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POWER QUALITY ASSESSMENT AND ITS IMPROVEMENT

BY USING SHUNT ACTIVE POWER FILTER

CASE STUDY: ARJO DEDESSA SUGAR FACTORY

MSc Thesis

By,

Diriba Kenasa Gaga

January 2026

Nekemte, Ethiopia



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BY USING SHUNT ACTIVE POWER FILTER
CASE STUDY: ARJO DEDESSA SUGER FACTORY**

**A Thesis Submitted to the College of Engineering and Technology
in partial Fulfillment of the Requirements for the Degree of
Master of Electrical Power Engineering**

By

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January 2026

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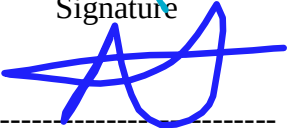
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**Dedicated
To
My Family**

STATEMENT OF THE AUTHOR

I Mr Diriba Kenasa Gaga here by declare and affirm that the thesis entitled “ Assessment of power quality problem and its improvement by using shunt active power filter: Case study Arjo Dedessa Sugar Factory” is my own work conducted under the supervision of Dr. Ginbar Ensermu. I have followed all the ethical principles of scholarship in the preparation, data collection, data analysis and completion of this thesis. All scholarly matter that is included in the thesis has been given recognition through citation. I have adequately cited and referenced all the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and I have not misrepresented, fabricated, or falsified any idea/data/fact/source in my submission. This thesis is presented to meet a portion of the requirements for a Wollega University postgraduate studies degree. I further declare that no other institution has received this thesis for the purpose of awarding a degree, diploma, or certificate. I understand that breaking any of the aforementioned rules will result in disciplinary action from the university as well as possible legal consequences from the sources that have not been properly cited or from whose appropriate authorization has not been obtained when necessary.

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DECLARATION

This is to certify this thesis entitled “Assessment of power quality problem and its improvement by using shunt active power filter. Case study: Arjo Dedessa Sugar Factory”, accepted in partial fulfillment of the requirements for the award of the degree of masters of science in Electrical Power Engineering by the school of graduate studies, Wollega University through the college of Engineering and Technology done by Diriba Kenasa Gaga is a genuine work carried out by him under my guidance. The matter embodied in this thesis work has not been submitted earlier for the award of any degree or diploma. The assistance and help received during the course of this investigation have been duly acknowledged. Therefore, I have recommend that it can be accepted as a fulfilling the MSc thesis requirement.

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BIOGRAPHICAL SKETCH

Mr. Diriba Kanasa was born on September 02, 1993 in East Wollega Zone, Gida Ayana woreda, from his father Ato Kanasa Gaga, and mother W/ro. Ayantu Fufa. He completed his elementary school education at Gobu Gudda and at Gida Ayana senior secondary school. The author joined Wollega university during the 2016 academic year and graduated on June 28, 2021 with a B.Sc. in Electrical and Computer Engineering (Industrial Control Engineering). The author has been working an Electrical Engineer at Nekemte water supply and sewerage service Enterprise since Januaey 27, 2021. He enrolled in the Wollega University Postgraduate School for the 2023/2026 Academic year as a graduate student pursuing a Master of Science in Electrical Power Engineering

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ABSTRACT

These days, maintaining a high-quality supply requires dealing with the power quality issue. This study examines power quality issues in the Arjo Dedessa Sugar Factory power distribution system and offers suitable methods for mitigation. ADSF is the largest sugar industry in Ethiopia. Harmonic distortion, which is mostly brought on by nonlinear loads, is one of the main issues with power quality on the power distribution network of Arjo Dedessa Sugar Factory. The most effective and efficient modern electronic power device used in power distribution networks, the Active Power Filter (APF), can immediately mitigate abnormal current, voltage, and frequency in the system and restore the rated voltage, current, and standard frequency. The Fluke 435 Power Quality Analyzer is used to gather the data needed for the study from both reported (recorded) data and the ADSF power distribution board. The measurement results have led to the recording of the following data. Here, various distortions ($THD_v=9.8\%,10.1\%,10.0\%$ & $THD_i=49.1\%,49.2\%,49.4\%$) are also found to be the cause of harmonic distortion in the ADSF power distribution system. Voltage sag is additionally related to three phase imbalance levels and three phase short circuit fault circumstances. The MATLAB/SIMULINK model is implemented in the simulation to demonstrate the effectiveness of mitigation strategies for power quality issues. Voltage total harmonic distortion decreased from 49.1% to 4.32%. In order to restore the normal current, voltage, and frequency in the power distribution system, Active Power Filter is the appropriate mitigation solution for harmonic distortion that occurs in the ADSF. Several mitigation alternatives, namely APF shunt, APF series, APF shunt-series, and APF Combination, were chosen at an acceptable cost and low power quality problem solving values. SAPF is the most effective and preferred of those.

Keywords: APF, Harmonic mitigation, power electronic, power quality, VSI.

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ACRONYMY

ADSF	Arjo Dedessa Sugar Factory
ANSI	American National Standard Institute
APF	Active Power Filter
CBEMA	Computer Business Equipment manufacture Association
CVT	Constant Voltage Transformer
DSP	Digital Signal Process
DSTATCOM	Distribution Static Compensators
DVR	Dynamic voltage restorer
EEU	Ethiopian Electric Utility
EMI	Electromagnetic Interference
GTO	Gate Turn Off Transistors
I/O	Input Output
IEC	International Electronics Commissioning
IEEE	International Electrical and Electronics Engineering
IGBT	Insulated Gate Bipolar Transistors
ITIC	Information technology industry council
LED	Light Emitted Diode
MCC	Main Cane Carrier
MDB	Main Distribution Board
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
NEMA	National Equipment Manufactory
NFPA	National Fires Protection Association
NLL	Non Linear Load
PCC	Point of Common Coupling
PDU	Power Distribution Units
PLCs	Programmable Logic Controllers
PQ	Power Quality
PQAP	Power Quality Assessment Procedure
PQP	Power Quality Problem
PU	Per Units

PWM	Pulse Width Modulation
RMS	Root Mean square
SCB	Static Current Breaker
SCL	Static Current Limiter
SEMI	Semi-Conductor Equipment and Materials International
SITs	Static Induction Thyristors
STS	Static Transfer Switch
TDD	Total Demand Distortion
THD	Total Harmonic Distortion
TVSC	Transient Voltage Surge Capacitors
U.P.S	Un Interrupt Power Supply
UL	Under writers Laboratories
UPFC	Unified Power Flow Control
UPQC	Unified Power Quality Conditioner
VUB	Voltage Un Balance
PLL	Phase Locked Loop
SRF	Synchronouse Reference Frame
MASI	Melasma Area And Severity Index
DCS	Distirbuted Control System
CNC	Computer Numerical Control
SHM-PWM	Selective Harmonic Mitigation Pulse Width Modulation
EN	European Norm

CHAPTER ONE

INTRODUCTION

1.1 Background of study

Power quality is becoming a major concern for every electric company in the world. The main reason for this is that system switching equipment should be built to function without any latency, and consumption equipment has become more sensitive. Maintaining electrical power quality is the utility's responsibility whenever the matter arises up; End-use factories, on the other hand, are accountable for limiting the currents of harmonics that their electric loads introduce into the utility system. Therefore, the utility must provide a minimum quality electrical energy to all of its plants, and each plant has to minimize the power quality disturbances it generates into the power system. Because the electric supply often consists of a highly integrated and complicated system, any component failure could result in issues with power quality. These issues have an influence on the economy that goes beyond utility revenue losses and industry energy consumption declines [3][5][11].

These issues arise in the power distribution systems of the Arjo Dedessa Sugar company because of disturbances and the existence of nonlinear loads, such as motors, furnaces, and drives with variable speeds. Noise, vibrations, excessive current from motor starting, rotor heating, dielectric breakdown, interference with communication systems, malfunctioning breakers, and more are examples of problems with power quality. Increased losses indicate low efficiency in the power distribution system and electric machines. Furthermore, a bus voltage is taken to have adequate power quality if it closely resembles a sinusoidal waveform of the required magnitude. Because of the expanding number of devices that are sensitive to changes, the need for reducing losses, and the behaviors of interconnected networks, the power quality concept has grown increasingly important. IEEE Standards ara that provide measurement methods and identify various power quality disruptions and describe the methods used to calculate and evaluate the many power quality measures that have been created in response to the growing concern about power quality issues among numerous stakeholders.

Power quality issues change daily due to the presence of some non-linear loads in the Arjo Dedessa Sugar factory power distribution system, including motors, transformers, AC and DC drives, water pumps, cooling fans, and other non-linear loads. Many microprocessor-based controls, the complex nature of industrial processes, three-phase short circuit faults, power electronics equipment used to improve system of stability Function and effectiveness. The main reasons why end-user devices are more sensitive to different problems are the deregulation of the industry power supply and problems with power quality. Investigating and designing remedies for the power quality problems found in the Arjo Dedessa Sugar factory's power distribution system is the aim of this thesis.

1.2 Statements of the problem

Numerous indicators indicate to the ADSF sugar processing factory's extremely low electric power quality. According to information gathered from the factory's employees, the factory was dealing with a number of power quality issues, the most prevalent of which were motor overheating, lamp dimming and burning, poor power, reactive power burden, unbalanced voltage, unexpected voltage increases and decreases, waveform distortion (harmonics), power interruption, voltage fluctuations, and power frequency. Because of the presence of nonlinear devices, a variety of industrial load equipment also contaminate the supply system by drawing (distorting current and voltage). Motor drive failure, circuit breaker tripping, motor overheating, fuse blowing, contactor burning out, and insulation cable failures are all consequences of PQP in the ADSF's main distribution network. Since the research study demonstrated a significant power issue, the ADSF power distribution system requires changes in power quality. This thesis focuses on determining and assessing the ADSF electric power quality problems; causes, effects, and potential solutions.

1.3 Research Questionaries

The following inquiries will be addressed at the study's conclusion:

1. What PQP is present in power distribution system of the Arjo Dedessa Sugar factory?
2. What are the reasons for the factory's issues with electrical power quality?
3. How will power distribution system's issues with power quality be resolved?

1.4 Objectives

1.4.1 General objectives

Investigation Power Quality problem and its improvement technique by using Active Power Filter in Arjo Dedessa sugar Factory power distribution system

1.4.2 Specific objectives

- To identify power quality problem in the Arjo Dedessa Sugar Factory
- Compare the degree of the disruptions to the allowable levels established by IEEE standards.
- Determine the main reasons behind the power quality issues in the current ADSF system.
- Improving design power quality issues with an active power filter

1.5 Scope and the limitation of the study

Examining power quality problems and how they impact power quality in the electrical power distribution system is the first step in the study thesis. This study investigates the mitigation strategies for the Arjo Dedessa Sugar factory power distribution system as well as power quality issues (harmonics difficulties) that exceed the IEEE standard. One restriction is that this research study used MATLAB/Simulink simulation software instead of hardware for all component design and modeling, including power quality mitigation methods. Therefore, the investigation of power quality problems, particularly the harmonics problem within the Arjo Dedessa sugar factory's power distribution system, and its mitigation strategies applying an Active Power Filter in Action are the main focus of our investigation.

1.6 Significances of the study

The study's findings will help the ADSF in indentifying the problem and mitigation techniques. As a result, the study provided the factory with recommendation for implementing power quality improvement techniques, with the active power filter being the most important. Assess and formulate suitable solutions for today's Power quality problem. Draw appropriate results and propose solutions for the industry's future. It will help the industry by: Improved system structure can increase power supply continuity. An improved power quality system

will reduce the risk associated with safety problems. As electric power quality improves, sugar production will increase . to reference for engineers work on that company.

1.7 Geographical location of the study

The research was carried out at Arjo Dedessa Sugar Factory located in east wollega zone of Oromia Regional State. Arjo Dedessa Sugar Factory is located at $09^{\circ} 41^m 48^s 6^{ms}$ N latitude and $036^{\circ} 26^m 01^s 9^{ms}$ E longitudes, with an altitude of 1053-1600masl. The area has mean maximum and minimum monthly temperature is 31.1c and 19.1c respectively with annual rain fall of 358.4. Figure 1 Geographical location Arjo Dedessa sugar Factory mm (source: Arjo metrological station). Arjo Dedessa Sugar Factory is situated in the Dedessa rift valley within the West Oromia Regional State. Founded in 2009, it was originally owned by Al-Habesh Plc, a Pakistani company. The site lies approximately 395 km west of Addis Ababa in the Oromia region.

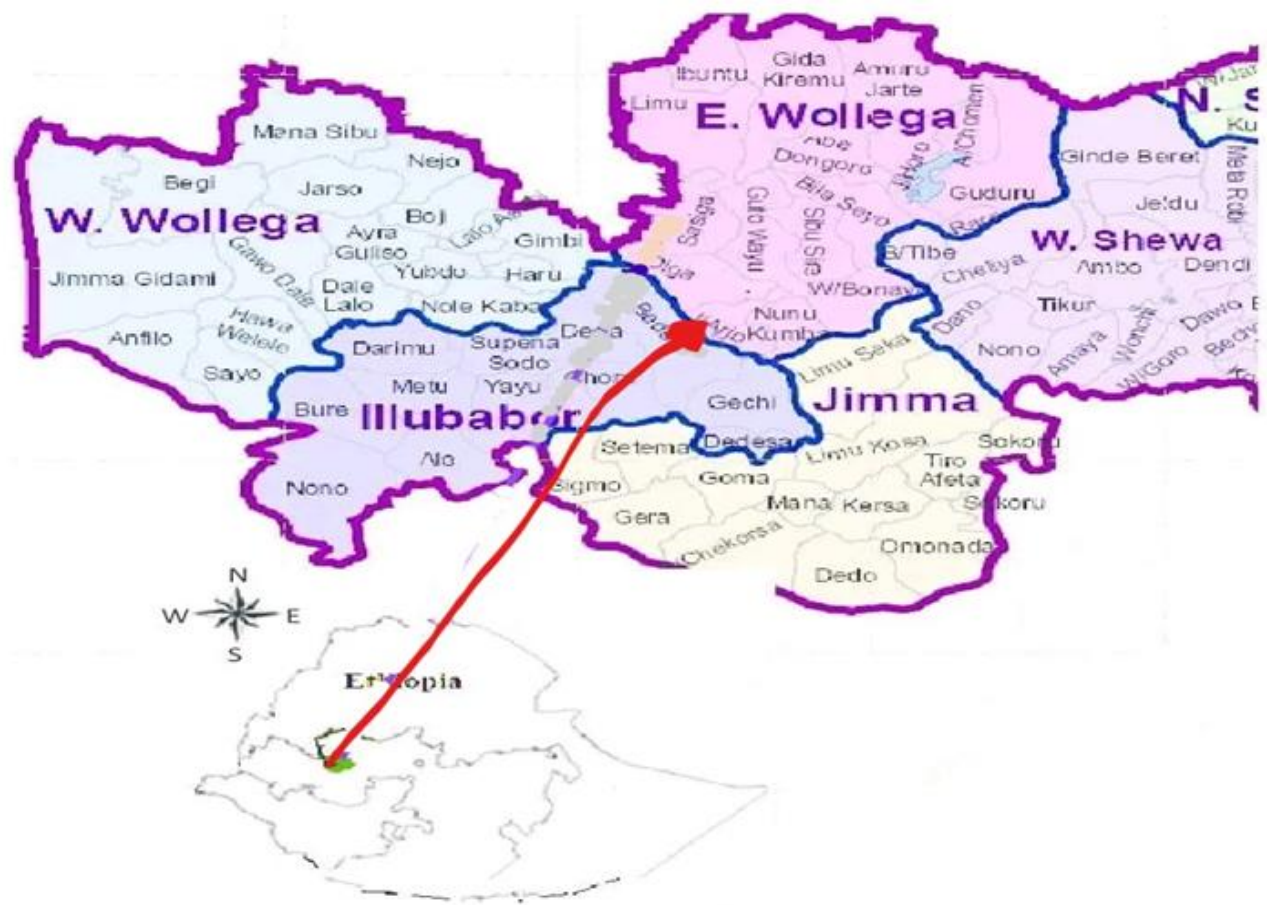


Figure 1.1: Geographical location ADSF(from google)

1.8 Overview of Arjo Dedessa Sugar factory

Arjo Dedessa sugar factory was a sugar development projects that are given due attention by our developmental government. The total concessions area of the factory is about 50 thousand hectares and 49 kebeles of east Wallaga, Buno Bedele, Jimma and Ilu Aba Bora Zones are included within its commend areas. The produced Sugar is Refined sugar and meets export standard so that our country will earn foreign currency by exporting it for world market. The factory was crushing capacity of 8000 tone cane per day(TCD). The factory can have the crushing capacity of 12000 TCD by further improving its design capacity in the future.

Some important factors that make Arjo Dedessa Sugar Factory different from other factory. E.g. the factory is found by the side of the asphalted Nekemte Buno Bedele route, It is only factory that produced Refined sugar, Cane handling and cane preparation units operates hydraulically and this makes cane preparation operation is very easy and it is the only factory that wood chopper. Two wood choppers that are found in the factory easily prepare woods that are needed as a fuel for boilers.



Figure 1.2: Arjo Dedessa Sugar Factory picture from the top view

In Arjo Dedessa Sugar Factory there are many electrical system distribution: Bioler, Steam turbine, Diesel Generator and Substation. Power distribution is delivering of the power from generation station to sub distribution station. Busbars after it gets step down. Continuouning the power is distributed to distribution panels or directly to the load. Most of the factory loads

gets their power demand from distribution panels. In this factory there are three power generating with rates of electric power. Steam power generating, EEU or ELPA and Diesel generator. The primary sources of energy to generate electricity is the dry steam from Biolers having pressure $65 \frac{kg}{cm^2}$ to drive prime movers (steam turbine). The steam generator has a capacity of generating electric power 8MW and also Diesel generator has a capacity of 1MW with voltmeter reading of 380-415V. The electric power which comes from EEU OR ELPA where 15KV. The types of Steam turbine used ADSF is Impulse turbine and the rates of capacity of turbine where: Rated output 8MW, Rated speed 7034 rpm, Operating pressure 24 bars and Operating temperature 350°C. Then this turbine is connected to the AC generators to the rotor parts. If the turbine is running more then 1HRS with no loads then the exhaust hot temperature will get increase. there is a timer in DCS.

If the turbine speed reaches to its 90% of the rated speed, this timer will start its count down for 1HRS. after one 1Hrs automatically DCS will give the trip commend to Governors. The over speed prevention system monitors the speed of the turbine and it initiate a trip commend if an over speed condition occurs. alternators the steam turbine is coupled to on alternators . the alternator convert an machanical energy of the turbine in to electrical energy. The electrical output from the alternators is delivered to the busbars through a vacuum circuit breaker, transformer(stepdown 3.3KV to 415V), Isolators. The capacity of the Generators or alternators are: Rated output 8MW, Voltage 3.3KV , Current 2000Amp, Power factor 0.8 lags, Frequency 50Hz and Speeds 1500 rpm

1.9 Thesis Organization

There are six chapters in the thesis. The research study's general introduction, problem statement, goals, research questions, scope, and limitations are all included in the first chapter. In the second chapter, theoretical ideas are discussed and the literature from earlier studies is reviewed. The third chapter presents the measurement, benchmarking, and examination of power quality events. Power quality mitigation technique design and modeling will be covered in the fourth chapter. Results and discussion will be given in Chapter 5. Lastly, chapter six offers the findings and suggestions for further research.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

The IEEE Standard Dictionary of Electrical and Electronics Engineering defines power quality as the practice of grounding and supplying power to sensitive electronic equipment in a way that supports proper operation. In terms of bus voltage assessment, analysis, and improvement, power quality can also be understood as maintaining a sinusoidal load-bus voltage at the rated magnitude and frequency. Modern electrical and power-electronic equipment can both contribute to and be affected by power-quality problems. Overall, the term “electric power quality” refers to keeping the distribution-bus voltage as close as possible to a pure sine wave at the correct voltage level and frequency, while also ensuring uninterrupted power delivery for reliability.

Traditionally, electric power is produced by synchronous alternators driven by steam turbines. An ideal power supply would provide continuous availability with stable voltage, frequency, and waveform. However, voltage fluctuations frequently occur in distribution systems. According to IEC standards, the permissible voltage variation for low-voltage systems is $\pm 5\%$, which aligns with the operating tolerance of most electric motors. Voltage imbalance can lead to increased motor temperature and potential faults. Waveform distortions may arise from harmonics, interharmonics, DC offsets, noise, or notching. Many electrical devices including motors, transformers, generators, computers, printers, communication systems, and household appliances can malfunction or fail when exposed to these types of power-quality disturbances.

Depending on how serious the problems are, any of these devices are susceptible to power quality difficulties. Power quality, which is described as "any power problem manifested in voltage, current, or frequency deviation those results in failure or main operation of consumer's equipment," is typically a consumer-driven issue [1] [1] [2].

2.2 The definitions of power quality with specific function

Utilities often equate power quality with the reliability of the electrical supply. From the load perspective, it refers to providing power that enables all devices including sensitive ones to function correctly, which varies based on the user's needs. According to the IEEE dictionary, power quality involves supplying and grounding sensitive equipment in a manner that supports its proper performance. The IEC (International Electrotechnical Commission) defines power quality as the combination of parameters that describe voltage characteristics such as magnitude, frequency, and waveform as well as the continuity of supply under normal operating conditions [3] [4].

2.3 Identify Power Quality Problem

Power quality has emerged as a significant concern for several reasons. First, modern power systems increasingly use devices such as shunt capacitors and adjustable-speed motor drives to enhance efficiency. However, these components also contribute to higher harmonic levels in the system, creating additional complications[14]. Moreover, today's electronic load which rely heavily on microprocessor and microcontroller-based controls are much more susceptible to power disturbances. Because power networks are highly interconnected, any disturbance or fault in one component can affect the entire system. Additionally, utility customers are now more aware of power quality problems such as undervoltage, overvoltage, and flicker, increasing the demand for cleaner and more reliable power. According to IEEE Standard 1159-1995, power quality disturbances fall into seven main categories: transients, long-duration voltage variations, short-duration voltage variations, voltage imbalance, waveform distortion, voltage fluctuations, and frequency variations[10][18].

2.3.1 Transient

These disturbances are defined as power-quality deviations that involve damaging spikes in current, voltage, or both, occurring suddenly and undesirably. In low-voltage systems, their magnitudes can rise to several thousand volts or amperes. However, they last for only a very short period typically from under 50 microseconds to about 50 milliseconds.

Power Quality transient source:

Lighting strikes, switching operations, capacitor bank switching, disconnect opening and closing on electrified lines, and transformer tap changes. Additionally, a few more were:

The distribution system's loose connections cause arcing and unintentional mistakes made by people, animals, and weather conditions.

Power Quality Transient Effects

Electronic Equipment: Equipment will malfunction and yield compromised results. Electronic device efficiency will go to decrease. In motor: Motors will operate at a greater temperature due to transient causes device failure by damaging the motor winding's insulation. increases the motor's operating temperature and excitement losses. Lights: Ballast failure and fluorescent bulbs. The fluorescent tube ends appear to have black rings, which are an indication of trust. Early filament degradation causes the incandescent light to fail.

Transient classification: They are classified as either oscillation or impulsive transients.

An Impulsive Transient (IEEE 1159) refers to sudden fluctuations in the steady state conditions of either positive or negative voltage and current. Like lighting, it is typically a single, extremely strong impulse. Rise and decay times are commonly used to characterize impulsive transients. An Oscillation transient is a sudden disturbance in the steady-state condition of voltage, current, or both, characterized by alternating positive and negative polarity values. An Impulsive transient can be further classified into: Impulsive transients in nanoseconds, milliseconds, and microseconds. There are three different kinds of oscillation transients [5] [6].

2.3. 2 Long duration voltage variation:

Voltage variation is considered extended duration when it lasts more than one minute. There are three categories for long-duration voltage variation. Sustained disruption, undervoltage, and overvoltage. Overvoltage a condition in which the RMS AC voltage exceeds 110% of its nominal value at the power frequency for more than one minute. It is commonly caused by events such as the disconnection of a large load or the switching on of a substantial capacitor bank.

Undervoltage: A situation where the RMS AC voltage falls below 90% of its rated level at the power frequency for more than one minute. As noted by Santoso et al., undervoltage can lead to several negative effects, including improper equipment operation, decreased efficiency, reduced performance, and potential equipment damage due to increased stress on components.

Long duration voltage variation-effects

Undervoltage and overvoltage are produced by variations in the system's load rather than system problems. Incorrect tap settings on transformers can also lead to undervoltage and overvoltage. Because they last longer than a minute, they exert stress on computers, controllers, and motors and reduce the lifespan of power system components and motors. A sustained interruption refers to a long-duration RMS voltage variation in which one or more phase conductors experience a complete loss of voltage (below 0.1 pu) for a period exceeding one minute [7][8].

2.3.3 Short duration voltage variation

Short-duration voltage variations are defined as changes in RMS AC voltage lasting from more than 0.5 cycles up to one minute (60 seconds). These fluctuations often occur due to intermittent loose connections in the wiring. There are three main types of short-duration voltage variations: sag (dip), swell, and disruption. Sag (dip): A sag is characterized by a reduction in RMS voltage or current to between 0.1 and 0.9 p.u. at the power frequency, lasting from 0.5 cycles up to one minute.

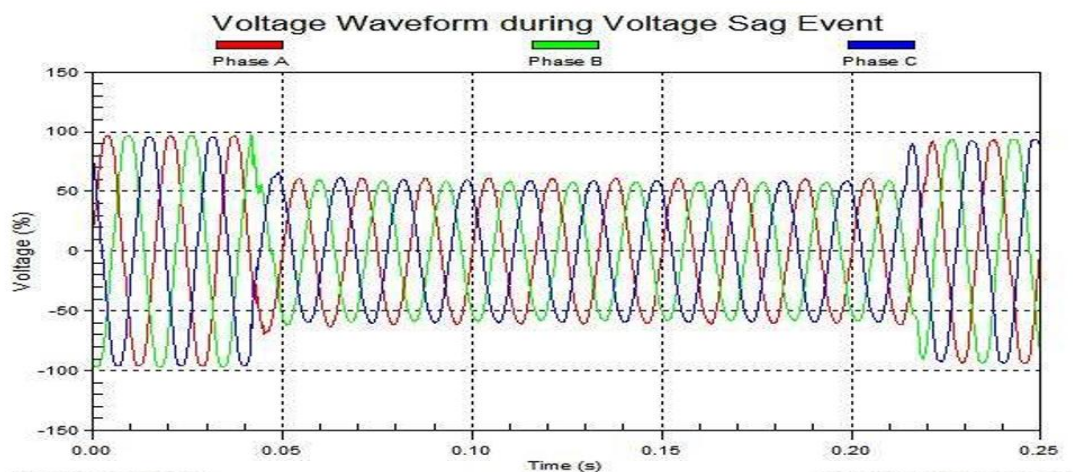


Figure 2.1: Diagram of voltage sag

Causes of Sag: Sags are typically caused by voltage drops resulting from fault currents or the startup of large motors. **Swell:** A swell is a temporary increase in RMS voltage, ranging from 1.2 to 1.8 p.u., lasting from 0.5 cycles up to one minute.



Figure 2.2 : Diagram of voltage swell

Among the many curves developed to assess equipment sensitivity, the CBEMA, ITIC, and SEMI curves are the most significant. The CBEMA curve, created by the Computer Business Equipment Manufacturers Association, illustrates computer equipment tolerance to voltage sags and swells by plotting allowable sag/swell magnitude against event duration. Later, a CBEMA working group developed the Information Technology Industry Council (ITIC) curve, which in recent years has replaced the CBEMA curve for single-phase 120V equipment. In contrast, the SEMI curve was specifically designed for semiconductor manufacturing equipment. **Interruption:** Defined as a reduction in load current or supply voltage below 0.1 p.u. for up to one minute. Interruptions can be further classified as instantaneous, momentary, or transient.

Sag: Instantaneous: 0.5–30 cycles, Momentary: 30 cycles–3 seconds, Temporary: 3 seconds–1 minute

Swell: Instantaneous: 0.5–30 cycles. Momentary: 30 cycles–3 seconds. Temporary: 3 seconds–1 minute. Interruptions (momentary): 0.5–30 cycles [9] [10].

2.3.4 Voltage unbalance:

Voltage unbalance can be described as the deviation of each phase voltage from the average of the three-phase voltages or as variations in the relative magnitudes of the three-phase voltages. It is typically caused by large single-phase loads, such as traction systems or induction furnaces, and by uneven load distribution across the power distribution network.

Effects: It can result in network issues like malfunctioning protection relays and voltage control devices, as well as overheating transformers and motors. Three-phase loads, or three-

phase machines, are impacted. Voltage regulators may reduce the impact. The largest deviation from the three-phase voltage average divided by the three-phase voltage average, presented as a percentage, can be used to assess voltage imbalance [11].

$$VUB = \frac{\text{Max.deviation from average voltage}}{\text{average voltage}}$$

2.3.5 Waveform Distortion

It is described as a steady-state departure from the ideal sine wave of power frequency. The main characteristics of waveform distortion are its spectrum contents, which are examined with a Fourier transformer expressed as

$$F(t) = F_o + \sum_{h=2,4,6 \dots}^{\infty} F_h \cos(h \times \omega_o t + \theta_h) + \sum_{h=1,3,5 \dots}^{\infty} F_h \sin(h \times \omega_o t + \phi_h) \quad 2.1$$

Where, $F(t)$ = Voltage or current waveform, F_o = DC components, F_h = Spectral constant, h = harmonic number, ω_o = Fundamental angular frequency

ϕ_h = phase shift of the spectral constant

Five types of waveform distortion DC-offset, Harmonic, Inter-Harmonics, Notching and Noise

DC-Offset: It is the presence of DC voltage or current in the AC power supply. In mathematical terms, a voltage or current waveform's DC offset is

$$DC \text{ offset} = \frac{1}{T} \int_0^T F(t) dt \quad 2.2$$

$F(t)$ is the voltage or current waveform as a function of time t , and T is the voltage or current waveform's period.

Causes: Power converter asymmetry, *effects* include heating and a shorter lifespan. **Inter-Harmonics** : It is a sinusoidal voltage or current with frequencies that are not the fundamental frequency's integer multiples. They may show up as a wide-band spectrum or as single frequencies. It should be mentioned that time-varying harmonics may be captured as interharmonics because of the limits of power quality devices. There are currently no technically sound techniques for accurately recording interharmonics. Interharmonics' effects are poorly understood. It has been demonstrated that they impact power line carrier signaling.

Inter-harmonic f = $f_o \times n$ for a non integer $n > 0$

Sources: Carrier signals from power lines, cyclo converters, and static frequency converters

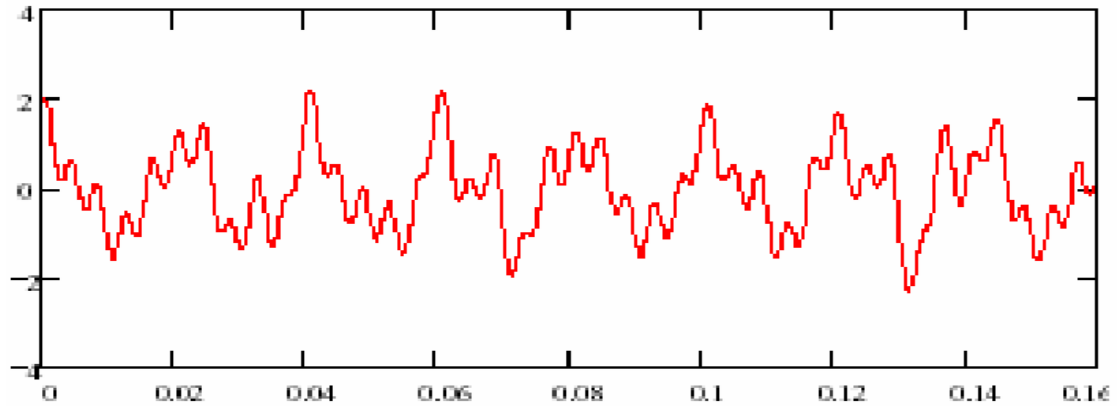


Figure 2.3: wave form with harmonic and interharmonic components

Noise: Unwanted electrical signals with broadband frequency components below 200 kHz are classified as noise. It can appear on neutral conductors, signal lines, or be superimposed on the voltage or current in the phase conductors of a power system. Such electrical noise distorts or disrupts the fundamental sine wave. *Causes:* Microcomputers and programmable controllers are affected by power electronic devices and arcing equipment [12] [13].

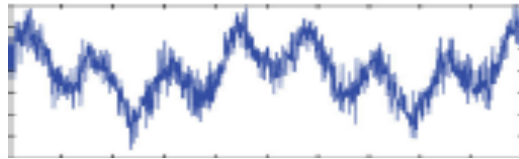


Figure 2.4: voltage noise

Notching: This is a periodic voltage disturbance caused by the normal operation of power electronic devices, occurring when current is switched from one phase to another, temporarily creating a short circuit between two supply phases.

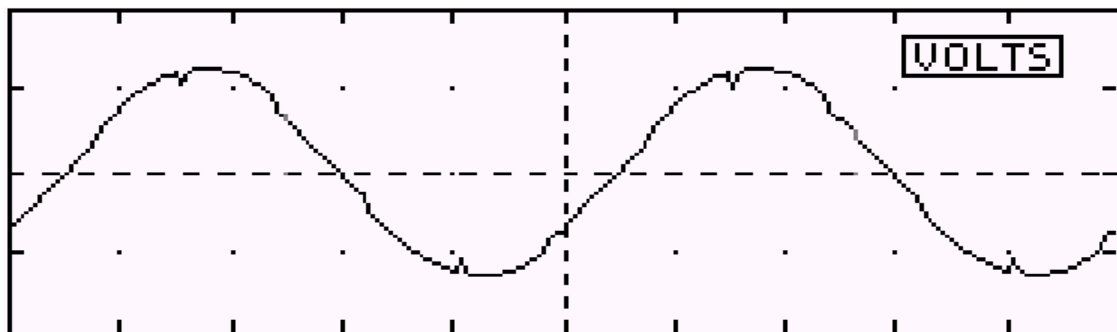


Figure 2.5 : voltage notching due to power electronic devices

2.3.6 Voltage Fluctuation or Flicker:

rapid voltage changes that fall within the nominal voltage's permitted bounds. For instance, 0.9 to 1.1pu [14] [15]. Causes: Flicker is caused by loads that exhibit rapid and repetitive changes in current. The term “flicker” refers to the visible effect of voltage fluctuations on lighting, as perceived by the human eye. The term “voltage fluctuation” is commonly used because it is directly related to flicker and both concepts are addressed together in standards.

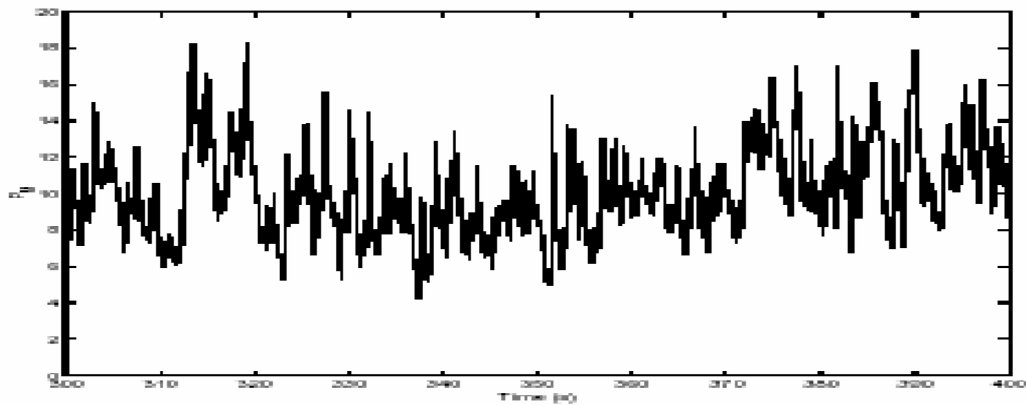


Figure 2.6 : voltage fluctuation scenarios

2.3.7 Power Frequency Variation

Frequency variation is defined as the deviation of the power system's fundamental frequency from its nominal value (typically 50 Hz or 60 Hz). Such deviations can occur due to events like the disconnection of a large load, the loss of a major generation source, or issues in the bulk power transmission network. However, substantial frequency fluctuations are rare in modern interconnected power systems [16] [17].

2. 4 Harmonics:

A harmonic is a sinusoidal component of a periodic waveform whose frequency is an integer multiple of the fundamental frequency, usually 50 or 60 Hz. Distorted waveforms can be analyzed by expressing them as the sum of the fundamental frequency and its harmonics. Nonlinear devices such as static power converters, arc furnaces, synchronous motors, and

adjustable-speed drives used in fans, pumps, and blowers are common sources of harmonic generation [18] [19].

These days, harmonics up to the 63rd can be measured using current equipment. However, harmonics between the 3rd and 25th are the most frequently encountered.

$$h=kq\pm 1$$

where q- is the number of humps on the DC bus per electrical cycle and h- is the harmonic number. K is an integer [2].

Table 2.1: below load type and harmonics

Load type	Harmonics
1, 6-pulse	5 th , 7 th , 11 th , 13 th , 17 th
2, 12-pulse	11 th , 13 th , 23 rd , 25 th
3, 18-pulse	17 th , 19 th , 35 th
4, 24-pulse	23 th , 25 th , 35 th
5, Switch mode power supply	3 rd , 5 th , 7 th , 9 th , 11 th
6, LED	3 rd , 5 th , 7 th , 9 th , 11 th
7, Arcing devices	2 nd , 3 rd , 4 th , 5 th
8, Transformer	2 nd , 3 rd , 4 th

Notes: number 1-harmful.

Number 2-low harmful and Number 3 and 4 least harmful

Number 5-8 very harmfully. Harmonics are sinusoidal voltage or current components of the waveform. They are mathematically given as follows [20] [10].

Once the system was turned on, the main circuit breaker opened, putting all system off-line.

$$Hh = \frac{1}{T} \int_0^T F(t) \cos(h\omega t + \theta h)$$

Conversely, hth is Hh . T: The duration of the voltage/current waveform. F (t) is the voltage and current waveform as a function of time. The harmonic number is denoted by h, while the fundamental angular frequency is denoted by ω . ϕh represents the phase angle of the hth harmonic. The wave shape with harmonic spectral (odd) components can be defined using the formula eqn.(2.3).

$$F(t) = \sum_{h=1}^{h_{max}} A_h \sin(2\pi h f_0 t + \theta_h) \quad 2.3$$

In contrast, f_0 is the basic frequency and A_h is the greatest harmonic spectrum magnitude. Harmonics originate from the nonlinear characteristics of devices and loads that require currents other than a sinusoid on the power supply. The most common of these loads are electrical power converters, although there are other non-sinusoidal loads as well, including the following [7]. There are several reasons why a system may have harmonics. In medium-voltage networks, equipment connected to low, medium, or high voltage networks may result in harmonic voltages. This reduces a piece of equipment's performance and leads to other problems because it can only produce a portion of each appropriate harmonic voltage level. As a result, harmonics play a major role in the drop in the power performance rating [4]. Total Harmonic Distortion (THD) is a common way to measure the harmonics in a system. A system's total harmonic distortion, or THD, is defined as "a measure of the distortion or defect occurring in an electrical system's voltage or current waveform due to the presence of harmonics." To determine a system's THD, use the following expression: Variable speed drives and other power electronics-based equipment are common generators of harmonics. Harmonic resonance is one of the main issues with harmonic disturbances. Resonance has the potential to amplify harmonic aberrations to the point where they could hurt or malfunction equipment. Harmonic resonance is mostly caused by power factor correction capacitors in distribution systems. Additional consequences of harmonics include overloaded equipment, higher losses, and occasionally malfunctioning equipment [21]. The harmonics index that is most frequently utilized.

$$THD_V = \frac{\sqrt{\sum_{h=2}^{\infty} V_h^2}}{V_1} \times 100\% \quad 2.4$$

$$THD_I = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1} \times 100 \quad 2.5$$

The ratio of the RMS value of the fundamental component to the RMS value of the harmonic components is known as total harmonic distortion, and it is commonly stated as a percentage. At the basic frequency, the THD value for a pure sine wave is 0.

In a similar vein, the voltage and current individual harmonic distortion measurements at h -th order are defined as V_h/V_1 and I_h/I_1 , respectively.

Table 2.2 Summaries of power quality problems, causes, and effects

PQ problem	Source(cause) of PQ problem	Effect/consequence of PQ problem
Impulsive transient	Lightning capacitor switching, load switching	Destroys electrical and electronic equipment's like TV, computer chips, regulator
Oscillation transient	Line/cable switching, load and capacitor switching	Destroys electrical and electronic equipment's like TV, computer chips, regulator
Sag or swell RMS	Faults on transmission and distribution network, a connection of heavy loads, and starting up of motors.	Process halt, contactor tripping, and decreased efficiency in electric rotating machines can result from malfunctioning IT systems, PLCs, ASDs, etc.
Under voltage	Motor starting, load variation	Shorten lives of motors and lightning Filaments.
Harmonics	Nonlinear loads such as arc furnaces, welding machines, power electronic converters ASDs, etc	Electric machine inefficiency and cable, transformer, and motor overheating
Voltage unbalance	Large single-phase loads and an inaccurate distribution of all single-phase loads among the system's three phases (which could potentially be caused by a failure).	A negative sequence that is detrimental to all three-phase loads, including induction machines, is implied by imbalance systems.
Voltage flicker	Intermittent load Motor starting Arc furnace	Light flicker Irritation

The harmonic current restrictions are discussed in the table of IEEE standard current and the load's size in relation to the power system's size. The short-circuit current available at the PCC divided by the highest fundamental load current is called the ratio ISC, IL . According to the standard, a facility's potential to introduce harmonics into the utility's distribution system depends on how much current it draws. The table outlines the utility's requirements for providing high-quality voltage. The table shows the general distribution system's current distortion limitations (120V to 69000V). The IEEE 519-1992 standard displays the current distribution distortion limit [22] [23].

While the current distortion surpasses the permissible limitations established by IEEE standards, the voltage THD levels observed across the three phases are within these limits. The primary side of the transformers that supply the industrial loads where the point of common coupling (PCC) is taken into consideration. Triple harmonics, or multiples of three, produced on the load side cannot reach the primary side because the transformer is set up in a delta-wye connection. The maximum current THD measured at the PCC is 18.10% when these triple harmonics are eliminated[7] [24].

2.5 Power quality terms

A set of power electronic components called an active filter is used to remove harmonic distortion. Current distortion: Any variation in the current flowing through the AC line. Any variation from an AC signal's typical sinusoidal waveform is called distortion. The conductor that connects non-current-carrying sections of conduits, raceways, or equipment shelters to the neutral and ground electrode at the main service panel or secondary of a system that is independently derived (such as an isolation transformer) Fault: Usually refers to a power system short circuit. Fault transient: A short-circuit incident that can be cleared by momentarily cutting off current and is frequently brought on by lightning, contact with trees, or animals. Ferroresonance: An irregular or occasionally chaotic resonance involving the nonlinear characteristics of iron-core inductors; often undesired in power systems but purposefully employed to improve power quality in devices such as constant-voltage transformers.

The feeling of visual instability brought on by variations in light intensity or spectral distribution across time is known as flicker. Frequency deviation: An increase or decrease in

system frequency that can last anywhere from a few cycles to many hours. Frequency response: This describes how the impedance of the system or metering transducer changes with frequency in terms of power quality. Fundamental (component): The first-order (50 or 60 Hz) part of a periodic waveform's Fourier series. The term "harmonic" refers to a sinusoidal component whose frequency is an integer multiple of the basic frequency.

Harmonic content: The portion of an AC quantity obtained by subtracting the fundamental component. Harmonic distortion is a sine wave's periodic deviation brought on by harmonics.

Harmonic filter: An apparatus that eliminates one or more harmonics from the power system; it can be active (which may also deal with reactive power) or passive (combinations of resistors, capacitors, and inductors). The integer ratio of a harmonic's frequency to the basic frequency is known as the harmonic number. Harmonic resonance: This phenomenon amplifies distortion when the system resonates close to a main harmonic generated by nonlinear loads.

Impulse: A brief pulse that resembles a unit or Dirac pulse; "impulsive transient" is favored in power quality. Impulsive transient: An abrupt, unidirectional, non-power-frequency shift in voltage or current (mostly positive or negative). A steady-state departure from an ideal sine wave that is distinguished by its spectral content is known as waveform distortion. The loss of supply voltage on one or more phases is known as a voltage interruption, and it is frequently characterized by its length (momentary, transient, or continuous).

Any distortion of the AC voltage waveform is referred to as voltage distortion. Voltage fluctuation: Variations in voltage magnitude that occur often or cyclically. When three-phase voltages are not 120° apart or have different amplitudes, this is known as voltage imbalance (unbalance). frequently stated as the percentage of positive-sequence voltage divided by negative- or zero-sequence voltage. Odd multiples of the third harmonic, known as triple harmonics, are noteworthy because they inherently create zero-sequence currents.

Total Harmonic Distortion (THD) is calculated as a percentage by dividing the RMS value of the harmonic content by the RMS value of the fundamental. Transient: A phenomena that happens briefly between two steady states; it can be a damped oscillation or a unidirectional impulse. Temporary: Describes brief fluctuations that last between three and one minute. The RMS value of harmonic currents divided by the RMS value of the rated or maximum demand

basic current yields the total demanding distortion (TDD), which is represented as a percentage. Sympathetic tripping: When sensitive ground-fault protection is used, a circuit breaker on an unaffected feeder may unintentionally trip as a result of backfeed from another fault.

2.6 Power quality standards

Power quality standards are established to protect utility and end-user equipment from malfunctions caused by deviations in voltage, current, or frequency from normal levels. These standards set measurable limits on how much these electrical parameters can vary, providing a benchmark for safe operation[22][23]. They allow both utilities and customers to define acceptable and unacceptable levels of service. Since delivering a perfectly stable voltage waveform to every customer is impractical, standards ensure that each customer receives a level of power quality suitable for their equipment. Consequently, networks define permissible and acceptable disturbance levels at various points in the system.

2.7 Standard levels in power quality:

IEEE Standard 446-1995 – Industrial and Commercial Emergency and Standby Power Systems: Recommended Practice provides engineering guidelines for selecting and implementing backup and emergency power systems. It offers facility owners, operators, and designers standards to ensure a continuous power supply that is largely free from voltage sags, surges, transients, and frequency deviations.

Owners, operators, and designers can follow IEEE Standard 519-1992, Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems, to ensure a continuous power supply with few voltage dips, surges, transients, and frequency changes. All varieties of static power converters used in commercial and industrial systems are covered by this standard, which also discusses problems with harmonic control and reactive power compensation for these converters.

Although this advice does not address the effects of radio frequency interference, it is advised to reduce disruptions in the AC power distribution system that may harm communication equipment and other delicate devices. In order to minimize power-related noise in

sophisticated electronic processing equipment utilized in commercial and industrial settings, IEEE Standard 1100-2005 Recommended Practice for Grounding and Powering Sensitive Electronic Equipment offers recommendations for electrical system design, installation, and maintenance. Procedures for gathering and transferring power quality data are outlined in IEEE Standard 1159.3-2003: Recommended Practices for Power Quality Data Transfer.

The IEEE Shunt Power Capacitor Standard 18-2002 lays forth specifications and guidelines for shunt capacitors used in power systems. Guidelines for detecting voltage fluctuations and related light flicker are provided by IEEE Standard 1453-2004, Recommended Practice for Voltage Fluctuation Measurement, Limits, and Light Flicker on AC Power Systems. This standard establishes acceptable limits to preserve power quality [2].

Guidelines for monitoring the quality of AC power systems are provided by IEEE Standard 1159-2009: Recommended Practice for Electric Power Quality Monitoring. The standard describes how to measure electromagnetic events, defines terms related to power quality, and describes how low power quality affects customer and utility equipment. It stipulates that the allowable steady-state voltage at the delivery point must stay within $\pm 5\%$. The suggested tolerance window for end-use equipment is between $+6\%$ and -13% , and the voltage imbalance should be kept within $\pm 3\%$ [25]. The NEMA Standards Publication LS1-1992, Low Voltage Surge Protective Devices, establishes a standard for the superior construction of surge-proof devices.

The compatible levels for low-frequency conducted disruptions and signals in public power systems are defined by IEC 61000-2-2, Public Supply System Compatibility Levels. Equipment input current restrictions, as specified by IEC 61000-3-2, limit harmonic current discharge from equipment with input currents up to 16 A per phase. The voltage quality standards for public electricity distribution networks are established by EN 50160, Voltage Characteristics of Public Distribution Systems.

Table 2.5: Power quality requirements for IEEE

Categories	Typical duration	Typical voltage magnitude
Transients:		
Impulsive	50ns<duration<1ms	0-8pu
Oscillatory	30ns<duration<5μs	
Short duration variations:		
Instantaneous		
Sag	0.5-30 cycles	0.1-0.9pu
Swell	0.5-30 cycles	1.1-1.8pu
Momentary		
interruption	0.5-3 sec	Less than 0.1pu
Sag	30 cycles-3sec	0.1-0.9pu
Swell	30 cyclse-3 sec	1.1-1.4pu
Temporary		
Interruption	3 sec-1 min	Less than 0.1pu
Sag	3 sec-1 min	0.1-0.9pu
Swell	3 sec-1 min	1.1-1.4pu
Long duration variations:		
Sustained interruptions	Less than 1 min	0.0pu
Under voltage	Less than 1 min	0.8-0.9pu
Over voltage	Less than 1 min	1.1-1.2pu
Voltage unbalance	Steady state	0.5-2pu
Wave form distortion:		
DC offset	Steady state	0.0-0.1%
Harmonics	Steady state	0.0-20%
Inter-harmonics	Steady state	0.0-20%
Notching	Steady state	
Noise	Steady state	0.0-0.1%
Power frequency variation	Less than 10 sec	

2.8 Computer Business Equipment Manufacturers Association Curves(CBEMA)

The CBEMA curve is a widely used power quality acceptance curve that illustrates how mainframe computers tolerate voltage fluctuations in both voltage and time. Developed by the Computer Business Equipment Manufacturers Association using historical and experimental data, the curve highlights methods to ensure reliable operation of electronic equipment. Although modern computers generally have higher tolerance than depicted in the original CBEMA curve, it remains a standard reference for reporting power quality variations and as a design target for sensitive devices.

The CBEMA curve, which originated in IEEE Standard 446, plots voltage percentage on the vertical axis against event time on the horizontal axis. Voltages exceeding the envelope can cause overexcitation, overvoltage trips, or insulation failure, while voltages below the envelope may result in equipment dropout due to insufficient energy. The underlying principle is that sensitive devices such as computers, telecom equipment, instrumentation, PDUs, and PLCs will operate reliably if voltage remains within the acceptable range.

Afterwards, a CBEMA working group changed the CBEMA curve to create the ITIC curve (Information Technology Industry Council). It more accurately depicts the functionality of standard single-phase 120V, 60Hz PCs and their accessories, as well as other IT devices like copiers, fax machines, and point-of-sale terminals. The voltage tolerance capability of different loads is defined by both curves, but their application goes beyond computer systems to other solid-state device-based equipment. The ITIC curve gives a greater acceptable range in the ΔV -time plane than the original CBEMA curve, indicating wider application. Steady-State Tolerance: Depending on distribution and load losses, the steady-state voltage may fluctuate up to $\pm 10\%$ from nominal indefinitely.

Low-Frequency Decaying Ring Wave: Depending on system resonance, this region's frequencies usually range from 200 Hz to 5 kHz. It involves transients from switching power factor correction capacitors in the AC distribution system. The transient magnitude increases linearly from 140% at 200 Hz to 200% at 5 kHz and is reported as a percentage of the peak 60 Hz baseline voltage. The forbidden area is occupied by any surge or tsunami that surpasses the upper envelope limitations. All things considered, these curves are crucial instruments for

guaranteeing that delicate equipment functions dependably in the face of common power quality disruptions

[11] [25] [26].

2.9 Mathematical Description:

A deformed voltage waveform can be written as the sum of the basic component V_1 and harmonic component V_h , as shown by equation (2.6).

$$V_s = V_1 \sin(2\pi f_1 t) + \sum_{h=2}^p V_h \sin(2\pi f_h t + \phi_{vh}). \quad 2.6$$

where ϕ_{vh} is the phase of the harmonic voltage and f_h is the frequency of the voltage's harmonic component. A deformed load current waveform can also be expressed as the sum of the basic component I_1 and the harmonic component I_h using equation (2.7).

$$I_L = I_1 \sin(2\pi f_1 t + \phi) + \sum_{h=2}^m I_h \sin(2\pi f_h t + \phi_{ih}) \quad 2.7$$

Where ϕ_{ih} is the phase of harmonic current [27] [28].

2.10 Classification of Harmonics

Here is a basic description of the several types of harmonics [16]. The importance of each category is also discussed.

Strange Harmonics: The harmonic frequencies that come from a deformed waveform that is symmetrical about its average centerline are only odd multiples of the fundamental frequency; even multiples are absent. Odd harmonics are more frequently seen in power systems since most loads produce such current waveforms. **Even Harmonics:** Because the positive and negative portions of the waveform are symmetrical, even-numbered harmonics (such as the second, fourth, sixth, etc.) are typically missing in power systems. As a result, even harmonic limits are usually looser than odd harmonic limits [29]. **Triplen Harmonics:** Odd combinations of the third harmonic, or triplen harmonics, are particularly problematic in three-phase power systems. They significantly raise the zero-sequence current, which raises the neutral conductivity current. Frequencies that are non-integer multiples of the base frequency are

known as inter harmonics. They provide more signals to the power system, which may have a number of consequences, particularly if resonance amplifies them.

Interharmonics are more likely to cause resonance since they span a wider range of frequencies. The non-periodic nature of interharmonics makes some of their effects distinct, while others are comparable to those of normal harmonics [30].

Subharmonics: Subharmonics are frequencies lower than the fundamental frequency. When series capacitors are installed to reduce inductive reactance and increase real power transfer, they can introduce subharmonic currents into the system, creating additional challenges.

Harmonics in Positive, Negative, and Zero Sequences: Harmonics can be classified based on their sequence relative to the fundamental. The seventh harmonic is an example of a positive sequence harmonic that rotates in the exact same direction as the basic. The fifth harmonic is an example of a negative sequence harmonic that rotates in the opposite direction. Zero-sequence harmonics, which include triple harmonics, are in phase with each other and do not rotate [31] [32].

2. 11 Effects of Harmonics on Electrical Utility System.

Both voltage and current harmonics affect electrical utility systems, each in different ways:

Voltage harmonics: Current harmonics frequently result in voltage harmonics. The source voltage is distorted when current harmonics pass through the source impedance. The resulting voltage harmonics are negligible if the source impedance is low. The fundamental voltage waveform can resemble the real value because voltage harmonics are often much less than current harmonics. Because of this, current harmonics typically have little effect on the actual power supplied to the load[6][12]. Current harmonics may add to the real power delivered when voltage harmonics are more noticeable. **Present Harmonics:** Current is typically sinusoidal at the system frequency (50 or 60 Hz). Non-linear loads result in distorted, non-sinusoidal current waveforms, whereas linear loads draw sinusoidal current at the same frequency as the voltage. In addition to semiconductor devices like diodes, MOSFETs, IGBTs, and transistors that produce harmonics, rectifiers are a typical example of non-linear loads. Unless they are over-excited or saturated, which might result in the production of additional harmonics, electric motors typically do not emit substantial harmonics.

Non-linear load currents can cause resonance in the utility's otherwise sinusoidal voltage waveform. Uneven phase loading often results in zero-sequence currents in the neutral conductor, which are amplified by triplen harmonics (3rd, 9th, 15th, etc.). The accumulation of these harmonics can overload the neutral conductor, potentially causing wiring failures. Increased neutral-to-ground voltage from high neutral currents can also lead to malfunctions in sensitive electronic equipment. Transformers can also be impacted by harmonics. The secondary current's crest factor rises with high harmonic currents, potentially saturating the transformer. When the distorted secondary current passes through a series impedance, this saturation may result in flattened or suppressed voltage peaks, further altering voltage waveforms [33].

2.12 Harmonics Assessment and Quantification

A three-phase AC source is linked to a non-linear load at the point of common coupling (PCC) in order to quantify harmonics. By creating a reference current, harmonics in the load current are reduced. The FFT tool in MATLAB/Simulink is used to assess the current waveform's harmonic content. The degree of harmonics in both voltage and current signals is then measured using Total Harmonic Distortion (THD). The Total Harmonic Distortion for current, or THDi, is defined mathematically as "a ratio of adding of all the harmonic components of the current waveform to the basic component of the current waveform" [20]. by Equation (2.8).

$$THDi = \sqrt{\frac{I_2^2 + I_3^2 + I_4^2 + \dots + I_n^2}{I_1^2}} \times 100\% \quad 2.8$$

$$THDv = \sqrt{\frac{V_2^2 + V_3^2 + V_4^2 + \dots + V_n^2}{V_1^2}} \times 100\% \quad 2.9$$

2.13 Standards governing Harmonics:

2.13.1 IEEE-519 Standard

Guidelines for comprehending harmonics and applying harmonic limitations in power systems can be found in the IEEE-519 standard. To evaluate the system's harmonic levels, it

is helpful to represent harmonics as a percentage of the fundamental. IEEE-519 limits individual harmonics to 3% and permits a maximum voltage distortion of 5% THD for power systems running at 69 kV and lower.[34] The system's short-circuit strength determines current harmonic restrictions; the stronger the system, the more harmonic current a customer can inject. IEEE-519's primary objective is to guarantee high-quality power by preventing a single consumer from producing harmonic issues for the utility or other users.

2.13 .2 IEC-61000-3-2 Standard

The primary voltage parameters at user supply terminals in public low- and medium-voltage distribution systems under typical conditions of operation are specified by the EN50160 standard. EN50160 establishes the anticipated bounds or ranges that voltage characteristics should stay within rather than outlining a typical situation. The standard states that the supply voltage's total harmonic distortion (THD), which includes harmonics up to the 40th order, cannot be greater than 8% (37).

2.13.3 EN50160.

In common low-voltage and medium-voltage electrical systems for distribution, the EN50160 standard describes the main voltage characteristics at network users' supply terminals under normal operating conditions. EN50160 establishes the bounds or values whereby the voltage parameters can be supposed to retain, rather than describing the typical case in a public supply network. According to this standard, the THD of the supply voltage, which includes all harmonics up to the 40th order, must be less than or equal to 8% [6].

2.13.4 ANSI C82.77

For lighting equipment, this standard specifies both harmonic limits and testing procedures. It deals with harmonic and interharmonic emissions in the low-frequency region of 0–9 kHz. Comparably, under typical operating conditions, the EN50160 standard specifies the primary voltage characteristics at user supply terminals in public low and medium voltage distribution networks[37] It establishes the expected ranges for voltage characteristics rather than defining a typical situation. EN50160 states that the supply voltage's total harmonic distortion (THD), which includes harmonics up to the 40th order, cannot be higher than 8%.

2.14 Why Harmonics Mitigation.

Harmonic currents in power systems have several detrimental effects, including lowering the power factor and degrading voltage quality. The increasing use of consumer equipment that generates harmonics, such as power electronic devices, has led to a rise in harmonic currents in electrical distribution networks. The widespread adoption of nonlinear loads in industries has caused significant disruptions in power systems. Along with high reactive power consumption, harmonic emissions and current imbalances are becoming more common. Harmonic currents can also induce voltage harmonics as they flow through the grid.

These currents may have an adverse effect on protective devices, control systems, power system components, and other harmonically sensitive loads. Harmonic currents raise the RMS and peak values of line currents in addition to generating voltage distortion at the point of common coupling (PCC), resulting in higher losses, overheating, equipment overloading, and potential failures of transformers, capacitors, and motors. They can also trigger frequent circuit breaker trips, blown fuses, resonance in distribution networks, metering errors, and interference with telecommunications. Due to these widespread impacts, harmonics are a major power quality concern and must be effectively mitigated [29].

2.15 Power quality solutions:

There are four main strategies for addressing power quality problems. The first approach is to design electrical systems and equipment to prevent disturbances that could cause malfunctions. Manufacturers of sensitive devices can reduce or even eliminate the effects of power quality issues by making their equipment more resilient to such disruptions. Depending on the situation, additional components like capacitors to temporarily supply energy during voltage dips can be integrated into the equipment to maintain proper operation [2][1]. There are four primary strategies for addressing power quality issues. First, equipment can be modified to reduce its sensitivity to power disturbances. For example, specialized K-factor transformers can be designed to withstand harmonic currents. Second, identifying the root cause of power quality problems and addressing it directly is crucial, as the origin and nature of the issue often determine the most effective solution. Third, the medium through which electrical disturbances are transmitted can be identified and mitigated or eliminated to reduce

their impact. Finally, power conditioning equipment can be used to manage the symptoms of power quality problems. Such equipment provides essential protection by reducing or eliminating the effects of disturbances and can be applied at the source, along the transmission path, or at the point of use.

Power quality issues can be addressed using a variety of devices and techniques, each with its own strengths and limitations. These include voltage regulators, surge suppressors, motor-generator sets, low-voltage line reactors, isolation transformers, noise filters, dual feeders with static transfer, uninterruptible power supplies (UPS), harmonic filters, and dynamic voltage restorers (DVR). At ADSF, power quality problems were severely affecting both the power system and industrial equipment, highlighting the need for the implementation of multiple mitigation strategies to reduce their impact.

2.16 Power Quality Monitoring

The act of gathering, evaluating, and interpreting unprocessed measurement data in order to generate valuable information about the electrical system is known as power quality monitoring. Parameters including voltage, current, average and instantaneous power factor, active and reactive power, frequency, and other disturbances are usually continuously measured and recorded. For electric power equipment and the detection of power quality issues at particular places, monitoring is crucial. The main objectives of power quality monitoring include identifying appropriate mitigation strategies, predicting the performance of connected equipment, and diagnosing issues in both the supply network and consumer loads[2].

2.17 Power Quality Mitigation Techniques

Public, industrial, and residential power distribution systems all need to pay close attention to power quality issues. Electronic equipment or specialized power devices can be used to do mitigation. The employment of power electronic controllers in distribution networks to improve the dependability and quality of power supplied to customers is referred to as "custom power." Network reconfiguration and compensation devices are the most widely used types of custom power devices.

2.17. 1 Network Reconfiguring Type of Custom Power Devices

Gate stop thyristors (GTOs) and ordinary thyristors are two examples of devices that can be used to reconfigure networks. In order to rapidly limit or interrupt current during faults, static circuit breakers and current limiters are frequently used. Loads are transferred to alternate feeders via Static Transfer Switches (STS), which shield them from malfunctions or voltage swells or sags on the primary feeder. Uninterruptible Power Supplies (UPS), which guarantee steady and continuous power to sensitive loads, are another way to reduce voltage dips, harmonics, and brief disruptions. [35][36].

2.17.2 Compensating type of Custom a Power Devices

Problems including active filtering, balance of load, correction of power factors, and voltage regulation (sags and swells) are addressed by custom power devices. The Unified Power Quality Conditioner (UPQC), Dynamic Voltage restaurateur (DVR), and Distribution Static compensated (DSTATCOM) are the three primary varieties of these devices. In order to mitigate voltage sags and disruptions from the AC supply, a specialized device called a Dynamic Voltage Restorer (DVR) injects compensatory voltage into power distribution circuits. A voltage source inverter, a series injecting transformer, an AC filter, a control unit, and a power-storing device-which could be batteries, superconductivity magnetic storage, or another DC source-are its components.

A Distribution Static Compensator (DSTATCOM) is a solid-state device that is linked in parallel to distribution networks to improve the overall stability and quality of the electrical supply by correcting power quality problems such flicker, harmonics, voltage imbalance, and sags. [21].[27. An isolating transformer, filter, two-level voltage source inverter, and DC energy storage unit are the components of an Uniform Power Quality Conditioner (UPQC), which is connected in pairs to the distribution network. In order to develop compensatory devices for UPQC, parallel and series-connected filters are combined. It makes use of two series voltage source inverter bridges that share an energy storage unit and act as active series and active shunt compensators. Due to the numerous solid-state devices involved and the intricate control needed, the UPQC's primary drawbacks are its high cost and operational complexity.

2.18 Voltage Source Converter

A voltage source converter (VSC) is a power electronic system that can generate a sinusoidal voltage with a chosen frequency, amplitude, and phase angle. It is made up of switching devices and a storage unit. During disruptions, the VSC can either temporarily replace the lost voltage or restore it in active power filter (APF) applications. Insulated Gate Bipolar Transistors (IGBTs), Integrated Gate Combined Thyristors (IGCTs), Gate Turn-Off Thyristors (GTOs), and Metal Oxide Semiconductor Field Effect Transistors (MOSFETs) are all typical switching devices utilized in VSCs. IGBTs are typically preferred for voltage sag compensation because of their low ON-state power loss and ability to operate at high switching frequencies with short switching durations [16] [37].

2.19 Harmonics Mitigation Techniques

Power electronic converters are frequently used in power systems. These converters have certain advantages, but because of the non-sinusoidal current they draw, they also have significant drawbacks. Furthermore, the use of energy-efficient equipment has become much more popular in recent years. The injection of harmonics into the distribution systems is a disadvantage of these loads [22]. A summary of harmonic analysis and mitigation strategies is given in [23]. Outlining the benefits and drawbacks of each. Techniques for active power factor adjustment, which use clever algorithms to eliminate distortive power, have been examined for additional study. The nonlinear physics of harmonic phenomena is explained in order to investigate its potential uses. An optimal selective harmonic mitigation (OSHM) is described in [24]. The method is applied using the lowest switching frequency possible to comply with three grid codes: IEC 61000-3-6, CIGRE JWG C4.07, and EN 50160[38].

Additionally, the suggested approach minimizes the individual harmonics to the greatest extent feasible. The harmonics up to the 40th are decreased from both individual harmonic and THD viewpoint in order to satisfy three voltage harmonic standards: EN 50160, CIGRE JWG C4.07, and IEC 61000-3-6. [25] Harmonics in the load current can be filtered out using a shunt-APF,(39)[39]. presents a unique SHM-PWM control method that can meet grid requirements even when DC link voltages are not equal.

The approach is based on the interpolation of multiple sets of angles obtained for specific imbalance situations. The proposed control approach is demonstrated to be supported by both simulation and experiment results. In most countries, the standard frequency for power systems is 50 or 60 Hz. The connection of non-linear loads to the supply is the primary cause of harmonics. Harmonics can cause large currents in neutral conductors in a three-phase, four-wire systems [26][40].

Furthermore, the waveforms of voltage and current are no longer sinusoidal [27]. Power electronic devices are widely used at almost all power levels due to their efficient performance and control features [28]. Consequently, the problem of power harmonics has grown significantly. Harmonics have negative effects like as circuit breakers tripping, transformers and cables overheating, capacitor failure, an increase in resistive losses or voltage stress, and a drop in power factor [29]. The representation of a distorted waveform is Eq. (2.10).

$$x(t) = x_0 + \sum_{k=1}^{\infty} x_k \sqrt{2} \sin(k\omega t - \phi_k) \quad 2.10$$

Additionally, the cost of power is raised by poor power quality [30, 31]. Harmonics are mitigated using both passive and active methods [32][38]. A brief discussion of these methods is provided here. To best fit the application, the benefits and drawbacks of different methods are also mentioned.

2.19.1 Passive Harmonic Mitigation Techniques

In order to prevent harmonic currents from entering the system, a high series impedance is placed between the supply and the load in a number of passive techniques used in electrical networks [39]. As an alternative, a low-impedance parallel circuit can be connected to deflect harmonic currents, enabling the undesirable currents to avoid sensitive components.

Passive Filters: In passive filters, a resonant circuit is built using reactors and capacitors that are adjusted to remove an exact sequence of harmonics [24]. Each harmonic order requires a dedicated filter. While passive filters are generally less expensive than active filters, they are designed for a single operating point, making them less efficient under partial load conditions. Additionally, the arrangement of capacitors and inductors in passive filters can lead to a reduced power factor. By adjusting inductors and capacitors to exhibit high impedance at particular harmonic frequencies, series passive filters restrict harmonic currents while permitting the fundamental

current to flow. In parallel passive filters, harmonics are provided with a low-impedance path that directs them to ground.

2.19.2 Active Harmonics Mitigation Techniques

Active methods can lessen harmonic distortion by adding voltage or current distortion of the same amplitude and antiphase at PCC. Active power filters are commonly employed to eliminate harmonic distortion within the constraints of the IEEE-519 standard [13]. An efficient substitute for managing harmonic levels in power systems is an active filter. They have a number of benefits over passive filters, such as the capacity to adjust to shifting load conditions, compensate for reactive power, target particular harmonic frequencies, and prevent resonance issues.(4). The active filter initially generates a reference current that is the inverse of the extracted harmonics current in order to cancel each particular harmonic. The reference current is then injected at the PCC via power electronic switching [5].

Table 2.6: the comparission of passive and active filter devices.

Active filter	Passive filter
Use of active componenets such as OP-AMP and transistors	Use of passive components such as capacitors, Inductors, Resistors etc
Provide high gain	Provide Low gain
Easy tuning	Tunning is not easy
Cheaper and contains less components	Inductors are costly
Frequency response is sharp	Frequency response is not sharp
Large input impedance along with low output impedance do not cause loading issues.	They are experiencing loading issues.

2.20 Basic steps in solve of power quality problems

Examining the relationship between the utility supply system and the customer facility is frequently necessary to address power quality concerns because both parties may be involved in or impacted by these issues. As a result, several mitigating techniques could be used. The strategy selected should take into account whether the problem is a current power quality issue or one that might arise from a new design or suggested system modifications[2][7].

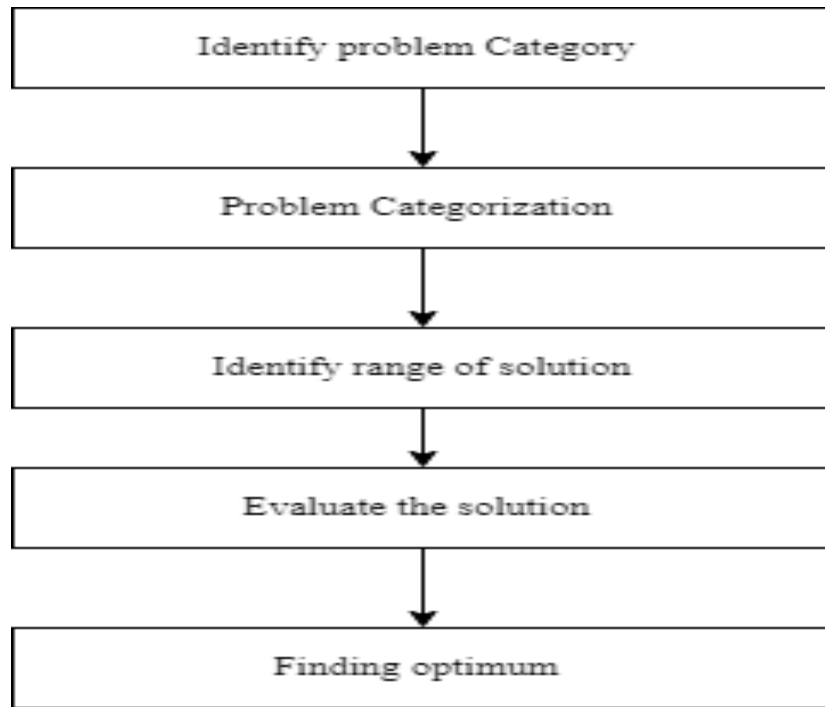


Figure 2.7: Steps in solve power quality problems

Finding the root of power quality problems is the first step in resolving them because it serves as the foundation for possible fixes. It is crucial to comprehend the several kinds of power quality issues, including voltage swells and sags, interruptions, and harmonics. The problem must then be described via measurements and data gathering. The main technique for identifying the issue or evaluating the existing system is measurement. Potential solutions can be suggested once the issue has been thoroughly recognized. These solutions are assessed at every stage of the system, from the utility to the impacted end-user equipment, taking into account ride-through capabilities and mitigation devices.

After proposing solutions, they are assessed from both technical and economic perspectives, taking into account any limitations. Only solutions that are technically feasible are considered further, and among these, the most cost-effective options are identified. The optimal solution is therefore the one that effectively resolves the power quality issue while minimizing cost. The ultimate decision is influenced by a number of factors, including the type of power quality issue, the number of impacted end users, and the available solutions.

2.21 literature review

Depending on the viewpoint of various stakeholders, such as consumers and equipment makers, the phrase "power quality" might have different meanings. To put it another way, any electrical supply fault such as variations in voltage, current, or frequency that causes client equipment to malfunction is seen as a power quality issue [12]. Power quality, as defined by IEEE Standard 1159, is the appropriate grounding and delivery of electrical power to delicate equipment in a way that guarantees proper operation. Today, many consumer installations rely heavily on power electronics-based devices. Residential users commonly operate household appliances such as dishwashers, dryers, microwave ovens, televisions, VCRs, personal computers, and HVAC systems. Workstations, PCs, copiers, printers, and lighting systems are among the equipment used in commercial and office settings. Conversely, industrial users use technologies including CNC machines, variable speed drives, automation and data processing systems, PLCs, soft starters, and inverters. Many of these devices are quite sensitive to fluctuations in power quality [5].

The impact of power quality (PQ) problems on consumers has been the subject of research in a number of nations, as reported in the literature. Manufacturers of electrical and electronic equipment as well as end users are putting more and more pressure on utilities to enhance the quality of their power supply. However, utilities occasionally place restrictions on the quality of power that end consumers can draw. National rules have been established in a number of nations due to worries about the quality of energy. Garg and Nijhawan (2015), for instance, observed that consumers are becoming more worried about power quality at all utilization levels.

.Sensitive equipment and non-linear loads are becoming more common in both residential and industrial sectors. Power quality involves three primary stakeholders: utility companies, equipment manufacturers, and end users. The first and perhaps most critical step in addressing power quality problems is conducting a power quality survey, which aims to identify, recognize, and eliminate electrical disturbances that can affect data collection networks. Various mitigation devices are then employed to resolve these issues.

Birdi (2006) proposed a method for automatically classifying and analyzing power quality events using relay-recorded data. According to IEEE Std. 1159-1995, this method identifies

and categorizes events based on the duration and magnitude of three-phase voltages, followed by intuitive graphical representation of the results. The power system's basic frequency and its harmonics are both estimated using Fast Fourier Transformation (FFT).

Other studies, such as those on coordinated voltage control in distributed generation systems, emphasize active strategies to maintain voltage quality, improve dispersed generation penetration in distribution networks, and ensure adequate power quality for consumers. In 2016, Kumar and Seetharamudu discussed the role of power electronic equipment and technical assessments at various levels of power engineering. For effective power regulation in transmission networks, Flexible AC Transmission Systems (FACTS) are frequently utilized. Power electronic-based conditioners are also used to solve power quality problems. The operating concepts and applications of transmission and distribution equipment, including STATCOM, SSSC, UPFC, DSTATCOM, DVR, and UPQC, were analyzed and contrasted in order to mitigate power quality issues [21][27].

The application of Dynamic Voltage Restorers (DVRs) and Unified Power Flow Controllers (UPFCs) for reducing voltage swells and sags was covered by Bhaskar et al. (2010). A DVR is a specialized power device used in distribution networks to shield customers from abrupt voltage decreases or increases, whereas a UPFC is a device in electrical transmission networks that offers quick reactive power adjustment. Among the most important power quality problems utilities deal with are voltage sag and swell. By adding a three-phase regulated voltage source to the supply voltage during sag events, the DVR raises the load voltage back to its pre-sag level. It can recover voltage in milliseconds and is intended to safeguard loads within a given MVA range. UPFC and DVR components are frequently modeled separately and their performance assessed using MATLAB.

Sace (2008) presented a case study on the use of solid-state harmonic filters in the textile industry to improve energy efficiency and power quality. Detailed research was conducted at several Indian textile mills to assess the impact of poor power quality, particularly harmonics, on energy consumption and productivity. Harmonics in transformers, bus bars, and power cables contribute to losses, including increased eddy current losses in transformer windings. Mitigating these harmonic-induced losses helps conserve energy and reduce utility costs. The

study focused on a textile mill where the spinning section was powered by a 1.5 MVA transformer, with harmonic measurements taken both with and without the filter.

A methodology based on the event tree approach was also put out to assess the financial impact of voltage sag incidents on client operations. This method considers how equipment failures caused by voltage sags translate into monetary losses. The approach also allows for assessing the practicality and effectiveness of various mitigation strategies. A quantitative case study demonstrated its application, enabling customers to identify the most cost-effective solution for minimizing the impact of voltage sags on their operations [7].

An inquiry into the average 15/0.4kV, low voltage electric power distribution network is described, along with an analysis of weak voltages and significant economic losses. The MATLAB/Simulink Sim Power System toolbox was used to model the network using conventional network parameters for low voltage typical electric power distribution networks. The paper's summary offers suggestions for improving voltage profiles and bringing the imbalanced voltage back to an acceptable level [9][41][42]. One of the power quality concerns identified in this study is voltage sag, which is mitigated by the Dynamic Voltage Restorer (DVR).

Voltage sag, a sudden reduction in voltage from normal voltage, can cause damage and production loss, especially in the industrial sector. When starting motors that need a large amount of lagging current, voltage sag is always linked with short-circuit incidents. The researchers are close to finding a solution since voltage sag is exacerbating the effects. In order to reduce harmonic issues, numerous products have been developed recently, including Active Power Filter, Variable Voltage Restorer (DVR), Distribution Static of Compensator (DSTATCOM), and Uninterruptible Power Supply (UPS). The shunt active power filter system, which will be simulated using MATLAB/Simulink software to lessen the harmonics problem, is the only topic of this study. The voltage injection system and harmonic problem can also be computed mathematically [4].

2.22 Summary of literature review

There has been a rapid increase in consumers preference towards good power quality and energy saving. The role of SAPF in mitigation of current harmonics has been deeply studied.

Moreover, most of these studies have been mainly undertaken to understand the working principle of SAPF and control strategies used in development of active power filters. The Scopes of most of the existing studies are limited to either reference current generation or current injection part of active power filtering. Moreover, there are no or very few studies on the synchronization of shunt active power filters. This feature plays an important role in the generation of reference current and becomes more valuable under adverse distribution network conditions. Therefore, in the light of previous discussion, a hypothesis for the research is build which stated that, Shunt Active Power Filter synchronized with the distribution network voltage may shows better performance than its counterpart in the phase of introduced disturbances". Moreover the study and literature review reveals that existing techniques for reference current generation are not very effective under the effects of distribution network disturbances. The reason for that is the use of a conventional phase locked loop (PLL) technique like synchronouse reference frame (SRF) for estimation of frequency and phase inside the algorithm used for reference current generation. Literature study reveals that SRF-PLL is not very effective under the effects of network distribution voltage disturbances. Thus there is a necessary need to address the problem of synchronization of shunt active power filters. Finally, Therefore, there is a need for a comprehensive and robust technique to fix the problem of reference current generation under distorted network conditions. This will result in better harmonics compensation capability and robustness of shunt active power filter under the effects of distribution of network disturbances. Many studies have addressed power quality issues, exploring their causes, effects, and potential solutions for mitigating these problems in power systems. Power distribution networks often encounter challenges such that an harmonic distortion, voltage sags and swells, and voltage unbalances. Power distribution networks often encounter challenges such that an harmonic distortion, voltage sags and swells, and voltage unbalances. Consequently, implementing solutions to improve power quality is essential to minimize disruptions and their adverse impacts.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 BACKGROUND OF ARJO DEDESSA SUGAR FACTORY

Arjo Dedessa Sugar factory is one of the sugar factories in Ethiopia's western region, Oromia regional state East Wollega Zone Arjo Awuraja woreda at Jimma, Illu Abba Bor, Bunno Bedelle district, which are 395 kilometers from Addis Ababa and 8 kilometers from Arjo town. The entire factory's construction was completed in 2007 GC. In December 2010 GC, the factory began producing white sugar with an initial capacity of 8000 tons per day(TCD).

3.2 Power Distribution System of Arjo Dedessa Sugar Factory

The power distribution system at Arjo Dedessa Sugar Factory (ADSF) is fed from the Bunno Bedelle substation via a 15 kV Bedelle feeder line. The system includes nine distribution transformers, three rated at 3000 kVA and the remaining six at 2500 kVA. For usage throughout the industry, these transformers reduce the voltage from 3.3 kV to 0.4 kV (3.3kV/0.4 kV). Additionally, the factory has two diesel generators, each with a capacity of 2500 kVA, which provide emergency power to critical and sensitive loads such as the cooling tower, pumps, lighting, workshop equipment, welding machines, and offices. Power is also supplied by a single 8 MW steam turbine generator, which supports the transformers, diesel generators, and factory loads. This capacity is sufficient for factory operations, which reach a maximum load of approximately 11 MW, as confirmed from equipment nameplates during a field visit.

The factory's power distribution system includes various nonlinear loads, which are identified as the primary source of power quality issues. These nonlinear loads include motors, DC and AC drives, variable frequency drives (VFDs), adjustable speed drives, and cooling fans. The study focuses primarily on the loads supplied through the nine distribution transformers. The distribution panels serve a wide range of equipment, including variable speed drives, AC and DC drives, and squirrel cage or wound rotor motors, which operate machinery such as cane unloading equipment, belt conveyors, cane carriers (auxiliary, inclined, and anvil types),

horizontal cane handling systems, cane preparatory equipment, milling units, raw juice crystallizers, cooling tower pumps and fans, centrifugal machines, agitators, elevators, and air compressors.

The factory's electrical power distribution is organized through seven Central Main Distribution Boards (CMDBs) and seven Main Distribution Boards (MDBs), all of which can be represented in a single-line diagram. Cutter 1 : stands by a motor 400 KW with 600 rpm and with a drive turbine steam power, Cutter 2: stands by motor 400 KW with the speed 600 rpm and with a drive turbine steam power, Shredder: its rotor speed of motor is 1000-1200 rpm. The drive steam turbine has a speed of 1000 rpm. Milling Room: There are five mills, each of which has its own power rating. The motor in this milling for each of the five mills has 800 kW with a speed of 1200 rpm.

Mixed Juice: it has two motors that contain the power of 110 kW with 1485 rpm. Defecation room: the motor power is 110 kW with 1485 rpm. Sugar research institute: the number of motors used is four, and their power rating is 30 kW with 1460 rpm. *Syrup*: its motor rating is 110 kW with a speed of 1485 rpm. A Centrifugal: it has 22 motors. 11 motors have a power rating of 75 kW with a speed of 1480 rpm, and 11 motors have 90 kW with a speed of 1480 rpm. Sugar handling: It has six motors for carrying sugar past to the elevator, which contains a motor power rating of 4 kW with a speed of 1435 rpm and a belt conveyor motor. The main central Distribution board of Arjo Dedessa Sugar Factor were seven, i.e from CMDB1-CMDB7.

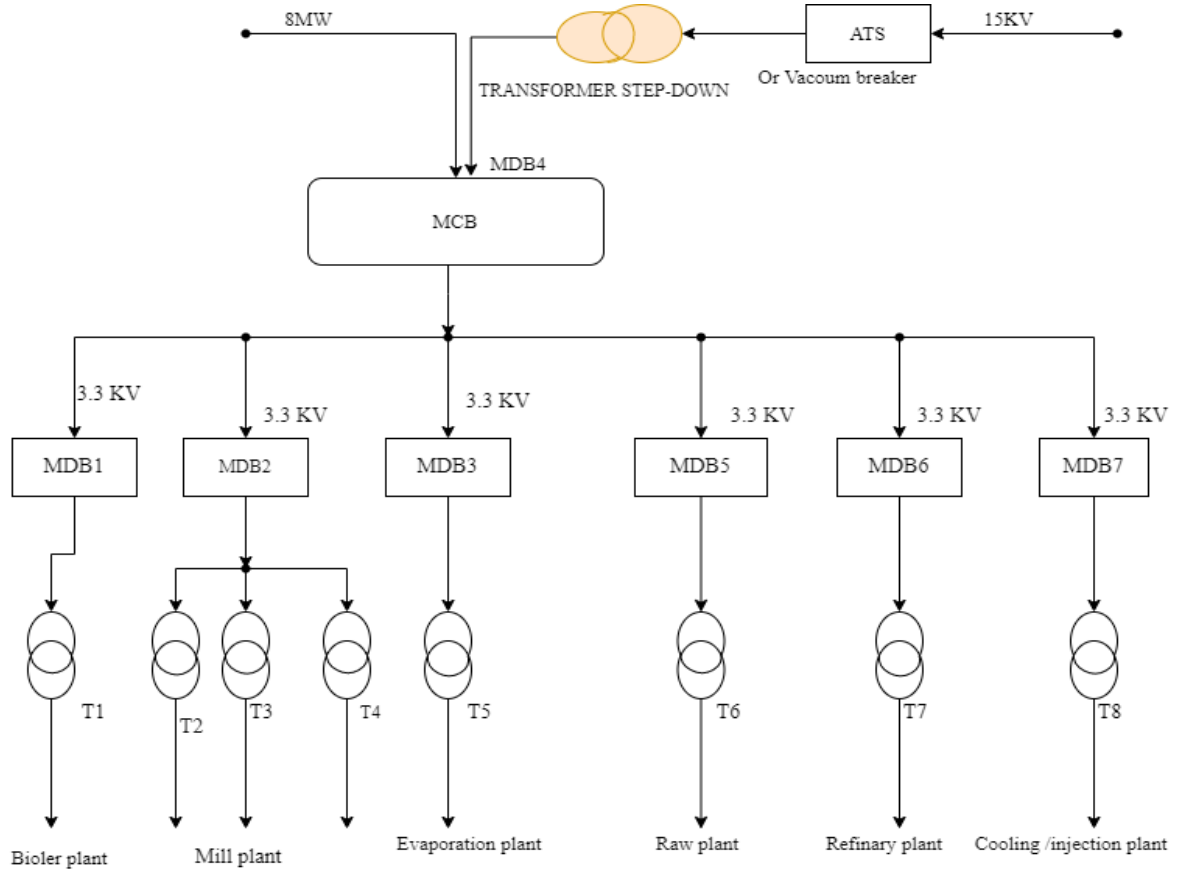


Figure 3.1:Single line diagram main distribution board network of ADSF

3. 3 Installed loads to central main distribution oards (CMDB)

Table 3.1 displays the tabulated measurements of active power, reactive power, and power factor for the electrical loads linked to the central main distribution boards. The apparent power for the loads attached to transformer 1 can be computed as follows:

$$S_{INS} = \frac{P_{ins}}{F_f} \quad 3.1$$

Then, the reactive power become

$$Q_{INS} = \sqrt{S_{ins}^2 - P_{ins}^2} \quad 3.2$$

Table 3.1: total active and reactive at each main distribution board.

Types of source	Main distribution board	Power factor	P_{ins} (KW)	Q_{ins} (KVAR)	P_{ins} Total (KW)	Q_{ins} Total (KVAR)
Transformer 1	MDB for mill one and two	0.81	1150	579.189	1150	712.7
Transformer 2	MDB for mill three and four	0.85	1150	800	148.5	828.5
Transformer 3	MDB for mill five	0.80	240	495.79	1150	801.9
The installed sum of active and reactive power					2448.5	2343.1

Table 3.1 shows that the total active and reactive power connected to the main central distribution board of the mill plant is 2448.5 KW and 2343.1 KVAR, respectively. Among the loads found in the plant are motors, air compressors, water pumps, AC and DC motors, ASD (Adjustable Speed Drives), VFD (Variable Frequency Drives), welding machines, lighting, and office equipment (computers, printers, etc.). the table 3.6, 3.7 and 3.11 is the voltage distortion measured from the load disturbance of the Mill plant.

3.4 Software Requirement

MATLAB/Simulink 2015a software is used for the simulation of the designed and modeled system. Draw.jo, 5-1window installer is used for drawing of single line diagram of the Arjo Dedessa Sugar factory power distribution system.

3.5 Material Requirement

Fluke 435, a power quality analyzer is an electrical device that can measure active power, reactive power, voltages, currents, frequency, and harmonic distortion in electrical power distribution networks.

3.6 Methodology of the Research

The research methodology is structured into five main components: Literature Review: The first part involves gathering information on power quality issues in power distribution systems from various published sources, including books, research papers, articles, journals, lecture notes, and other relevant materials. Data Collection: The second part focuses on investigating power quality problems in the Arjo Dedessa Sugar Factory's distribution system using both primary and secondary data. Primary data sources include equipment nameplate specifications, machine manuals, direct measurements from the Central Main Distribution Board using a Fluke 435 power quality analyzer, and available recorded data from the factory's power distribution system. Secondary data are collected through interviews with electrical technicians, the factory's power manager, and other staff members.

Mitigation Design: The third part involves designing appropriate mitigation strategies for the power quality issues identified in the factory. This includes mathematical modeling of the existing system and the mitigation devices. The overall system is modeled using MATLAB/Simulink based on the mathematical analysis of the total system. Simulation: The fourth part simulates the modeled system in MATLAB/Simulink, demonstrating the power quality issues and the effectiveness of the proposed improvement techniques. Analysis and Conclusions: Finally, the collected and simulated data are analyzed and compared with IEEE power quality standards. Conclusions are drawn, and recommendations are provided based on the results of the research.

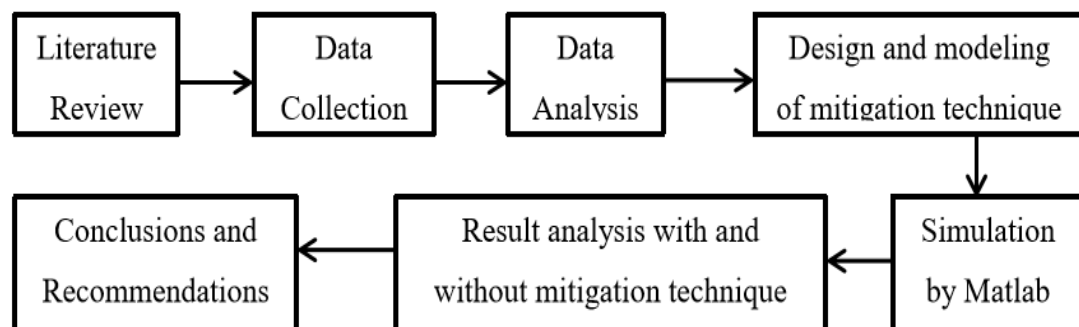


Figure 3.2: flow daigram of methodology

3.7 Measured load parameters of major drivers (Motors)

The Arjo Dedessa Sugar Factory (ADSF) operates multiple low-voltage (400 V) motors across different sections of the plant. Measurements were conducted at the main incomer MCC panels (CMDB) while the plant was in operation. The study of these major low-voltage motors focused on evaluating their electrical load parameters, including voltage, current, active power, apparent power, reactive power, and power factor, as shown in Figures 3.2, 3.3, 3.4, and 3.5.

Table 3.2: Load parameter of major drives in boiling house

Name	Voltage(v)	Current(I)	Active power(kw)	Apparent power(KVA)	Reactive power(KVAR)	Power Factor(pf)
Sugar driver ID fan	386.6	61	29.8	40.6	28.7	0.74
Cane wash pump	392.2	161.3	88	11	66.6	0.74
Centerfugal	382	79	39	53	36.49	0.79
Messcute pump	388.6	13.25	3.21	9	8.3	0.76
Final molasses transfer pump	390.6	14.26	8.56	9.24	1.67	0.85
Boiler feed back pump	385	200.5	150	180.5	9.6	0.94
Boiler of fan	387	153.4	102.5	103.5	7.3	0.95

Table 3.3: Load parameter of major drives in sugar clarifications

Name of motor	Volt(v)	Current(I)	Active power(KW)	Apparent power (KVA)	Reactive power (KVAR)	Power factor (pf)
Weight juice pump	391.8	202.3	118.5	139	70.3	0.85
Condensate Vacuum pump	388	15.5	8.36	9.5	6.25	0.75

Table 3.4: Load parameters of major drives in milling house

Name of motor	Volt(V)	Curent(I)	Active power(KW)	Apparent power(KVA)	Reactive power (KVAR)	Power Factor (pf)
MCC	388.1	58.2	27.9	38.9	28.1	0.72
Cane elevator	389.3	60.12	26.5	40.4	31	0.85
Intercane carrier	388.5	25.85	10.15	18.5	15.5	0.75
Cane feeder table	388.6	49.21	28.29	32.45	15.89	0.71
Feed table elevator	387.9	28.12	6.50	19.18	16.95	0.65

Table 3.5: Load parameter of major drives in cooling tower

Name of motor	Volt (V)	Current (I)	Active power(KW)	Apparent power(KVA)	Reactive power(KVAR)	Power Factor (pf)
Water supply pump	383	42	24.15	28.57	12.36	0.88
Circulation water pump	410	355	125.8	163.0	99.5	0.79
Injection pump	405	430	240.2	302.7	141.25	0.72
Condenser ID fan pump	410	73.5	35.5	52.3	37.8	0.67

3.8 Power quality assessments in Arjo Dedessa Sugar Factory power distribution system.

3.8.1 Long duration voltage variation

Prolonged disruptions There have been numerous disruptions that lasted more than a minute during the monitoring period. According to Tables 3.6 and 3.7, the interruptions happened on the third and sixth days at 07:38:18 and 11:19:40, respectively, and on the fourth and sixth

days at 08:45:36 and 12:12:05, respectively. Utility system issues, such as three-phase short-circuit faults, are the root cause of the factory interruption.

Table 3.6: Long duration voltage variation phase to neutral line

Tiral no	Time	Type of problem	Voltage level			Duration
			L1	L2	L3	
1	05:20:35	Voltage sag	218.74	222.55	219.65	120msec
2	All day	Normal	Normal	Normal	Normal	All day
3	07:18:38	Sustained interruption	0	0	0	50msec
4	03:12:50	Voltage sag	205.30	206.58	207.50	15msec
5	08:39:45	Voltage sag	206.00	209.00	205.0	50msec
6	11:19:40	Suntained interruption	0	0	0	10min

Table 3.7 : Long duration voltage variation from phase to phase line (23-28/06/2018)

Trial No.	Time	Type of problem	Voltage level			Duration
			L1	L2	L3	
1	04:15:21	Voltage sag	395.40	389.62	380.00	30msec
2	11:01:39	Voltage sag	370.25	390.00	360.40	110msec
3	All day	Normal	Normal	Normal	Normal	All day
4	08:40:36	Sustaine interruption	0	0	0	40min
5	10:15:53	Voltage sag	374.25	340.15	362.55	152msec
6	12:12:05	Sustiane interruption	0	0	0	20min

3.8.2 Short duration voltage variation

fluctuations in the root mean square (RMS) voltage at power frequency lasting less than a minute are referred to as short-duration voltage fluctuations. Measurements were made from the distribution transformers' secondary side in order to precisely record these fluctuations.

Voltage Sag: As indicated in Tables, voltage sags were noted on phase-to-neutral and phase-to-phase lines over varied lengths of time. The primary cause of these sags is identified as three-phase short circuits within the Arjo Dedessa Sugar Factory's power distribution system. Data on voltage sags were collected through weekly recorded measurements, interviews with the electrical power section director and staff, and direct measurements at the Central Main Distribution Board using a Fluke 435 power quality analyzer. Consequently, identifying an effective mitigation strategy for voltage sags in the factory's distribution system is necessary.

Effects of Voltage Sag on the Arjo Dedessa Sugar Factory

Voltage Sags: Among all power quality disturbances at the Arjo Dedessa Sugar Factory, voltage sags are the most frequent. While they may not be as costly as full interruptions, their prevalence makes them a dominant issue, and they may occasionally have consequences similar to those of a supply disruption. Because equipment may not function effectively at lower voltage levels, even relatively shallow voltage sags can cause disruptions to production operations. Particularly impacted are sensitive components like motors, PLCs, and variable speed drives (VSDs). A few crucial parts of equipment can completely stop output in many manufacturing processes, causing significant financial losses as well as extra time for cleanup and restart.

According to documented data, winding insulation failures, mechanical damage to wires, or incorrect wiring by technicians that lowers the voltage profile are frequently the cause of short-circuit defects in the plant. Even for very brief periods of time (1–2 cycles, or less than 100 milliseconds), devices like electronic process controls, sensors, computer controls, PLCs, VSDs, and even conventional relays may trip if the voltage falls below 90% of nominal.

Following such unscheduled pauses, recovery times might vary from minutes to hours or even days. At the factory, voltage sags have been found to result in malfunctions such as malfunctioning sensors, prolonged short-circuit currents that prevent breakers from tripping, DC drive controls and PLCs tripping, and decreased lifespan and efficiency of electrical equipment, especially motors. Voltage swell was not seen on any of the three phases throughout the test time. Voltage swell is defined as an increase in RMS voltage or current from 1.1 to 1.8 pu that lasts between 0.5 cycles and 1 minute. An interruption happens when the load current or supply voltage falls below 0.1 pu for shorter than a minute. There were no brief disruptions found at the Arjo Dedessa Sugar Factory during the survey. As a result, brief

disruptions are uncommon in the production, and installing mitigation devices for such occurrences is not immediately necessary

3.8.3 Voltage Unbalance

When the voltages across several phases have differing magnitudes and phase angles, this is known as voltage imbalance. The Arjo Dedessa sugar factory's measured maximum voltage imbalance values are displayed below in order to calculate the percentage of voltage imbalance at the plant.

Table 3.7: Measurement results of max. voltage unbalances of ADSF(23-28/06/2018)

Voltage		Measured value in V
Phase to neutral voltage (Voltage unbalance =3.30%)	V1	218.74
	V2	222.55
	V3	219.65
Phase to phase voltage (Voltage unbalance=2.42%)	V12	395.40
	V13	389.62
	V23	380.00

$$V_{av} = \frac{V_{12} + V_{13} + V_{23}}{3} = \frac{395.40 + 382.62 + 380.00}{3} = \frac{1158.02}{3} = 386.00V$$

Voltage imbalance is defined by the NEMA (National Electrical Manufacturers Association, USA) standard as the percentage that results from dividing the three-phase voltages or currents' greatest deviation from their average by the three-phase voltages or currents' average. Phase-to-phase voltage averages are first calculated, and then the highest deviation from the average is found.

$$V_{12} - V_{av} = 395.40 - 386.00 = 9.4v$$

$$V_{13} - V_{av} = 389.62 - 386.00 = 3.62v$$

$$V_{23} - V_{av} = 380.00 - 386.00 = -6v$$

From the above deviation $V_{12} - V_{av} = 9.4V$ is the largest deviation.

$$\% \text{Voltage unbalance} = \frac{\text{largest deviation}}{V_{av}} \times 100 = \frac{9.4}{386.00} \times 100 = 2.43\%$$

Similarly, the percentage of voltage unbalance is calculated from phase to neutral voltage (3.30%). As can be seen from the result, the percentage of voltage unbalance (3.30% and

2.43%) is beyond the acceptable limit imposed by the IEEE limit of 2%. Therefore, it is important to design suitable mitigation techniques for voltage unbalance.

Causes and Effects of Voltage Unbalance in the Arjo Dedessa Sugar Factory

When the RMS voltage values or the phase angles between the three phases become unequal, voltage unbalances are linked to fluctuations in voltages for three-phase systems [2]. The presence of single-phase loads on a three-phase circuit is the cause of voltage imbalance in the Arjo Dedessa sugar factory. Its consequences include decreased motor performance efficiency, higher power losses, and shorter electrical equipment lifetimes.

3.8.4 Harmonics

IEEE Standard 519-1995 is the primary industry standard for harmonics in power systems. The IEEE Power Engineering Society and the IEEE Industry Applications Society worked together to establish this standard. The harmonic current restrictions according to the size of the load in relation to the size of the power system to which the load is connected are listed in Table 3.9.

The ratio is the highest fundamental load current divided by the short circuit current that is accessible at the PCC [14]. According to the standard, a facility's current consumption may affect the quantity of harmonics; this could cause the utility's distribution system to drop from 120V to 69kV.

Table 3.9: Current distortion IEEE standard for distribution systems (120V to 69kV)

Max. harmonics current distortion (% of IL)						
Individual harmonics order(odd harmonics)						
I_{sc}/I_L	$h < 11$	$11 < h < 17$	$17 < h < 23$	$23 < h < 35$	$35 < h$	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	12.00
$100 < 1000$	12.0	5.5	5.0	2.0	1.0	15.00
> 1000	15.0	7.0	6.0	2.5	1.4	20.00

Where IL is the maximum harmonic current distortion and Isc is the maximum short-circuit current at PCC. Both the short circuit current and the 400V feeder's rated current at the common coupling ratio point fall within the range of less than 20. Consequently, the voltage distortion level limit is displayed in Table 3.10, and the TDD values of the current harmonics should not be greater than 5% at the point of common coupling.

Table 3.10: Voltage distortion IEEE standard limits

Bus voltage at PCC	Individual voltage distortion, TDD(%)	Total voltage distortion THD(%)
69kv and below	3.0	5.0
69.001kv-161kv	1.5	2.5
161kv and above	1.0	1.5

Additionally, the effective degree of harmonic distortion is frequently measured using a single metric, the total harmonic distortion (THD). The voltage and current THD values are expressed mathematically as follows, accordingly.

$$THD_v = \frac{\sqrt{\sum_{h=2}^{\infty} v_{(h)}^2}}{V(1)} \times 100 \quad 3.3$$

$$THD_i = \frac{\sqrt{\sum_{h=2}^{\infty} I_{(h)}^2}}{I(1)} \times 100 \quad 3.4$$

IEEE Standard 519-1992 defines a different term, total demand distortion (TDD), to describe harmonic currents. This phrase is identical to the total harmonic distortion, but instead of being represented as a percentage of the fundamental current magnitude at the moment of measurement, the distortion is expressed as a percentage of a rated load current.

$$T_{DD} = \frac{\sqrt{\sum_{h=2}^{\infty} I_{(h)}^2}}{I(L)} \times 100. \quad 3.5$$

The voltage THD values measured in the three phases fall within the acceptable range of the IEEE voltage distortion limitations; however, the current distortion values exceed the limit. When transformers are used to serve industry loads, the PCC is considered their major side. Based on the observed values of the load side voltage and current, Table 3.11 displays the distorted harmonics level in accordance with the IEE harmonic distortion standard.

Table 3.11: Voltage and current harmonic distortion measured data(23-28/06/2018)

Harmonic order	Voltage			Current		
	L1	L2	L3	I1	I2	I3
3	7.9	8.1	8.1	39.4	39.4	39.6
5	3.9	4.0	4.0	19.6	19.6	19.7
7	0.2	0.1	0.1	0.1	0.1	6.1
9	3.9	4.0	4.0	19.6	19.6	19.7
11	0.1	0.1	0.1	0.0	0.0	0.0
13	0.1	0.1	0.1	0.0	0.0	0.0
15	0.2	0.0	0.0	0.0	0.0	0.0
THD%	9.8%	10.1%	10.0%	49.1%	49.2%	49.4%

Sources and Effects of Harmonics in the Arjo Dedesaa Sugar Factory

Harmonics are the most prevalent power quality disturbance in the Arjo Dedessa Sugar Factory. While they are generally less costly than interruptions, they occur more frequently and, in some cases, can have effects comparable to a supply interruption. Even moderate harmonic levels can disrupt factory operations by preventing equipment from functioning properly. Harmonics are primarily generated by nonlinear loads such as transformers, motors, rotating machines, adjustable speed drives, fluorescent lamps, and other power electronic devices.

In the factory, these nonlinear loads can cause equipment malfunctions due to excessive current variations, increased temperature rise, reduced motor efficiency, motor and transformer overheating, and lower overall productivity. Most of the motors in the factory are squirrel-cage induction motors controlled by variable speed drives (VSDs), specifically the MicroMaster Chip Automation Drive FC 300, which adjusts motor speed. The VSDs modify the input power frequency to control motor speed in processes such as the auxiliary cane carrier, elevator cane carrier, and band cane carrier motors in the milling house. Although the VSDs are designed to limit mechanical and thermal stress by providing low starting currents, they can contribute to harmonic generation due to the changes in motor speed. These harmonics can affect not only individual equipment but also have the potential to disturb the entire electrical network.

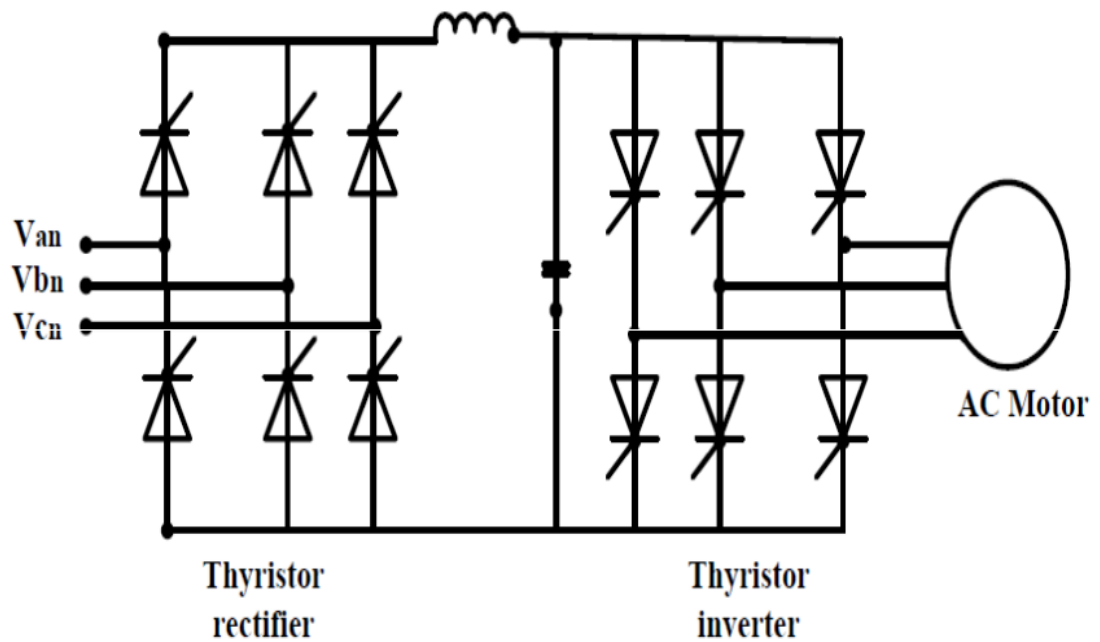


Figure 3.3: Adjustable speed drive micro master chip.

3.8.5 Flicker

Our brains can detect changes in light intensity brought on by variations in voltage. Flicker is the common name for this effect, which can be extremely uncomfortable for the body. More specifically, flicker is the perception of an uneven visual feeling caused by a light motivation whose brightness or spectral distribution appropriately varies over time. Since the Arjo Dedessa sugar factory is not a topic of this research, it is not measured.

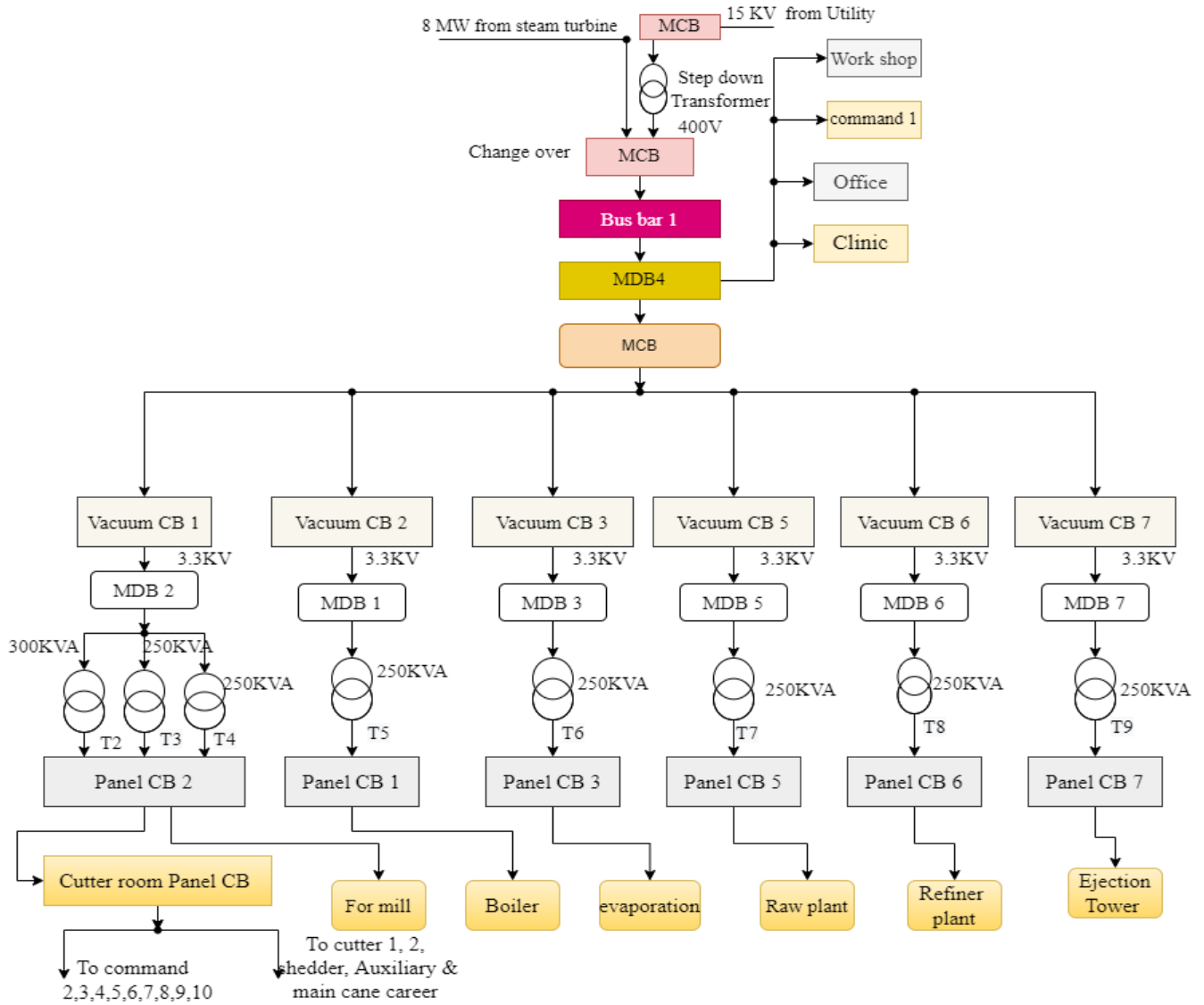


Figure 3.4: Block diagram electric system of ADSFS

Power supply of the company: the average daily consumption at full load is 38,260KWh for production machine and 2278KWh for utility. It has also stand by Generator with designed capacity of 800KWh. The main power consumption and distribution in ADSF are

Table 3.12: power consumption of ADSF for each plant

No	Company section	Incoming power	Output power	Rated output power transformer
1	Shredder and cutter	15KV	380v	3000KVA
2	Milling room	15KV	380V	3000KVA
3	Processing	15KV	380V	2500KVA
4	Refinement and S.R.I	15KV	380V	2500KVA
5	Lighting and Compressor room	15KV	380V	2500KVA

Table 3.13 :The ADSF's number of transformer with rating and number of motors

No	Plants	Rating of transformer(KVA)	No of transformer	No of motor
1	Milling room	3000KVA* 2 + 2500 KVA	3	5
2	Evaporation	2500KVA	1	3
3	Raw plant	2500KVA	1	23
4	Refinement	2500KVA	1	10
5	Bioler	2500KVA	1	6
6	Cooling tower	2500KVA	1	10
7	Cane preparation and handling	2500KVA	1	6

This section outlines the schedule and methodology for measurement-based data collection. After identifying the causes of power quality issues, the locations and timing for measurements are determined. The monitoring objectives directly affect the duration of the measurement period, which should ideally capture a complete power cycle or the interval over which the plant's power usage pattern repeats. For example, in an industrial facility, the pattern may repeat daily or per shift depending on the size of the plant and operating schedules of machinery.

Data collection is conducted using equipment nameplate information, recorded system data, wiring and equipment specifications, and input from staff working in the monitored areas. Different electrical events require distinct measurement systems and time schedules. Long-

term data (spanning months or years) is used to characterize interruptions caused by random events, while measurements covering the full operational cycle of industrial equipment are taken to comply with IEEE Standard 1159-1995.

To capture the cumulative characteristics of all industrial loads, measurements are taken while all machinery is operating. Data on fault occurrences, interruptions, and frequency variations is gathered from recorded plant and substation data, equipment readings, and information from technicians monitoring the system. Harmonic distortion, under/over voltages, voltage unbalance, voltage fluctuations, and waveform distortions are measured under full-load conditions to assess the combined effects of plant equipment. Monitoring locations are selected at the service entrance of each facility to evaluate both the quality of power delivered to the industrial plant and the impact of the plant on the utility system. Common connection points are identified at the 3.3 kV line tapping locations, while the primary side of distribution transformers serves as points of common coupling due to the minimal line impedance between the tapping point and transformer primary.

3.9 Measuring Locations of Power Quality Problems

For this investigation, measurements were made on the transformer's secondary low voltage side at the central main distribution boards (CMDB). The monitoring locations and points of common couplings (PCC) are shown figure 3.5

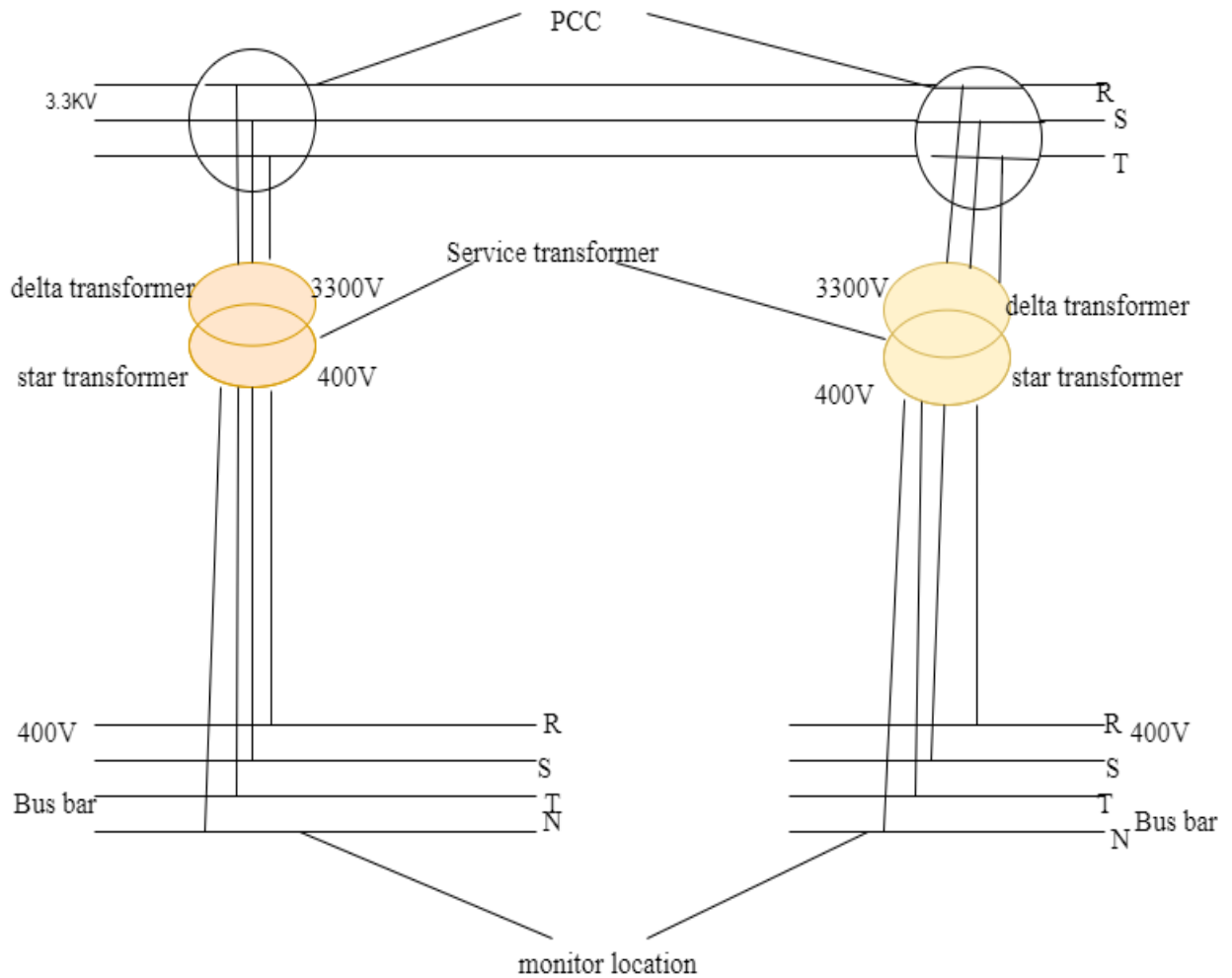


Figure 3.5: monitoring location and point of common coupling (PCC)

The Fluke 435 model power quality analyzer equipment was used to measure the harmonic distortion, voltage, current, and power as part of the research study and simulation of power quality enhancement. Careful physical observation, reading from nameplate specifications, measuring from the central main distribution board, communication with relevant personnel, and consulting previously recorded records have all been used to collect data.

Table 3.14: Transformer rating data at the Arjo Dedessa Sugar Factory

Transformer	Power factor	Voltage (KV)	Rated frequency(Hz)	Cooling type	Connection type	Impedance	Apparent power (KVA)
Transformer 1	0.85	15/0.4	50	ONAN	Star Delta	6	3000 + 2500 × 2
Transformer 2	0.85	15/0.4	50	ONAN	Star Delta	6	2500
Transformer 3	0.85	15/0.4	50	ONAN	Star Delta	6	2500
Transformer 4	0.85	15/0.4	50	ONAN	Star Delta	6	2500
Transformer 5	0.85	15/0.4	50	ONAN	Star Delta	6	2500
Transformer 6	0.85	15/0.4	50	ONAN	Star Delta	6	2500
Transformer 7	0.85	15/0.4	50	ONAN	Star Delta	6	2500

Table 3.15: diesel generator rating in Arjo Dedessa Sugar Factory

	Power factor	Voltage KV	Active power KW	Apparent Power KVA	Rated frequency Hz
Generator 1	0.85	0.4	200	250	50
Generator 2	0.85	0.4	200	250	50
Generator 3	0.85	0.4	400	500	50
Generator 4	0.85	0.4	400	500	50

3.10 Electric Motors (loads) in Arjo Dedessa Sugar Factory

Motors use the interaction of the magnetic fields in their stator and rotor windings to transform electrical energy into mechanical energy. Industrial electric motors fall into one of three categories: synchronous, direct current, or induction. Every type of motor uses the same parts to function. Power factor and efficiency are a motor's two most crucial factors. Between 50 and 100% loadings, induction motor efficiencies are almost constant (see Figure 3.8). A motor runs at part load when its rating is greater than what the device requires. The motor's efficiency is lowered in this condition. Replacement of under loaded motors with smaller motors

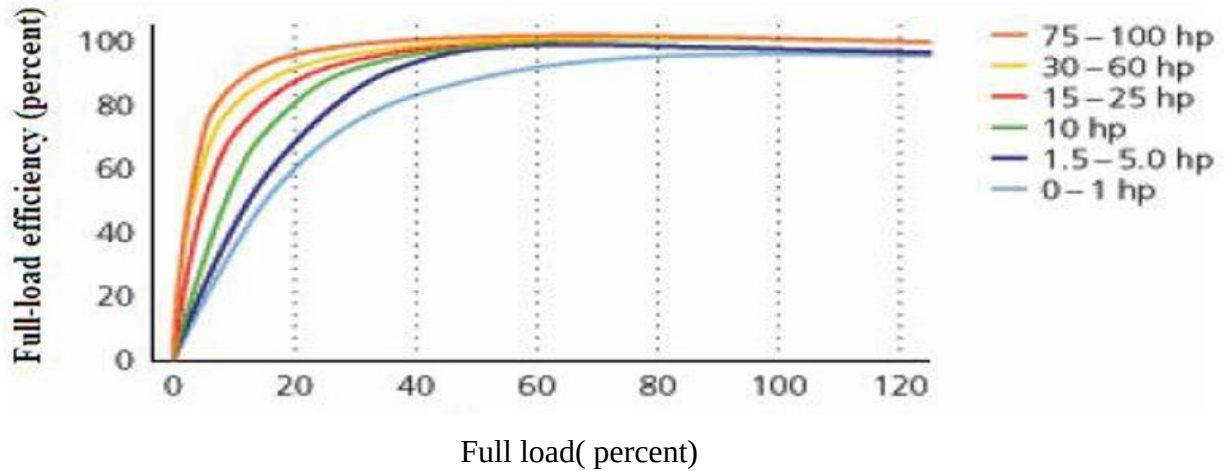


Figure 3.6: efficiency vs. loading

A Fluke 435 is used to measure the input power in order to calculate the motor loading. Alternatively, the power factor, voltage, and current can be measured using equation (3.1).

$$P_i = \frac{V \times I \times PF \times \sqrt{3}}{1000} \quad 3.6$$

P_i stands for three-phase power in kilowatts (kw), V for mean line-to-line three-phase voltage, I for mean three-phase current, and Pf for power factor. The motor name plate records the rated kilowatt and efficiency; if the nameplate is broken or removed, the rated KW is taken from the publication. The input power at full-rated load is obtained because the KW figures in the nameplate are for output conditions by:

$$P_i = \frac{\text{Name plate full rated load}}{\text{efficiency at full rated load}} \quad 3.7$$

P_i , input power at full rated load in KW. The percentage loading can now be calculated as follows:

$$\text{load} = \frac{p_m}{p_i} \times 100 \quad 3.8$$

Where: p_m = output power as a percentage of rated power, load. Three-phase power measured in KW p_i , input power at maximum load in KW. Each motor's part-load is calculated by comparing the measured input power under load with the power required when the motor operates at its rated capacity. The NEMA defines a motor's energy efficiency as the ratio of its useful power output to its total power input. This ratio is commonly expressed as a percentage, as the following calculation illustrates.

$$\text{efficiency} = \frac{0.7457 \times \text{load}}{p_m} \quad 3.9$$

Where: η - Efficiency as operated in percentage, hp= Nameplate rated horsepower Load
Load-Output power as a percentage of rated power P_m = Measured three-phase power in KW

3.11 Summary of power quality problems in the Arjo Dedessa Sugar Factory

The power quality issues at the Arjo Dedessa Sugar Factory and its entire power distribution system have been identified. The factory currently operates with one turbine generator, nine distribution transformers, and two of its four diesel generators. During 2019, measurements were taken using a Fluke 435 power quality analyzer to record phase voltages, line currents, active, reactive, and apparent power, power factor, individual voltage and current harmonic distortion, and total harmonic distortion under both full-load and half-load conditions, according to factory records. The primary power quality concerns investigated at the factory were harmonics and voltage sags.

CHAPTER FOUR

DESIGN AND MODELLING OF POWER QUALITY MITIGATION TECHNIQUES

4.1 Introduction

This section discusses the design and modeling of power quality mitigation techniques using the Active Power Filter (APF) concept. In the manufacturing power distribution system, harmonics caused by nonlinear loads, ADS, and motors are the most critical issue. Other power quality problems include voltage sags, temporary interruptions, voltage unbalance, and additional harmonics. A shunt active power filter is proposed as an effective solution to mitigate harmonic distortion. Power quality disturbances can be addressed by increasing equipment immunity, using mitigation devices, or modifying the power system configuration. Among these, reconfiguring the system is recognized as a means to improve power quality, while the active power filter is widely adopted specifically for harmonic mitigation. The APF provides voltage compensation, harmonic suppression, harmonic damping, harmonic isolation, reactive power compensation, and overall harmonic control. The system comprises switching control circuits and inverters, where the controller generates gate signals that direct the inverter to produce compensating harmonics. By injecting harmonics that are equal in magnitude but opposite in phase to the existing distortions, the APF effectively cancels the unwanted harmonics on the power line.

4.2 Harmonics Mitigation by using Shunt Active Power Filter

An efficient mitigation strategy is required since harmonics are one of the most common power quality problems in the power distribution system of the Arjo Dedessa sugar production. When it comes to solving harmonic issues, the Shunt Active Power Filter (SAPF) is one of the best electronic devices available. A solid-state inverter known as a SAPF injects compensatory voltage into the power distribution system in a shunt fashion. A three-phase injection transformer connects its AC side to the distribution feeder, while an energy source or storage device connects its DC side. The SAPF is typically mounted at the point of common

coupling (PCC) among the supply and the essential load feeder in low-voltage distribution circuits (0.4 kV).

4.2.1 Principle of Shunt Active Power Filter.

The SAPF generates a reference current and injects it at the point of common coupling (PCC) to lessen harmonic distortion. This is accomplished by carefully regulating the VSI's IGBT switching using pulses produced by an appropriate controller. Along with outlining the SAPF's primary components, this section also discusses how it operates.



Figure 4.1 : working principle of SAPF

The two primary parts of active power filters (APFs) are current injection and reference current generation. A two-step procedure is used to reduce harmonics. The first stage involves creating a reference current in the opposite phase but with the same amplitude as the harmonic current. Time-domain or frequency-domain methods can be used to create this reference current.

While frequency-domain techniques rely on Fourier analysis, time-domain techniques usually include coordinate transformations of voltage and current signals. While some methods, like the instantaneous reactive power theory, do not require knowledge of the frequency and phase of the source voltage, others, like the synchronous reference frame (d-q) theory, do. Since precise reference current generation might be difficult, synchronizing the APF with the grid voltage is also essential for dependable performance, particularly under complicated grid situations.

In the second stage, a current injection controller is used to inject the reference current at the PCC, creating switching pulses for the IGBTs of the VSI. By canceling the harmonic currents, this injection creates a waveform that is almost perfectly sinusoidal. Furthermore, accurate current injection depends on keeping the DC link voltage at the right level.

The following is a mathematical expression for the source current from the SAPF block diagram:

$$i_s = i_L + i_c. \quad 4.1$$

Where i_L is the load current and i_c is the compensating current. The APF is based on a voltage source converter consisting of semiconductor valves and a capacitor on the DC bus. By means of a coupling inductance, which is commonly represented by

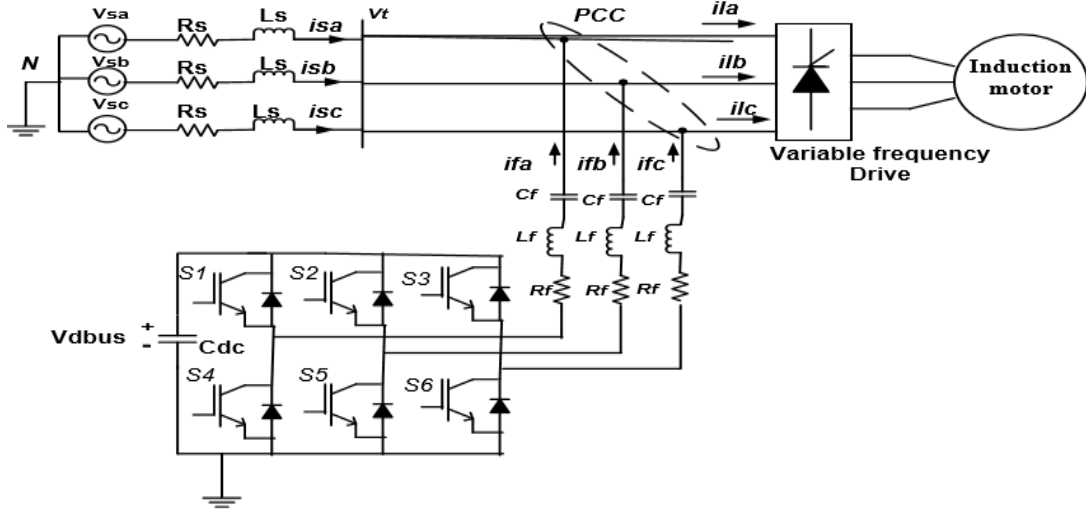


Figure 4.2: block daigram of Shunt Active Power Filter

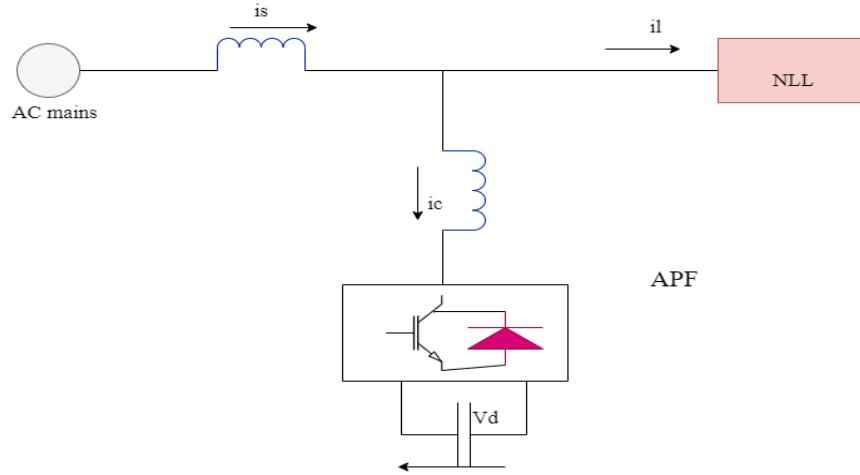


Figure 4. 3: single line diagram of Shunt Active Power filter

$$i_s + i_c = i_l \quad 4.2$$

$$i_l(t) = i_1 \sin(\omega t + \theta_n) + \sum_{n=3,5,7,\dots}^{\infty} I_n \sin(\omega n t + \theta n)$$

$$PL(t) = v_s(t) + i_{l(t)} \quad 4.3$$

$$PL(t) = Vm \sin \omega t [I1 \sin(\omega t + \theta1) + \sum_{n=3,5,7,\dots}^{\infty} In \sin(n\omega t + \theta n)]$$

$$PL(t) = Vm I1 \sin \omega t \cdot \sin(\omega t + \theta1) + Vm \sin \omega t + \sum_{n=3,5,7,\dots}^{\infty} In \sin(n\omega t + \theta n)$$

$$PL(t) = Vm I1 \sin \omega t [\sin \omega t \cos \theta1 + \cos \omega t \sin \theta1] + Vm \sin \omega t \times [\sum_{n=3,5,7,\dots}^{\infty} In \sin(n\omega t + \theta n)]$$

$$PL(t) = Vm I1 \sin^2 \omega t \cos \theta1 + Vm I1 \sin \omega t \cos \omega t \sin \theta1 + Vm \sin \omega t \times \sum_{n=3,5,7,\dots}^{\infty} In \sin(n\omega t + \theta n)]$$

$$PL(t) = Pf(t) + Pr(t) + Pn(t) \quad 4.4$$

$$Pf(t) = Vm I1 \sin^2 \omega t \cos \theta1$$

$$Pr(t) = Vm I1 \sin \omega t \cos \omega t \sin \theta1$$

$$Pn(t) = Vm \sin \omega t \times \sum_{n=3,5,7,\dots}^{\infty} In \sin(n\omega t + \theta n)$$

Where, Pf (t) is a fundamental power

Pr (t) is a reactive power

Pn (t) is a harmonic power

For source current, Is(t) to be a sinusoidal

$$Is(t) = \frac{pf(t)}{Vs(t)} = \frac{Vm I1 \cos \theta \sin^2 \omega t}{Vm \sin \omega t} = I1 \cos \theta1 \sin \omega t$$

Is (t) = $I_m \sin \omega t$ this is purely sinusoidal current and in phase with source voltage Vs(t)

Where, $I_m = I1 \cos \theta1$

$$I_{sa} = I_m \sin \omega t$$

$$I_{sb} = I_m \sin(\omega t - 120)$$

$$I_{sc} = I_m \sin(\omega t + 120)$$

$$I_{sarf} = I_m \sin \omega t.$$

$$I_{sbrf} = I_m \sin(\omega t - 120).$$

$$I_{scrf} = I_m \sin(\omega t + 120).$$

Shunt active power filters (SAPFs) can be categorized according to the supply system type, circuit topology (e.g., half-bridge or full-bridge converters), and converter type (e.g., voltage source converters (VSC) and current source converters (CSC)). SAPFs are generally classified into three supply system types: single-phase two-wire, three-phase three-wire, and

three-phase four-wire systems. A SAPF reduces harmonics, reactive power, voltage imbalance, neutral current, and voltage fluctuations while producing balanced sinusoidal currents in the supply by controlling the DC bus voltage. While the VSC is connected to a DC bus, the AC side of a SAPF is typically connected across the consumer load or at the point of common coupling (PCC). To reduce switching ripples, tiny ripple filters are required since VSCs use PWM control. A digital signal processor (DSP) or a DSPACE platform is usually used to build the control algorithms for producing the required gating signals for the VSC's solid-state devices. Hall-effect sensors are used to provide precise voltage and current feedback signals.

4.3 Objective and Objective Function[1].

The primary goal is to reduce source current harmonics caused by non-linear loads linked at the common coupling point. In mathematical terms, the objective function is defined as

$$\text{minimize } H(N) = \frac{1}{I_{s1}} \sqrt{\sum_{n=2,3,\dots}^{\infty} I_{sn}^2}. \quad 4.5$$

where I_{sn} denotes the harmonics, I_{s1} is the fundamental current, and $H(N)$ is the goal function for harmonic reduction. This function is constrained by the following equation.

$$THDis < THDlimit \quad 4.6$$

where the IEEE-519 standard defines a THD maximum of 5%. Consequently, the most effective way to reduce current harmonics is to use a shunt active power filter. Additionally, the control strategies employed for current injection and reference current generation are crucial to improving SAPF performance.

4.4 Mathematical Model of SAPF

By modeling a three-phase source with a filter placed in parallel to the distribution load, the analytical behavior of SAPF can be well understood. SAPF's fundamental architecture linked to a 3P3W system is shown in Fig. 4.4.

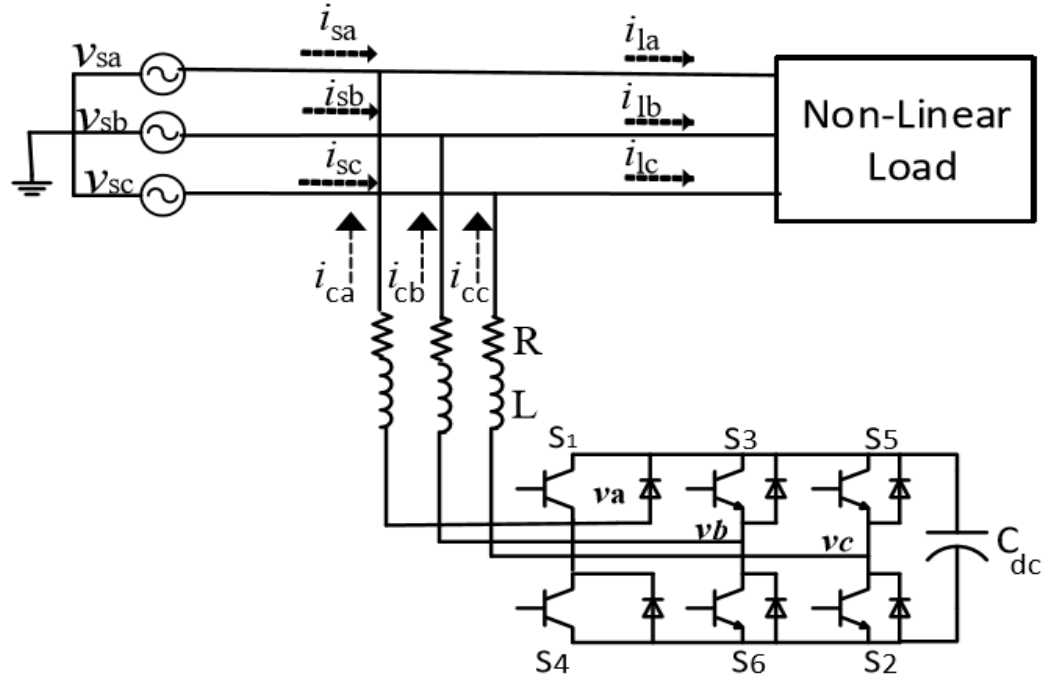


Figure 4.4: basic structure of SAPF

The symbols v_{sa} , v_{sb} , and v_{sc} stand for the three-phase source voltages. The compensatory currents that are actually injected are represented by i_{ca} , i_{cb} , and i_{cc} . The ABC frame depicts it.using Eq. (4.7)

$$\begin{bmatrix} L \frac{d}{dt} i_{ca} = & v_{sa} - & R i_{ca} - & v_a \\ L \frac{d}{dt} i_{cb} = & V_{sb} - & R i_{cb} - & v_b \\ L \frac{d}{dt} i_{cc} = & V_{sc} - & R i_{cc} - & v_c \\ C_{dc} \frac{d}{dt} v_{dc} = & f_a i_{ca} + & f_b i_{cb} + & f_c i_{cc} \end{bmatrix} \quad 4.7$$

where the switching functions are f_a , f_b , and f_c . The symbols L and R stand for the filter's resistance and inductance, respectively. At the DC link, C_{dc} is the capacitance. One way to express the equation above is in matrix form using Eq. (4.8).

$$\frac{d}{dt} \begin{bmatrix} i_{ca} \\ i_{cb} \\ i_{cc} \\ v_{dc} \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & 0 & 0 & 0 \\ 0 & -\frac{R}{L} & 0 & 0 \\ 0 & 0 & -\frac{R}{L} & 0 \\ \frac{fa}{Cdc} & \frac{fb}{Cdc} & \frac{fc}{Cdc} & 0 \end{bmatrix} \begin{bmatrix} i_{ca} \\ i_{cb} \\ i_{cc} \\ V_{dc} \end{bmatrix} + \frac{1}{L} \begin{bmatrix} v_{sa} & v_a \\ v_{sb} & v_b \\ v_{sc} & v_c \\ 0 & 0 \end{bmatrix} \quad 4.8$$

Equation (4.9) provides the transformation matrix needed to convert ABC to any rotating dq0 reference frame. This transformation helps in lowering the complexity of control.

$$T = \frac{2}{3} \begin{bmatrix} \cos \theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin \theta & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad 4.9$$

For simplicity a 3P3W system is considered, thus the addition of three-phase voltages and currents results in zero as shown in Eq. (4.10)

$$\begin{aligned} i_{sa} + i_{sb} + i_{sc} &= 0 \\ v_{sa} + v_{sb} + v_{sc} &= 0 \end{aligned} \quad 4.10$$

Eq. (4.11) represents the currents in dq frame.

$$\begin{bmatrix} i_{cd} \\ i_{cq} \\ v_{dc} \end{bmatrix} = \begin{bmatrix} \frac{R}{L} & \omega & -\frac{fd}{L} \\ -\omega & \frac{R}{L} & -\frac{fq}{L} \\ \frac{fd}{Cdc} & \frac{fq}{Cdc} & 0 \end{bmatrix} \begin{bmatrix} I_{cd} \\ i_{cq} \\ v_{dc} \end{bmatrix} + \frac{1}{L} \begin{bmatrix} v_d \\ v_q \\ 0 \end{bmatrix} \quad 4.11$$

Where the switching state functions of the system in dq reference frame are denoted by fd and fq and ω is the supply angular frequency. Eq. (4.11) can be re-written to get Eq. (4.12).

$$\begin{bmatrix} L \frac{d}{dt} i_{cd} = & Vd - Ri_{cd} + \omega Li_{cq} - fd * Vdc \\ L \frac{d}{dt} i_{cq} = & vq - Ricq - \omega Licd - fq * Vdc \\ Cdc \frac{d}{dt} v_{dc} = & fdicd + fqicq \end{bmatrix} \quad 4.12$$

4.5 Series Active Power Filters

Series active power filters (APFs) work very well for moderate harmonic current compensation. A hybrid approach is frequently employed in current-fed nonlinear loads: to improve overall filtering performance, a small-rated series active filter (usually 3–5% of the load rating) is combined with a high-capacity passive shunt filter. This hybrid filter is thought to be economical, particularly for high-power applications, and offers a versatile option for mitigating harmonics under various load situations. As a result, series APFs are frequently used to reduce voltage harmonics in the supply or produced by nonlinear loads at the point of common coupling (PCC), as well as to minimize current harmonics in both voltage-fed and current-fed loads.

Fast, self-commutating solid-state devices are the foundation of the series APF technology. BJTs and power MOSFETs were first used to build series APFs; later, SITs (static induction thyristors) and GTOs (gate turn-off thyristors) were used. IGBTs are now favored because of their higher performance and accessibility, which has greatly advanced the technology. Additionally, the availability of affordable Hall-effect voltage and current sensors and suitably rated isolation amplifiers has improved the performance of series APFs.

4.5.1 Control of Series Active Power Filters

The control algorithm of series active power filters employs feedback signals to determine reference voltages or currents based on the application in order to maintain a pure sinusoidal voltage across the load. As a result, a PWM voltage waveform is created and either added to or subtracted from the source voltage. Usually, a voltage-fed inverter without current-control loops is utilized in this configuration. Compared to parallel (shunt) active filters, series active filters are less frequently utilized in industrial settings. The primary reason for this is because series filters have to manage the entire load current, which greatly raises the necessary current rating, particularly on the coupling transformer's secondary side. Larger physical size, greater I^2R losses, and higher total costs result from this.

4.6 Hybrid Power Filters

The advancement of fast, self-commutating solid-state devices such as MOSFETs (metal-oxide semiconductor field-effect transistors) and IGBTs (insulated gate bipolar transistors) has been a key driver in the development of hybrid filter technology incorporating active filter elements. Additionally, improvements in affordable sensor technology have lowered costs and improved the performance of hybrid passive filters (HPFs). The availability of compact isolation amplifiers and high-speed Hall-effect sensors has made HPFs more cost-effective and responsive.

4.6.1 Principle of Operation of Hybrid Power Filters

A universal active filter can effectively address most power quality issues even when the supply system is contaminated, ensuring proper operation of consumer equipment. It uses a combination of two voltage source converters (VSCs) in series and parallel to provide balanced, sinusoidal currents while simultaneously compensating for voltage-related problems like harmonics, unbalance, sag, and swell, as well as current-related issues such as harmonics, reactive power, unbalanced and neutral currents, and load or supply fluctuations. This hybrid configuration benefits from the advantages of both series and parallel inverters. Nonetheless, its adoption is limited due to the complex control requirements stemming from the interdependent switching of the two circuits, making it less commonly used than other configurations.

4.7 Energy Storage Devices

During compensation, the SAPF's real-power needs are met by the DC energy storage device. The storage unit could be made up of flywheels, batteries, capacitors, or super magnetic energy storage. This study uses a battery as an energy storage device to provide the shunt active filter with DC voltage.

4.8 Voltage Source Inverter (VSI)

The energy storage unit's DC voltage is transformed into a regulated three-phase AC voltage by the Voltage Source Inverter (VSI), also known as an inverter. Usually, a sinusoidal pulse

width modulation (PWM) method is used to operate the inverter switches. The VSI frequently uses unbalanced switching for the three phases, managing each phase separately, since the majority of harmonic problems in utility systems impact each phase differently.

Solid-state switches that convert DC to AC, like IGBTs or GTOs, make up the VSI. The PWM control controls the switches to produce the necessary voltage magnitude and frequency, while the inverter injects AC voltage to make up for decreases in the supply voltage.

4.9 Harmonic Filter (LC filter)

To filter the harmonics that are present in the VSI's output voltage, a harmonic filter has been installed at the output. Since SAPF is made up of power electronic devices, there is a chance that harmonics will be generated, hence a harmonic filter is also included in SAPF. The filter unit is made up of a capacitor and an inductor (L). (C)

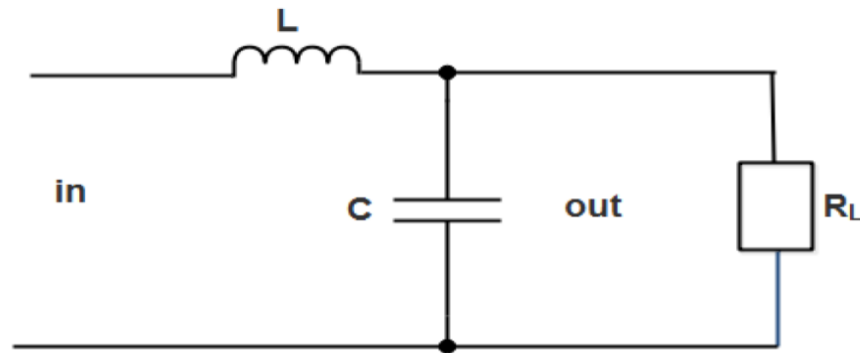


Figure 4.5: filter circuit diagram

Equation (4.13) and (4.14) shows the frequency (ω) and the damping factor (τ) expressions for the filter utilized.

$$\omega C = \frac{1}{\sqrt{LC}} \quad 4.13$$

$$\tau = \frac{1}{2RL} \sqrt{\frac{L}{C}} \quad 4.14$$

The principal harmonic mitigation technologies employed in this study are inverter-side filtering and line-side filtering. Because it is situated close to the harmonic source, inverter-side filtering has the advantage of keeping high-order harmonic currents from getting to the

series injection transformer. On the other hand, it may cause phase angle shifts and voltage drops in the basic component of the inverter output. By contrast, line-side filtering allows harmonic currents to flow through the series injection transformer but avoids difficulties associated to voltage drops or phase shifts.

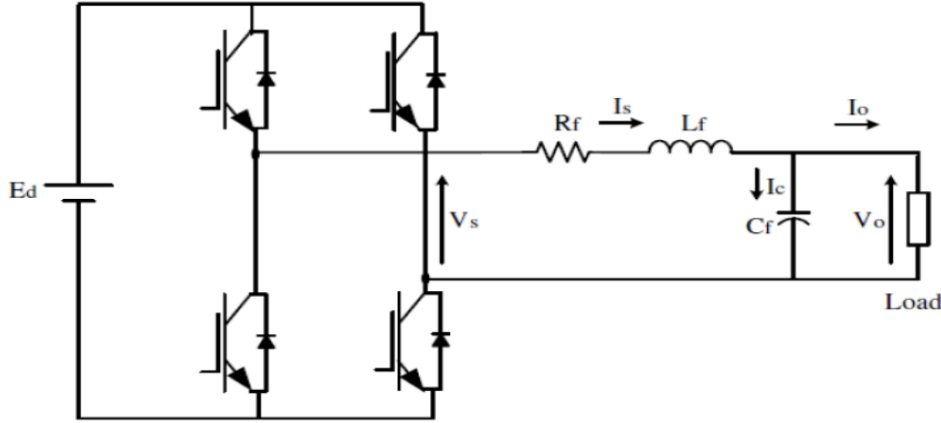


Figure 4.6: Inverter side filter

This thesis makes the following assumptions: The load is nonlinear, the dc source voltage is constant and ripple-free, the inverter switching devices are thought to be perfect switches, and the filter capacitor's equivalent series resistance is disregarded. It is possible to write the inverter's output voltage as equation 4.15:

$$v_s = v_o + R_f I_s + L_f \frac{dI_s}{dt} \quad 4.15$$

By taking into account the assumptions, the LC filter design process may be split into three stages. The detailed examination of derived formulas yields the following equations. The reference papers provide a more thorough examination of how formulas are derived.

Calculation of modulation index (m): Based on the dc source voltage and nominal load voltage, the modulation index ($0 < m < 1$) is calculated.

$$m = \sqrt{2} \frac{v_o}{E_d} \quad 4.16$$

$$m = \sqrt{2} \frac{230v}{480v} = 0.7$$

It is possible to presume that the voltage loss across the filter inductor is insignificant because it cannot be ascertained prior to the specification of the filter parameters. It is possible to assume that the RMS value of the inverter's output voltage is equal to the RMS value of the load voltage ($v_s \approx v_o$). The inverter factor is determined using the outcome (K).

Calculation of the capacitance of the filter (cf) : filter capacitance can be calculated by using equation 4.17

$$cf = \frac{Ed}{Lfs^2voav} \quad 4.17$$

$$cf = \frac{480v}{2.77mH(1.5kHz^2(230))} = 2.73\mu F.$$

The LC filter (L=6.42mH and cf=2.72μf) attenuates the harmonics by providing a shunt path for the harmonic current and series impedance for the harmonic voltages.

4.10 DC Link Voltage Control

To ensure that the distorted source current is corrected in SAPF, the extracted harmonic current with the opposite phase is injected at PCC. The two primary components of the APF power stage design are the DC-link capacitor and VSI. This power stage configuration is regarded as an affordable and effective alternative. The stored energy of the DC-link capacitor is used to inject current into the VSI.

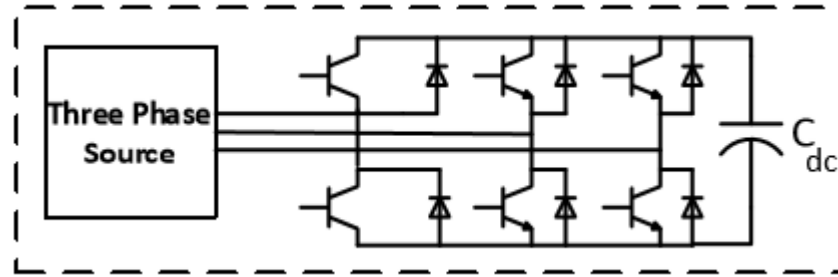


Figure 4.7: DC Link Capacitor connected to VSI[1].

$$E = \frac{1}{2}C_{dc}V_{dc}^2 \quad 4.18$$

The DC link capacitor will be charged using the same power source that drives the load. A voltage magnitude greater than the supply voltage's greatest peak must be applied to the capacitor. As a result, it is charged to a predetermined value chosen as a reference to guarantee the filter operates correctly. A boost circuit is comparable to how the capacitor gets charged. To increase the voltage, the VSC circuit uses an inductor. To guarantee reactive power, the basic component of the VSI output voltage must be greater than the peak value of the supply voltage. payment through APF. Eq. (4.19) can be used to estimate the proper

capacitor size, and Eq. (4.20) can be used to compute the power (Q) across the capacitor [16]. Because of its current ripple rating, an electrolytic capacitor should have a capacitance value of more than 2000 uf. In a traditional design, the capacitance value should be chosen to lower the voltage ripple to less than 0.5% [13]. The DC link capacitance is represented mathematically as follows:

$$if = Cdc \frac{dv}{dt} dc \quad 4.19$$

$$Q = ifVdc \quad 4.20$$

Putting value of if to get Eq. (4.4)

$$Q = (Cdc \frac{dv}{dt} dc)Vdc \quad 4.21$$

Eq. (4.21) can be rearranged to find Cdc using Eq. (4.22)

$$Cdc = \frac{Q}{\frac{dv}{dt} dc)Vdc} \quad 4.22$$

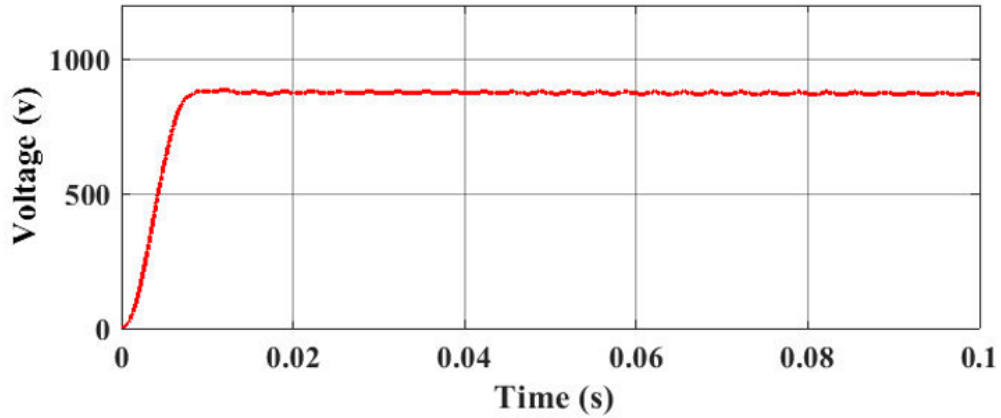


Figure 4. 8: DC Link Voltage plot

The voltage error Er and the DC charging current idc can be obtained by using Eq. (4.23) and Eq. (4.24) thus giving summary of the control approach.

$$Er = Vdc(ref) - Vdc \quad 4.23$$

$$idc = Er(kp + ki) \int dt \quad 4.24$$

By making sure that the real power of the supply equals the total of the real power of the load and the inverter's losses, the goal is to maintain power balance. In order to compensate for its switching losses, the SAPF uses actual power during switching to control the DC link voltage.

In order for the SAPF to draw the exact amount of real power required, the reference current's magnitude must be adjusted. Instantaneous variations in the power balance are reflected in the output of the PI controller.

The minimum DC bus voltage must be greater than double the system's phase voltage peak in order to guarantee precise current injection. The DC link voltage following PI controller installation is displayed in Fig. 4.8, with the reference DC link voltage set at 800 V. The DC link voltage is controlled by a tiny real power flow into the DC capacitor, which makes up for switching and conduction losses. Because voltage fluctuations are caused by small variations in instantaneous power, the electrolytic capacitor is carefully sized to prevent transient voltage shifts. Proper capacitor selection is therefore essential to control these fluctuations effectively.

4.11 Overall Modeled System

The Shunt APF is connected to a 33000 kV, 50 Hz grid to compensate for and mitigate the effects of nonlinear loads, representing the industrial zone load topology. The industrial loads are nonlinear and generate significant random harmonics, particularly the 3rd harmonic. To simulate this behavior, a single-phase AC–DC converter load with an 11 MW rating and 26% THD was selected.

4.12 Simulation Results Discussion

The Active Power Filter (APF) was installed in parallel with the industrial zone's grid to mitigate various harmonics and maintain a stable, pure sine wave output for voltage and current with low THD, even under load variations. The SAPF was positioned at the point of common coupling (PCC) between the industry's power supply and its nonlinear loads. Rated at 2500kVA, the SAPF was designed to compensate for harmonic currents up to the 50th order. Measurements of THD in voltage and current, as well as power factor, were taken before and after the SAPF installation. Following installation, power quality at the load improved significantly: THD levels were greatly reduced, the power factor increased, and the industry's energy consumption decreased by 5%. The modeled harmonic voltage and current in the Arjo Dedessa sugar factory's distribution system without the SAPF are also illustrated Figure 4.9

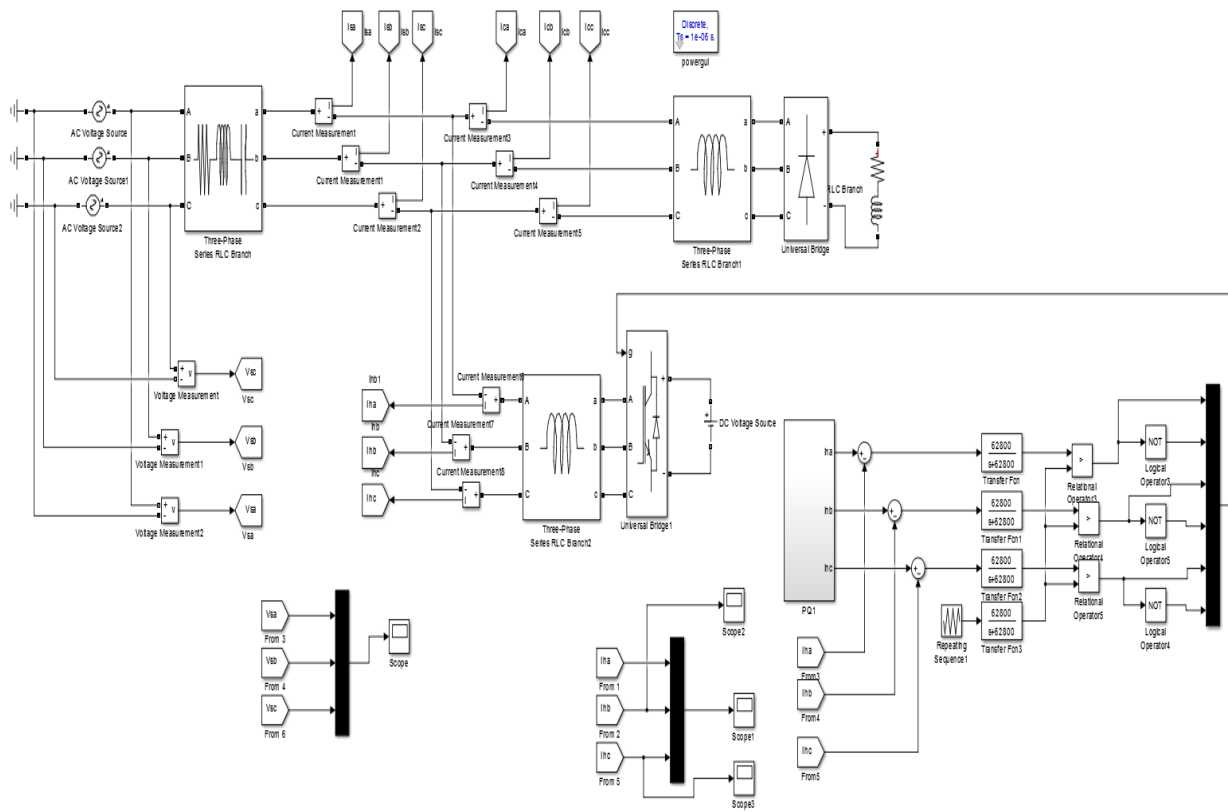


Figure 4.9: block diagram of the MATLAB/Simulink

CHAPTER FIVE

RESULTS AND DISCUSSIONS

5.1 Simulation Results from Different non linear load in Power Distribution System

Harmonics is a significant power quality issue in the Arjo Dedessa Sugar Factory power distribution system, primarily caused by nonlinear loads, ADS, and certain motors. A Shunt Active Power Filter (SAPF) is used to solve this issue. Matlab/Simulink was used to simulate the solution and examine the system with and without the SAPF. To keep the intended voltage and current levels at the load, harmonic correction is required. To reduce the harmonics produced by motors, ADS, and nonlinear loads, the SAPF is added to the load side of the power system in the simulation. The SAPF injects the proper voltage and current to offset the distortion during harmonic occurrences. The RMS voltage and current at the load are kept at the typical 400 V and 50 Hz when the SAPF is turned on because the voltage and current harmonics are successfully adjusted.

5.2 Fast Fourier Transform (FFT) Discuss of Total Harmonic Distortion of Voltage

The source current of the shunt APF compensates for reactive power and enhances power quality on the source side, resulting in improved current quality that closely approximates a sinusoidal waveform. The corresponding time-domain current waveforms are illustrated below.

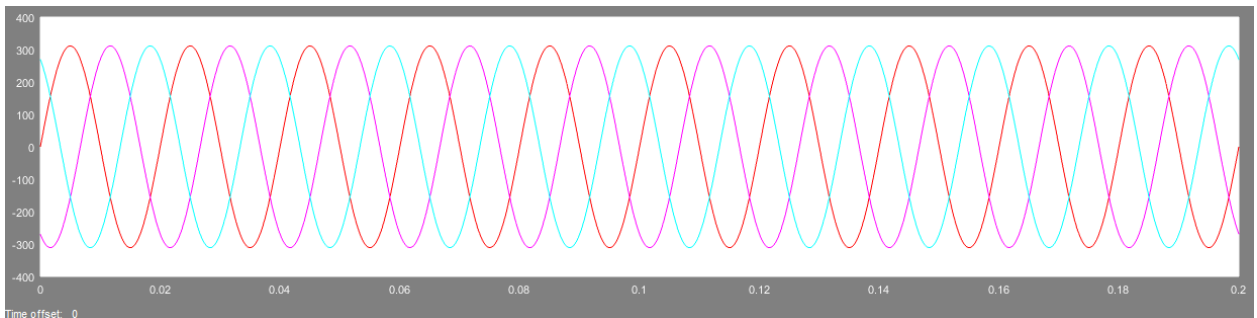


Figure 5.1: Source current and Source voltage simulink

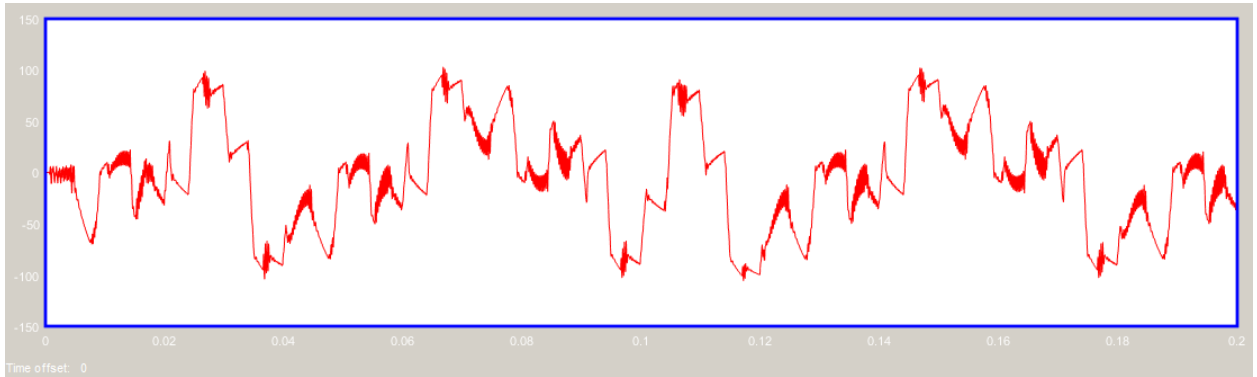


Figure 5.2: harmonic distortion (iha) without SAPF

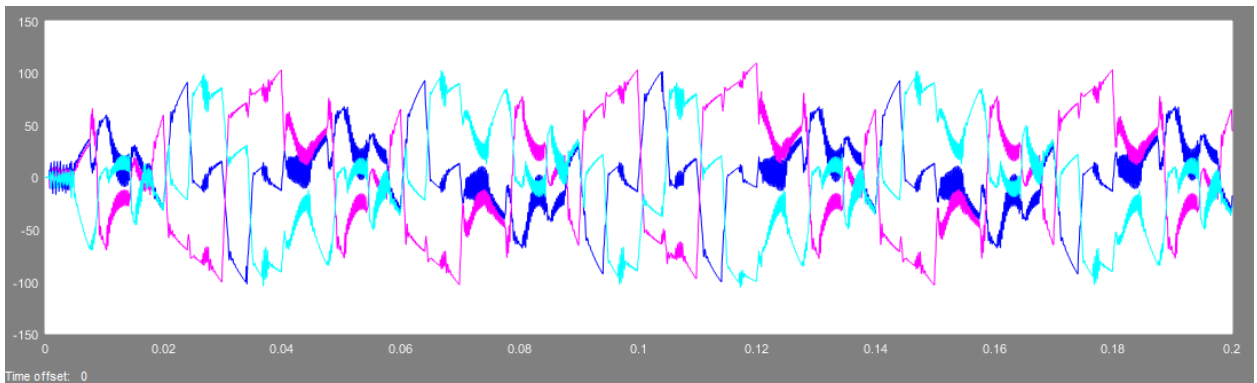


Figure 5.3: harmonic distortion (ihb) without SAPF

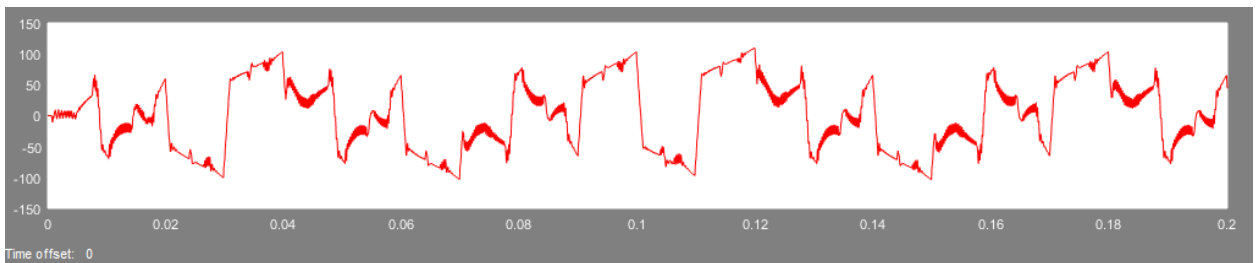


Figure 5.4 : harmonic distortion(ihc) without SAPF

The measured value of voltage harmonic distortion from central main distribution board is 9.8%, which means above the IEEE standard. Before apply power quality problem mitigation technique or before connect SAPF was analyzed harmonic using Fast Fourier Transform (FFT) analysis. The FFT analysis the voltage THD value is 11.6% which means above the standard IEEE 519 acceptable limit range (5%)

Figure 5.5: FFT analysis of load voltage THD waveform without SAPF

Figure 5.9 shown after SAPF connected, Fast Fourier Transform (FFT) analysis gives the voltage of THD 4.32%.

Figure 5.6: FFT analysis of load voltage THD waveform with SAPF

Based on IEEE 519 standard voltage of THD must be below 5%. So as shown in Figure 5.6 without SAPF shows voltage THD reach 49.1% and in Figure 5.7 after SAPF connected voltage THD reduced to 4.32%. Therefore, Shunt Active power Filter (SAPF) effectively reduced the distortion magnitude according to IEEE 519 standard limit range (5%).

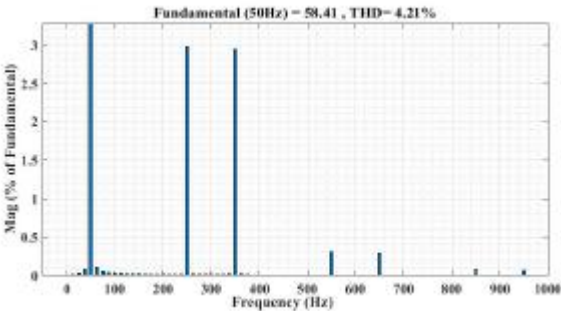


Figure 5.7:THD result of FFT MATLab at fundamental (50 Hz) 4.21%

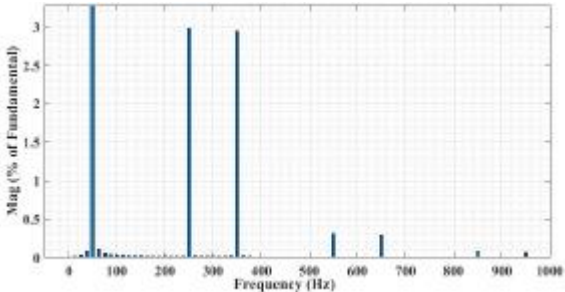


Figure 5.8 :THD result of MATLAB at fundamental (50 Hz) 4.32%

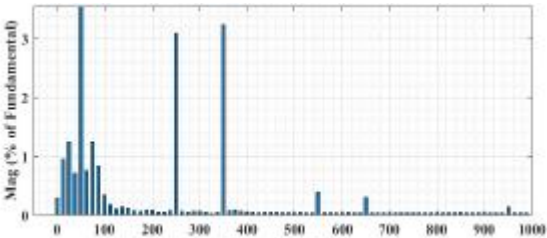


figure 5.9: THD result of MATLAB at fundamental (50Hz) THD 4.86%

Table 5.1: power quality measurements taken both before and after the SAPF was installed.

Parameter	Before SAPF	After SAPF
THDv	9.1%	1.5%
THDi	49.1%	4.32%
Power factor	0.8	0.96

CHAPTER SIX

CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORKS

6.1 Introduction

The main findings from the power quality assessments carried out on the ADSF power distribution system are summarized here. This chapter also provides practical recommendations and highlights key directions for future research.

6.2 Conclusions

The objective of this study was to investigate power quality issues and their mitigation in the power distribution system of the Arjo Dedessa Sugar Factory, comparing the results with IEEE standard limits. The research included a comprehensive review of literature, prior studies, data collection, and analysis to assess the factory's power quality problems. Measurements were taken to evaluate the extent of these issues, and appropriate mitigation strategies were proposed.

The study primarily focused on the impact of nonlinear loads on harmonics, which caused equipment damage, particularly to motors, and operational malfunctions. To address this, a Shunt Active Power Filter (SAPF) was installed at the point of common coupling (PCC) between the supply and critical load feeders. Voltage imbalance was also assessed, with measured phase-to-neutral voltages ranging from 205.30 V to 232.10 V and phase-to-phase voltages ranging from 352.45 V to 360.50 V at the central main distribution boards.

MATLAB 2015a/Simulink was used to model and simulate the power distribution system with the SAPF and its controller. The simulation confirmed that the nonlinear loads were the source of harmonic distortions. Results showed that the SAPF effectively reduced both current and voltage harmonics caused by sensitive loads. Its compact size, relatively low cost, and fast dynamic response make the SAPF a practical and efficient solution for improving power quality in the factory.

6.3 Recommendations

Based on the findings of this thesis, the Arjo Dedessa Sugar Factory should consider implementing the Shunt Active Power Filter as an effective method to mitigate power quality problems. By adopting this strategy, the factory can prevent damage to PLCs, ASDs, and motors while also enhancing profitability, productivity, and the overall efficiency and performance of its machinery. Furthermore, the factory must evaluate the power quality of its supply system and the sensitivity of its equipment to power quality disturbances, implementing appropriate and adequate mitigation measures to avoid consequences more severe than the existing power quality issues.

6.4 Future Works

This study employs a Shunt Active Power Filter (SAPF) as an electronic power device to demonstrate the mitigation of harmonic issues. Future research should explore the use of alternative control strategies, such as Fuzzy Logic Controllers and Artificial Neural Networks, in combination with SAPFs to further reduce power quality problems in the Arjo Dedessa Sugar Factory's power distribution system.

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APPENDIX

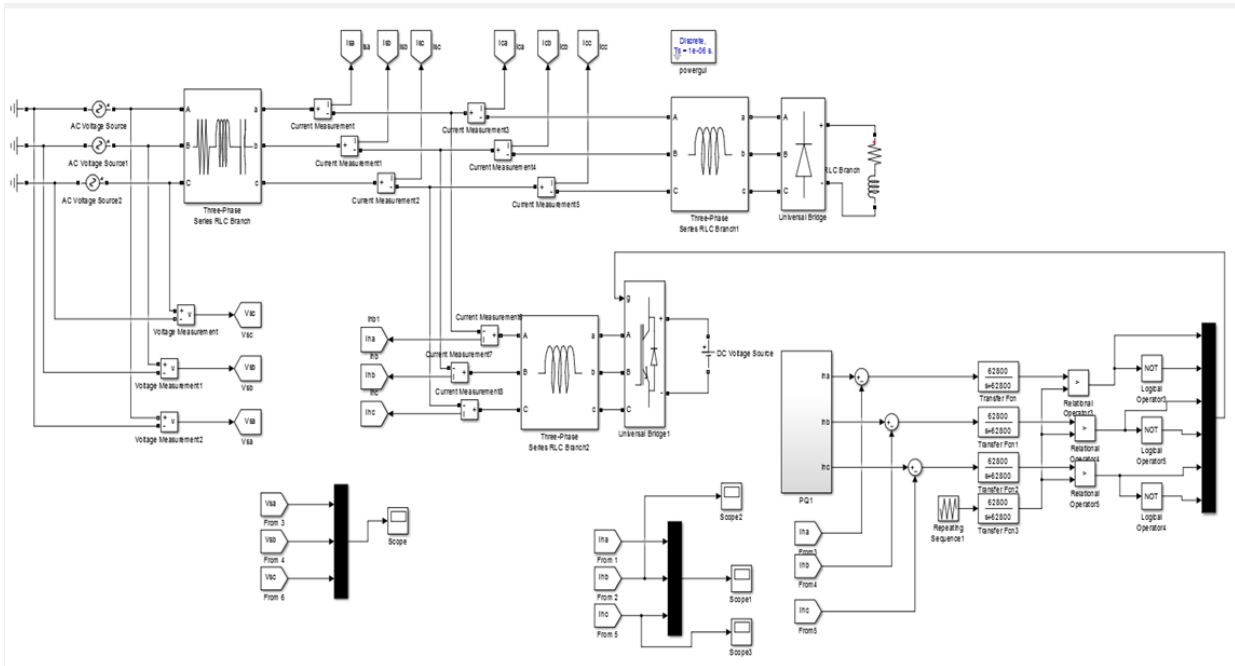


Figure 4.9 Block Diagram of the matlab/Simulink

Parameters	Values
System fundamental frequency	50Hz
Typical cause of distortion or faults	Harmonic, SG, LLG, and LLLG
Data of supply voltage	
Supply voltage phase to phase	33000V
SAPF characteristic	
Rated capacity	2500 KVA and 3000KVA
Max injection voltage	110v
DC link voltage	480v
Data of sensitive load	
Rating	2500Kva
Nominal phase to nutral voltage	230V
Nominal phase to phase voltage	400V
Data of inventer	
Capacity	2500kvA and 3000KVA
Semiconductor voltage	480VDC
Semiconductor current [peak]	1.9kA
Switching frequency	2kHz
Filter data	
Capacitance	2.73 microfrady
Inductance	6.42 mH
Injection transformer data	
Nominal power	2500kVA
Primary winding voltage	110v

Secondary winding voltage	0.28 0hm
Primary winding Resistance	0.056 ohm
Secondary winding Resistance	1.11mH
Primary winding Inductance	0.067mH
Secondary winding Inductance	500 ohm, 500 ohm
Load transformer data	
Nominal power	3000KVA and 2500KVA
Primary phase to phase voltage	15kv
Secondary phase to phase voltage	400v
Primary winding Resistance	2.16 ohm
Secondary winding Resistance	0.02 ohm
Primary winding Inductance	8.6mH
Secondary winding Inductance	0.08 Mh
Connection	Delta(ground)
Magnetization Resistance and Inductance	500 ohm, 500 ohm
Data of system simulated	