezaei et al., 2014). First, the load currents from the abc frame are transformed to the dq0 frame as follow:

$$\begin{pmatrix} id \\ iq \\ io \end{pmatrix} = 2/3 \begin{pmatrix} cos(\theta) & cos(\theta - \frac{2\pi}{3}) & cos(\theta + \frac{2\pi}{3}) \\ -sin\,\theta & -sin(\theta - \frac{2\pi}{3}) & -sin(\theta + \frac{2\pi}{3}) \\ 1/2 & 1/2 & 1/2 \end{pmatrix} \begin{pmatrix} ia \\ ib \\ ic \end{pmatrix} \tag{3.28}$$

Where, the three-phase PLL working on PCC voltages are used to obtain cos θ and sin θ.

A PLL signal is obtained from PCC voltages so as to generate basic unit vectors for the transformation of observed currents to the dq0 reference frame. The d- and q-axis currents are consist of the DC (fundamental) as well as ripple. Utilizing an SRF controller, an LPF extracts DC quantities to separate the non-DC features from the reference signal (Sai Kumar et al., 2023).

$$i_{Ld} = i_{dDC} + i_{dAC} \tag{3.28}$$

$$i_{Lq} = i_{qDC} + i_{qAC} \tag{3.29}$$

The resulting dq0 currents are again transformed using the inveverse park's transformation into the reference supply currents.

$$\begin{pmatrix} i_{sa}^* \\ i_{sb}^* \\ i_{sc}^* \end{pmatrix} = \begin{pmatrix} cos(\theta) & -sin\,\theta & 1 \\ cos(\theta - \frac{2\pi}{3}) & -sin(\theta - \frac{n\pi x}{L}) & 1 \\ cos(\theta + \frac{2\pi}{3}) & -sin(\theta + \frac{n\pi x}{L}) & 1 \end{pmatrix} \begin{pmatrix} i_d^* \\ i_q^* \\ i_0^* \end{pmatrix} \tag{3.30}$$

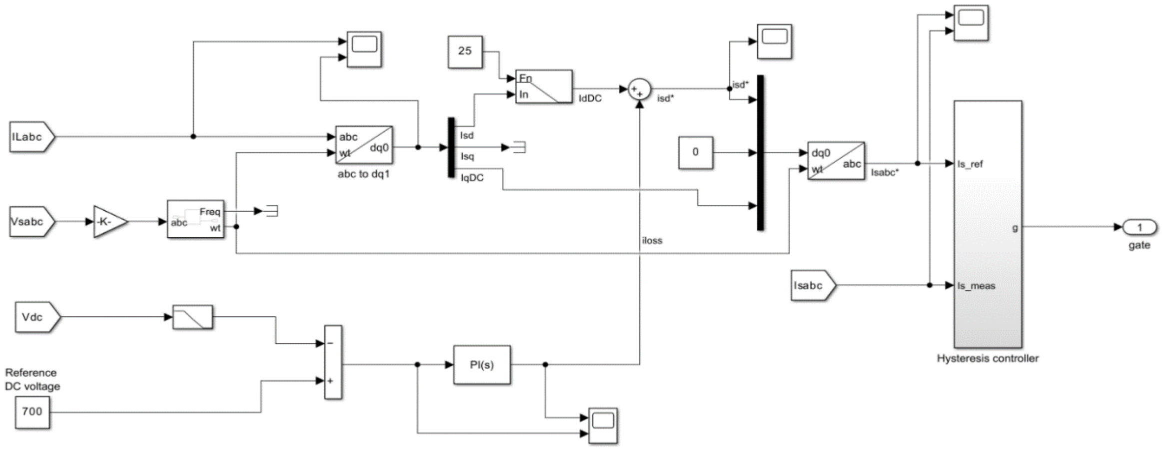


Figure 3.6: Control algorithm modelling for SHAPF portion of UPQC

The reference voltage V_{DC*} and the measured voltage V_{DC} are used by the PI controller in the aforementioned model to regulate the voltage of DC bus. This DC voltage across the capacitor is controlled by the Discrete PI controller, which has an integral gain of Ki=2.4 and a proportional gain of Kp=1.2. The gains are chosen using the manual tuning method. The SRF theory modelling, which is used for operation of SHAPF of UPQC, is shown in Figure 3.6.

3.9.1.2 Control of the SEAPF of the UPQC

The control modalling of the SEAPF of the UPQC, which uses the SRF theory to generate signals, is explained in Figure 3.7. To find the IGBT gate signals, the supply currents , PCC voltages, and load terminals voltages are detected. Using Park's transformation or the abc-dq0 conversion, the unit vectors (sin θ, cos θ) are extracted from the supply currents via a PLL and utilized to convert the PCC voltages to the rotatable reference frame (Kazmierkowski, 2015).

The control of the SEAPF of the UPQC using SRF theory aims to achieve sinusoidal voltage at the load terminal (v_{La}, v_{Lb}, v_{Lc}) with the required amplitude by mitigating the voltage sag that occur in the source side. This is accomplished by injecting voltages into the series filter that are the opposite of the disturbance found in the supply voltage. These voltages cancel each other out and resulting in a load side voltage that is disturbance free or sinusoidal voltage at the load side.

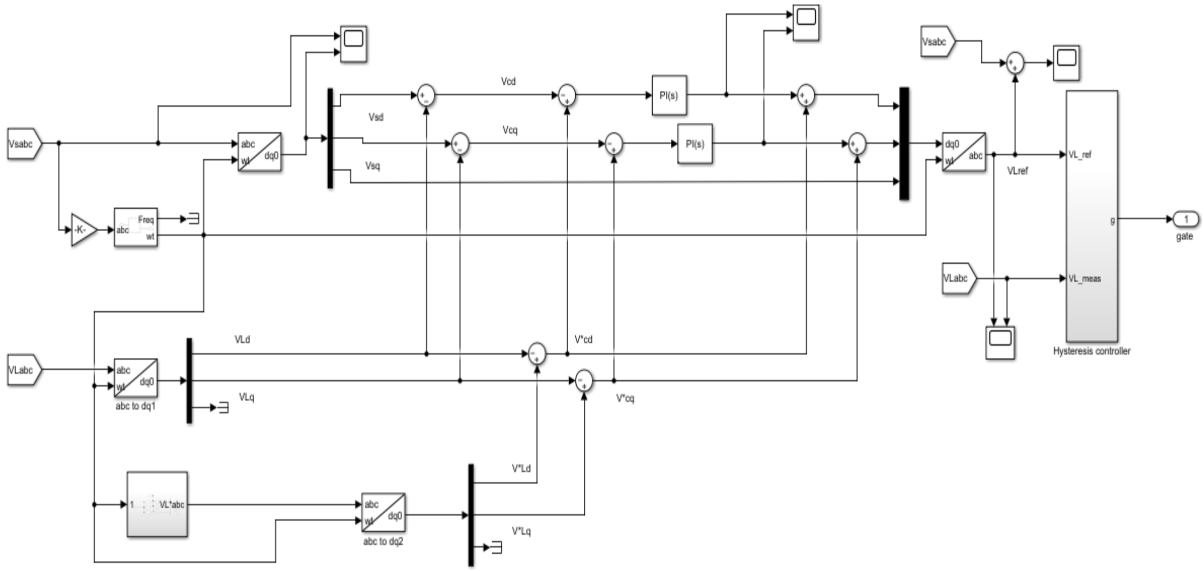


Figure 3.7: Control algorithm modelling for SEAPF portion of UPQC using SRF theory

Conversion of PCC voltages to a rotating reference frame by means of Park's transformation is shown in equation (3.31) below.

$$\begin{pmatrix} v_{sd} \\ v_{sq} \\ v_{s0} \end{pmatrix} = 2/3 \begin{pmatrix} cos(\theta) & cos(\theta - \frac{2\pi}{3}) & cos(\theta + \frac{2\pi}{3}) \\ -sin\,\theta & -sin(\theta - \frac{n\pi x}{L}) & -sin(\theta + \frac{n\pi x}{L}) \\ 1/2 & 1/2 & 1/2 \end{pmatrix} \begin{pmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{pmatrix} \quad (3.31)$$

Then, the voltages on the d-axis as well as q-axes are made up of both harmonic and fundamental DC components, or ripples as follows:

$$v_{sd} = v_{dDC} + v_{dAC} \quad (3.32)$$

$$v_{sq} = v_{qDC} + v_{qAC} \quad (3.33)$$

A PI controller is used to adjust the amplitude of the AC load terminal voltage (V_L) to its reference voltage, V_L^*. The voltage (v_{qr}) that the SEAPF is going to inject is obtained by the output of the PI controller (Kota & Vinnakoti, 2018).The load terminal voltages (v_{La}, v_{Lb}, and v_{Lc}) are used to compute the amplitude of the AC load terminal voltage (V_L) in the following way:

$$V_L = (2/3)^{1/2}(v_{La}^2 + v_{Lb}^2 + v_{Lc}^2)^{1/2} \quad (3.34)$$

The reference quadrature-axis load voltage is

$$v_{Lq}^* = v_{qDC} + v_{qr} \quad (3.35)$$

The reference direct-axis load voltage is

$$v_{Ld}^{*} = v_{dDC} \tag{3.36}$$

By reversing park's transformation and using v_{Ld}^{*} as in equation 3.36, v_{Lq}^{*} as in equation (3.35), and v_{L0}^{*} as zero, in the abc frame, the reference voltage at the load can be found as equaition (3.37):

$$\begin{pmatrix} v_{La}^{*} \\ v_{Lb}^{*} \\ v_{Lc}^{*} \end{pmatrix} = \begin{pmatrix} cos(\theta) & -sin\,\theta & 1 \\ cos(\theta - \frac{2\pi}{3}) & -sin(\theta - \frac{n\pi x}{L}) & 1 \\ cos(\theta + \frac{2\pi}{3}) & -sin(\theta + \frac{n\pi x}{L}) & 1 \end{pmatrix} \begin{pmatrix} v_{Ld}^{*} \\ v_{Lq}^{*} \\ v_{L0}^{*} \end{pmatrix} \tag{3.37}$$

3.9.2 Hysteresis Control

In contrast to other PWM methods, the hysteresis controller is simple to use, operates quickly, and is easy to construct (Pathan et al., 2014). This section focus on Simulink modelling for SHAPF and SEAPF of UPQC.

3.9.2.1 Hysteresis control for SHAPF of UPQC

Using the reference source currents and the measured source currents the hysteresis loop controller produces gating pulses to the VSC of the SHAPF of UPQC as shown in Figure 3.8.

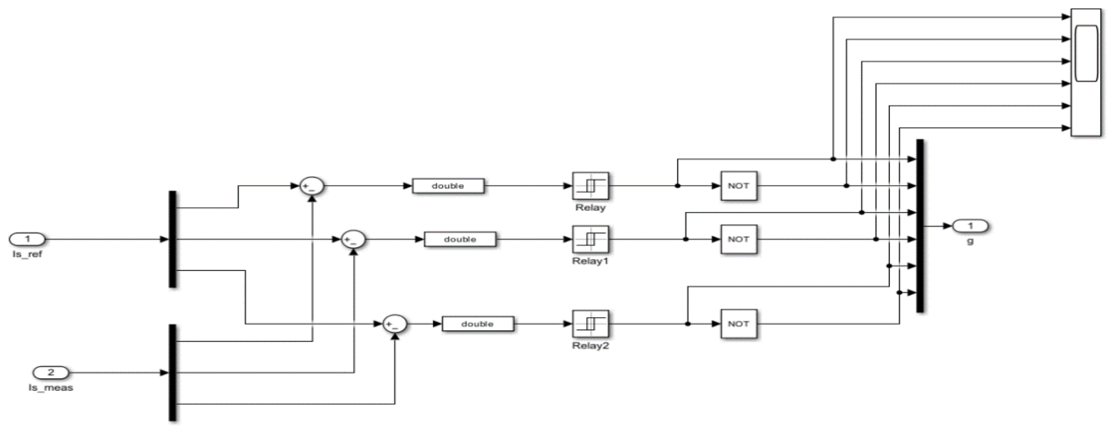


Figure 3.8: Hysterisis control for SHAPF of UPQC

3.9.2.2 Hyteresis control for SEAPF of UPQC

This hysteresis controller receives the error from the comparison of the load reference voltage produced by a SRF and the load voltage signals, and uses it to provide the necessary gating signal for the SEAPF of UPQC as shown in Figure 3.9. The inverters' switching pattern is determined by the hysteresis band controller (Sai Kumar et al., 2023). Hysteresis controllers operation is driven by the error signal generated by comparing the instantaneous loads voltage signals and the load reference voltage.

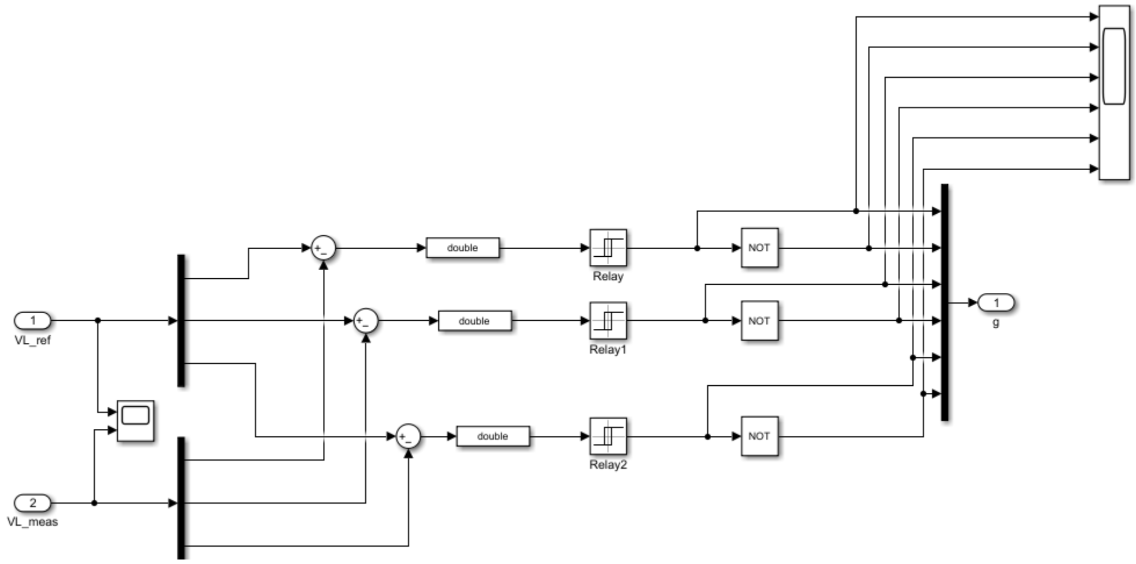


Figure 3.9: Hyteresis control for SEAPF of UPQC

3.10 Model of S&PGP Distribution Network with Insertion of UPQC

Figure 3.10 illustrates the overall schematic, which includes all of the system's characteristics as well as UPQC components (such as controllers, VSC, series transformers,filters, shunt inductor, series inductor and other supportive features). The below list are some of the component of the overall model of the distribution network with insertion of UPQC. The Table 3.5 shows the list of parameter of UPQC and parameter of S&PGP distribution network that is obtained for the purpose of the design of overall model of the distribution network.

I. Load Modeling

The total distribution system electrical loads connected to the distribution board of S&PGP are classified as follows:

Three phase non-linear load: For this study the simulation modelling of the distribution network use rectifier with RL at non-linear load for the purpose of simulation. This load have the inductive load of 216.625KVar and resistive load of 216.56kW.

Single phase non-linear load: The distribution network of the this study is connected with single phase lad which is represented by RL load fr simulation purpose. The inductive and resistive load of this distribution network.15.703KVar and 44.93kW are respectively

Three phase linear load: This load is expressed by three phase parallel RL load, with 538.93kW resistive load and 441.155KVar inductive load.

II. UPQC Modeling

It is connected between the load and the source bus at PCC for power quality problem mitigation as shown in Figure 3.10. At this point the injection of the voltage to mitigate voltage sag and injection of current to mitigate the current harmonics take place between UPQC and the distribution network of the system.

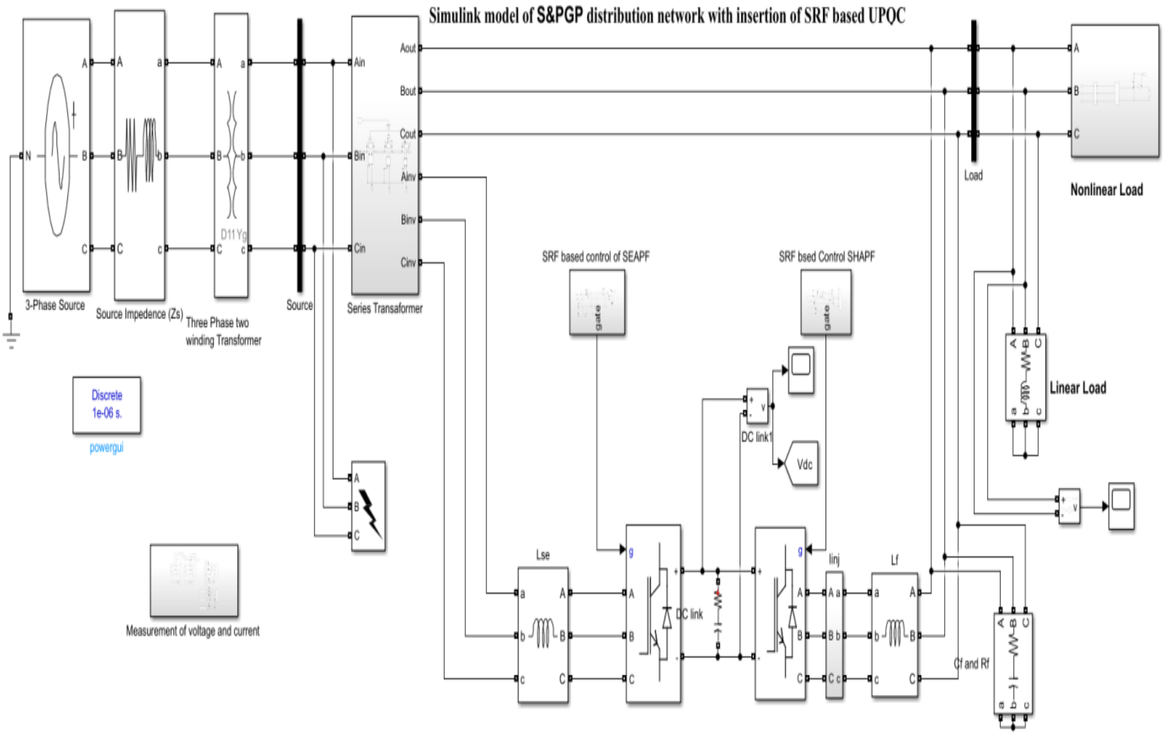


Figure 3.10: Simulink model of S&PGP distribution network with insertion of UPQC

Table 3.5: List of system parameter

<table>
<tr><th>S. No.</th><th>Name of the model</th><th>Detail description of parameter</th></tr>
<tr><td>1</td><td>Source</td><td>11kV/0.4 kV, Rs=2.6262Ω, Ls=0.0835H, fs=50Hz</td></tr>
<tr><td>2</td><td>PLL</td><td>Kp=180, Ki=3200, and sampling time=50μs</td></tr>
<tr><td>3</td><td>Shunt inductor</td><td>L_f=0.049mH</td></tr>
<tr><td>4</td><td>Series inductor</td><td>Ls=0.245mH</td></tr>
<tr><td>5</td><td>Ripple filter</td><td>C_f=5.5 μF and R_f=10Ω</td></tr>
<tr><td>6</td><td>DC Link</td><td>C=9500μF</td></tr>
<tr><td>7</td><td>Transformer</td><td>S=3150KVA, 11/0.4kV, 50Hz</td></tr>
<tr><td>8</td><td>VSI converter</td><td>IGBT based, 3 arm, 6 pulse, 10kHZ</td></tr>
<tr><td>9</td><td>PI Controller</td><td>Kp=1.2, Ki=2.4</td></tr>
<tr><td>10</td><td>Series transformer</td><td>N1:N2 =4, KVA=264.184KVA</td></tr>
<tr><td rowspan="3">11</td><td rowspan="3">Load</td><td>Linear three phase, 400V, 50Hz, P=538.93kW,
Q= 441.155KVar, R=0.303Ω ,L= 8.166μH</td></tr>
<tr><td>Non-linear three phase, 400V, 50Hz, P= 216.56kW,
Q= 216.625KVar, R=1.346 Ω , L=50mH</td></tr>
<tr><td>Non-linear single phase, 230V,50Hz, P=44.93kW,
Q=15.7025KVar, R=6.49 Ω, L=75mH</td></tr>
</table>

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Simulation Result without UPQC

Power quality problems like voltage sag and current harmonics exist in the distribution boards of S&PGP. The current harmonics exist due to the non-linear device used in the plant, and the voltage sag happens due to a fault in the distribution network. For this study, the load is represented by a rectifier load parallel with a linear load for the simulation purpose.

4.1.1 Simulation Result of Voltage Waveform without UPQC

Voltage sag is one of the power quality issues that occurred in the distribution network due to the fault occurring in the plant. Figure 4.1 and 4.2 show simulation results of voltage waveform and harmonic spectrum of voltage without UPQC connected to the distribution network.

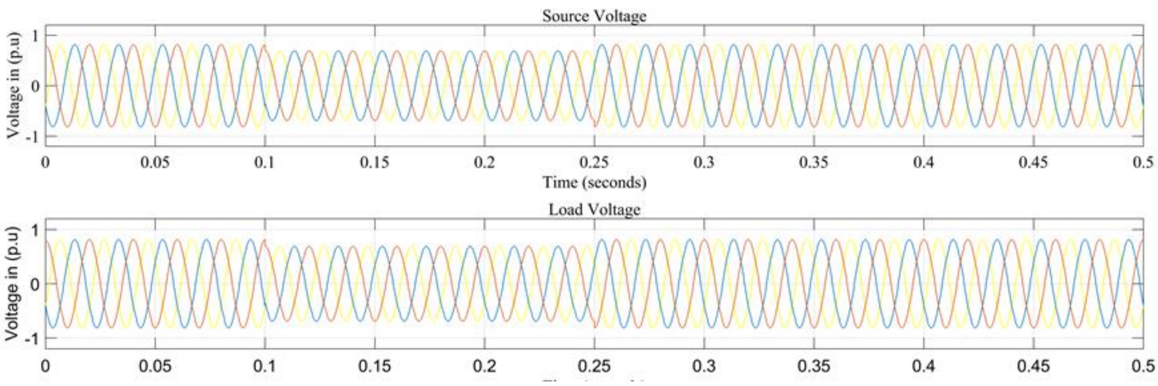
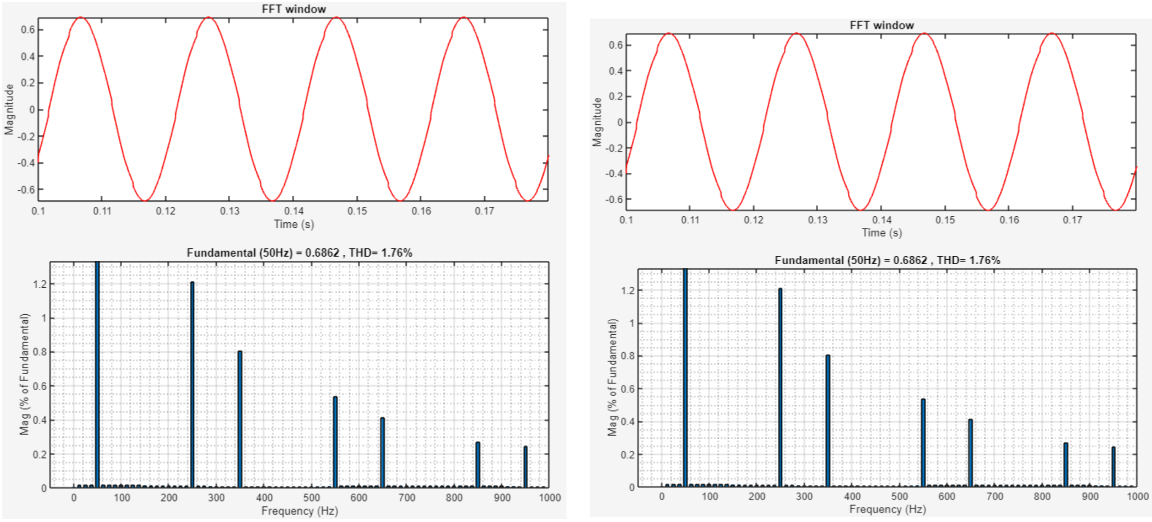


Figure 4.1: Simulation result of source voltage and load voltage without UPQC connected to the distribution network

The Figure 4.1 shows that there is voltage sag at load voltage and source voltage. The voltage sag occurs from 0.1s to 0.25s for a duration of 150ms. To mitigate this disturbance, the UPQC should be connected to the distribution network.



a. b.

Figure 4.2: The harmonic spectrum of voltage without UPQC connected to the distribution network a. Source voltage b. Load voltage

Figure 4.2 shows that the distribution board of S&PGP is free of voltage harmonics since the percentage of THDv is below the IEEE standard limit as it is observed from the harmonic spectrum.

4.1.2 Simulation Result of Current Waveform without UPQC

According to this study the current harmonics occur in the distribution board of S&PGP due to the different non-linear device used in the factory. Figure 4.3 and 4.4 shows simulation result for current waveform and harmonic spectrum of the current.

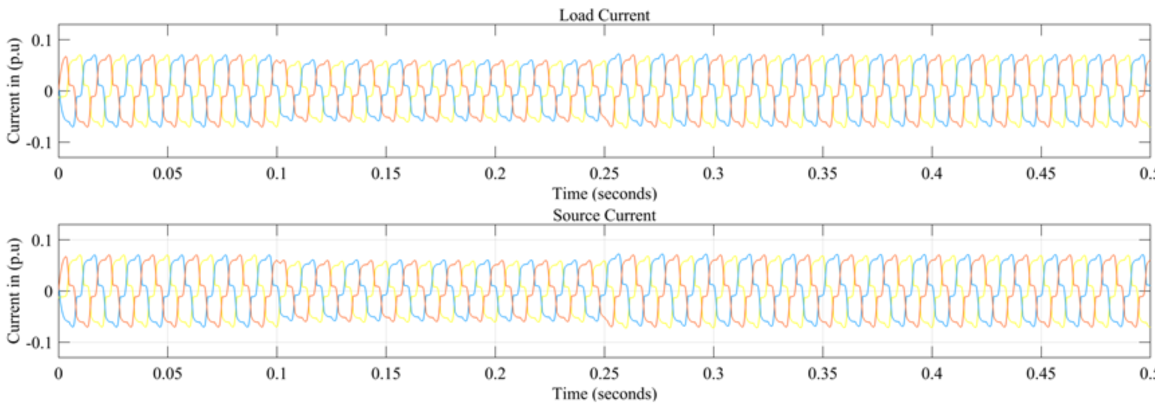
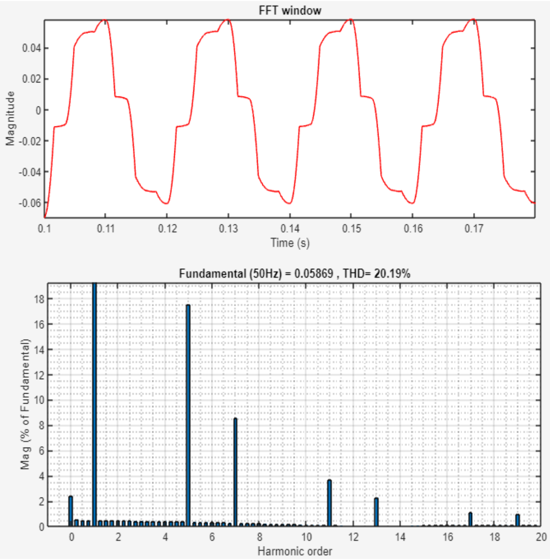
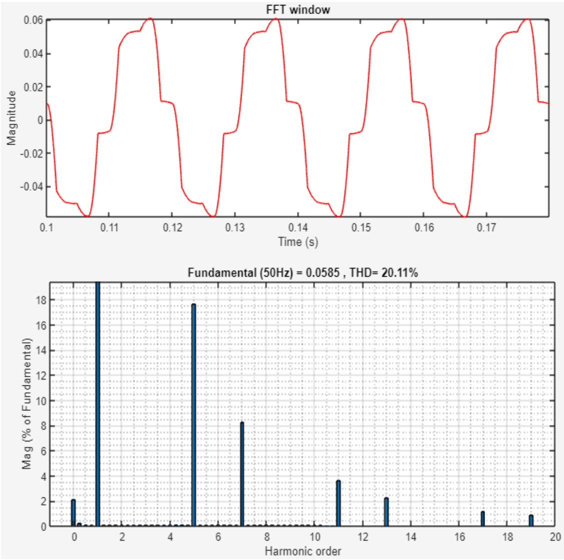


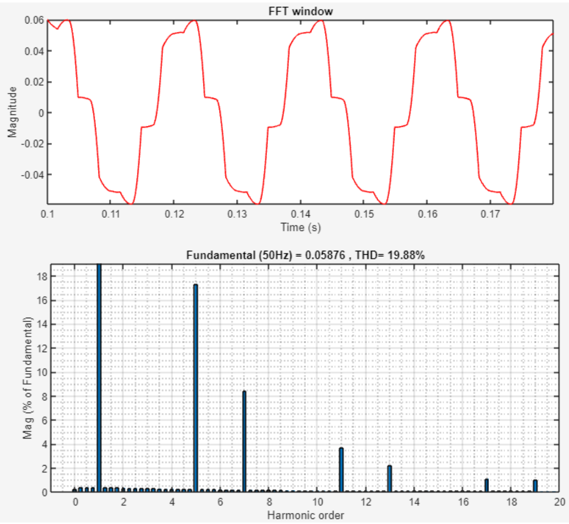
Figure 4.3: Simulation result of source current and load current without UPQC connected to the distribution network



a.



b.



c.

Figure 4.4: Harmonic spectrum of load and source current without UPQC connected to the distribution network a. Phase 1 b. Phase 2 c. Phase 3

The Figure 4.4 shows that, there is current harmonics across each phase of the distribution board of S&PGP, since the $\%THD_I$ from harmonic spectrum is above IEEE standard limit. So the UPQC should be allowed to mitigate the current harmonic distortion.

4.2 Simulation Result with SRF theory based UPQC

From simulation result of section 4.1, there is voltage sag and current harmonics. In order to avoid these problems, the SRF theory based UPQC is proposed as a mitigating technique.

4.2.1 Voltage Waveform Simulation Results with SRF theory based UPQC

The three phase voltage sag mitigation is presented in this section. Figure 4.5 show three different waveform. The first waveform show the source voltage(V_S) before UPQC connected, the second waveform show the injected voltage (V_{inj}) and the third waveform show the load voltage (V_L) after UPQC connectd to the distribution network.

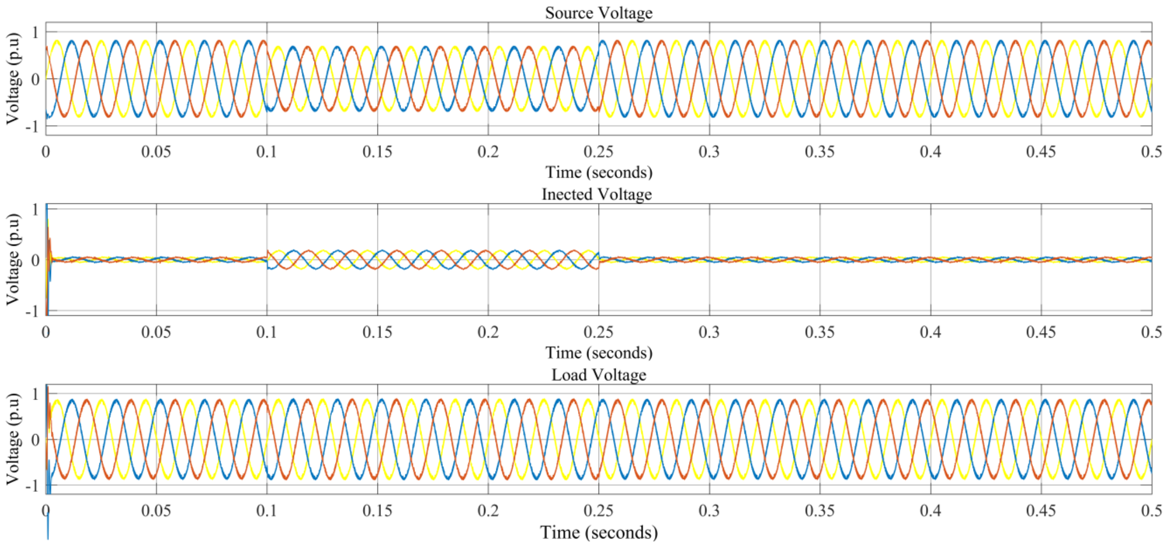


Figure 4.5: Simulation result of source voltage, the injected voltage and load voltage with SRF theory based UPQC

4.2.2 Current Waveform Simulation Resb ults with SRF theory based UPQC

The three phase current harmonic mitigation is presented in this section. Three different waveform shown in Figure 4.6 . The load current (I_L) was displayed in the first waveform before the UPQC connected, the injected current (Iinj) was displayed in the second waveform, and the source current (I_S) was displayed in the third waveform following UPQ C's connection to the distribution network.

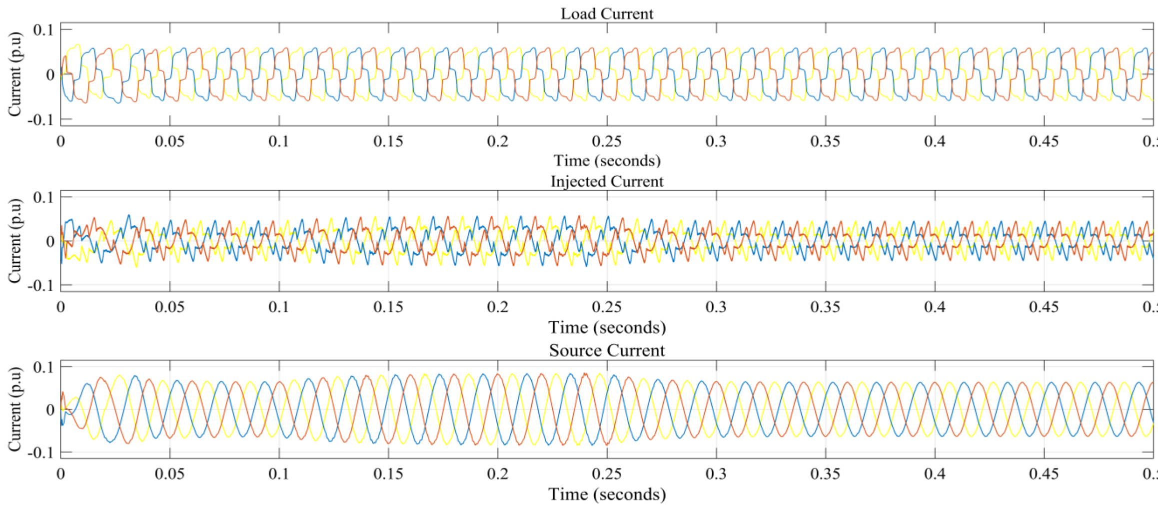
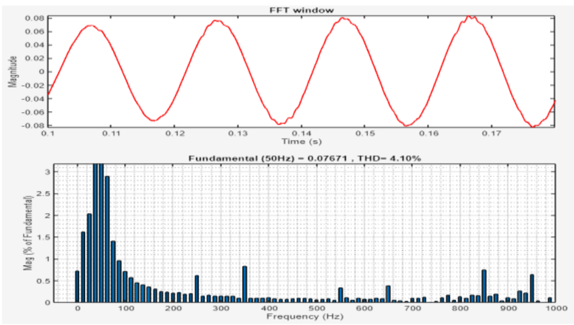
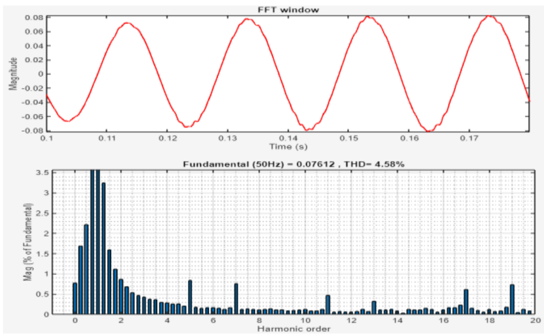


Figure 4.6: Simulation result of load current, injected current and source current with SRF theory based UPQC

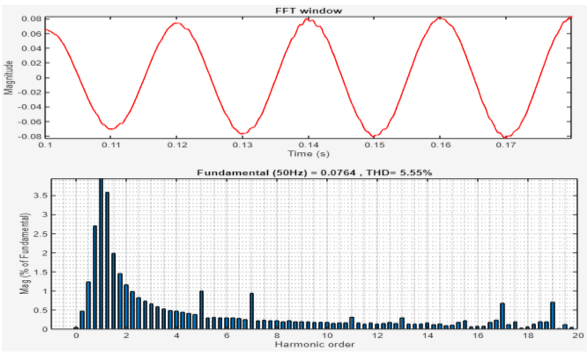
The Figure 4.7 shows that, there is no current harmonics across each phase of the distribution board of S&PGP, since the %THD_I from harmonic spectrum is below IEEE standard limit.



a.



b.



c.

Figure 4.7: Harmonic spectrum of source current with UPQC a. Source current of phase1 b. Source current of phase 2 c. Source current of phase 3

The simulation results demonstrate how the UPQC corrects for current harmonics caused by nonlinear devices. Following UPQC's installation in the network, the source current become a pure sinusoidal waveform. The harmonic spectrum of Figure 4.7 reveals that the source current THD_I dropped to 4.10%, 4.58% and 5.55% for each phase, which is below the IEEE standard limit.

4.3 Discussions

The simulation result of the current waveform shows that each phase of the three phases of load current and source current were disturbed with harmonics before UPQC was inserted into the distribution network. But, after the insertion of the UPQC into the distribution network, the source current waveform becomes pure sinusoidal. Before insertion of UPQC into the network, the %THD of the source and load current of phase 1, phase 2, and phase 3 are 20.19%, 20.11%, and 19.88%, respectively. After compensation with SRF-based UPQC, the %THD of the source current of phase 1, phase 2, and phase 3 becomes 4.10%, 4.58%, and 5.55%, respectively. Tables 4.1 compares %THD of current before and after compensation with a SRF theory based UPQC. The distribution board of S&PGP of the WSSF is free of voltage harmonics since, as shown in Figure 4.2, the $\%THD_V$ is below the IEEE standard limit.

Table 4.1: Comparison of %THD before and after compensation with SRF theory based UPQC

Parameter evaluated	Each phase with symbol	$\%THD_I$	
		Before compensation	After compensation
Supply current	I_{S1}	20.19%	4.10%
	I_{S2}	20.11%	4.58%
	I_{S3}	19.88%	5.55%

Based on the data collected at distribution network and the simulation result obtained on Figure 4.1 the voltage sag exist at the distribution board of the plant. The cause for this voltage sag is a fault that occur in the distribution network. Before compensation of load voltage with UPQC there is voltage sag and after insertin of UPQC to the distribution network the load voltage become perfectly balanced. The Table 4.2 shows the voltage magnitude before and after connection of UPQC into the network.

Table 4.2: The comparison load voltage before and after compensation with SRF theory based UPQC during occurrence of voltage sag

Parameter	Voltage magnitude before UPQC inserted	Voltage magnitude after UPQC inserted
Load voltage	0.8p.u	1p.u

4.4 Cost Analysis

Here, voltage sag and harmonics issues in the factory's are the main factors used to analyze the economic evaluation. Using basic financial metrics like the payback period, the cost analysis estimates the cost-effectiveness of the suggested unified power quality conditioner. The payback period is also determined by the cost of the bought device and the savings that are lost as a result of the factory harmonics and voltage sag issues. The payback period is the time needed to repay an investment's initial cost. Utilizing UPQC with a short payback period is essential (Yavari et al., 2018).

When deciding whether or not to take on a project, one of the key factors is the payback period of the particular investment (Akhtar & Mathew, 2016). It is calculated as follows:

$$Pay\ back\ period = \frac{Net\ investment}{Net\ annual\ return} \tag{4.1}$$

Due to voltage sag and harmonics at the distribution board of the plant, different equipment is damaged. Within the factory, the damaged materials were replaced with new ones that were bought. The Table 4.3 and Table 4.4 shows the list of material that was purchased to replace the damaged one and the cost for maintanace of the equipment that was affected by the disturbance, respectively.

Table 4.3: The cost of purchased equipment at study area

S/N	Type of device	Unit	Rating	cost in US$	Cost in ETB
1	Overload relay	2	80A	$59.379	6544.86
2	PS fan motor	1	45kW,145A	$4301.640	474126.948
3	SA fan motor	1	160kW,350A	$11441.045	1261032brr
4	Bagasse elevator	1	55kW,145A	$4325.00	476701.679
5	Contactor	1	145A	$103.85	11446.347
Total cost				$20230.914	2229851.834

Table 4.4: The cost for maintanace of equipment at study area

S/N	Type of device	Unit	Rating	Cost in ETB
1	Bagasse conveyor motor	1	55kW	69,000.00
2	Soot blower motor	1	1kW	8,000.00
3	Other motor	4	5kW	50,000.00
Total in ETB				127,000.00

The total cost for maintenance and purchase of equipment as a result of voltage sag and current harmonics problem is (127,000.00 + 2229851.834) = 2356851.834 ETB. This means the factory lost 2356851.834 ETB due to the mentioned issues.

The initial investment cost of UPQC as per AEP and EPRI is $60/KVA (Bitew, 2020). For this study, the 803KVA UPQC costs about $48180.00. By assuming 5% of the initial cost of UPQC for maintenance and other related costs, the net installation cost for investment becomes $48180.00 + 5% * $48180.00 = $50589.00. The investment cost in ETB is 5575919.580 .

Pay back period for this study is calculated as follows:

$$Pay\ back\ period = \frac{5575919.58}{2356851.834} = 2.365 year$$

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study identifies power quality problems, and it suggests the UPQC as an appropriate mitigating tool for the disturbances that occur in the distribution network. The data used in this study were obtained through direct measurement and an examination of the factory's documents. According to data collected and simulation of distribution network analysis, there are current harmonics and voltage sag in S&PGP of WSSF distribution networks. The current harmonics occur due to numerous nonlinear devices in the distribution network, including computers, fluorescent lamps, and ASDs. The voltage sag problem occurred due to a three-phase short circuit fault in the distribution network. According to this study evaluation, the distribution boards of S&PGP are free of voltage harmonics because the voltage harmonic distortion is within the IEEE standard limit.

In this research, the study of a UPQC for mitigation of power quality problems like voltage sag and harmonics was conducted. UPQC uses shunt APF to remove current harmonics and series APF to remove voltage sag issues that occur in the distribution network. By using SRF theory, the series APF and shunt APF models of the UPQC using MATLAB/Simulink software have been developed. The study uses the SRF algorithm for reference signal generation and uses a hysteresis controller to produce gating pulses to the VSC of UPQC.

After the simulation is complete, the load voltage is perfectly balanced, the source voltage sag is mitigated properly, the current harmonics for each phase are mitigated, and the source current is entirely sinusoidal. The source current $\%THD_I$ for each phase is reduced to 4.10%, 4.58%, and 5.55%, which is below the IEEE standard of 8%.

Finally, an economic study was done to determine whether the suggested remedy would be financially feasible. According to the economic research, installing UPQC would cost 5,575,919.580 ETB. According to the payback period of the study, it will take about 2.365 years to recoup the investment. This suggests that implementing UPQC equipment will reduce the issue and improve the power quality's performance while also being financially feasible.

5.2 Recommendations

The factories have to research 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 focus heavily on raising society's awareness of power quality issues and identifying their contributions to improvements of power quality. Currently, end users are relatively unaware of these issues and how they affect electric equipment. The device used for harmonic measurement in this study is fixed and does not store data needed. So, it is better for the factory to use power quality meter like FLUKE 435**.**

Finally, based on the result obtained in this result, the WSSF is recommended to use the UPQC for the purpose of reducing the voltage sag and current harmnics and to be economical.

5.3 Future Works

This work primarily addresses issues related to voltage and harmonics, therefore it should adequately address how well the UPQC control strategy performs when dealing with other power quality issues including transient, imbalance, and flicker. To increase the system's effectiveness, UPQC can also be utilized with more sophisticated controllers such artificial neutral networks , and other intelligent methods theories.

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APPENDICES

Appendix A: Loads Types and Size Data

Table A.1: The active power load and energy consumption of loads data at transformer of S&PGP

S/N	Load types	pf	P(kW)	Hrs. of operation /day	Energy consumption in kWh/day
i	Auxiliary for boiler 1				
	Pulsating hydraulic pump		18.5	12	222
	Rotory soot blower 1		1.52	16	24.32
	Rotory soot blower 2		1.52	16	24.32
	Retractable soot blower 1		4.09	16	65.44
	Retractable soot blower 2		4.09	16	65.44
	Retractable soot blower 3		4.09	16	65.44
	Retractable soot blower 4		4.09	16	65.44
	Bagasse feeder 1		9.21	12	110.52
	Bagasse feeder 1		9.21	12	110.52
	Bagasse feeder 1		9.21	12	110.52
	Bagasse feeder 1		9.21	12	110.52
	Bagasse feeder 1		9.21	12	110.52
	Bagasse feeder 1		9.21	12	110.52
	Screw bagasse conveyer 1		18.5	8	148
	Screw bagasse conveyer 1		18.5	8	148
	Screw bagasse conveyer 1		18.5	8	148
	Screw bagasse conveyer 1		18.5	8	148
	Screw bagasse conveyer 1		18.5	8	148

	Screw bagasse conveyer 1		18.5	8	148
	SA-Fan1		3.7	16	59.2
	SA-Fan2		3.7	16	59.2
	PS Fan		3.7	16	59.2
	Oil burner fan		1.3	12	15.6
	Subtotal	0.707	216.56		2273.12
ii	Cooling tower				
	Subtotal	0.759	41.87	12	502.44
iii	Water treatment MCC/C/Selendra				
	Water spray pump 1		7	16	112
	Water spray pump 2		7	16	112
	HP Dosing pump 1		17.36	8	138.88
	HP Dosing pump 2		17.36	8	138.88
	HP Dosing pump 3		17.36	8	138.88
	Circulation pump1		15	12	180
	Circulation pump2		15	12	180
	Subtotal	0.77	96.08		1000.64
iv	Boiler 1 Electro-Stat Participate1				
	Furnas economizer, air heater and ESP ash handling Conveyor 1		11.3	12	135.6
	Furnas economizer, air heater and ESP ash handling Conveyor 2		11.3	12	135.6
	Furnas economizer, air heater and ESP ash handling Conveyor 3		11.3	12	135.6
	Furnas economizer, air heater and ESP ash handling Conveyor 4		11.3	12	135.6

	Furnas economizer, air heater & ESP RAV & economizer RAV 1		14.35	8	114.8
	Furnas economizer, air heater & ESP RAV & economizer RAV 2		14.35	8	114.8
	Furnas economizer, air heater & ESP RAV & economizer RAV 3		14.35	8	114.8
	Furnas economizer, air heater & ESP RAV & economizer RAV 4		14.35	8	114.8
	ESP RAV 1		13.85	12	166.2
	ESP RAV 2		13.85	12	166.2
	ESP ash screw conveyer 1		14.3	12	171.6
	ESP ash screw conveyer 2		14.3	12	171.6
	Subtotal	0.729	158.9		1677.2
v	Other load				
	Subtotal	0.981	33.17	8	265.36
vi	Bagasse handle MCC				
	Bagasse belt conveyor BC1		11.2	12	134.4
	Bagasse belt conveyor BC3		11.1	16	133.2
	Bagasse elevator(BE-04)& BC(4)2		11	12	132
	BC-(8) & BC(6)BC(5)1		11	12	132
	BC-(8) & BC(6)BC(5)2		11	12	132
	BC-(8) & BC(6)BC(5)3		11	12	132
	BC(10)		11.2	12	134.4
	BC(11)		11.2	12	134.4
	Bagasse elevator(BE-04)& BC(4)1		11	12	132

	Subtotal	0.783	99.7		1196
	Main Socket				
	Subtotal	0.879	34.41	16	550.56
viii	MCC-2 Common Auxiliary				
	Startup water pump		5.60	12	67.2
	Hot well water pump 1		11.00	12	132
	Hot well water pump 2		11.00	12	132
	Transfer water pump 1		5.55	12	66.6
	Transfer water pump 2		5.55	12	66.6
	Cooling water pump		5.55	12	66.6
	HP Dosing pump 1		5.60	12	67.2
	HP Dosing pump 2		5.60	12	67.2
	HP Dosing pump 3		5.60	12	67.2
	HP Dosing pump 4		5.60	12	67.2
	LP Dosing pump 1		5.60	12	67.2
	,LP Dosing pump 2		5.60	12	67.2
	HP and LP Dosing tank stirrer 1		5.55	12	66.6
	HP and LP Dosing tank stirrer 2		5.55	12	66.6
	HP and LP Dosing tank stirrer 3		5.55	12	66.6
	HP and LP Dosing tank stirrer 4		5.55	12	66.6
	Subtotal	0.784	100.05		1200.6
ix	Work Shop				
	Subtotal	0.789	11.76	16	94.08
Total		**0.762**	**792.48**		8760

Appendix B: Harmonic Measurement Data

Table B.1: Measured current harmonic distortion for phase 1

Date	Time	**Current harmonics(%)**							
		1^{st}	3^{rd}	5^{th}	7^{th}	9^{th}	11^{th}	13^{th}	THD_I
19/02/2024	10:30PM	100	4.67	12.87	13.75	4.70	2.89	1.41	18.5
20/02/2024	09:15AM	100	3.16	13.69	12.05	2.67	2.19	2.16	18.59
21/02/2024	08:20AM	100	0.27	12.74	8.39	0.26	2.22	2.40	15.06
22/02/2024	03:00PM	100	3.96	13.49	12.58	3.13	2.31	1.98	20.5
22/02/2024	04:20Pm	100	2.13	14.51	6.99	0.21	2.46	2.73	16.93
22/02/2024	04:50PM	100	3.06	10.82	13.09	1.67	2.40	1.07	17.55
23/02/2024	03:40PM	100	4.98	14.44	11.60	1.13	2.57	3.01	18.90
23/02/2024	03:50PM	100	3.62	10.96	10.09	4.15	1.51	2.20	17.25
26/02/2024	8:30AM	100	5.06	15.22	14.32	3.7	2.13	1.81	19.51
27/02/2024	8:40AM	100	4.63	13.91	12.70	4.70	2.77	1.23	19
Average harmonic current for phase 1		100	1.95	12.96	10.45	2.13	5.75	3.6	18.55

Table B.2: Measured voltage harmonic distortion for phase 1

Date	Time	Voltage harmonics							
		1st	3^{rd}	5^{th}	7^{th}	9^{th}	11^{th}	13th	THD_V
19/02/2024	10:26PM	100	0.03	2.51	1.04	0.08	0.09	0.23	2.73
20/02/2024	09:11AM	100	0.02	0.06	0.07	0.01	0.06	0.07	3.21
21/02/2024	08:15AM	100	0.00	0.06	0.07	0.01	0.06	0.07	3.34
22/02/2024	02:51PM	100	0.26	0.75	0.47	0.16	0.41	0.30	1.31
22/02/2024	04:10PM	100	0.15	0.28	0.31	0.08	0.13	0.37	2.04
22/02/2024	04:41PM	100	0.01	0.04	0.06	0.01	0.05	0.06	3.32

23/02/2024	03:32PM	100	0.03	0.33	0.27	0.06	0.06	0.05	2.85
23/02/2024	03:47PM	100	0.05	0.94	0.6	0.02	0.52	0.39	1.43
26/02/2024	8:25AM	100	0.01	0.95	0.62	0.01	0.51	0.39	1.45
27/02/2024	8:23AM	100	0.04	0.94	0.6	0.02	0.52	0.39	1.43
Average harmonic voltage for phase 1		100	0.06	0.68	0.41	0.05	0.7	0.65	2.79

Table B.3: Measured current harmonic distortion for phase 2

Date	Time	Current harmonics(%)							
		1^{st}	3^{rd}	5^{th}	7^{th}	9^{th}	11^{th}	13th	THD_I
19/02/2024	10:25PM	100	0.09	14.07	6.33	2.35	1.86	2.50	16.10
20/02/2024	09:09AM	100	3.02	11.98	8.72	4.6	2.31	1.88	15.51
21/02/2024	08:14AM	100	0.07	11.97	7.45	1.49	1.35	1.10	17.74
22/02/2024	02:50PM	100	1.58	12.92	11.3	4.36	1.45	1.11	16.92
22/02/2024	04:09PM	100	0.98	12.42	3.14	1.82	1.30	1.01	17.08
22/02/2024	04:39PM	100	2.02	14.04	12.3	2.02	1.65	1.47	18.31
23/02/2024	03:31PM	100	3.09	13.56	11.1	2.49	1.41	1.00	17.53
23/02/2024	03:45PM	100	0.37	15.59	5.84	0.90	1.96	1.92	16.90
26/02/2024	8:24AM	100	2.02	12.46	11.5	2.04	1.20	2.25	18.35
27/02/2024	8:22AM	100	3.10	12.57	12.2	2.38	1.38	1.06	16.59
Average harmonic current for phase 2		100	1.23	12.55	7.39	0.75	4.38	3.03	17.91

Table B.4: Measured voltage harmonic distortion for phase 2

Date	Time	Voltage Harmonics (%)							
		1st	3rd	5th	7th	9th	11th	13th	THD_V
19/02/2024	10:32PM	100	1.04	0.79	0.17	0.51	0.37	0.22	1.15
20/02/2024	09:17AM	100	0.02	0.06	0.06	0.01	0.05	0.07	0.16
21/02/2024	08:22AM	100	0.05	0.87	0.61	0.15	0.35	0.35	1.36
22/02/2024	03:02PM	100	0.00	0.05	0.07	0.01	0.06	0.08	1.32
22/02/2024	04:22Pm	100	0.23	0.89	0.73	0.12	0.44	0.44	1.55
22/02/2024	04:52PM	100	0.01	0.96	0.63	0.01	0.5	0.01	1.45
23/02/2024	03:42PM	100	0.15	0.28	0.31	0.08	0.13	0.37	2.04
23/02/2024	03:52PM	100	0.01	0.04	0.06	0.01	0.05	0.06	1.31
26/02/2024	8:32AM	100	0.03	0.33	0.27	0.06	0.06	0.05	1.85
27/02/2024	8:42AM	100	0.01	0.95	0.63	0.03	0.49	0.44	1.44
Average harmonic voltage for phase 2		100	0.25	0.52	0.35	0.1	0.3	0.21	2.95

Table B.5**:** Measured current harmonic distortion for phase 3

Date	Time	Current harmonics(%)							
		1st	3rd	5th	7th	9th	11th	13th	THD_I
19/02/2024	10:35PM	100	1.31	10.57	8.85	2.4	1.98	1.55	18.13
20/02/2024	09:20AM	100	2.17	14.85	13.34	2.08	1.28	1.68	18.46
21/02/2024	08:25AM	100	4.27	15.08	14.76	4.64	1.52	1.43	18.51
22/02/2024	03:05PM	100	3.26	14.15	13.76	3.45	1.57	1.46	19.38
22/02/2024	04:25Pm	100	1.21	15.25	8.5	1.30	1.37	1.82	17.55
22/02/2024	04:55PM	100	4.67	15.87	14.75	4.70	1.89	1.41	19.75

23/02/2024	03:45PM	100	3.63	14.5	13.65	4.19	1.12	1.94	18.52
23/02/2024	03:54PM	100	2.09	12.00	7.56	1.28	1.42	2.40	17.10
26/02/2024	8:33AM	100	3.13	14	11.36	3.08	1.29	1.72	17.14
27/02/2024	8:44AM	100	2.48	12.33	10.12	2.86	1.15	1.87	20.2
Average harmonic current for phase 3		100	2.42	13.06	10.46	2.54	4.15	3.13	18.20

Table B.6: Measured voltage harmonic distortion for phase 3

Date	Time	Voltage harmonics(%)							
		1st	3rd	5th	7th	9th	11th	13th	THD_V
19/02/2024	10:37PM	100	0.01	0.04	0.06	0.01	0.05	0.05	3.28
/20/02/2024	09:22AM	100	0.00	0.05	0.07	0.01	0.05	0.05	3.20
21/02/2024	08:27AM	100	0.23	0.89	0.73	0.12	0.44	0.44	1.55
22/02/2024	03:07PM	100	0.00	0.05	0.07	0.00	0.06	0.07	3.38
22/02/2024	04:27Pm	100	0.08	0.06	0.17	0.19	0.07	0.08	3.01
22/02/2024	04:57PM	100	0.24	0.85	0.75	0.13	0.43	0.43	1.54
23/02/2024	03:47PM	100	0.03	0.33	0.27	0.06	0.06	0.05	3.85
23/02/2024	03:56PM	100	0.04	0..94	0.64	0.02	0.51	0.39	1.47
26/02/2024	8:35AM	100	0.01	0.96	0.63	0.01	0.51	0.39	1.46
27/02/2024	8:46AM	100	0.15	0.28	0.31	0.08	0.13	0.37	4.04
Average harmonic voltage for phase 3		100	0.07	0.04	2.05	0.06	0.22	0.23	2.53

Appendix C: Sample Events Data for Voltage Sag

Date	Time	Voltage level			Duration	Types of the problem
		Line 1	Line 2	Line 3		
12/02/2024	04:20AM	210v	210.5v	211.5v	200msec	normal
13/02/2024	10:45AM	215.40v	214.50v	215.00v	100msec	normal
14/02/2024	09:08AM	195.00v	196.40v	194.00v	150msec	voltage sag
15/02/2024	09:25PM	212.50v	213.40v	212.60v	200msec	normal
16/02/2024	08:10AM	201.50v	200.00v	201.00v	150msec	normal
19/02/2024	02:50PM	218.00v	219.20v	219.00v	210msec	normal
20/02/2024	03:30PM	215.20v	217.00v	218.00v	250msec	normal

Appendix D: WSSF Monthly Energy Consumption Report

	Factory name: **Wonji Shawa Sugar Factory(WSSF)**	**Form No:** OF/WSF/FD/030
Title	**Annual Electric Energy Consumption**	**Fiscal year:2023/2024**
Active Energy BlockRate(Birr/KWh)	0.92800000	**Property number: wp018662**
Maximum demand rate(birr/KW)	87.6400000	
Meter constant	1.00	
Service charge	54.00	

S/N	**Date**	**Active energy**		**Reactive energy (kvarh)**	**Maximum demand**		**Power factor**		**Previous reading**	**Current reading**	**Total Payment (birr)**
		(kwh)	**cost in (birr)**		**MD (kw)**	**MD (birr)**	**pf**	**pf. Penalty (birr)**			
1	19/02/2023	3840762	3564,227.14	2930,614.724	7857	688,587.48	0.795	90,945.19	2697130	30813892	4,343,813.81
2	21/03/2023	3597609	3338,581.15	3192,142.277	7782	682014.48	0.748	138,591.48	30813892	34411501	4,156,241.11
3	19/04/2023	1672536	1552,113.41	1443,671.277	7310	640648.40	0.757	12,1021.05	34411501	36084037	2,313,836.86
4	19/05/2023	384987	35,267.94	296,769.022	1360	119190.40	0.792	16,253.28	36084037	36469024	492,765.62
5	22/06/2023	21973	202,278.94	168,026.654	1206	105693.84	0.792	14,412.83	36469024	36686997	322,439.61
6	19/07/2023	352601	327,213.73	266,287.149	1386	121469.04	0.798	15,526.17	36686997	3703958	464,262.94
7	18/08/2023	143475	33,144.80	109,849.740	778	68183.92	0.794	9,102.62	3703958	37183073	210,485.34
8	17/09/2023	1188912	110,350.34	103,913.134	681	59682.84	0.753	11,651.22	37183073	37301985	181,738.40
9	19/10/2023	103850	96,372.80	106,541.000	334	29271.76	0.698	8,471.29	37301985	37405835	134,169.75
10	18/11/2023	460058	426,933.82	384,868.790	2335	204639.40	0.767	35,485.00	37405835	37865893	667,112.31
11	20/12/2023	398028	369,369.98	324,564.724	2878	252227.92	0.775	40,681.84	37865893	22978409	662,333.4
12	19/01/2024	2878203	2670,972.38	2507,448.039	8258	723731.12	0.754	1,40138.95	22978409	41142124	3,534,896.45
Total		**14168994**		**11834697.195**							

Appendix E: Simulink Model of S&PGP Distribution Network without UPQC