# Investigation and Mitigation of Power Quality problems using Dynamic Voltage Restorer with Super Capacitor based Energy Storage
(Case study St. George Brewery, BGI Ethiopia)

Mesafint Ayalew Assefa
A thesis Submitted to the department of Electrical Power and Control Engineering
School of Electrical Engineering and Computing
Presented in Partial Fulfilment of the Requirement for the Degree of Master's in Electrical Power and Control Engineering (Power Engineering)
Office of Graduate Studies
Adama Science and Technology University

July, 2023
Adama Ethiopia

# Investigation and Mitigation of Power Quality problems using Dynamic Voltage Restorer with Super Capacitor based Energy Storage
(Case study St. George Brewery, BGI Ethiopia)

Mesafint Ayalew Assefa
Advisor: Dr. Shubhashish Bhakta

A thesis Submitted to the department of Electrical Power and Control Engineering
School of Electrical Engineering and Computing
Presented in Partial Fulfilment of the Requirement for the Degree of Master's in Electrical Power and Control Engineering (Power Engineering)

Office of Graduate Studies
Adama Science and Technology University

July, 2023
Adama Ethiopia

## Declaration and Recommendation

### Declaration

I hereby declare that this Master Thesis entitled "**Investigation and Mitigation of Power Quality problems using Dynamic Voltage Restorer with Super Capacitor based Energy Storage"** is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other University. All source of materials that are used for this thesis have been duly acknowledge through citation.

| ______________________ | ______________________ | ______________________ |
|---|---|---|
| Name of Student | Signature | Date |

## Recommendation

I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled "**Investigation and Mitigation of Power Quality problems using Dynamic Voltage Restorer with Super Capacitor based Energy Storage"** prepared under my guidance by Mesafint Ayalew Assefa submitted in partial fulfilment of the requirements for the degree of Masters of Science in Electrical Power and Control Engineering (Power Engineering).

Therefore, I recommend the submission revised version of the thesis to the department following the applicable producers.

| Dr. Shubhashish Bhakta | Shubhashish Bhakta | 13-07-2023 |
| --- | --- | --- |
| Major Advisor | Signature | Date |

## Approval Sheet

I, the advisor the thesis entitled "**Investigation and Mitigation of Power Quality problems using Dynamic Voltage Restorer with Super Capacitor based Energy Storage** "developed by Mesafint Ayalew Assefa, here by certified that the recommendation and suggestion made by the board of examiners are appropriately and incorporated into the final version of the thesis.

| Dr. Shubhashish Bhakta | | 13-07-2023 |
|---|---|---|
| Major Advisor | Signature | Date |

We, the undersigned, member of the board of Examiners of the thesis by Mesafint Ayalew Assefa have read and evaluated the thesis entitled "**Investigation and Mitigation of Power Quality problems using Dynamic Voltage Restorer with Super Capacitor based Energy Storage"** and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfilment of the requirement of the degree of Masters of Science in Electrical Power and Control Engineering (Power Engineering).

| Prof. Ravikumar Hiremath | | |
|---|---|---|
| Chairperson | Signature | Date |
| | | |
| Internal Examiner | Signature | Date |
| | | |
| External Examiner | Signature | Date |

Final approval and acceptance of the thesis is contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

| | | |
|---|---|---|
| Department Head | Signature | Date |
| School Dean | Signature | Date |
| Office of Post Graduate Studies | Signature | Date |

# ACKNOWLEDGMENT

I am honored to express my deepest gratitude and appreciation to all who have contributed to the completion of this thesis. Initially, I want to express my gratitude to God for his mercy and grace, which permitted me to initiate and achieve this thesis endeavor efficiently.

Secondly, I would like to extend my heartfelt thanks to my Advisor, **Dr. Shubhashish Bhakta,** for his vital guidance, patience, and support throughout this journey. His insightful feedback, encouragement, and willingness to answer my questions have been instrumental in shaping this thesis work. I am also grateful to the faculty members and experts in my field who have generously shared their knowledge and expertise with me. Their valuable insights and constructive criticism have been immensely helpful in refining my thesis and improving the quality of this thesis.

I would like to express my gratitude to all the BGI Ethiopia employees, especially Electrical Department members who took their time to participate in this research and provide me with valuable data. Without their willingness to share their experiences and thoughts, this thesis would not have been possible My sincere appreciation also goes to my wife for her unwavering support, encouragement, and love throughout this endeavor. Her constant encouragement and belief in me helped me to overcome the challenges and obstacles along the way.

Finally, I would like to thank all those who played a role, big or small, in the successful completion of this thesis.

Table of Contents

## LIST OF TABLES

## LIST OF FIGURES

## LIST OF ACRONYMS AND ABBREVIATION

| | |
|---|---|
| AC | Alternative current |
| AF | Active filter |
| ANSI | American National Standards Institute |
| ATS | Automatic Transfer Switch |
| CDVR | Cost of dynamic voltage restorer |
| CPD | Custom power devices |
| CVS | Cost of voltage sag |
| DC | Direct current |
| DLGF | Double Line to Ground Fault |
| DSTATCOM | Distribution Static Synchronous compensator |
| DVR | Dynamic Voltage Restorer |
| FACTS | Flexible Alternative Current transmission systems |
| FCTCRS | Fixed capacitor thyristor-controlled reactors |
| FFT | Fast Fourier Transform |
| GTO | Gate Turn-off Thyristor |
| HMI | Human-machine Interface |
| IEEE | Institute of Electrical and Electronics Engineering |
| IGBT | Insulated Gate Bipolar Transistor |
| IGCT | Integrated Gate Commutated Thyristors |
| IPFC | Interline Power Flow Controller |
| KHz | Kilo Hertz |
| KJ | Kilo Jules |
| KV | Kilo Volt |
| KVA | Kilo Volt |
| KVAR | Kilo-volt-Ampere-Reactive |
| KW | Kilo Watt |
| LC | Inductor Capacitor |
| MATLAB | Matrix Laboratory |
| MOSFET | Metal Oxide Semiconductor Field Effect Transistors |
| MVA | Mega Volt Ampere |
| NVS | Number of voltage sag per year |
| PCC | Points of Common Coupling |

| | |
|---|---|
| PF | Power Factor |
| PI | Proportional Integration |
| PID | Proportional integral derivative |
| PLL | Phase Locked Loop |
| PLCs | programmable logic controllers |
| PQ | power quality |
| PU | Per unit |
| PWM | Pulse Width Modulation |
| RMS | Root Mean Square |
| SCESS | Super Capacitor-based Energy Storage System |
| SCR | Silicon-Controlled Rectifiers |
| SLGF | Single Line to ground Fault |
| SPWM | Sinusoidal Pulse Width Modulation |
| SSG | Static Synchronous Generator |
| SSSC | Static Synchronous Series Compensator |
| STATCOM | Static Synchronous Generator |
| SVCS | Static VAR Compensators |
| TCR | Thyristor Controller Reactor |
| TCSC | Thyristor-Controlled Series Capacitor |
| TDD | Total Demand Distortion |
| THD | Total Harmonic Distortion |
| THDI | Total Current Harmonic Distortion |
| THDU | Total Voltage Harmonic Distortion |
| TLGF | Three Line to Ground Fault |
| TSC | Thyristor- Switched Capacitor |
| UPFC | Unified Power Flow Controller |
| UPQC | Unified Power Quality Conditioner |
| VSC | Voltage source convertor |
| VSD | Variable Speed Drives |
| VSI | voltage source invertor |

***Abstract***

*Electricity is an easy source of energy that has become more and more important with the development of technology. However, various conditions of the power system can affect the quality of the electricity, leading to power quality issues that can reduce the efficiency of the system. Nowadays, power quality has grown to be a serious issue. in modern power systems due to the increasing use of sensitive loads. Many industries in our country are facing issues with power quality, which has various causes. This thesis presents a comprehensive investigation of power quality problems in St. George Brewery and proposes a Dynamic Voltage Restorer (DVR) with a Super Capacitor based Energy Storage system as a solution. The proposed system was designed and simulated using MATLAB SIMULINK. The research work begins with a detailed analysis of power quality problems and their impact on electrical systems. The necessary information for the study is gathered by using a Fluke 435 Power Quality and energy Analyzer as well as recorded data. The measurements have been collected, and it has been recorded that the voltage sags are below 65% of the root-mean-square voltage and the total harmonic distortion of current (THD) value reaches 25.07%. After collecting the data, an analysis has been conducted, comparison with IEEE standards and computer simulations have been executed using the MATLAB/Simulink model to exemplify the effectiveness of the mitigation methods. The proposed DVR system is then introduced, including a discussion of its operation, design considerations, and control techniques. The integration of super capacitors as the energy storage in the DVR system is also analyzed. Furthermore, single tuned multi-branch passive filters have been developed and simulated for the reduction of harmonics distortion. The filters were successful in attenuating the harmonics, which ultimately led to a decrease in the total harmonics distortion value from 25.07% to 2.89%. The results demonstrate that the proposed DVR system with super capacitor-based energy storage provides an effective solution for mitigating power quality problems and improving the overall quality of power supply.*

***Key Words:*** *DVR, IEEE standards, MATLAB/SIMULINK, Power quality, Power quality problems, Super capacitor and THD.*

# CHAPTER ONE

# 1. INTRODUCTION

## 1.1.Background

Electricity is invisible form of electrical energy that is widely accessible across the globe and is now acknowledged as an essential requirement for everyday consumers. (N. Patel, 2017). Over several decades, the power sector has been transformed from low power generation restricted to a specific area, to the networking of highly connected systems that serve a large number of countries or even continents. Nowadays, it is quite challenging to survive in modern society without access to electricity. Transmission lines enable the transfer of power across great distances, and the quality of the power changes because of various equipment or abnormal network conditions, making it less suitable for any further applications. Any power issue that manifests as variations in voltage, current, or frequency that causes the failure or improper operation of end user equipment is referred to as having poor power quality (IGI Global, 2019).

Among the most significant factors determining the electrical power's quality is the magnitude of the voltage (Rosli, 2011).The quality of the power supply was not taken into account in power distribution until the early 20th century. Utility companies were only concerned with achieving a state of power delivery with little or no interruptions. However, in recent years, as technology advanced, allowing for the development of very sensitive loads, power quality has emerged as a fundamental and prevalent concerns in modern power systems (Padmanaban, 2020).

Consequently, power quality is an ever more critical concern for electricity consumers of varying consumption levels. Power outages and interruptions are an inconvenience that affect households, businesses, and especially industrial customers. This leads to significant financial losses and greatly impacts production expenses. Furthermore, developing nations such as Ethiopia lack awareness regarding energy conservation and prioritize generating more energy instead of utilizing existing energy efficiently. There are several PQ problems the primary power quality concerns consist of short and long term changes in voltage, waveform distortions, voltage imbalances, fluctuations, and power frequency variations. These problems are a major concern for many industries due to the growing number of sensitive loads impacted by power disturbances. There are numerous influencing variables of power quality, and it is almost unavoidable for these types of issues to arise within the power system network. So so to ensure that power quality is preserved, it is crucial to operate appropriate devices that can prevent the negative outcomes of these issues. The electrical power distribution often faces the issue of voltage sags that result in reduced efficiency of equipment, while voltage spikes lead to power wastage. To address this problem, Dynamic Voltage Restoration (DVR) is utilized, which involves a procedure of injecting voltage that can manipulate the phase and shape of the supplied power, leading to energy savings (Namita R. Chavan1, 2020).

Power quality involves voltage, frequency, and waveform (Soomro, 2021). Generally speaking, power efficiency may be described as the degree of harmony between the electricity that is provided by an outlet and the equipment that is connected to it. High-quality power is characterized by a consistent voltage supply that remains within the accepted range. It is the overall result of the integration of the generation, transitional and distribution stations. Hence, the power quality has to be checked and appropriate mitigation measures should be applied for efficient use of electric power. In order to mitigate the power quality problems, the literature describes the use of two main tools. These are Passive Power Filters and Custom Power Devices (CPDs). Passive Power filters are filters that is able to carry out the task of harmonic reduction. The latest power electronics equipment, known as CPDs, have been developed to improve the dependability and efficiency of electricity delivery in low-voltage distribution networks. Included in the group of CPDs are devices such as the Dynamic Voltage Restorer (DVR), Distribution Static Compensator (DSTATCOM), and Unified Power Quality Conditioner (UPQC). In this paper DVR has employed to enhance the quality of power flows.

There are several reasons why DVR is considered better in the mitigation of voltage sag, especially when compared to DSTACOM and UPQC.

1. Faster response time: DVR is known for its extremely fast response time, typically within a few milliseconds. This means it can rapidly sense and mitigate voltage sags in real-time, preventing sensitive equipment from being affected by the sag. In comparison, DSTACOM and UPQC may have a slower response time, leading to a delay in voltage restoration and potential damage to equipment.

2. Targeted compensation: DVR provides targeted compensation only at the point of installation, which makes it more efficient in dealing with voltage sags it injects the necessary voltage to correct the sag at the precise location, ensuring a faster and more accurate voltage restoration. On the other hand, DSTACOM and UPQC provide global compensation which may not deal with the voltage dip at the specific location using the same level of precision.

3. Compact size and ease of installation: DVRs are typically smaller and more compact in size compared to DSTACOM and UPQC. This makes them easier to install and integrate within existing electrical infrastructure. The compact size also allows for more flexibility in placement, enabling DVRs to be installed in areas where space is limited.

4. Cost-effectiveness: DVRs often offer a more cost-effective solution for voltage sag mitigation compared to DSTACOM and UPQC. The sleek design and targeted compensation mean that fewer additional components are required, resulting lower overall costs for installation, maintenance, and operation.

While DSTACOM and UPQC have their own advantages in certain power quality applications, DVRs stand out in terms of their fast, targeted compensation, instantaneous voltage support, compact size, and cost-effectiveness. These features make DVR an ideal choice for mitigating voltage sags efficiently and effectively.

This thesis has concerned about issues with power quality and mitigation techniques in St. George Brewery, BGI Ethiopia Mexico branch.

#### 1.1.1. Sources of Power Quality Problems

Nonlinear loads are major sources of PQ problems. Nonlinear loads refer to electrical devices or equipment that do not draw electrical current in a linear relationship with the applied voltage. These loads can cause distortions in current and voltage waveforms, which can result in issues such harmonic distortion, electromagnetic interference, and voltage sag. Nonlinear loads include, for example computers, variable speed motor drives, and fluorescent lighting.

When using a nonlinear load, the relationship between current and voltage is not linear. In industrial nonlinear loads, the dominant factor can vary depending on the specific load and its characteristics. However, in the case study site current is dominant factor due to the existing nonlinear loads, such as variable frequency drives and power electronics converters, draw non-sinusoidal currents from the power supply as shown in Appendix VI.

Nonlinear loads happen when the equipment has electronic parts that help regulate its functions to fulfil the demands of the load, and it is not purely resistive or inductive.

This can lead to the creation of harmonic distortion, which can cause equipment to overheat and potentially be vulnerable to voltage dips (sags) if appropriate protection measures are not in place.

Most of the sources of power quality problems are:

- Customer loads
- User electrical distribution grounding elements
- Lighting, wind rain, etc.
- Utility distribution
- Utility transmission.
- Utility generation
- Power electronics devices
- Office and IT equipment
- Arcing devices
- switching loads and starting a large motor
- Interconnection of power system
- Lighting strike and environmental related damage.

#### 1.1.2. Case Study Site Description

BGI Ethiopia plc is a branch of Group Castel that specializes in brewing and producing beverages on a large scale. Since 1998, BGI has been distributing beer, wine, and other alcoholic beverages in more than 53 nations. The company possesses and manages five well-known breweries, these include the Addis Abeba-based St. George Brewery, the Kombolcha Brewery, the Hawassa Brewery, the Zebidar Brewery, and the Maychew Northern Brewery. These breweries collectively produce 3.6 million Hectoliters of beer each year, in both bottled and draft forms. The case study site called St. George Brewery located in Addis Ababa, Mexico square Lideta sub-city. Currently the production capacity of 550,000 Hectoliter per annual.

The factory gets power through 15KV power lines from Ethiopian electric power, Mexico substation to produce the aforementioned brewing products, which are then stepped down to 380V by a service transformer. The power consumption of the factory is 3.25 MVA from two 1000KVA and one 1500KVA step down transformers, the detail specification of the transformer is shown in Table 1.1.

Table 1.1. The case study existing Transformer rating

| | Voltage, KV | Apparent power | Power factor | Active power, KW |
|---|---|---|---|---|
| Transformer -1 | 15/0.38 | 1500 | 0.85 | 1200 |
| Transformer -2 | 15/0.38 | 1000 | 0.85 | 800 |
| Transformer -3 | 15/0.38 | 1000 | 0.85 | 800 |

## 1.2.Statement of the Problem

The title implies a study focused on investigating and mitigating power quality issues related to harmonics and voltage sag using a DVR with Super Capacitor based Energy Storage, specifically at the St. George Brewery in BGI Ethiopia.

The St. George Brewery, located in BGI Ethiopia, is experiencing PQ issues primarily linked to voltage and harmonics. These issues have led to disruptions in the brewery's operations, causing equipment malfunctions and production inefficiencies. The existing power supply infrastructure has been unable to provide consistently stable voltage levels and mitigate harmonic distortions adequately.

Therefore, an investigation is needed to understand the extent of voltage and harmonics power quality problems at the St. George Brewery. Additionally, a suitable mitigation strategy is required to address these issues effectively and ensure the smooth functioning of the brewery's operations. The investigation were focused on the implementation of a DVR with Super Capacitor based Energy Storage as a potential solution, while DSTACOM and UPQC have their own advantages in certain power quality applications, but DVRs stand out in terms of their fast, targeted compensation, compact size, and cost-effectiveness. Additionally, in the case study site the detected power quality problem is voltage sag, therefore the potential solution is to use DVR in series in order to inject the missed voltage during voltage fault. The research has assessed the feasibility, effectiveness, and economic viability of deploying this technology at the St. George Brewery.

By conducting a case study at the St. George Brewery, this research aimed to provide recommendations and guidelines for the implementation of a DVR with Super Capacitor based Energy Storage system to mitigate voltage and harmonics power quality problems effectively. The findings of this study can then be used to improve the overall power stability and consistency of the brewery's operations and improve the quality of beer production.

## 1.3. Objective of the Study

### 1.3.1. General Objective

The general objective of this thesis is investigation and mitigation of power quality problems using a Dynamic Voltage Restorer with Super Capacitor based Energy Storage at St. George Brewery, BGI Ethiopia to assess the effectiveness of the DVR with a Super Capacitor-based Energy Storage System (SCESS) in mitigating power quality issues, specifically voltage sags and harmonics, and to evaluate its potential to improve the overall power quality at the factory.

### 1.3.2. Specific Objectives

The specific objectives are:

- To provide quality power in the factory power system.
- Reduce technical and economic impacts of poor power quality in the factory.
- Mitigate voltage sag and reduce total harmonics distortion (THD) in the factory.
- Compare and confirm Total harmonic distortion and voltage disturbance level with acceptable IEEE standards.
- Analyze the level of power quality enhancement with and without DVR.

## 1.4.Significance of the study

In this study power quality problems were identified and their mitigation techniques has been proposed taking St. George Brewery, BGI Ethiopia as a case. The study results have significant implication for other related industries too.

The main significances of this paper are:

- Industries change the techniques for mitigation techniques of PQ problem.
- Industries develop strategies and initiatives to address their PQ issues.
- Industries improve equipment performance and efficiency while extending the equipment's useful life.
- Industries increase their productivity and overall performance.
- It helps managers to make good decisions to address the power quality problem.
- It gives inputs for further reference for researchers and practitioners.

## 1.5. Delimitation and Limitation

### 1.5.1. Delimitations:

1. The scope of the study is limited to investigating power quality problems and proposing a solution using a DVR with a SCESS.
2. The effectiveness of the proposed solution is limited to addressing issues with harmonics and voltage sags in the power supply.
3. The study is limited to the use of MATLAB SIMULINK for simulating and analyzing the proposed solution.

### 1.5.2. Limitations:

1. The proposed solution may not be applicable to all types of electrical systems and may require customization based on specific system requirements.

2. The study only assesses the proposed solution's economic feasibility and practicality and does not take into account other factors such as environmental impact or social implications.

3. The research is limited by the availability and accuracy of data for simulating and analyzing the proposed solution using MATLAB SIMULINK.

# CHAPTER TWO

# 2. LITERATURE REVIEW

## 2.1. Background of the Study

The increment of power quality is very important as the field of electrical systems have become more complex and more susceptible to power quality problems such as voltage sags, voltage swell, harmonics, transient, surges, and interruptions.

The idea of supplying power and make grounding sensitive equipment in a way that is acceptable for the equipment's operation is known as "power quality." (IEEE-1100, 1992). However, the phrase "power quality" has no universal definition. For instance, consider the next sentence: (Heydt, 1998) sates as “Power quality is the delivery of voltages and system plan that allow an electric power end user to effectively use electric energy from the supply system free from interruption or interference. (Carnovale, 2006) Explains “Voltage and current quality synchronizes to make up power quality, hence, PQ is focused with voltage and/or current variation from the ideal”.

Initially, Power Quality (PQ) referred solely to the ability of utilities to deliver uninterrupted electrical power. However, recent times, power quality has become a significant concern for both customers and utility providers. This is due to the elevated demand for higher power quality from customers, driven by the proliferation of critical loads and electronic devices. Unlike reliability, power quality focuses on the duration of events it addresses and encompasses very brief disturbances lasting only a few cycles or seconds. Emerging power quality issues such as harmonic distortion, voltage sags, voltage swells, transients, flicker, and unbalance can have adverse effects on customer devices, leading to malfunctions, production losses, and costly downtime. These problems should be measured and assessed more accurately than before (Won, 2003).

In recent years, the electrical power networks have incorporated more and more delicate loads. As a result, there is now a much higher need for high PQ and voltage stability. (Meyer, 2008). The fundamental standards for power quality encompass stable RMS value, symmetrical three-phases, constant frequency, pure sinusoidal wave pattern, and restricted THD. Power interruptions may be quite expensive, due to sensitive devices are widely used in industries to manage the operation. Industrial enterprises often encounter numerous power quality issues that can negatively impact their performance, productivity, and profitability. The prevailing power quality enterprises typically include voltage sags, voltage swells, and harmonic distortion. It is crucial to find effective solutions to mitigate these various disturbances and minimize their adverse effects.

Numerous studies have been conducted in the field of power quality and their mitigation techniques. Basically, they focused elimination of voltage sage/voltage swell and harmonic distortion by using different mitigation techniques.

FACTS devices were utilized to tackle the issue and provide clean energy. To address different needs, multiple variants of Flexible AC Transmission Systems (FACTS) controllers have been deployed worldwide. Based on the connectivity, these FACTS devices are divided into four classes such as series controller, shunt controller, combined series/series controller and combined series/shunt controller (Negendrabu, 2012).

### 2.2.Sources and Effects of Power Quality Problems

Customers should have a constant supply of energy from power distribution systems at the smooth sinusoidal voltage at the contracted magnitude level and frequency. However, in actuality, power quality is greatly impacted by a significant number of nonlinear loads present in distribution systems. There is no Cleanliness of power supplies sinusoidal waveform because of the non-linear loads, this ends up producing PQ problems (Jena, 2010).

Power quality problems can arise from a variety of sources. There are different devices responsible for the quality of power supply distortion, and some of the leading sources of distortion are enumerated below:

Nonlinear loads:-Power electronics device, adjustable speed drive, and electronics ballast for fluorescent lamp and power supply for welding machine.

- Office and IT devices
- Arcing devices
- Load changing during operation
- Large motor starting
- Interconnectedness of power system
- Lighting strike and environment related causes.

The rise in non-linear loads, such as devices equipped with switching power supplies, has resulted in an escalation of current harmonics, superfluous reactive power, and power losses. As a consequence, this leads to the occurrence of line voltage disturbances such as distortion, harmonics, flicker, imbalance, sag, and swell conditions. (Inchi, 2013).

## 2.3.Power Quality Problems and categories

Power quality problems refer to any issue that affects the quality of electrical power in a system. All the power quality problems can cause significant damage to electrical equipment and disrupt operations, leading to costly downtime.

To address power quality problems, it is essential to identify the root cause of the issue. This may involve conducting a power quality analysis to identify the specific type of problem and determine the best solution. Solutions can include installing custom power devices. In addition to addressing power quality problems, it is also essential to implement preventative maintenance programs to ensure that electrical equipment is regularly inspected and maintained. Before this become significant issues, this will assist in identifying potential issues, reducing the risk of downtime and associated costs. Ultimately, addressing power quality problems is crucial for guaranteeing the safe and efficient operation of electrical systems.

As per the IEEE Standard 1159-1995, power quality problems can be classified into seven major categories.

### 2.3.1. Voltage Sag

One of the main issues with power quality in distribution systems is voltage sags. These sags are characterized as a decline in RMS voltage at the power frequency to a range of 0.1 to 0.9 per unit for periods lasting from cycles to one minute. The primary culprits behind voltage sags are short-circuit faults, like single-line-to-ground faults, and the activation of large induction motors. Voltage sags can cause voltage-sensitive equipment in industries, hospitals, and buildings to malfunction (Kangarlu, 2010).

Voltage sags can lead to the tripping of relays, motor starters, and contactors, as well as the need to restart computers and even the complete shutdown of production lines. The main reasons of voltage sags are faults within the transmission or distribution network, often on neighboring feeders, lighting, short circuits, improper VAR compensation, the activation of heavy loads, the energizing of transformers, and the starting of motors (Anu G. Pillai, 2019).

### 2.3.2. Voltage Swell

Voltage Swell, is a rise in voltage or current on power frequency, occurring in the range of 1.1 to 1.8 pu of RMS voltage. This can persist from 0.5 cycles up to 1 minute.

### 2.3.3. Transients

Transients are brief, high-voltage disturbances that can occur in electrical power systems. They can result from a variety of causes, including lightning strikes, switching operations, and motor starting. Transients can cause power quality problems, which can have a significant impact on sensitive electronic equipment and other devices that rely on stable power. One of the most common types of transients is known as voltage spikes or surges. These occur when the voltage in a power system suddenly increases above the normal level. This can cause damage to electronic equipment and can start fires in extreme cases.

A transient can be defined as the portion of a change in a variable that diminishes during the transition from one stable operating condition to another. Another frequently used term that is often regarded as interchangeable with transient is "surge." (Dugan, 2003). This phenomenon is an aperiodic function of time and has a short duration, is voltage or current surge.

There two types of main transients divisions. "Impulsive" and "oscillatory":

- Impulsive transients: These are categorized by abrupt changes in voltage, current, or both that happen at frequencies other than the power frequency.
- Oscillatory transients: These refer to voltage or current fluctuations that rapidly change polarity with their instantaneous values.

Several factors give rise to current or voltage transients, with the terms used to describe their waveform. The presence of transients can lead to the following outcomes:

- Electronic devices may be adversely affected, resulting in incorrect operation or malfunctioning.
- Motors may operate at elevated temperatures, potentially leading to overheating.
- Ballasts in fluorescent lights may fail due to the impact of transients.
- The efficiency and lifespan of equipment may be reduced.

Long-duration voltage variations: It refer to the root-mean-square (rms) deviations at power frequencies that persist for more than 1 minute. The ANSI (American National Standards Institute) provides guidelines on the acceptable steady-state voltage tolerances in a power system. If the voltage deviation exceeds the ANSI limits for a duration longer than 1 minute, it is classified as a long-duration voltage variation (engineeringenotes.com, 2017).

Long-duration variations can be either overvoltage or under voltages. The consequence of the system fault are not due to the change in in these voltage level, but it can be in the following mistakes.

- Errors committed by people
- When safety equipment are working wrongly
- The change in electrical loads in the system
- Switching on and off the system operations

Plots of rms voltage against time are frequently used to demonstrate these fluctuations. As a result of this kind of voltage variation power is fully cut off for a while until the issue is fixed. As mentioned below, the continuous interruption, undervoltage, or overvoltage that causes the extended duration voltage fluctuation are all possible.

#### 2.3.4. Under Voltage

An under voltage event occurs when the root mean square (rms) alternating current voltage decreases to below 90 percent of the power frequency for more than 1 minute. Under voltages can be attributed to:

Under voltage can occur due to excessive impedance within the power system, resulting in a significant drop in terminal voltage when operating under heavy load. The potential consequences of under voltage include:

- System shutdown
- Malfunctioning of specific equipment
- Decreased operational efficiency of equipment

#### 2.3.5. Overvoltage

Overvoltage refers to the occurrence of an elevation in the rms alternating current voltage that exceeds 110 percent of the power frequency for a duration longer than 1 minute.

Over voltages are commonly triggered by actions such as switching off a large load or energizing a capacitor bank. The repercussions of overvoltage include:

- Insufficient system strength for achieving the desired voltage regulation
- Inadequate voltage controls
- Transformers with inappropriate tap adjustment.

A cause of under voltage is availability of high impedance in the power system.

Therefore, the terminal voltage drops too low under heavy load.

#### 2.3.6. Sustained Interruptions

An interruption is considered sustained if the supply voltage stays at zero for over a minute. This type of interruption can occur due to control malfunctions, faults, or incorrect breaker tripping.

Shorty duration voltage variations

Short duration voltage variations include root mean square rms voltage variations at power frequencies for a period of less than 1 minute. The causes of these short duration voltage variations are-

- The opening of automatic circuit breaker
- Insulation removal

- When large loads are started with high current starting
- When power wiring loose connections occured

### 2.3.7. Waveform Distortion

Waveform distortion is present when the waveform of steady-state voltage or current deviates from the ideal sine wave form of the power frequency. Typically, there are five main types of waveform distortion, which include dc offset, harmonics, interharmonics, notching.

### 2.3.8. Dc offset

DC offset refers to the existence of a direct current (DC) voltage or current within an alternating current (AC) power system. This occurrence is often associated with the impact of half-wave rectification. The presence of DC within AC networks can have detrimental repercussions, leading to increased heating and potential damage to transformers.

### 2.3.9. Interharmonics

Interharmonics refer to electric currents or voltages that contain frequency components that are not integer multiple of the supply system's designated frequency. Interharmonics can be found in networks of all voltage classes (Yau, 2014). Interharmonics mainly originate from cycloconverters, static frequency converters, and devices that produce arcing. They typically arise as a consequence of frequency conversion processes and typically not but rather vary with the load. This can occur when the fluctuating interharmonic frequency coincides with the system's natural frequencies, resulting in intense resonant effects.

### 2.3.10. Notching

Notching is a regular interruption in voltage produced during the typical functioning of power electronic tools as current shifts between phases. It is a continuous occurrence that can be identified by assessing the harmonic range present in the impacted voltage.

### 2.3.11. Noise

In power systems, noise is characterized by undesired electrical signals that are present in phase conductors and have a spectral content below 200 kHz. This type of noise can result from a range of sources such as power electronics, control circuits, arcing equipment, and loads that utilize solid-state rectifiers or switching power supplies. Poor grounding is also known to worsen noise issues; effective grounding can help to remove noise from the power system.

### 2.3.12. Harmonics

Harmonics pose a rising challenge for both electricity providers and consumers. Harmonics refer to sinusoidal components of a periodic signal or quantity, with frequencies that are multiples of the fundamental frequency (usually 50 Hz or 60 Hz). Waveforms that are distorted can be broken down into the sum of the fundamental frequency and harmonics. These distortions occur due to the nonlinear properties of devices and loads connected to the power system.

Harmonics encompass both current and voltage harmonics. Voltage harmonics are generated by current harmonics, which are caused by nonlinear electronic loads. These nonlinear loads consume a distorted current waveform from the power supply system. (Abas, 2020).

Sources and Effects of Harmonics

The various sources of harmonics in electrical power systems can be classified in the following manner:

Magnetization nonlinearities of transformers**:** The non-linear property of the magnetic material in transformers is responsible for harmonics during excitation.

Rotating Machines**:** Rotating machines are another instance of equipment that can generate harmonics.

Arcing Devices: Electric Arc Furnaces, discharge-type lighting, and arc welders are examples of equipment that exhibit highly non-linear voltage and current patterns. In the case of arc ignitions, short-circuit is created which leads to a decrease in voltage. As a result, these devices represent a major contributor of power system harmonics.

Power supplies with semiconductor devices: Harmonics generated in this types of devices depend up on the type of semiconductor devices used, operating point, nature of load variation, etc.

Thyristor controlled reactors: Various forms of thyristor-controlled reactors - including series controllers, shunt controllers, static VAR compensators (SVCs), fixed capacitor thyristor-controlled reactors (FCTCRs), and thyristor-switched capacitor thyristor-controlled reactors (TSCTCRs) - can act as sources of harmonics in power systems.

Phase controllers and AC regulators: Harmonic generation can occur if phase controllers are used to provide balanced electric power or if AC voltage regulators are applied both online and offline for voltage regulation.

Effects of Harmonics: Harmonics can have effects of on rotating machine, transformer and transmission line, and effects on consumer equipment**.**

2.3.13. Flicker

The term "flicker" is used to describe the effect of voltage fluctuations on lamps, which causes them to as though they are flickering to the human eye. To measure and quantify the flicker signal, its magnitude is calculated using the root-mean-square method and expressed as a percentage of the fundamental frequency. However, the perception of voltage flicker by the human eye is the main factor considered when evaluating its severity. Even low magnitudes as low as 0.5% and frequencies within the range of 6 to 8 Hz can cause lamps to flicker. One common source of voltage fluctuations in utility transmission and distribution systems is the presence of arc furnaces.

2.3.14. Power Frequency Variation

Power frequency variations refer to any deviation from the standard value of the fundamental frequency in the power system, typically either 50 Hz 60 Hz. The frequency of the power system is directly linked to the rotational speed of the generators that supply it. Changes in frequency occur when there is a shift in the dynamic balance between load and generation. Frequency variations can lead to faults in the power transmission system, disconnection of large loads, or the shutdown of a significant source of generation. These variations are more likely to occur when loads are supplied by a generator that is isolated from the utility system. In such cases, the response to sudden changes in load may not be quick enough to meet the stringent requirements of frequency-sensitive equipment. As a result, there is a risk of data loss crashes, and damage to equipment.

2.3.15. Voltage Unbalance

Voltage unbalance occurs when there is an unequal distribution of voltage among the three phases.

Voltage imbalances of less than 2 percent are mostly caused by: -

- Loads that operate on only one of the phases in a three a three phase circuit.
- Fuses that has been blown in one phase of a three-phase capacitor bank.
- A situation when only one phase in operating conditions.
- Single line to ground faults that have not been identified.
- When an open circuit on the distribution system.
- Unstable power supplied from the utility.

Normally, a power system works smoothly when equipment is carrying normal load currents, and the bus voltage are within allowed limits. However, if there is a problem within the system, this condition can be disturbed. If the electrical faults surpasses the limit of the protective device, it can lead to catastrophic outcomes. It can put human life at risk and also cause severe damage to equipment.

Short circuits are considered as one of the major sources of power quality problems. Power quality issues often arise due to short circuits in the power system. The occurrence of short circuits can significantly impact the quality of power being supplied. Short circuits can create power quality issues like voltage sags, swells, fluctuations, and interruptions. These faults can additionally lead to negative impacts on power quality through harmonics and transients. Short circuit faults are typically classified by type, either symmetrical or asymmetrical, and further subdivided into one of five specific types. These five variations are categorized by the order of their frequency of occurrence.

## 2.4. Faults in Power System

### 2.4.1. Asymmetrical Faults:

When dealing with asymmetrical faults, it is necessary to compute each component individually, including the positive, negative, and zero sequence components. There are three types of faults. The Single Line to Ground fault (SLGF) is caused by one phase (either A, B, or C) being connected to the ground.

The Line to Line Fault happens if one of the phases (A, B, or C) is shorted out to another line.

Finally, the Double Line to Ground fault (DLGF) occurs when two phases are shorted out to the ground simultaneously.

### 2.4.2. Symmetrical Faults:

Since symmetrical faults keep the system completely balanced, they do not result in negative sequence or zero sequence components. As a result, these errors include only positive sequence values. Three-phase line-to-ground faults refer to a situation where all three phases (A, B, and C) are simultaneously short circuited and grounded.

Three-phase to line faults happen when all three phases (A, B, and C) are short-circuited simultaneously without any grounding. To address this issue and provide reliable and clean power, FACTS devices can be employed. Numerous FACTS devices are currently utilized in electrical networks, including the Static Synchronous Compensator (STATCOM), static synchronous series compensator (SSSC), Unified Power Flow Controller (UPFC), and Interline Power Flow Controller (IPFC). Actually, FACTS devices were designed for the transmission system but can be used in distribution systems, named Custom Power Devices. Custom power equipment such as DVR, DSTATCOM, and Active Filter (AF) are frequently utilized. Of these, the DVR is especially valued for as one of the most effective and efficient power custom devices due to its fast response (Chow & Juan J. Sanchez-Gasca, 2020). The DVR is an electronic device employed to minimize voltage sags or swells on the load side by injecting voltage in series with a distribution feeder. To restore the load voltage, active and/or reactive power should be injected into the distribution feeder (Pal, 2015).

In a three-phase, three-wire power distribution system, this research intends to propose a model for a PI-controlled DVR that enhances the power quality. The model employs a three-lag voltage source inverter, an LC filter, and an injection transformer to adequately counteract distorted supply voltage by injecting or absorbing required voltage. The control scheme of the VSI is implemented using the parks transformation algorithm. Using MATLAB/Simulink, this study successfully conducted modeling and simulations of a DVR to demonstrate its effectiveness in enhancing power quality during various fault conditions.

**2.5. Power Quality Standards**

Standards have established specific attributes of the supply voltage that are utilized to assessed the quality level concerning frequency, voltage level, waveform, and the symmetry of the three-phase voltage (Inchi, 2013). The requirements for equipment connected to the network, as well as the permissible emissions limits from devices, are outlined in the IEEE 519-1992 and IEEE 1159-1995 standards (IEEE, 1992).

The defining characteristics of disturbances are listed in Table 2.1.

Table 2.1. Characteristics of disturbance

| Disturbance Type | Typical Voltage Magnitude | Typical Duration |
|---|---|---|
| Sag | 0.1-0.9 pu | 0.5-30 cycle |
| Swell | 1.1-1.9 pu | 0.5-30 cycle |
| Flicker | 0-1 % | Steady state |
| Interruption | <0.1 pu | 0.5 cycle -3 s |
| Imbalance | 0.5-3 % | Steady state |
| Harmonics | 5 % | Steady state |

**2.6. Solution for Power Quality Problems**

To address power quality issues, there are two available approaches - one from the perspective of the customer and the other from the standpoint of the utility. The first approach, known as load conditioning, aims to enhance the resilience of equipment against power disruptions, allowing it to operate smoothly even in the face of substantial voltage distortion. The second approach entails the installation of line-conditioning systems that can mitigate or neutralize disturbances within the power system. In addition, there custom power devices like DSTATCOM, DVR, and UPQC that offer a versatile solution to power quality concerns by connecting to low and medium voltage distribution systems either in parallel or in a sequence utilizing PWM converters. Among these devices, the DVR, which is connected in series, can promptly and dynamically address power quality issues, thereby improving the overall power quality in the distribution system.

## 2.7. Custom Power Devices

According to (Naeem Abas, 2020), custom pertains to of electronics controllers within distribution systems in improve the caliber and dependability of the power provided to consumers. This approach is driven by an increasing requirement for power of exceptional quality. Custom power primarily targets the specific needs of industrial and commercial customers. To deliver consistent, superior power to delicate customers, it entails installing power electronic or static controllers in the medium voltage distribution system.

Power electronic devices form the basis of custom power devices including active filters, converter-based devices, and static transfer switches. By utilizing a custom power system, customers can receive predetermined power quality levels from either a utility company or a service provider. Alternatively, this can be achieved by installing equipment in coordination with the utility. The equipment ensures a satisfactory blend of the following characteristics: minimal or no power interruptions, reduced harmonic voltage, decreased phase unbalance, and controlled voltage reductions and over voltages in terms of magnitude and duration.

The requirement for custom power devices arises from the fact that modern automated equipment, including adjustable speed drives, arc furnaces, switching power supplies, and automated production lines, is more vulnerable to disruptions compared to older equipment and less automated systems. While power generation in developed nations is relatively dependable, distribution can be stable. Nowadays, consumers prioritize both the quality and reliability of power. As the electric power energy market is deregulated, there is a growing awareness of power quality among different customer groups. At all levels of electricity usage, power quality is becoming an increasingly crucial factor for consumers. Types of custom power devices: Various Custom Power devices are available. Some of them are: DSTATCOM, DVR, UPQC, Power Filters, Static VAR Compensator (SVC), and Uninterruptible Power Supply (UPS).

### 2.7.1. Static VAR Compensator

An SVC is an electrical equipment that regulates voltage and stability on high-voltage electricity transmission networks and its Schematic diagram of static VAR compensator shown in Figure 2.1. It belongs to the FACTS family and provides quick-reacting reactive power. The name "static" implies that the SVC lacks any moving parts except for circuit breakers and disconnects. In the past, power factor compensation required enormous spinning equipment such as synchronous condensers before the SVC by (Mahmoud, 2012). The SVC is designed to automatically adjust the system's power factor to approach unity by regulating the system's impedance. It can consume VARs using reactors to lower the system's voltage if the system's reactive load is capacitive (leading). Conversely, it automatically switches on capacitor banks when the load is inductive (lagging), which increases the system's voltage. Additionally, it can be used to stabilize voltage near high and rapidly varying loads, such as arc furnaces (Mahmoud, 2012).

There are two types of SVC:

1. Fixed Capacitor-Thyristor Controlled Reactor (FC-TCR).
2. Thyristor Switched Capacitor - Thyristor Controlled Reactor (TSC- TCR).

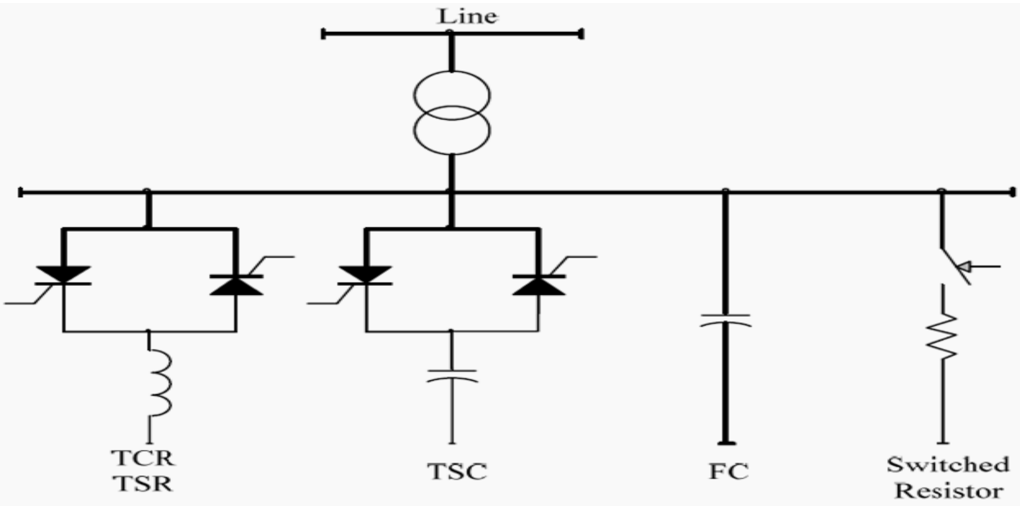



Figure 2.1 Schematic diagram of static VAR compensator

2.7.2. Distribution Static Synchronous Compensator

The shunt-connected static synchronous compensator was designed to be a more advanced static VAR compensator that replaces controlled reactors and switching capacitors by utilizing a VSC. Unlike the variable impedance SVC that uses thyristor devices, VSCs need self-commutated power semiconductor devices like IGBT, integrated gate-commutated thyristor, gate turn-off, and others (which are more expensive and have higher losses) (Ryan, 2013).

The DSTATCOM configuration, presented in Figure 2.2 includes two-level VSC, a dc energy storage unit, a coupling transformer connected in shunt with the ac system, and a corresponding control circuit (Tasneem Akhtar, 2018). With the VSC, the dc voltage of the storage device is converted into a group of three-phase ac output voltages that are in sync and linked to the ac system through the reactance of the coupling transformer. It's possible to efficiently manage the transmission of active and reactive power between the

DSTATCOM and the AC network by adjusting the magnitude and phase of the DSTATCOM's output voltage. The VSC provides a multifunctional topology that can be used for up to three unique purposes when linked in shunt with the ac system (Padiyar, 2007): Voltage regulation and compensation of reactive power, Elimination of current harmonics and Correction of power factor.

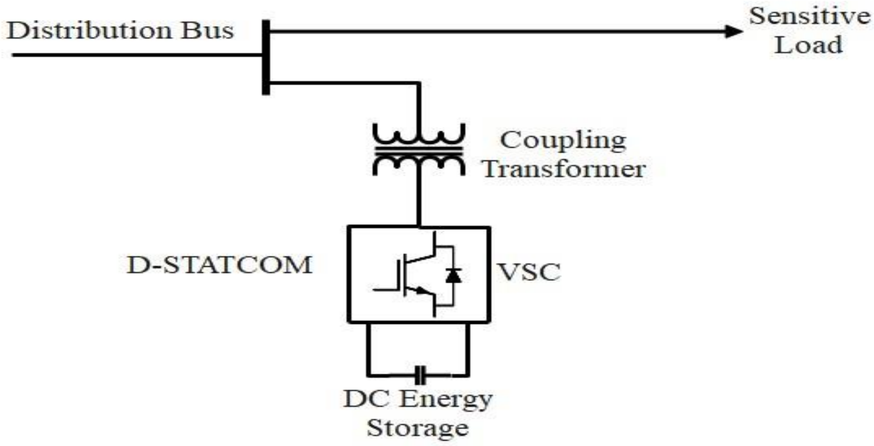



Figure 2.2 Schematic diagram of the DSTATCOM

2.7.3. Unified Power Quality Conditioner

This custom power device is combines the features of shunt and series active filters as presented in Figure 2.3 , that offers the benefits of both. It can effectively mitigate a variety of power quality issues that arise in the power system. The circuit diagram is shown below.

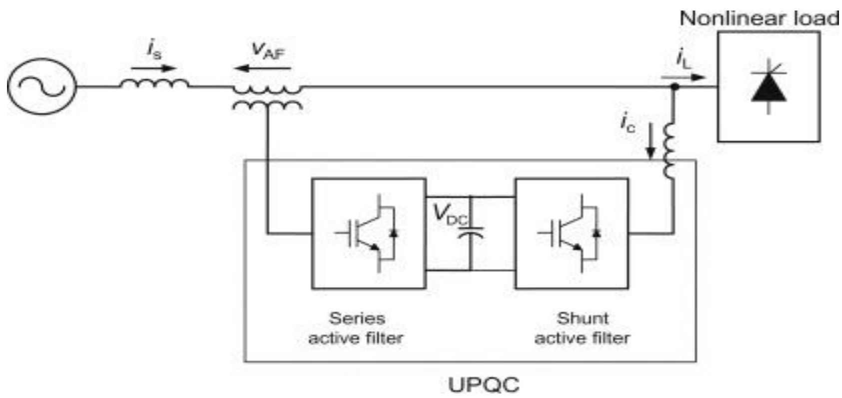



Figure 2.3 UPQC Circuit diagram

## 2.8. Review of related literature

In this section related literature were conducted focusing on prior research regarding power quality issues and potential mitigation approaches. Specifically, studies explored involving the use of DVR with and without SCESS in combination to address power quality problems.

Therefore, several studies have investigated the use of DVR systems to mitigate power quality problems.

(R. Pal, 2016), presents simulation of DVR to mitigate voltage sag during three-phase fault. The aim of this paper was presented for modeling, analysis and simulation of a Dynamic Voltage Restorer that addresses power quality concerns, particularly those related to voltage sags, utilizing a Sinusoidal Pulse Width Modulation (SPWM) method in MATLAB. Through the simulation of a three-phase fault both with and without the DVR, it was demonstrated that incorporating the DVR resulted in an improved voltage profile and reduced sag occurrence. But he didn't address the possible solution of for harmonics and mitigation technique and didn't use super capacitor as storage device.

The (S.Balaji, 2021), paper was focused on utilizing MATLAB/SIMULINK to model and analyze voltage sags, as well as improve power quality through power factor correction. The approach involves employing a PI controller and a discrete PWM generator to control a DVR. The system were provided the voltage regulation and harmonics reduction for the faults but didn't consider cost analysis of installing DVR and battery energy storage was used as storage device.

(Muhammad, 2021), improved the stability of micro-grids and protecting sensitive loads and also showcases the use of a two-stage PID control strategy in the DVR system topology to ensure maximum protection. The results obtained in the study demonstrated that the THD is within the permissible range of less than 5% according to IEEE1159 standards during voltage variations, except for the double line to ground fault instance which exhibited a THD greater than 5%. However, the expense of installing a DVR was not taken into account, while the battery as energy storage device was used.

(Gupta, 2020), presents the design and implementation of super capacitor based DVR circuit power quality enhancement. This paper briefly explains the operational behavior of the super capacitor, discussing its unique features and how it can be used in conjunction with a DVR to compensate for voltage sag in distribution systems. The paper also examines the advantages and disadvantages of using a super capacitor but the expense of installing a DVR was not taken into account.

(Abas, 2020), successfully addressed the issue of distorted load voltage by using DVR control strategy as a result, the voltage profile became stable and smooth, with minimal harmonics. The DVR played a crucial role in rectifying voltage supply problems and ensuring a consistent load voltage within the desired range. Due to this compensation, THD was significantly reduced, dropping from 18.5% to 2.69% but the cost of installing a DVR was not taken into account.

(Eltamaly, 2018), the usefulness of including DVR in distribution system for the purpose of voltage sag and swell mitigation is described. Furthermore, the paper outlines the techniques and controls used for operating the DVR. The use of a DVR in conjunction with distribution networks has proven to be an exceedingly effective means of quickly identifying and rectifying power quality issues within the distribution system. Results of simulation using MATLAB/Simulink are demonstrated to prove the usefulness of this DVR design and operation to enhance the power system quality. But he didn't address the possible solution for harmonics mitigation technique.

**Summary of reviewed literature gaps**:

A number of surveys have discussed different methods to demonstrate the importance of power quality mitigation techniques and the use of DVR systems, both with and without super capacitor-based energy storage, to improve power quality in electrical systems and the use of MATLAB/SIMULINK Simulation tools applied since it is become essential for analyzing and optimizing power quality mitigation solutions.

However, none of the research papers took into account the installation cost of a DVR in order to analyze the economic benefits and assess the feasibility of the study, which would help determine whether or not to proceed with the installation. Additionally, most of the literature did not utilize super capacitor-based energy storage, despite its many advantages over other devices, such as significantly faster charging and discharging times.

# CHAPTER THREE

# 3. MATERIALS AND METHODS

## 3.1. Power Quality Problems and Proposed Mitigation Technique

The approach utilized in this thesis to attain the intended objectives is explained in this section. The methodology employed in this research is illustrated by the block diagram presented in Figure 3.1. The methodology for investigating and mitigating power quality problems using Dynamic Voltage Restorer with Super Capacitor-based Energy Storage using MATLAB SIMULINK involves the following steps:

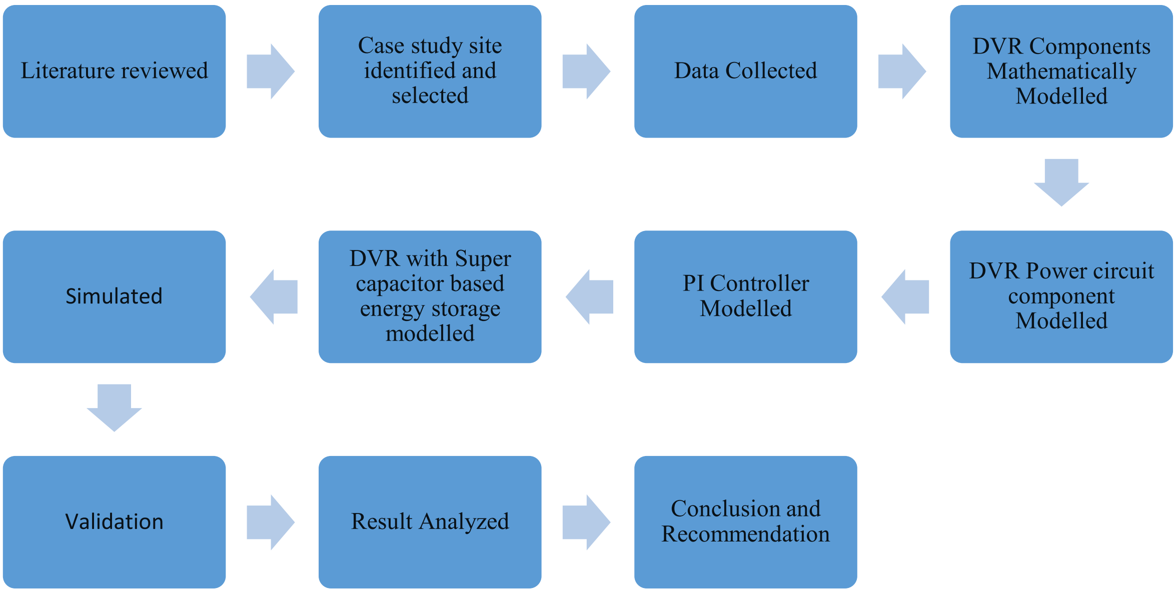



Figure 3.1.The research methodology block diagram

1. Literature review – This step involved a broad review of existing literature on power quality problems, Dynamic Voltage Restorer, and super capacitor-based energy storage systems. The aim was to identify the gap in knowledge and research that the study sought to address.

2. Identification and selection of case studies – The study identified and selected appropriate case studies to investigate power quality problems in St. George brewery. Suitable case studies were chosen based on their relevance, feasibility, and availability of data.

3. Data Collection- Information was collected from the employees, observation of the power quality problem took place while the machineries were under operation, and the required data was collected by means of Fluke 435 power quality and energy analyzer. Additionally, the technical logbook records of the case study were considered. Both

primary and secondary data collecting method were employed, quantitative techniques via direct measurement, interview and observation. The data were collected by direct measurement, connecting the Fluke power analyzer to the power system. Additionally, data were collected through interviews and observations by asking questions to the employees and by observing the machine operation activity in the factory. The technical logbook, previously recorded power analysis data as shown in Appendix V, and machine alarm history were also considered as secondary data.

3. Modeling – The next step involved modeling the power system, Dynamic Voltage Restorer, and super capacitor-based energy storage system using MATLAB SIMULINK. The modeling included selected appropriate system parameters, boundary conditions, and input profiles to develop a simulation environment for the system.

4. Simulation – In this step, the simulation model developed in MATLAB SIMULINK was used to analyze the effects of power quality problems on the power system, and investigate the effectiveness of the Dynamic Voltage Restorer with Super capacitor-based Energy Storage for mitigating power quality issues.

5. Validation – Once the simulation was finished, the accuracy of the results was confirmed by comparing them with the real data obtained from the chosen case studies. The validation ensured that the simulation model accurately represented the real system.

6. Conclusion – The study concluded with a summary of the findings, recommendations, future directions for research, and a discussion of the implications of the research.

### 3.2. Assessment of power quality problems

As a common rule, it is important to test each site at the points of common coupling (PCC) the DVR location as shown in Figure 3.2, for at least 7 to 15 days. The feeders from the Addis Abeba Mexico substation supply the factory's electrical power to the site. The Single line diagram of St. George Brewery factory is presented in Figure 3.3.

The monitoring studies were conducted at the secondary side of the service transformers for both feeders, under various operating conditions. Measurements were taken using a power quality analyzer instrument on the 380-voltage side for each individual source.

Power quality analyzer (Fluke 435 Power Quality and energy Analyzer): The Fluke 435 Power Quality and Energy Analyzer is capable of measuring various electrical parameters such as voltage, current, power, energy, phase angle, harmonics, and inter-harmonics. It has the capabilities to capture waveforms and voltage events, analyze distortion, and examine transients. Furthermore, the analyzer is useful for checking power factor, monitoring energy usage, and troubleshooting power quality problems.

For 10 days, measurements were made on the service transformer's secondary parts at 380 volts, at locations of common coupling under various operating circumstances.

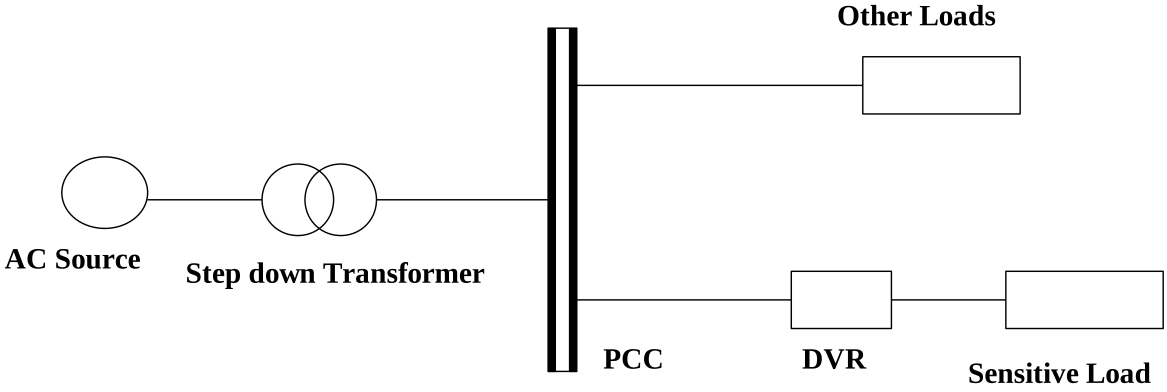



Figure 3.2. DVR location

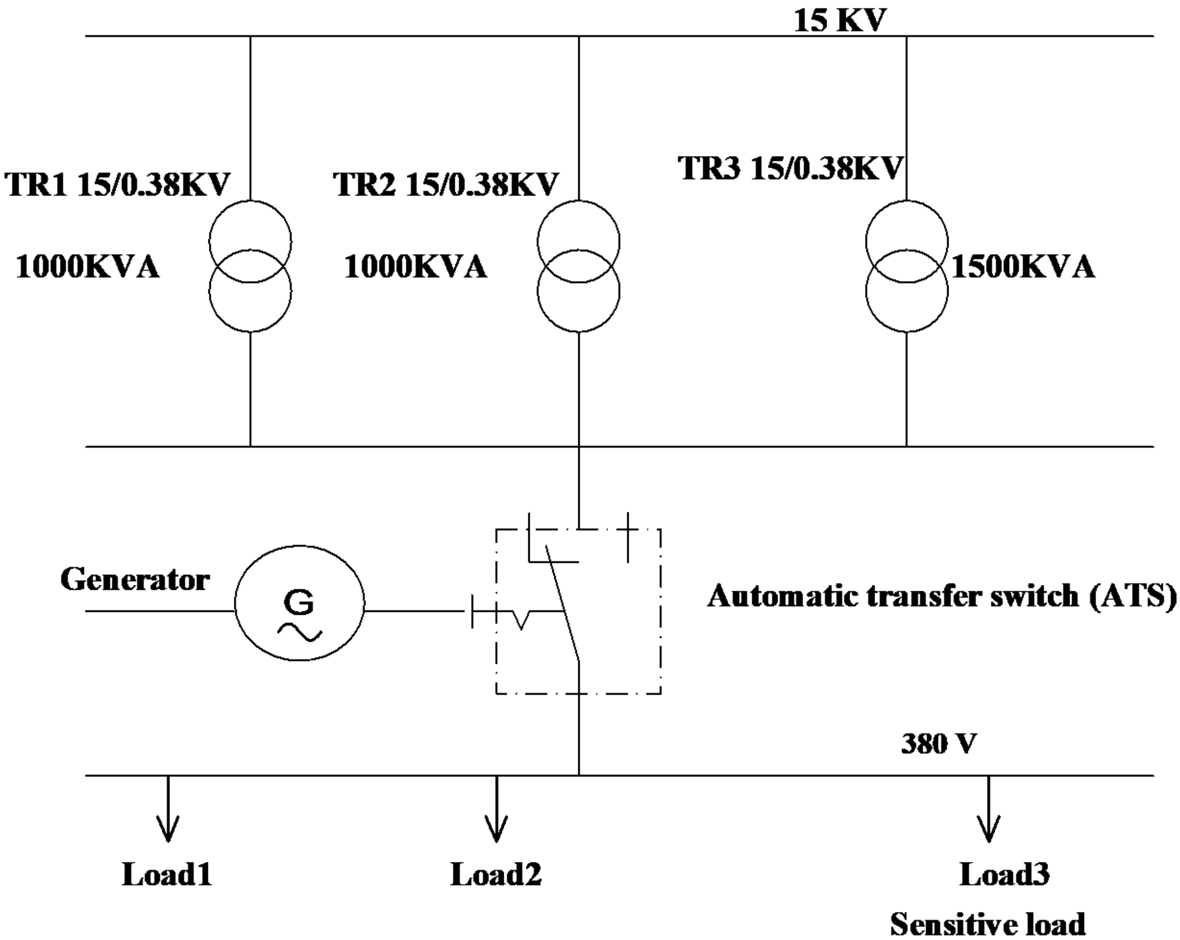



Figure 3.3. Single line diagram of St. George Brewery factory

### 3.3. Measurement Results

The Fluke 435 Power Quality and Energy Analyzer, which is described in Appendix IV, is employed for power quality measurement. This instrument provides measurements and analysis for various power quality issues, including:

3.3.1. Transient measurement result

Transients are not seen throughout the monitoring period because lightning protection devices are installed at the substation and across the industry, and measurements show no impulsive transients as well as oscillatory transient.

3.3.2. Over voltage measurement result

Neither the monitoring time nor the data reported in the site follow-up format show any significant overvoltage.

3.3.3. Under Voltage measurement results

Even when a capacitor bank is turned off and heavy loads are switched on and off, under voltage does not appear during the monitoring time.

3.3.4. Voltage sag measurement results

The recorded data of voltage sags in the factory power system is presented in Figure 3.4.

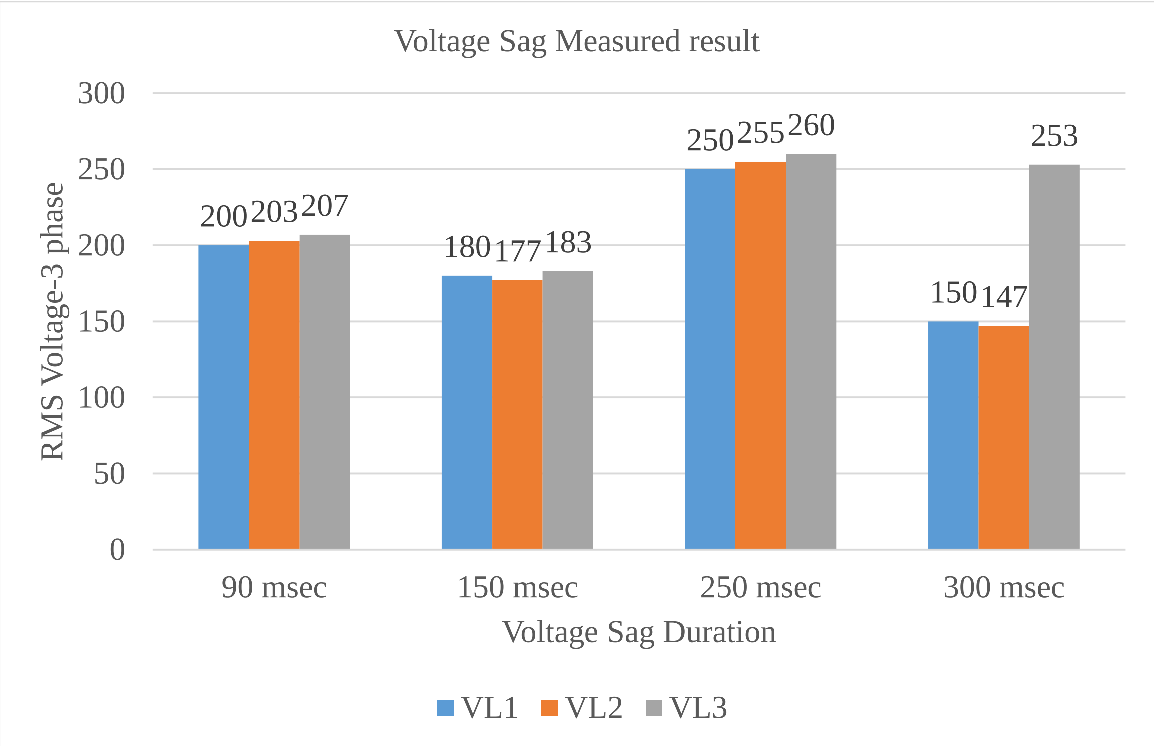



Figure 3.4. Voltage sags and swells measurements

These measurements are not permanent results for both voltage sag and swells; they are only taken as a sample during the monitoring period. Different values will be observed on different days and times. However, the current measurements during the monitoring period and the factory's secondary data indicates there is voltage sag issues in the factory. I have measured results of voltage sag for a period of 4 days out of a 10-day duration from May 09 up to May 19, 2023. The voltage sag was measured using a power quality analyzer that was connected to the electrical system of the facility. During the 10-day duration, a total of 4 voltage sag events were recorded. The results indicate caused by various factors such as equipment faults, lightning strikes, and power system disturbances. The measured results of the voltage sag events for a period of 4 days out of a 10-day duration indicate that voltage sag events occur frequently and can have varying durations and magnitudes. In addition to the measured value, the data from the technical log book and the machine alarm history shows the duration and the magnitude of the interceptions are voltage sags. The measured data during voltage sag was caused by a 3 phase short circuit fault that occurred in the power system. Aside from other types of faults, the three phase to ground fault was the most observed during the monitoring period and the machine alarm and the technical log book indicated that this fault was the most frequent. Since, three phase to ground fault is a very savior fault compared to other faults the study also focused to compensate the missed voltage because this fault. The 3 phase short circuit that caused the voltage sag was due to breakers to fail to trip even after protective relays detect a fault. The short circuit caused a sudden surge of current in the system, which resulted in a voltage drop or sag.

The whole data for the voltage sag is gathered via an interview with the section head and yearly collected data. Hence, it is important to take measures to mitigate the effects of voltage sag to ensure uninterrupted operations and prevent damage to electrical equipment.

The consequence of Voltage Sag in the Industry: among all power quality disturbances, voltage sags are the most common. Although they are not as expensive as interruptions, voltage sags are still more significant and can have equal consequences as a supply interruption in certain cases. Even shallow voltage sags can disrupt manufacturing operations by causing equipment to malfunction at reduced voltage levels.

Voltage sags can have a significant impact on industrial equipment, especially variable speed drives (VSDs), PLCs, and certain control systems. In most manufacturing operations, the failure of a few crucial pieces of equipment due to voltage sags can result in a complete production shutdown, causing substantial financial losses. Additionally, the time required to clear up and resume the production process should also be taken into account.

Voltage sags, or a momentary reduction in the voltage level, can have significant effects on industrial operations. These sags might lead to equipment failure or even shut down, leading to production loss, safety hazards, and financial losses. The consequences of voltage sags can be particularly severe in industries such as manufacturing, data centers, and transportation.

3.3.5. Voltage Swell measurement results

The issue of voltage swell was not detected in any of the three phases during the measurement event.

3.3.6. Harmonics measurement results

IEEE Standard 519-1995 is a technical standard published by the Institute of Electrical and Electronics Engineers that provides guidelines for controlling harmonics in electrical power systems. The standard sets limits on the amount of harmonic distortion that can be allowed in the power system, in order to prevent negative effects such as equipment damage, power quality issues, and increased energy consumption.

The standard applies to systems with a voltage greater than 120 V and a frequency of 50 Hz. It includes recommendations for measurement and analysis of harmonic distortion, as well as methods for controlling harmonics through the use of filters, transformers, and other techniques.

The following Table 3.1, outlines the limits for harmonic currents dependent on the magnitude of the connected load in relation to the size of the power system. The ratio $\frac{I_{sc}}{I_L}$ represents the ratio of the short circuit current available at the PCC, as defined by (M. Rusli, 2015) to the maximum fundamental load current.

Table 3.1. Current distortion limits for systems rated 120V through 69kV.

| **ISC/IL** | **2≤h<11** | **11 ≤h<17** | **17 ≤h<23** | **23 ≤h35** | **35 ≤h<50** | **TDD** |
|---|---|---|---|---|---|---|
| **<20*** | 4.0 | 2.0 | 1.5 | 0.6 | 0.3 | 5.0 |
| **20<50** | 7.0 | 3.5 | 2.5 | 1.0 | 0.5 | 8.0 |
| **50<100** | 10.0 | 4.5 | 4.0 | 1.5 | 0.7 | 12.0 |
| **100<1000** | 12.0 | 5.5 | 5.0 | 2.0 | 1.0 | 15.0 |
| **>1000** | 15.0 | 7.0 | 6.0 | 2.5 | 1.4 | 20.0 |

where, $I_{sc}$= maximum short-circuit current at PCC.

$I_L$–Is the maximum demand load-current (fundamental frequency component) at PCC.

The ISC/IL ratio, which represents the short circuit current and rated current of the 380V feeder at of common, should not exceed a range of <20. Consequently, the Total Demand Distortion (TDD) values for current harmonics should not surpass 5% at the point of common coupling. Additionally, the limit for voltage level can be found in Table 3.2.

Table 3.2. (IEEE 519-2022) Voltage distortion limit

| **Bus voltage V at PCC** | **Individual harmonics (%)** | **Total harmonics distortion THD (%)** |
|---|---|---|
| **V≤1.0kv** | 5.0 | 8.0 |
| **1kv<V≤69kv** | 3.0 | 5.0 |
| **69kv<V≤161KV** | 1.5 | 2.5 |
| **161KV and above** | 1.0 | 1.5* |

At St. George brewery, the THD as shown in Figure 3.5 were measured values 21.25%, 23.89%, 27.45%, 25.07%, 26.50% during full load operation, for all three phases exceeded the allowable range according to IEEE standards. To measure this, a Fluke 435 Power Quality and Energy Analyzer was used over a period of 10 days, with 1-hour average values recorded. The PCC is considered the secondary side of the transformers that serve the industry loads in order to stop triple harmonics from entering the primary side of the transformer from the load side, the transformer is connected in a delta-wye configuration. The plant is supplied by three transformers, two with 1000 KVA and one with 1500 KVA as shown in Appendix VII. However, this study's major objective is to keep the voltage level and mitigate harmonics at the point where sensitive loads are connected. The factory sensitive loads are supplied from 1500 KVA step down transformer. The measurements mentioned above were made with power quality analyzer instrument on the 380-voltage side of 1500 KVA transformer. The factory sensitive loads are 151KW.

Measured THD in %

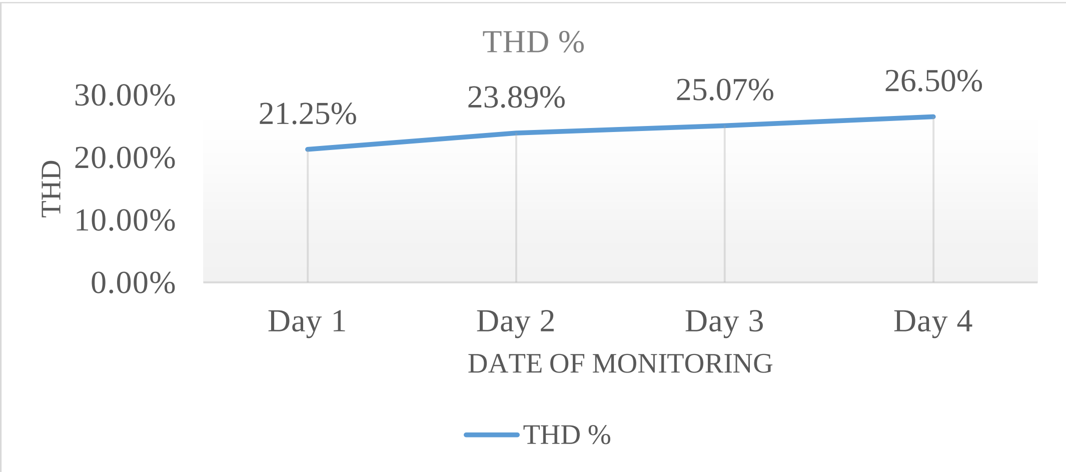



Figure 3.5. Total harmonics distortion (THD) measured result

3.3.7. Power Frequency Variation measurement results

The electric power network is designed to run at a specific frequency, which in our nation is 50Hz. If there is any discrepancy between supply and demand, it results in frequency changes. Large fluctuations in frequency are brought on by rapid load changes or generator failure. Throughout the monitoring period, data samples were collected to examine whether frequency variations exist or not. Figure 3.6 displays the measured value of the fundamental frequency at a specific time.

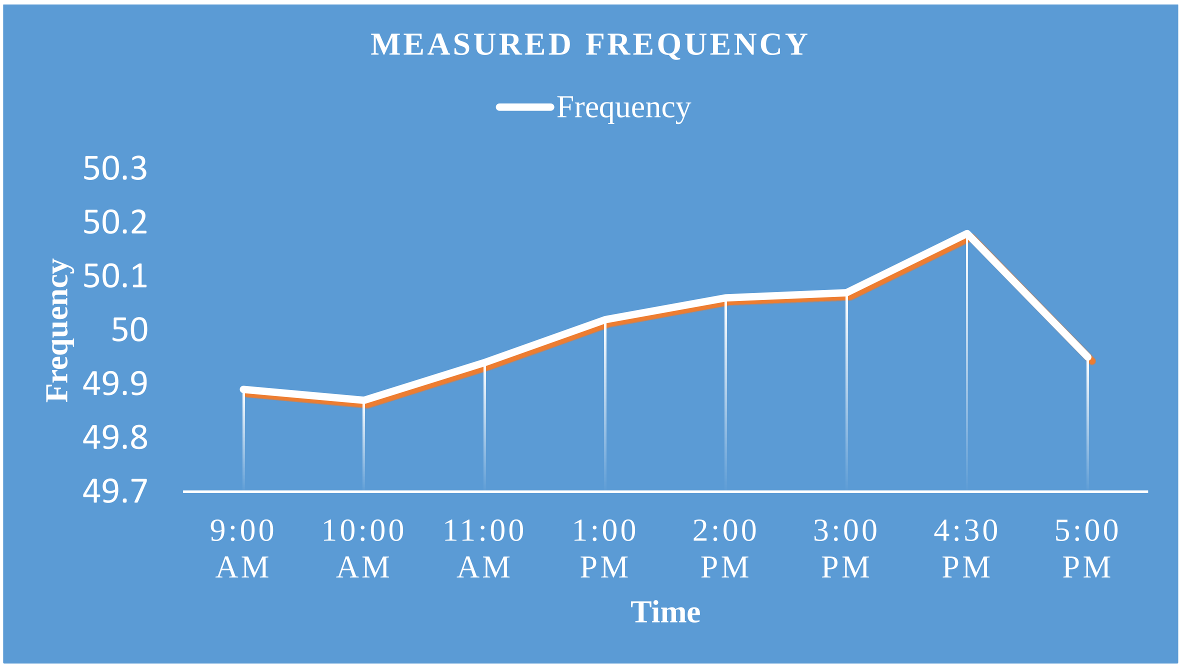



Figure 3.6. Power frequency measurement result

According to the IEEE standard, the allowed range for power frequency changes during normal operation is 0.5 (49.5 Hz to 50.5 Hz at 50 Hz nominal frequency), which is 1%. The measurement result presented in Figure 3.6 above shows that there is no deviation from the power frequency significantly from the allowable limits based on this standard.

Hence, the power frequency variation is not an issue for the industry as per the measured value and the previously recorded data.

3.3.8. Voltage unbalance measurement results

Measured value of Voltage unbalance:

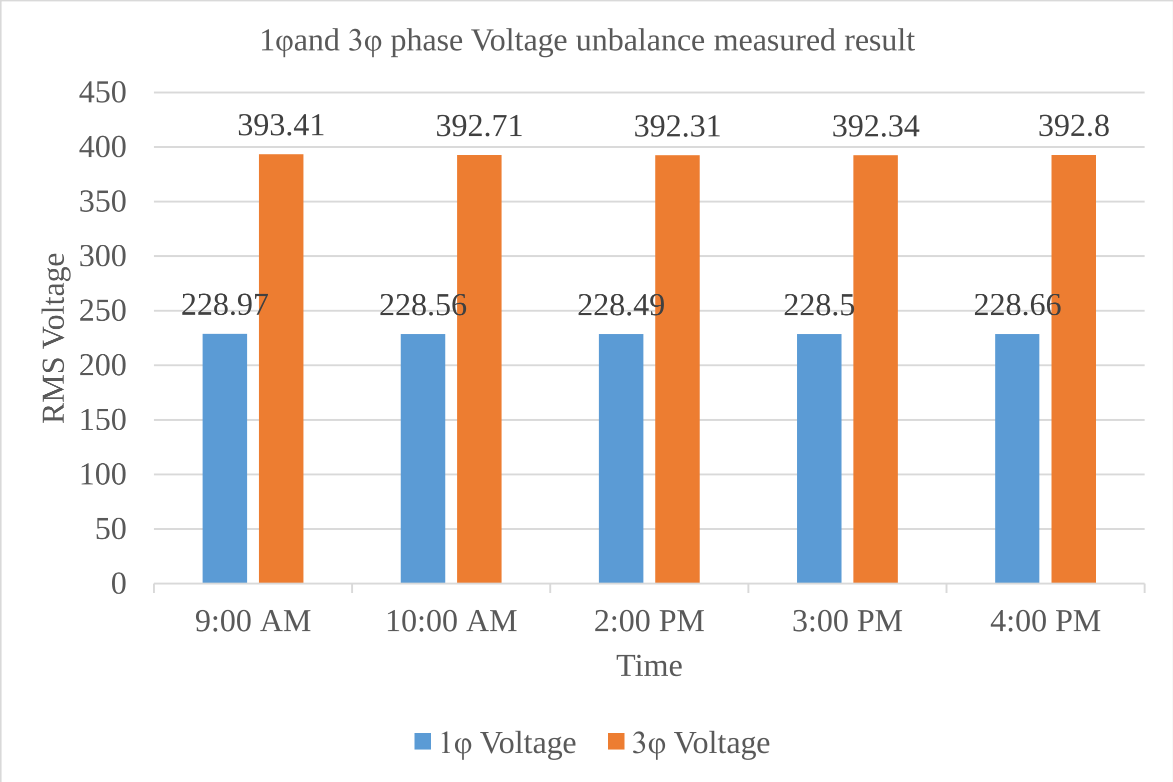



Figure 3.7. Voltage unbalance measured result

As stated in the standard set by the NEMA (National Electrical Manufacturers Association of the USA), the largest deviation from the average of the voltages or currents across the three phases, divided by the average of the voltages or currents across the three phases, is referred to as voltage imbalance, and stated as a percentage. This can be computed using the following equation. The above Figure 3.7 displays the measured value of voltage unbalance during operation.

First calculate average value of phase to phase voltages,

$$V_{average} = \frac{V_{1-2} + V_{1-3} + V_{2-3}}{3} \qquad (3.1)$$

$$V_{average} = \frac{393.41 + 394.17 + 394.61}{3} = 394.06$$

Then, calculate the maximum deviation from the mean:

$$V_{1-2} - V_{mean} = 393.41 - 394.06 = -0.65$$

$$V_{1-3} - V_{mean} = 394.17 - 394.06 = 0.11$$

$$V_{2-3} - V_{mean} = 394.61 - 394.06 = 0.55$$

From the above equation 3.1:

$$\%Voltage\,unbalance = \frac{L\arg est\; deviation}{V_{mean}} \times 100$$

$$\%Voltage\,unbalance = \frac{0.55}{394.06} \times 100 = 0.14$$

It is not necessary to implement a strategy for voltage unbalance mitigation since, as can be seen from the result, the proportion of voltage unbalance is within the IEEE limit of 2%.

3.3.9. Flicker measurement results

Fluctuations in voltage can lead to variations in the intensity of light that we observe, which is referred to as flicker. This phenomenon has the potential to cause significant physical discomfort. Flicker occurs when the luminance or spectral distribution of a light source fluctuates unevenly over time, resulting in an uneven visual experience. During a 10-day experiment, no flicker was detected or reported by participants. While this is not a concern for the industry, it is not being measured.

Based on the measurements taken, it is evident that there are voltage sag and harmonics distortion in the selected site electrical system. Voltage sag and harmonics distortion can cause equipment failures, disrupt production processes, and lead to financial losses.

**3.4. Design and Modelling of Dynamic Voltage Restorer**

The power system network at the case study site is currently facing a significant issue of sag, which can cause equipment failure if not dealt with properly. To address this problem, custom devices such as DVR are recommended as they offer an efficient method for compensating voltage sag or swell. DVRs have the ability to safeguard crucial loads against supply disruptions originating from sources other than power outages. They can generate or absorb controllable real and reactive power and respond quickly to changes in power. With proper design and implementation, DVRs can help power systems operate efficiently, reliably, and safely. This chapter presents the information on the basic structure and working principle of DVRs.

3.4.1. Equivalent Circuit of DVR

The DVR equivalent circuit is a crucial tool for comprehending how it works and how to reduce the current power quality issues that have been found. A DVRs equivalent circuit is made up of a number of parts that enable it to control the voltage in a power system. A DVR is really just a voltage source that is linked to the electrical system by a transformer.

With the help of the transformer, the DVR is able to introduce a voltage into the electrical system that is in phase with the system voltage but has a different magnitude. This makes it possible for the DVR to control the voltage in a particular area of the power system.

The main components of a DVR's equivalent circuit include a voltage source, a transformer, and a power electronics converter as shown in Figure 3.8. The converter is responsible for adjusting the voltage and injecting it back into the power system. It typically consists of a series of switches, capacitors, and inductors that work together to create a high-frequency voltage waveform. This waveform is then synchronized with the power system voltage and injected into the system through the transformer. Overall, the equivalent circuit of a DVR is complex and requires a thorough understanding of power. The DVR consists of several key components, including the energy storage devices, the power converter and control system.

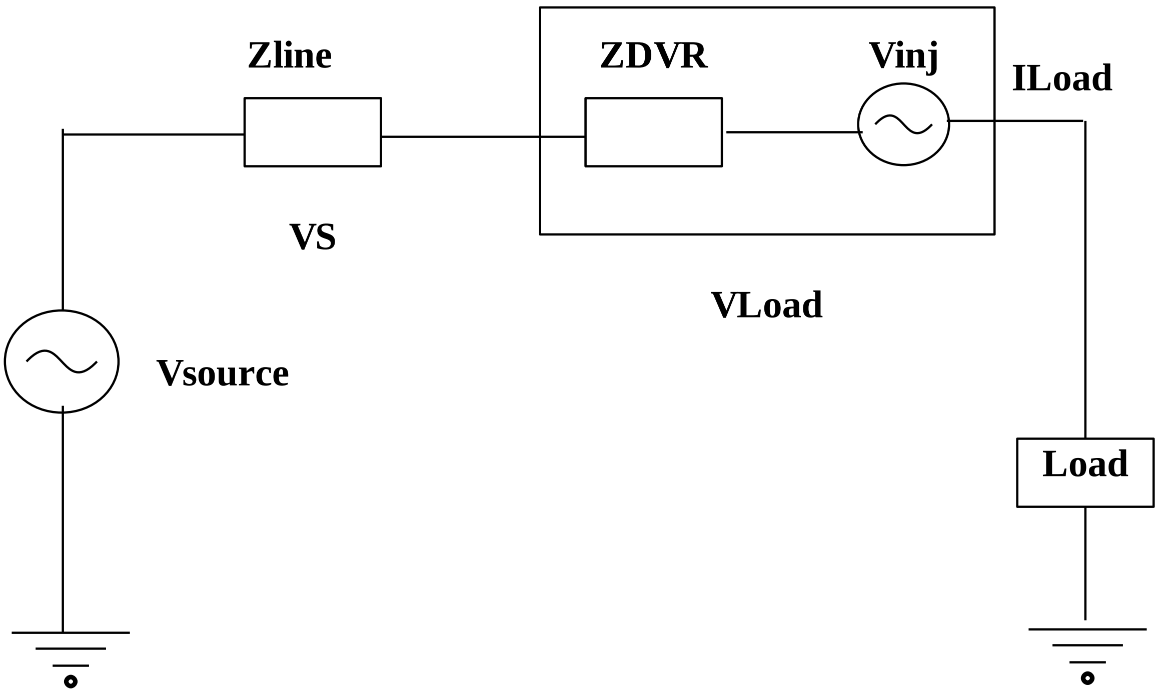



Figure 3.8. Equivalent circuit of DVR

3.4.2. Configuration of Proposed DVR

The Proposed Schematic Diagram of power quality enhancement using DVR presented in Figure 3.9. To tackle voltage sags and imbalances in the system, the DVR utilizes self-commuting power electronic switches. Additionally, it employs voltage-controlled two-level three-phase PWM inverters operating at a frequency of 15 kHz to generate compensating voltage. These inverters are connected to an external DC voltage source, which supplies the necessary DC voltage for AC voltage generation. By adopting this method, the DVR effectively addresses voltage concerns within the system.

To address the issue of a higher frequency harmonic content waveform produced by the IGBT-based VSI, a passive (LC) filter is utilized on the inverter side. This filter blocks high frequency harmonics caused by DC to AC conversion, which helps improve the power quality supply. Additionally, the output waveform of the filter unit is boosted by three single-phase injection transformers. To protect the DVR, bypass switches and solid-state bypass breakers are placed in parallel with the injection transformers. This helps reduce distortion in the output and enhance the overall power quality.

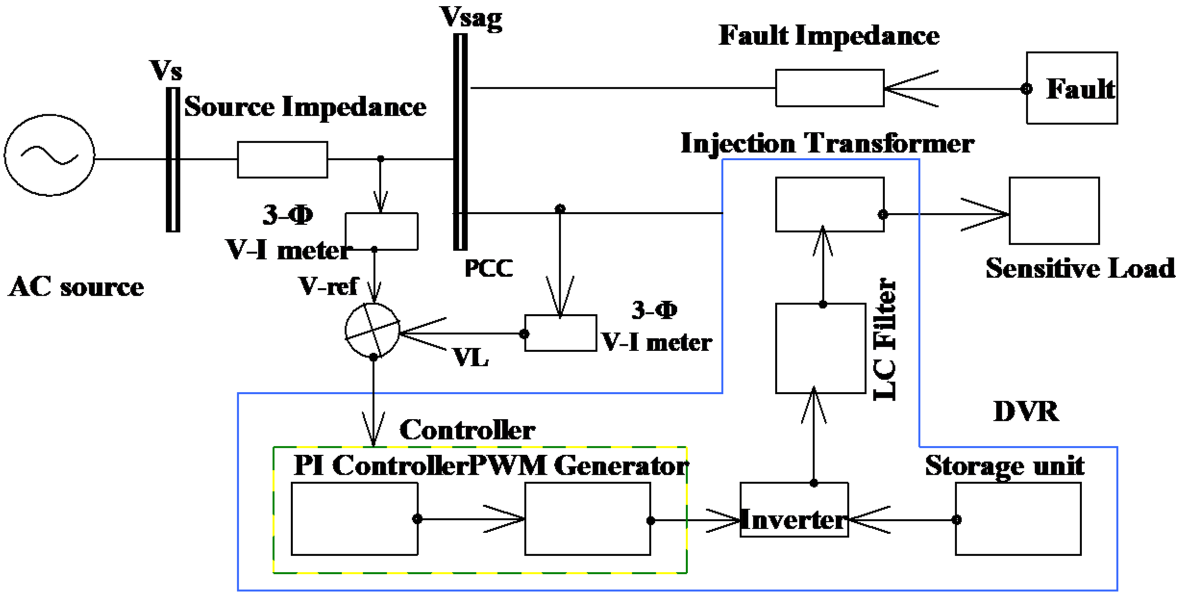



Figure 3.9. Proposed Schematic Diagram of power quality enhancement using DVR

3.4.3. Mathematical Modeling of Voltage Compensation in DVR system

Mathematical modeling of DVR involves the formulation of mathematical equations that describe the electrical behavior of the device. The modeling process requires the identification of the different components of the DVR, such as the voltage source, inverter, and energy storage system. The mathematical equations are then derived based on the electrical characteristics of these components.

The mathematical model of DVR was used to analyze the device's performance under different operating conditions. This was important in optimizing the design and control strategies for efficient voltage restoration. The modeling process also helps in understanding the dynamic behavior of the device and how it interacts with the power system. This knowledge was crucial in ensuring the stability and reliability of the power system. It provides a foundation for the optimization of the device's design and control strategies.

3.4.3. Basic Components of DVR

The basic components of a DVR include the booster transformer, Harmonic filter, storage device, voltage source converter as shown in Figure 3.10. The VSC is responsible for converting the input voltage into a controllable AC voltage that is used to regulate the output voltage. The control system of the DVR was responsible for monitoring the input and output voltage levels and adjusting the VSC accordingly. It uses a feedback loop to maintain the voltage level within the acceptable range. The control system also includes protection features to prevent damage to the equipment in case of faults in the power system.

In summary, the basic components of a DVR include a VSC, storage device, injection transformer, and a control system.

The SIMULINK Model of a DVR includes a power electronics circuit, a control algorithm, and a power system model. Together, these elements accurately simulate the behavior of the device under different operating conditions and provide insights into its effectiveness in ensuring power quality.

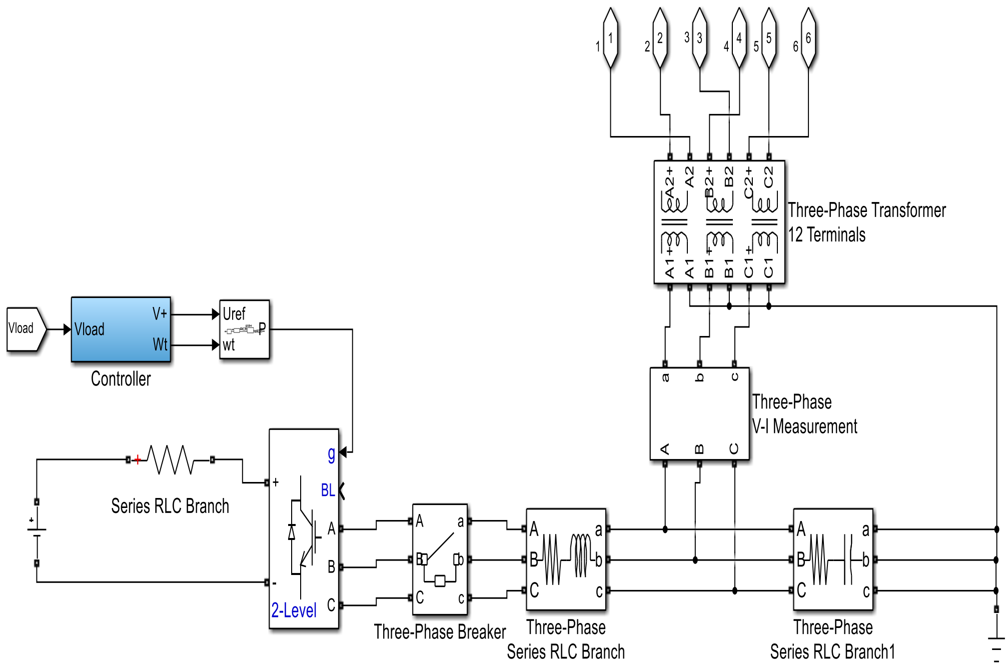



Figure 3.10. SIMULINK DVR model

A. Series Voltage Injection Transformer/Booster Transformer/

The injection/booster transformer's function is to prevent noise and transient energy from being blended or coupled from the primary side to the secondary side. The distribution system is often connected in series with the high voltage part of the injection transformer, while the low voltage side can be used to connect the DVR's power circuit. The injection transformer serves two main purposes. Firstly, it establishes a link among the DVR and the distribution system by means of the high voltage winding. Secondly, it converts and connects the compensating voltages, generated by the VSC, to the incoming supply voltage. As a result, it boosts the voltage level provided by the filtered VSI output to the required level. Additionally, it serves to isolate the load from the system's VSC and control mechanism. The transformer winding ratio was predetermined based on the desired voltage at the secondary side of the transformer, which was chosen to be equal to the supply voltage, ensures that compensate for any voltage sag.

B. Voltage Source Inverter (VSI)

A VSC, a power electronic system comprised of storage and switching devices, has the ability to produce a sinusoidal voltage with specific frequency, magnitude, and phase angle. In a DVR system, an inverter is utilized to convert the DC voltage from the energy storage device into an AC voltage. This allows for temporary substitution or supplementation of the supply voltage. The two-level or multilevel three-phase converters are among the most used circuit topologies for the VSC. These converters feature a shared DC capacitor among all phases. Since the capacitor's primary function is to absorb harmonic ripples, it only needs a little amount of energy to operate, especially when functioning in balanced conditions. The capacitor's size may need to be increased to provide voltage support in the case of imbalanced situations. Since the capacitor is shared among the three phases, any voltage sag in one phase can lead to distortion in the injected current waveforms in the other phases. An alternative converter topology that is commonly employed is the H-bridge cascade inverter. This particular topology well-suited for high-voltage and high-power systems, as it allows for the generation of waveforms with superior harmonic spectrums and the attainment of higher voltages without exceeding the maximum device rating limits.

C. Storage Device

To address significant voltage sags and ensure power supply to the load, various energy storage technologies such as lead-acid batteries, flywheels, ultra capacitors, and super capacitors are utilized. A secondary bridge converter that receives power from a secondary AC source also supplies the necessary power to the VSI's DC side. The auxiliary bridge used as rectifier to charge the super capacitor. During voltage disturbances in the distribution system, the DVR requires real power for compensation purposes. During such events, the real power needed by the DVR must be sourced from the energy storage system. In this context, the energy storage mechanism discussed in this paper is a super capacitor, responsible for supplying energy in the form of DC power.

Super capacitor: A super capacitor is a type of capacitor that possesses a much larger capacitance compared to a standard capacitor. It operates based on a double-layer mechanism where energy is stored through charge movement at the boundary between the anode and electrolyte. The level of stored energy is limited by the surface area of the electrolyte, therefore, the super capacitor consists of two (anode and electrolyte) separated by a separator. The use of carbon anodes in the super capacitor provides a high surface area, allowing for efficient energy storage. Unlike traditional capacitors, the super capacitor does not involve any chemical reactions and stores energy purely electrostatically. In essence, a super capacitor operates as a double-layer energy storage device.

Due to the following advantages Super Capacitor has chosen.

1. It allows for unlimited cycling without degradation.

2. It does not require overcharging protection or a circuit for full charge cut-off.

3. The charging and discharging time is significantly faster compared to other energy storage devices.

4. It has low impedance, enabling delivery of high currents.

It is cost-effective for storage and power applications.

6. It exhibits high efficiency in energy storage and discharge.

7. Its compact size, lightweight design, and absence of moving parts make it highly reliable, with a reliability rate of 99.9%.

8. It has a minimal contamination rate, leading to a significant reduction of up to 99% in pollution compared to batteries and fuel-powered devices.

9 The overall efficiency of the Super Capacitor is higher when compared to batteries.

10. The use of a Super Capacitor eliminates noise production, harmful emissions, and pollutants, making it a fuel-free and environmentally friendly option. Additionally, the modular nature of a Super Capacitor system allows for easy installation, minimal maintenance, and no risk of worn-out or faulty moving parts.

D. Harmonic Filter

In a DVR system, harmonic filters might be either on the high voltage side or the converter side of the injection transformers. These filters comprise an inductor (L) and a capacitor (C). Their purpose is to convert the inverted PWM waveform into a sinusoidal waveform by eliminating the undesired harmonic elements generated during the VSI process. The presence of higher harmonic components can distort the compensated output voltage. Hence, in order to maintain a desirable amount of Total Harmonic Distortion, it is essential to eliminate the extra switching harmonics generated by the VSI from the injected voltage waveform.

E. Control and Protection System

The control system of a DVR is crucial, particularly when faced with voltage sags and fluctuations in the connected load, as it must respond quickly. The control system's primary objective is to sustain a consistent voltage magnitude where sensitive loads are connected, despite disruptions in the system. The three primary types of voltage controllers are Feed-forward (open loop), Feedback (closed loop), and Multi-loop controllers. For the DVR system, the Feed-forward voltage controller is preferred due to its simplicity and fast response.

The primary tasks of a controller in a DVR system include:

A. Identifying voltage sag/swell occurrences within the system.

B. Calculating the corrective voltage required.

C. Creating sinusoidal PWM-based trigger pulses for the DC-AC inverter.

D. Correcting any abnormalities observed in the series voltage injection.

E. To stop the trigger pulses after the voltage disturbance has passed in the system.

Through this procedure, a balanced two-phase orthogonal stationary system's vectors are transformed into an orthogonal rotating reference frame as shown in Figure 3.11. The chosen control system utilizes the dqo technique control algorithm in order to generate an error signal, the supply voltage is compared to a reference value, which is then used as a reference sine wave in the gate pulse generation circuit. These generated pulses are further compared with a carrier signal to produce pulses for the inverter. The supply voltage continuously compensates and adjusts the faults, bringing it back to its pre-fault condition. While the load voltage may be restored to its optimal state using this approach, the injected active power cannot be managed since it is affected by outside variables like the kind of defect and the load. To implement this method, a fault detector is employed to freeze the output from the Phase Locked Loop (PLL) circuit when a fault occurs. Subsequently, the frozen angle is utilized to return the load voltages to their previous balanced state through the utilization of the Park transformation.. (Mohank, 2013)

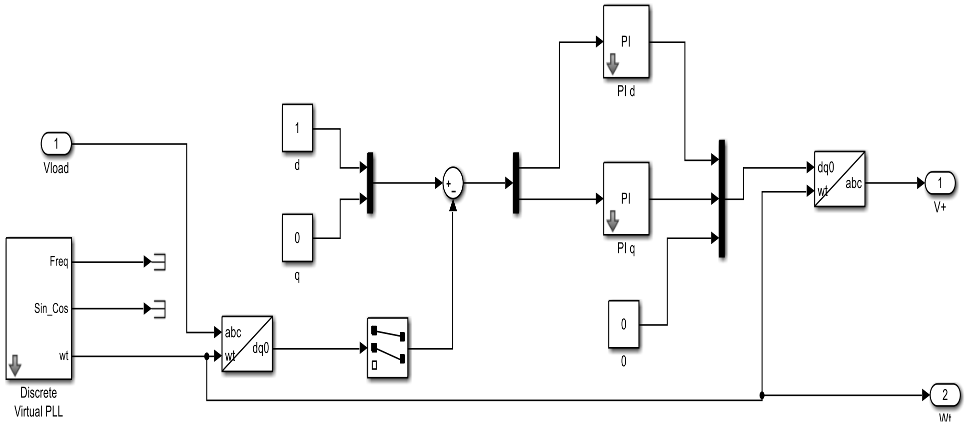


Figure 3.11. Simulink Model of controller circuit

PI Controller: The PI controller a type of feedback controller that computes the controlled output by summing the proportional and integral errors as presented in Figure3.12. It consists of two components; proportional gain ($Kp$) and integral gain ($Ki$). To decrease the error input into the controller and enhance the speed response of the controller, the proportional gain has to be correctly set. On the other hand, the integral gain is responsible for reducing the settling time in the waveform.

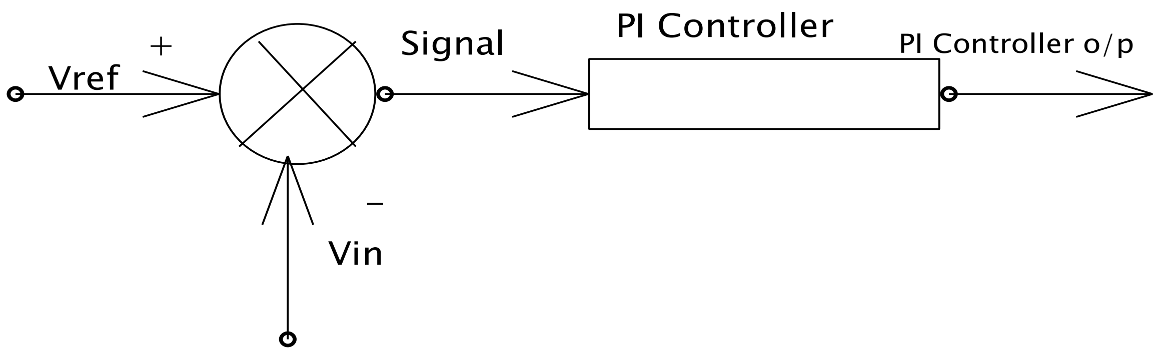


Figure 3.12. PI Controller block diagram

The PI controller is represented by a general characteristic modelled according to the following equation.

$$y_{(t)} = K_p e(t) + K_i \int_0^t et\, dt \qquad (3.2)$$

where $y_{(t)}$ is the output of the controller and $e(t)$ is the signal error. The state space transfer describes and defines the PI controller as provided below.

$$G_{pi}(s) = K_p + \frac{1}{s} k_i \qquad (3.3)$$

The error signal $e(t)$ is defined as:

$$e(t) = (v_{ref} - v_l) \qquad (3.4)$$

The PI controller-based DVR system block diagram to keep consistent voltage magnitude during system disrubance ‘d’ and ‘q’ are shown in Figure 3.10.

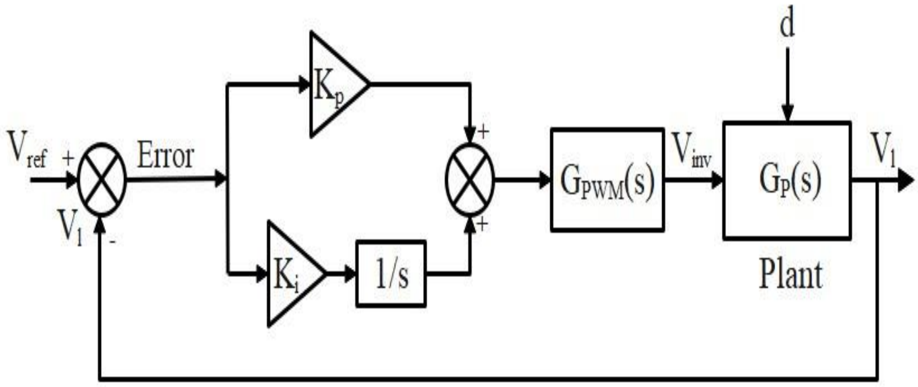



Figure 3.13. Block diagram of voltage control PI based DVR system

The working principle of a voltage control proportional-integral (PI) based DVR shown in the Figure 3.13. The block diagram represents the key components and their interconnections. The input to the system is the disturbed voltage which needs to be corrected. This disturbed voltage is compared with the reference voltage, which represents the desired voltage level. The voltage error is then fed into a PI controller.

The role of the PI controller is to generate an appropriate control signal based on the voltage error. The PI controller consists of two components: a proportional gain (Kp) and an integral gain (Ki). The proportional gain adjusts the control signal proportionally to the voltage error, while the integral gain integrates the error over time to account for steady-state errors.

The control signal from the PI controller is then passed through a (VSC). The VSC is responsible for injecting the necessary voltage to restore the disturbed voltage to the desired level.

In order to return the system voltage to the reference level, the corrected voltage from the VSC's output is first combined with the load voltage.

Following equations are describing the control diagram open loop transfer functions.

$$G(s) = G_{pi}(s)G_{pwm}(s)G_p(s) \qquad (3.5)$$

In the s-domain one sample period delay $e^{-Tds}$, as $T_d$ is the sampling period, when the PWM reference is held on and compared to the signal carrier to generate the duty cycle. Hence, the transfer function of the PWM ($s$) is given by:

$$G_{pwm}(s) = \frac{1}{1.5T_s s + 1} \qquad (3.6)$$

where ($T_d = 1.5T_s$) is the total time delay.

The effectiveness of the PI controller is significantly impacted by the values assigned to $Kp$ and $Ki$. Therefore, tuning the controller parameters is crucial in achieving the desired output, optimizing the process, and reducing the discrepancy between the process variable and the set point. Ziegler Nichols (ZN) method is commonly applied for controller tuning in this scenario, as it minimizes steady-state error and settling time.

To control the two coordinates,'d' and 'q', two separate PI controllers were utilized. Each of these controllers was adjusted individually using the ZN method to determine their settings, following the rules of the ZN controller setting. The PI controller takes in the discrepancy between the actual and reference voltage as input. The PI controller's outcome is changed to a three-phase voltage and provided PWM to trigger the IGBT of the VSI. The Simulink model of the control circuit with PI controller is shown in the below Figure 3.14.

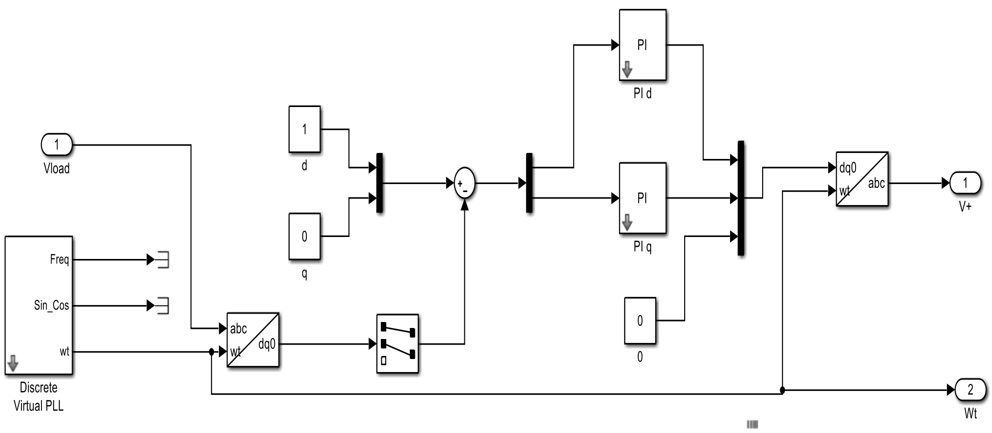



Figure 3.14. The Simulink model of the control circuit with PI controller

Parks Transformation: The dq0 transformation also known as Park's transformation, is utilized in regulating DVR. By applying the dq0 method, which uses start and end times, the depth of sag and phase shift are determined. The expressions of these vectors are based on instantaneous spatial representation. Firstly, the voltage is transformed from the abc reference frame to the dq0 reference frame. In the system's proposed control technique, the measured terminal voltage (Va, Vb, Vc) is compared to a voltage reference. Upon detecting a voltage sag, when the power supply falls below 90% of the reference value, or a voltage swell, when the supply voltage rises to 10% above the reference value, an error signal is generated. This error signal is then utilized to create a modulation commutation pattern, which controls the power alterations of the voltage source converter. The commutation configuration is generated using the SPWM technique. The modulation controls the voltages. This thesis employs Park's transformation to determine the missed voltage. The abc to dq0 conversion changes the 3-phase stationary coordinate system into a rotating dq coordinate system. The abc to dq0 transformation listed below is utilized.

$$V_d = \frac{2}{3}\left[V_a \sin wt + V_b \sin\left(wt - \frac{2\pi}{3}\right) + V_c \sin\left(wt + \frac{2\pi}{3}\right)\right] \qquad (3.7)$$

$$V_q = \frac{2}{3}\left[V_a \cos wt + V_b \cos\left(wt - \frac{2\pi}{3}\right) + V_c \cos\left(wt + \frac{2\pi}{3}\right)\right] \qquad (3.8)$$

$$V_0 = \frac{1}{3}\left[V_a + V_b + V_c\right] \qquad (3.9)$$

The comparison between the reference value and the $dq$ coordinate results in the computation of the disturbance in the $dq$ coordinate. Then, the transformation shown below is utilized to convert these disturbances back to $abc$ coordinates. The parameter $\omega$ in the transformation represents the speed of rotation in radians per second of the rotating frame.

$$Va = \left[V_d \sin wt + V_q \cos wt + V_0\right] \qquad (3.10)$$

$$V_b = \left[V_d \sin\left(wt - \frac{2\pi}{3}\right) + V_q \cos\left(wt - \frac{2\pi}{3}\right) + V_0\right] \qquad (3.11)$$

$$V0 = \left[V_d \sin\left(wt + \frac{2\pi}{3}\right) + V_q \cos\left(wt + \frac{2\pi}{3}\right) + V_0\right] \qquad (3.12)$$

The PLL determines the frequency of the system and provides the phase-locked angle θ for the $dq$ coordinate system.

### 3.5. Operating Principle of Dynamic Voltage Restorer

The main goal of the DVR is to produce a dynamically controlled voltage, VDVR, using a forced commutated converter. This voltage is then injected into the bus voltage through a booster transformer. The three phase voltages of this injected voltage are instantaneously controlled in order to eliminate any harmful impacts of a bus fault on the load voltage. As a result, any differences in voltage resulting from transient disturbances in the AC feeder are compensated for by an equal voltage created by the converter, which is then injected onto the medium voltage level using the booster transformer. If the entire system remains connected to the supply grid without the line breaker tripping, the DVR can operate regardless of the type of fault or event that takes place within the system. In the majority of real-world scenarios, it is more economical to merely correct for the positive and negative sequence components of the voltage disturbance seen at the DVR's input. This strategy makes sense since the step-down transformer in a common distribution bus arrangement has a very high resistance to this component, preventing the zero sequence part of a disturbance from passing through. The DVR functions in three different modes: protection mode, standby mode, and injection/boost mode.

1. Protection Mode

In situations where load-side over-current exceptional limit values are exceeded due to either a load short-circuit or an excessive inrush current, the DVR is disconnected from the system, achieved through the opening of bypass switches.

2. Standby Mode

During the standby mode of the DVR, where VDVR is set to zero, the low voltage winding of the booster transformer is essentially connected in a short-circuit manner through the converter. By intentionally triggering the converter legs to create a short-circuit path for the transformer connection, no semiconductor switching takes place in this operational mode. Consequently, only the semiconductors' relatively low conduction losses within this current loop contribute to overall losses. Most of the time, the DVR operates in this standby mode.

3. Injection/boost Mode

In this mode (VDVR>0), the DVR is injecting a compensating voltage through the booster transformer as a result of the detection of a disturbance in the supply voltage.

### 3.6. Parameter Design of DVR

When it comes to choosing of DVR there are several factors to be considered (M.M. Abdel Aziz, 2004). The capacity of a DVR in a power system depends on several factors such as the load size, the voltage level, and the duration of the voltage sag. Generally, the capacity of a DVR should be sufficient enough to handle the maximum expected voltage sag or surge that can occur in the system. The components of DVR simulation parameter are described in Appendix I.

To determine the appropriate capacity of a DVR, it is necessary to first conduct a power quality analysis of the system to identify the magnitude and duration of voltage sags and surges. This analysis provided the information required to select the appropriate capacity of the DVR.

Additionally, it is essential to consider the cost and benefits of installing a DVR in the system. The cost of the device and installation should be compared to the potential benefits of reducing downtime and improving the reliability of the system.

As per the electrical system of BGI Ethiopia brewing factory and measured results,

$$Vrms = 0.38Kv$$

$S = 1500KVA, PF = 0.94$, taking the maximum capacity of the transformer which is connected to sensitive loads.

The maximum three phase voltage sag response =75%

Duration of sag to protect =250ms.

Capacity of DVR in KVA=?

The required energy of DVR$(KJ)$ =?

DVR technology is commonly used to compensate for voltage sags in bus systems. To adopt DVR technology for voltage sag compensation, it is recommended to first analyze the voltage sag characteristics of the bus system. This includes identifying the frequency and duration of the voltage sags, as well as the magnitude of the voltage drop. This information helped in selecting the appropriate DVR rating and configuration. Furthermore, it is advisable to utilize DVR technology to counteract drop in bus voltage and reinstate it to its full rated value. In conditions where the voltage dip is less than 75%, the compensatory voltage of the DVR must be 0.8 PU or 80%. It is also essential to consider the cost-benefit analysis of implementing DVR technology. While it provides effective voltage sag compensation.

Table 3.3. Sensitive Load Data

| Description | Maximum Load, KW |
|---|---|
| Variable frequency drive (VSD) | 101 |
| Programmable logic control (PLC) | 18 |
| Human-machine interface (HMI) and other Electronics devices | 36 |
| Total | 155 |

By taking into consideration of sensitive load 151Kw or188.75 KVA with power factor of 0.94 as shown in the above Table 3.3.

$$Compensation\ power = 0.8 \times sensitive\ load\ KVA\ rating \tag{3.13}$$

$$Compensation\ power = 0.8 \times 188.75KVA = 151KVA$$

$$Energy = Power \times Time \tag{3.14}$$

The duration of sag to protect is 250 msec. So,

$$Required\ Energy\ of\ DVR = KVA \times Time \times PF \tag{3.15}$$

$$E = (151 \times 0.94) \times 250 \times 10^{-3}$$

$$E = 35.5KJ$$

To enhance reliability and availability, a DVR with a capacity of (200 KVA, 50 kJ) has been chosen.

### 3.6.1. Cost and Payback Period of DVR

The cost of a DVR varies depending on the specification and capacity of the device. The DVR's payback period can vary depending on several factors, including the frequency and severity of voltage sags and surges, the cost of downtime due to equipment failure, and the cost of replacing damaged equipment. In general, the payback period for a DVR is depending on the specific application, industries and their loss per event are shown in Appendix II.

While the initial cost of a DVR may seem high, the long-term benefits of protecting sensitive equipment from voltage sags and surges can far outweigh the cost. By reducing downtime and equipment replacement costs, a DVR can provide significant cost savings over the life of the time.

Cost of single voltage sag: The truth is no really knows monetary cost of poor power quality. Iindustries & their Cost of Momentary interruption are shown in Appendix III. But the cost of a single voltage sag can be calculated by considering the impact it has on the equipment or system it affects. The cost can be estimated by calculating the lost revenue due to downtime, repair and maintenance cost, and the cost of replacing the damaged equipment.

To estimate the lost revenue, you need to calculate the number of hours the equipment was out of service and multiply it by the hourly revenue generated by the equipment. The repair and maintenance cost can be estimated by considering the cost of equipment repair, labor cost, and any other associated expenses. The cost of replacing the damaged equipment can be calculated by considering the cost of new equipment, transportation, installation, and commissioning.

It is significant to note that the cost of a voltage sag can vary depending on the severity and duration of the sag, as well as the type of equipment affected.

$$Assume\ cost\ of\ DVR = Cdvr$$

$$Cost\ of\ single\ voltage\ sag = Cvs$$

$$Number\ of\ sag\ per\ year = Nvs$$

$$Payback\ period = T(year)$$

The cost of DVR is $1500 per KVA

Then,

$$Cdvr = Cvs \times Nvs \times T \qquad (3.16)$$

$$Cdvr = \frac{\$1500}{KVA} + 5\%\left(\frac{\$1500}{KVA}\right)\left[Operation\, and\, Maintenance\, cost\right]$$

$$Cdvr = \frac{1575}{KVA}$$

$$Cdvr = \frac{1575}{KVA} \times 200KVA$$

$$Cdvr = \$315,000$$

The cost of food/beverage industry caused by voltage sag is $5/sag (Davanagere, 2016). The cost of voltage sag, at BGI Ethiopia plc at Mexico branch is ($730/year), and by taking the average number of voltage sag occurrence, NVS is 146/year.

Then, the payback period is:

$$T = \frac{Cdvr}{Cvs \times Nvs}$$

$$T = \frac{315,000}{730 \times 146}$$

$$T = 2.9Years = 3Years$$

Considering the DVR's average lifespan of approximately 20 years, this solution demonstrates significant economic feasibility.

3.6.2. Sizing of injection transformer

It is crucial to carefully calculate the MVA rating, the primary winding voltage and current ratings, the short circuit impedance, the turn ratio, and winding characteristics in order to properly integrate the injection transformer into the DVR.

A. MVA Rating

MVA rating is calculated using a power calculation equation:

$$P = k_s \times V_{pr} \times I_{pr} \qquad (3.17)$$

$$Where; Ks - safty\, margine$$

$$V_{pr} - Injection\, transformer\, Primary\, voltage$$

$$I_{pr} - Injection\, transformer\, current\, rating$$

The instantaneous voltage and current values during the switching period are included in the proper safety margin value while designing the system. To prevent saturation, the injection transformer should be built to maintain at least double the typical steady state flux.

The appropriate $KVA$ size of three phase injection transformer is determined by:

$$Three\,Phase\,KVA = \frac{Load\,voltage \times Load\,current \times \sqrt{3}}{1000} \qquad (3.18)$$

In a three-phase system, electrical power and voltage are typically considered as base values. The base power determined as the three-phase power $MVA$ or $KVA$ while the base voltage is considered as the line-to-line voltage in $KV$ is taken as base voltage. The base impedance of the system can be derived by utilizing these base power and base voltage values.

$$Base\,impedance\left(ZB\right) = \frac{Kv}{KVA} \qquad (3.19)$$

B. The secondary winding voltage and current rating

The secondary side voltage rating of a series injection transformer has an impact on the maximum voltage sag depth, energy storage strategy, filtering unit, and voltage sag characteristics. The injection transformer can be calculated in below.

$$Vinj = Dvr \qquad (3.20)$$

$$Vs = \left(1 - D\right)Vr \qquad (3.21)$$

where, $Vr$ - $rms$ voltage of primary feeder, And

D-The maximum single phase voltage sag to be compensated

$\left(D < 1\right)$;

$Vinj$ -Injection voltage

C. Turn ratio

The principal voltage and current ratings are determined by the turn ratio. The switching devices that are available, their current carrying capacity, blocking voltage, and cost, as well as the DC-link capacitor, are taken into account while determining the best secondary parameters.

D. Short circuit impedance

Typically, the system runs smoothly, but it's important to understand its behavior in abnormal situations, such as short circuits. The values of fault current, filtering system design, and transformer voltage drop are all linked to the short circuit impedance value. If the distance between the DVR and the fault is shorter, the voltage characteristics measured at the DVR location more closely resemble those at the fault location.

E. Winding parameters

So as to fulfil with the industry, the resistance and inductance of the windings should be specified in per-unit $\left( pu \right)$ value. The values of the winding parameters are based on the transformer rated power $Pn$ $(VA)$, nominal frequency $fn$ (Hz) and nominal voltage $Vn$ ($rms$) of the corresponding winding. The per-unit resistance and inductance are given as follows for each winding: $R\left( Pu \right) = \frac{R\left( \Omega \right)}{Rbase}$

$$L\left( Pu \right) = \frac{L\left( H \right)}{Lbase}$$

For each winding, the base resistance and base inductance are:

$$Rbase = \frac{Vn^2}{pn}$$

$$Lbase = \frac{Rbase}{2\pi\, fn}$$

3.6.3. Sizing of Voltage Source Inverter

There are four main types of switching devices: Insulated Gate Bipolar Transistors (IGBT), Gate Turn-Off thyristors (GTO), Metal Oxide Semiconductor Field Effect Transistors (MOSFET), and Integrated Gate Commutated Thyristors (IGCT). Each type offers its own advantages and disadvantages. The MOSFET, for example, has a fast switching time and a high on-resistance. It can operate at frequencies beyond 20 kHz. However, its usefulness is limited to applications with only a few hundred volts due to the increase in on-resistance at higher voltages. The GTO is a type of device that can be turned on with a positive pulse to its gate and off with a negative pulse. It is ideal for use in high voltage applications. However, GTO-based devices do not meet the dynamic needs demanded by the DVR. In comparison, the IGBT is relatively new when compared to the MOSFET and GTO. It functions as a controllable three terminal switch that has both fast switching times and high voltage capabilities. This makes it suitable for use in medium power applications. The IGCT is a newly developed, compact device with heightened performance and superior reliability. These features enable the construction of VSC with substantial power ratings, beyond the limitations of previous DVRs that utilize conventional devices. As a result of these sophisticated converter designs that implement IGCTs, the DVR can compensate for dips that were previously beyond the capabilities of previous generation DVRs.

IGBT Sizing*:* Determining the capacity of an IGBT involves several factors that must be considered. The capacity of an IGBT is determined by its voltage rating, current rating, switching speed, and thermal characteristics.

The voltage rating of an IGBT is the maximum voltage it can withstand without breaking down. The current rating, on the other hand, is the maximum current that the IGBT can handle without overheating or failing. Switching speed refers to how quickly the IGBT can turn on and off, which affects its efficiency and performance. To determine the capacity of an IGBT, it is necessary to study its datasheet, which provides information about its voltage rating, current rating, switching speed, and thermal characteristics.

In high-power applications, inverters or converters typically employ "bridge" configurations to generate AC power at the line frequency or deliver bi-directional PWM drive to loads such as motors or transformers. These bridge circuits incorporate IGBTs, where the emitters serve as switching nodes operating at high voltage and frequency. As a result, the gate drive PWM signal and the associated drive power rails, which use the emitter as a reference, must be "floating" in relation to the system ground, known as "high side" drives. Additionally, the drive circuit must be resistant to the high "dV/dt" of the switch node and exhibit a minimal coupling capacitance. The gate of an IGBT must be charged and discharged through Rg (internal and external gate resistance). For every switching cycle, the relationship between the gate charge curve and the IGBT data sheet can be determined. $P_{gd} = Q_g \times F \times V_s \qquad (3.22)$

$Where; P_{gd} - Gate\,drive\ power$

$Q_g$ -Data sheet charge for a chosen gate voltage swing.

$V_S$ -Positive to Negative Voltage Swing

As per (IEC 60747-9, 2019) data using the IGBT data below, we may approximation the parameter as follows:

$Ic = 200A, Vce = 150V, Vge = \pm 15V$, internal and external gate resistance is 2Ω respectively. $Tc = 25℃\ and\ Tj = 150℃$.

where: $I_C$ -is collector current

$V_{ce}$ -is collector- emitter voltage

$V_{ge}$ -is gate emitter voltage

$T_C$ -is case temperature, And

$Tj$ -is junction temperature

Unless a charge curve is included in the data sheet but just a $Q_g$ value at specific gate voltages, by dividing by the ratio of the actual voltage swings to those on the data sheet, one may estimate the value of additional gate voltage swings. (www.infineon.com I. , 2015). Let see gate charge $Q_g$ value of 3.7 $\mu c$ with ±15 V gate voltage swing (30 V total). For a swing of +15 to -9 V (24 V total) gate charge approximates to 3 $\mu c$.

In the other case, $Pgd = E \times Fsw \qquad (3.23)$

By substituting $E = Q_{gx}\left(Vg_{on} - Vg_{off}\right)$

$$P_{gd} = \frac{1}{2} \times Q_g \times \left(V_{gon} - Vg_{off}\right) \times F_{sw}$$

Therefore, $F_{sw} = \dfrac{2 \times P_{gd}}{Q_g \times \left(Vg_{on} - Vg_{of}\, f\right)}$

$Where; P_{gd}$ – Gate drive power

$Q_g$ -Gate Charge

$F_{sw}$ -Switch frequency

$T_{sw}$ -Switching period

According to average charge and discharge current provided by $P_g / V_{ge}$ is 30 mA. The peak current $Ipk$, needed to charge and discharge the gate is a function of $V_{ge}$, gate resistance of the IGBT internal resistance $R_g$ and external resistance $R_g$.

$$I_{pk} = \frac{V_{sw}}{Rg_{\text{int}} \times Rg_{ext}} \qquad (3.24)$$

where, $I_{pk}$ – The required peak current to charge and discharge.

$V_{sw}$ – The Gate voltage swing

$Rg_{\text{int}}$ – The Internal gate resistance, And

$Rg_{ext}$ – The resistance of gate resistance

The total gate drive energy E per cycle is given by:

$$E = Q_g \times V_{ge}$$

The supplied by the bulk capacitors on the +15 V and -9 V rails is proportional to their respective voltages. In this case, the +15 V rail provides 45 units of energy. Assuming the bulk capacitor on the +15 V rail should not experience a drop greater than 0.5 V in each cycle, we can calculate the minimum capacitance "C" by equating the energy supplied to the difference in capacitor energies between the start and end voltages.

$$E = \frac{1}{2} c \times (Vinitial \times Vfinal)^2 \qquad (3.25)$$

DC-DC converters are used to drive high side IGBTs by providing the switched 'DC-link' voltage across their isolation barrier. This voltage can reach kilovolts and has very fast switching edges, starting from 10 kV/and higher. With the latest gallium nitride (GaN) devices, switching at 100 kV/ or more is possible. Such high voltage results in displacement current flowing through the capacitance of the DC-DC isolation barrier, which has a specific value. $I = C.dv/dt$

The maximum allowable power dissipation $(Pdis)$ in the IGBT for a specific case temperature using the datasheet parameters is given by (www.Semikron.com, 2007):

$$(P_{dis}) = \frac{\Delta T}{R_{th}} = \frac{Tj - Tc}{R_{th}} \qquad (3.26)$$

The size of the inverter should be required for this system is determined as follows:

$$Size\,of\ inverter = \frac{Total\,load + 20\% Al}{E\%} \qquad (3.27)$$

where;

$Al$ -Additional load, 20% of total load

$E\%$ -Iinverter efficiency (80%) And

Total load – Actual load, active power

3.6.4. Sizing of bidirectional DC-DC converter mode with Super capacitor

From IGBT designing parameter data ‘Vce’ of IGBT switch device is 150V (IEC 60747-9, 2019), which is become 300V for two IGBT switches taken as initial dc-link voltage and the inverter output voltage requirement is 415V. The duty cycle of bidirectional DC-DC converter is determined from the below equation.

$$D = \frac{V_{out} - V_{in}}{V_{out}} \qquad (3.28)$$

Also if we adjust our duty cycle at ‘D’ for bidirectional DC-DC converter switch, the voltage at DC-storage device can be calculated as follows:

$$V_{dc} = \frac{1}{1-D} \times V_c \qquad (3.29)$$

where $V_{dc}$ – dc-link voltage, And

$Vc$ - Voltage at Super capacitor/storage device.

3.6.5. Sizing of super capacitor storage device

The Super capacitor Based Energy Storage System can be utilized to achieve voltage smoothing and address critical tasks such as power fluctuation mitigation, real power release, and charging. These tasks may be necessary to accommodate peak demand, transient faults, and other circumstances. The Simulink Diagram of DVR integrated with Super capacitor energy storage presented in Figure 3.15.

To interface the higher voltage and proper energy storage capacity the Super capacitor should be connected in series and parallel combination.

$$Ns = \frac{V\max}{Vcell} \qquad (3.30)$$

where; $Ns$ -Number of cell connected, And

$Vcell$ -The rating of Super capacitor cell

The Super capacitor bank's parallel branch count (Np) can be expressed as follows:

$$\frac{Ns \times Ceq}{Ccell}$$

where, $Ceq$ -Equivalent capacitance of super capacitor in farad, And

$Ccell$ -Capacitance of each cell in farad

From number of series and parallel cell combination the total number of cell ($NT$) required in Super capacitor is given as follows:

$$NT = Np \times Ns \qquad (3.31)$$

The super capacitor bank Maximum energy storage is calculated by:

$$E_{\max} = \left(C_{eq} \times U_{2\max}\right) \qquad (3.32)$$

where:

$E_{\max}$ = Maximum energy storage capacity

$U_{\max}$ = Super capacitor maximum voltage, And

$Ceq$ = Super capacitor equivalent capacitance bank (Farad).

The super capacitor bank voltage discharge ratio is given by:

$$\%d = \frac{\left[\{U_{\max}\}\right]}{U_{\min}} \times 100$$

where; $U_{\min}$ = Super Capacitor voltage boundary (minimum allowable)

The maximum power of the super capacitor bank can be calculated by:

$$PD_{\max} = \left[\frac{U_{2\max}}{4_{\mathrm{Re}q}}\right] \qquad (3.33)$$

where: $PD_{\max}$ = Power KW (maximum dischargeable)

$\mathrm{R}_{eq}$ = Super capacitor bank equivalent series resistance, And

$E_u = C_{eq}\left[\left(U_{\max} - U_{\min}\right)^2\right]$ is provided when $U_{\min} < U < U_{\max}$

3.6.6. Sizing of Equivalent Series DC Resistance of Super Capacitor

The sizing of equivalent series DC resistance of a super capacitor is an important consideration for its proper functioning. The equivalent series DC resistance is the sum of all the internal resistances present in a super capacitor. A high ESR can lead to voltage drops, reduced efficiency and heating of the super capacitor. When designing the super capacitor energy storage bank numbers of super capacitor cell are connected in series and parallel there by total series resistance of bank increase is called equivalent series resistance of the bank. It is expressed by the following formula.

$$\mathrm{Re}q = \frac{\left(Rs \times Ns\right)}{Np} \qquad (3.34)$$

where: $\mathrm{Re}q$ -Equivalent serious resistance of super capacitor bank ohms, And

$Rs$ -Series resistance of each cell in ohm.

The maximum energy stored in Super capacitor is depends on its equivalent capacitance.

$$E_{\max} = P \times t = \frac{1}{2}\left(Ceq \times V^2{}_{\max}\right) \qquad (3.35)$$

We can infer from the equation above that an increase in discharge time will result in an increase in the total capacitance needed. According to IEEE 1159-1195 and IEEE 519-1992 standards a typical duration of voltage sag and swell is 10ms to 1 minute. So for the temporary fault of the system let say for the duration of 90msec, 150msec, 250msec and 300ms the equivalent capacitance needed to mitigate the missing voltage is determined as follows:

From equation (3.34) the total load requirement is P (kW) which used as a reference to decide the total capacitance.

For a period of 250msec:

$$C_{eq} = \frac{2 \times p \times T_{250ms}}{V_{\max}{}^2} \qquad (3.36)$$

To calculate the total number of capacitor it's linked in series to increase the voltage value.

Total number of Super Capacitor connected in series Cs= $\frac{V_{max}}{V_{cell}}$

$$\text{The rated capacitance ( C )value } = C_{eq} \times C_s$$

Hence, this study proposes a discharge duration of $250ms$ to evaluate the useful energy rating (E), percentage of discharge (%d), and power (P).

$$\%d_{\min} = \frac{\sqrt{\mathrm{R}_{eq} \times P_d}}{V_{\max}} \times 100 \qquad (3.37)$$

$$V_{\min} = \mathrm{R}_{eq} \times I_d = \sqrt{\mathrm{R}_{eq} \times P_d} \qquad (3.38)$$

$$I_d = \sqrt{\frac{P_d}{\mathrm{R}_{eq}}}$$

$$V_{\min} = \mathrm{R}_{eq} \times I_d$$

$$\%d_{\max} = \frac{\sqrt{\mathrm{R}_{eq} \times P_d}}{V\min} \times 100 \approx 100$$

The determination of useful energy and maximum energy depends on the prescribed discharge duration.

$$E_{usefull} = \frac{1}{2} \times Ceq\left(V\max - V\min\right)^2$$

$$E_{\max} = \frac{1}{2} \times C_{eq} \times \left(V_{\max} - V_{\min}\right)^2 \qquad (3.39)$$

$$E_{\max} = \frac{1}{2} \times C_{eq} \times \left(V_{\max}\right)^2$$

Maximum power drawn from the super capacitor bank for duration of $250ms$ is:

$$E_{\max} = P_{\max} \times T250ms, P\max = \frac{E_{\max}}{250ms}$$

Maximum rated capacity (Ah) for a period of $250ms = \frac{E_{\max}\left(KWS\right)}{Vc(v)}$

Rated capacity (Ah) during discharge for a period of $250ms = \frac{Eusefull\left(KWS\right)}{Vc(v)}$

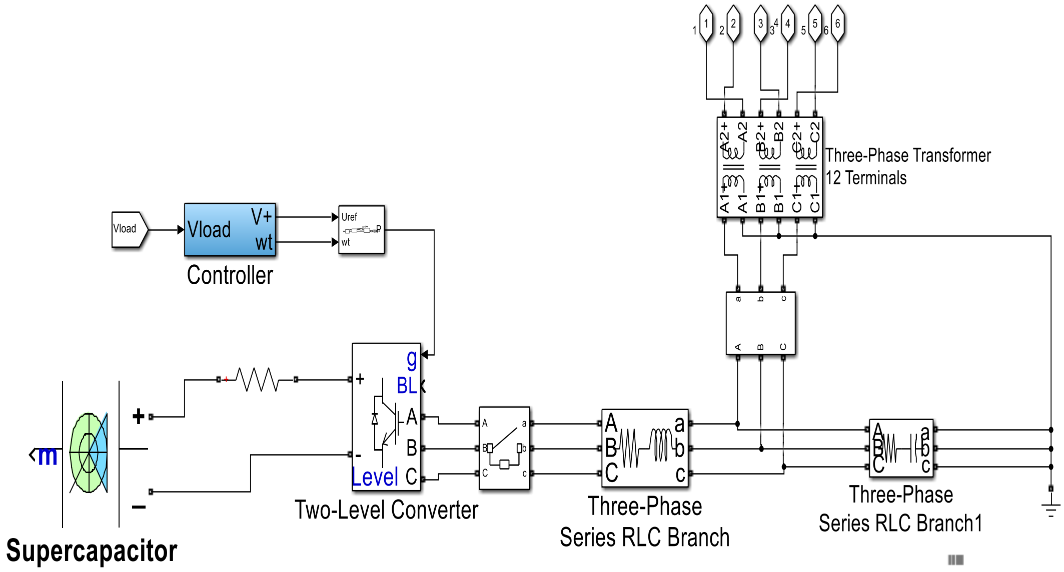



Figure 3.15. Simulink Diagram DVR integrated with Super capacitor energy storage

### 3.7. Mitigation of Harmonics

To reduce a system's harmonic distortion levels, it is advisable to select and employ installation practices that prevent the occurrence of harmonics. Over the years, several techniques for mitigating harmonics have been suggested and implemented. In situations where the harmonic distortions exceed the limits specified by the IEEE Standard 519-1992, filters are designed specifically to address these distortions. There are two types of filters commonly used for filtering harmonic distortions: passive filters and active filters. Passive Filters: Passive filters are made up of inductance, capacitance, and resistance components that are configured and adjusted to manage harmonics. They are extensively employed and are relatively cost-effective compared to other methods used to eliminate harmonic distortion. Despite their advantages, passive filters possess a significant drawback in that they may have adverse interactions with the power system, necessitating the evaluation of all likely system interactions during their design. Passive filters typically serve to either shunt harmonic currents off the line or obstruct their flow between system components. This is accomplished through the tuning of the filter's elements to create a resonance at a specific frequency.

Shunt passive filters: The most commonly used passive filter type is the single-tuned "notch" filter, which is both economical and often sufficient for various applications. A notch filter is designed to be series-tuned, presenting a low impedance specifically for a certain harmonic current. Upon being connected in shunt with the power system, the filter redirects the usual flow path of harmonic currents on the line, effectively preventing their transmission. Series passive filters, however, function in a different way. They are linked in series rather than in shunt with the power system to connect to the load. In order to display high impedance at a certain harmonic frequency, the inductance and capacitance components are adjusted and coupled in parallel. As a result, the flow of harmonic currents at the specified frequency is effectively blocked by the high impedance.

Active Filter: Active filters are a newer type of device used to eliminate harmonics in electrical systems. They rely on advanced power electronics and are considerably more expensive compared to passive filters. The design process of active filters involves generating harmonic currents that offset the existing harmonic components as they occur in the distribution system. One major advantage of active filters is that they do not experience resonance issues with the system and can address multiple harmonics simultaneously. Additionally, they are capable of addressing other power quality concerns like flicker. Active filters are especially valuable when dealing with significant loads that cause distortion from relatively weak points on the power system. They are commonly employed in challenging situations where passive filters fail due to parallel resonance issues.

Passive filters are more effective for power system harmonic mitigation than active filters because it is less expensive.

Design of multi-branch Single tuned Filter:

This section provides an example of how to create harmonic filters for use in industrial settings. Passive filters may really be created with the twin goal of delivering filtering action and adjusting power factor to the necessary level. Passive filters always give reactive compensation to a degree determined by the volt-ampere size and voltage of the capacitor bank utilized. At the tuning frequency, these passive filters exhibit extremely low impedance in comparison to line impedance, via which the whole current at that specific frequency is redirected.

A single tuned shunt filter can only remove a single current harmonic component, notwithstanding the advantage of reactive power compensation. To individually suppress each current harmonic, a broad range produced harmonic single tuned filter needs to be built. The design of multiple single tuned filters is to mitigate multi harmonics. The filter provided reactive power to the system as a result the capacitor size was selected. The nonlinear load produces 18% of fifth harmonic and 13% of seventh harmonics of the fundamental current (Lumbreras, 2020).

THD is the primary metric used to distortion, which is applicable to low-voltage, medium-voltage, and high-voltage systems. This measure is expressed as a percentage of the fundamental and is precisely defined as:

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \quad (3.40)$$

where, $V_n$ is the magnitude of $n^{th}$ harmonic voltage And

$V_1$ is the magnitude of fundamental voltage.

The equations provided above are used to obtain the capacitances associated with the $h^{th}$ harmonics in a multiple parallel single-tuned filter system. These capacitances determine the necessary compensation from the filter.

$$Qeff = S\left(\sin\left(\cos^{-1}(\theta_1)\right) - \sin\left(\cos^{-1}(\theta_2)\right)\right) \quad (3.41)$$

$$Qfth = Qeff \frac{Ith}{I2 + I3 + ...} \quad (3.42)$$

where, $h = 2, 3, .......$

The calculation to determine the voltage across the capacitor:

$$Vc = \left(\frac{h^2}{hs^2 - 1}\right)_{Vsystem} \quad (3.43)$$

The calculation to determine the reactive power that needs to be supplied by the capacitor:

$$Qc = \left(\frac{h^2}{hs^2}\right) Qfth \quad (3.44)$$

Then $X_C$ and $X_L$ is calculated as:

$$X_C = \frac{V_{c\ rated}^2}{Q_{c\,rated}} \quad (3.45)$$

$$X_L = \left(\frac{X_C}{h^2}\right) \quad (3.46)$$

$$C = \frac{1}{2\pi fxc} \quad (3.47)$$

$$L = \frac{XL}{2\pi f} \quad (3.48)$$

## CHAPTER FOUR

## 4. RESULTS AND DISCUSSTIONS

### 4.1. Mitigation of Voltage Sag Problems

Mitigation of voltage sag and harmonics has been carried out in a case study three phase system, a 15 KV power supplied from the substation feeder. As discussed on chapter one BGI Ethiopia plc has a power consumption of 3.50 MVA from two 1000 kVA and one 1500 kVA step down transformers. Each transformer is connected to different loads.

MATLAB/Simulink software were modeled and simulated to mitigate voltage sag as show in Figure 4.1. The findings also indicated that the suggested control method was successful in reducing Total harmonics distortion and in compensating voltage sag. The voltage level at critical points in the system remained stable even when voltage sags occurred.

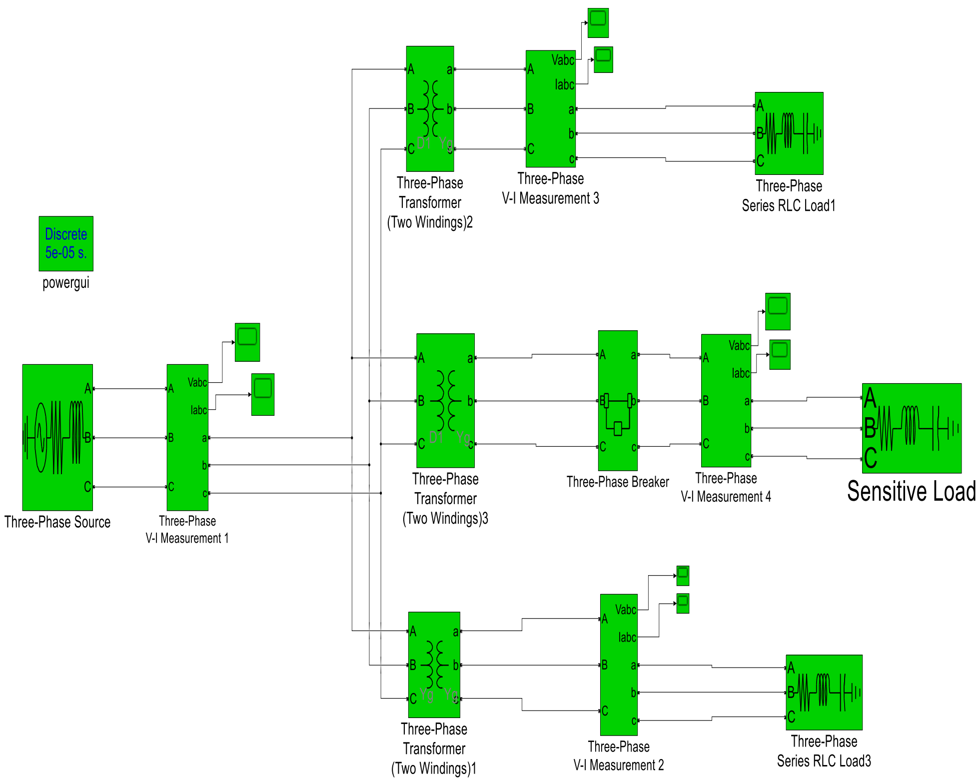



Figure 4.1 SIMULINK model of factory without fault and without using DVR

During gathering information from factory mostly occur on factory distribution system three phase to ground fault. This is the reason why this type of fault is considered first. Three phases to ground fault, each individual phases is decreased to 65 % from their nominal values for duration of 90 ms, 250 ms, 150ms and 300 ms.

The simulation experiment was conducted and its findings revealed that DVR was successful in compensating for the voltage sag caused by a three-phase to ground fault and also reduced harmonics originating from nonlinear loads that causes unbalanced loading.

Case I: SIMULINK model three phase to ground fault without DVR

The three-line to ground fault (TLGF) occurred and resulting in a decrease of voltage from their rms values. SIMULINK model of the factory with three phases to ground fault without DVR is shown in Figure 4.2. The entire fault lasted for 0.05 seconds, spanning from 0.03 seconds to 0.08, Figure 4.3 shows the source load voltages under TLGF.

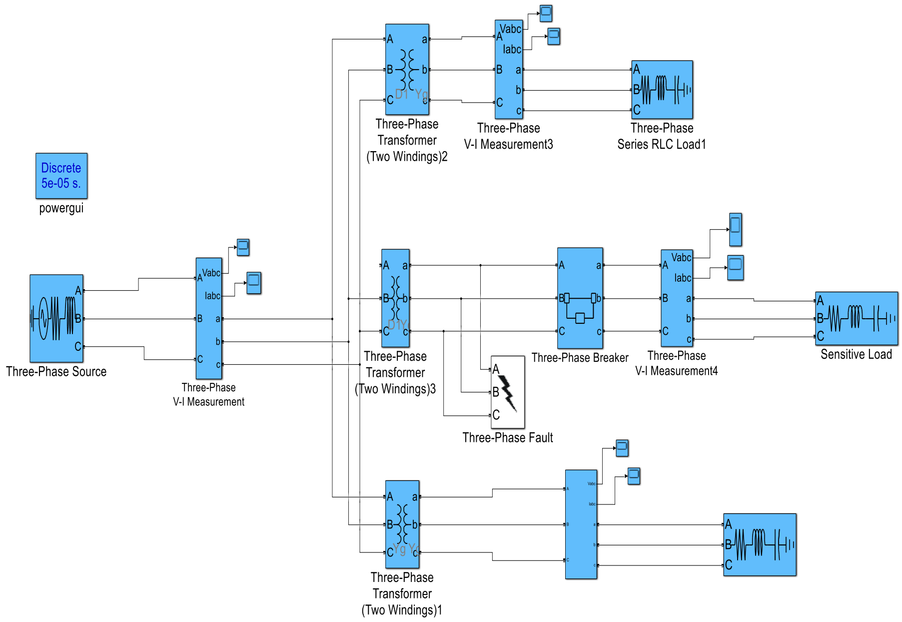



Figure 4.2 SIMULINK model of factory with TLGF without DVR

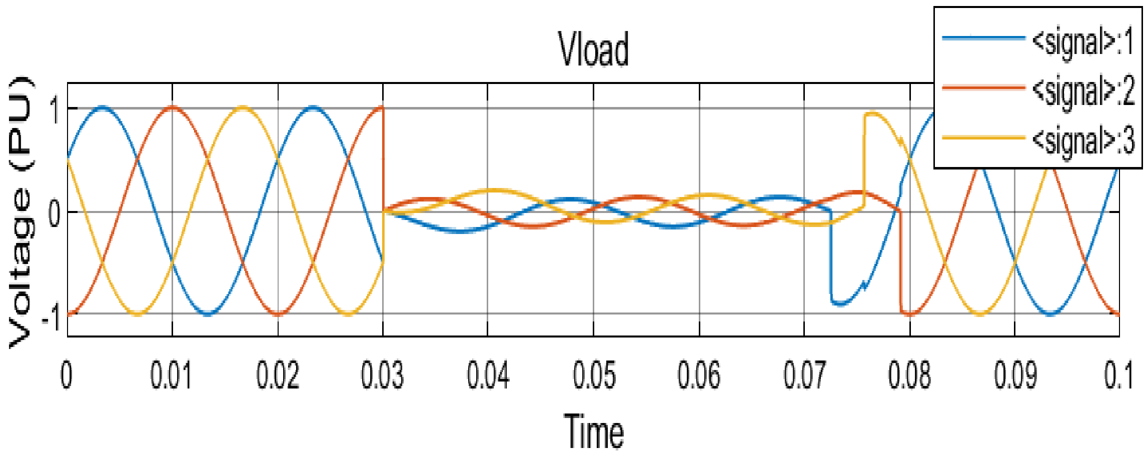



Figure 4.3 SIMULINK wave form of the factory with TLGF without DVR

Case II: SIMULINK model without three phase to ground fault with DVR

Figure 4.4 shows SIMULINK model of the factory without three phase fault with DVR. Since there was no instance of a three-line to ground fault (TLGF), there was no requirement for DVR to compensate for any voltage drop as shown in the Figure 4.5. Consequently, the injection voltage remained at zero volts as well.

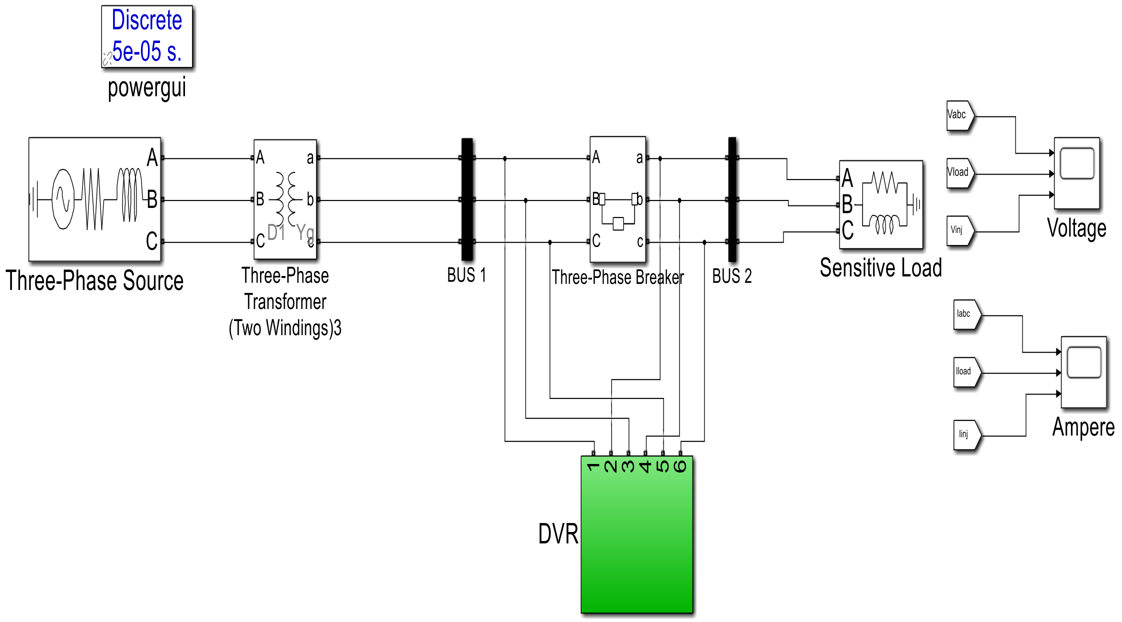



Figure 4.4. SIMULINK model of factory without TLGF with DVR

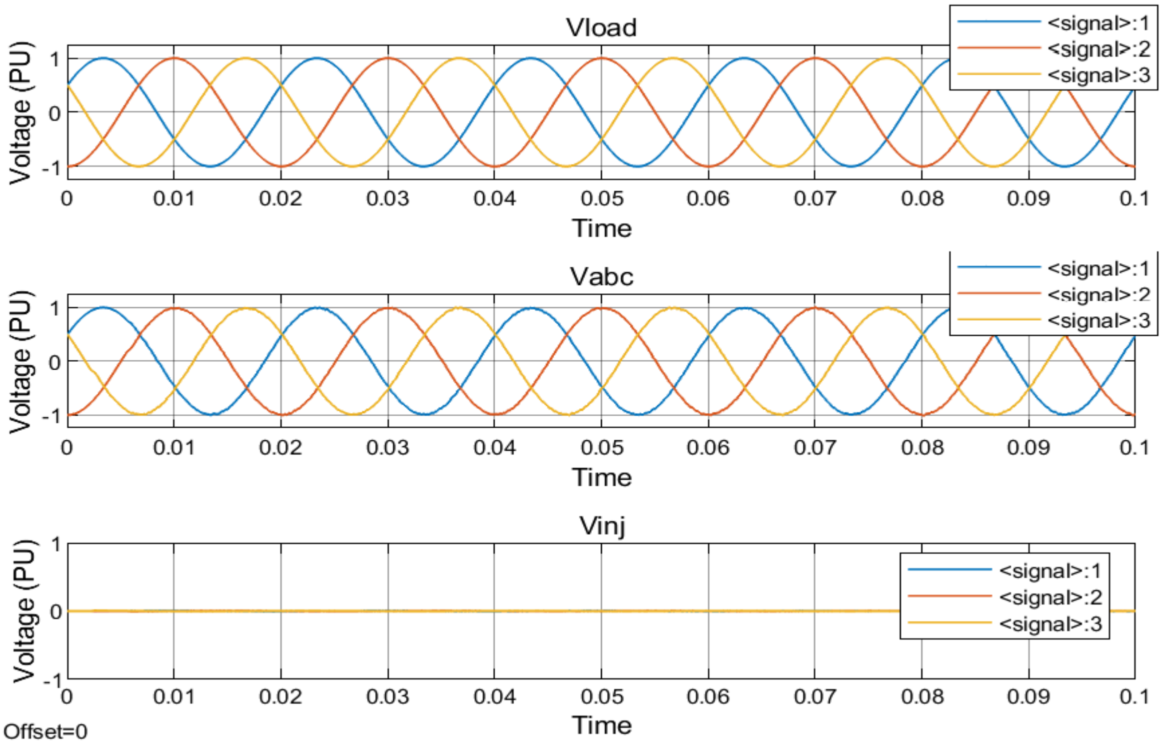



Figure 4.5. SIMULINK result of rms value without TLGF with DVR.

Case III: SIMULINK model with three phase to ground fault with DVR.

The three-line to ground fault (TLGF) occurred as shown in Figure 4.6, resulting in a decrease of voltage from their rms values. The entire fault lasted for 0.05 seconds, spanning from 0.03 seconds to 0.08. As can be seen from the results in Figure 4.7, the DVR injects the voltage with proper polarity and phase angle to compensate for the period of 0.05 second spanning from 0.03 seconds to 0.08 seconds so the load voltage is kept at the nominal value with the help of the DVR. To charge the super capacitor for each cycle of voltage sag the DC side of the DVR is connected to the rectifier and the other side of the rectifier can be from a main power line or from an auxiliary feeder.

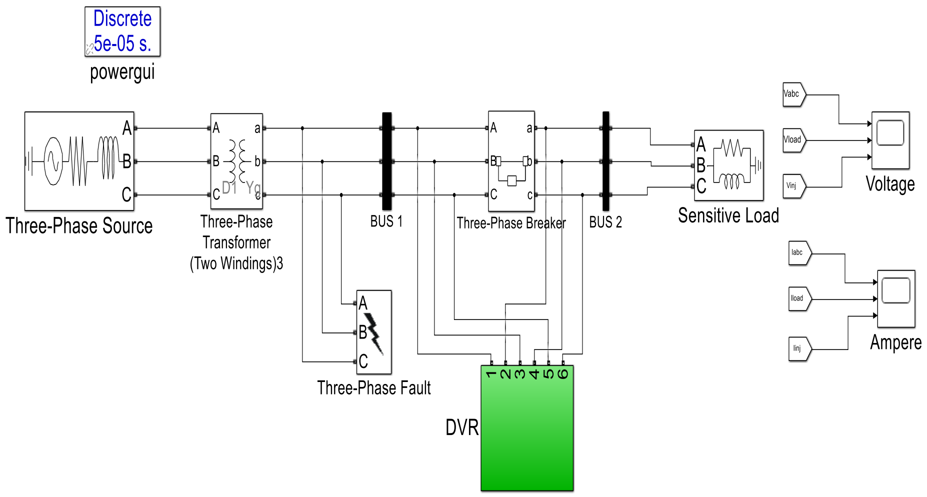



Figure 4.6. SIMULINK model of factory with TLGF and DVR

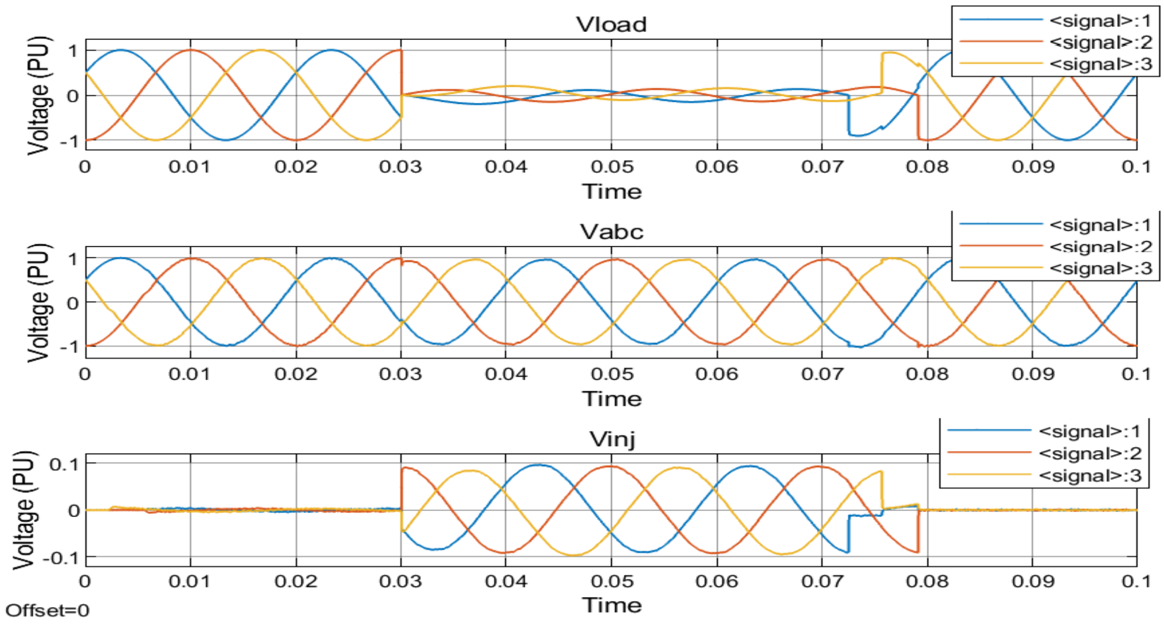



Figure 4.7. SIMULINK voltage wave form TLGF with using DVR

## 4.2. Mitigation of Total Harmonics Distortion (THD)

Figure 4.8 and Figure 4.9 shows the FFT analysis of the source voltage and load voltage for a three phase to ground fault. This shows that the THD is reduced from 25.07% to 2.89%.

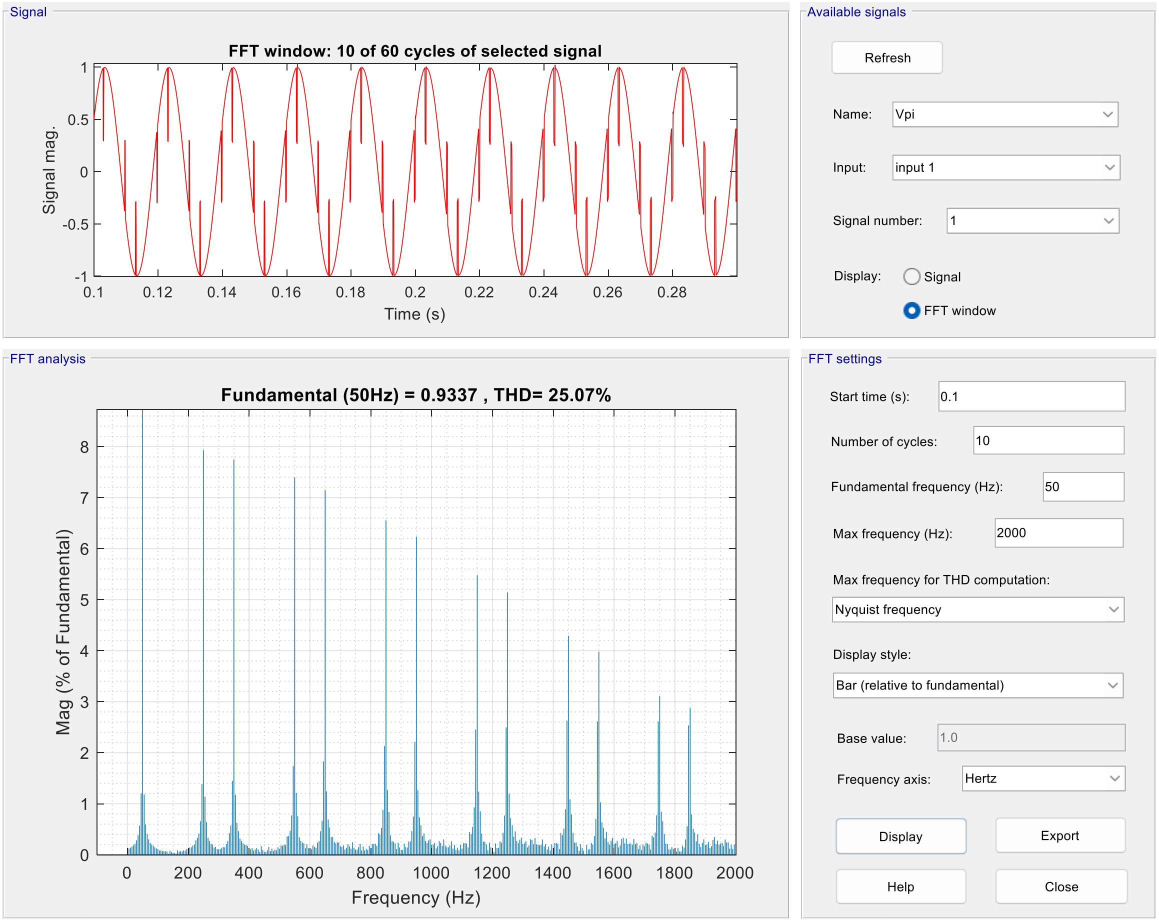



Figure 4.8. FFT analysis of the source voltage without DVR

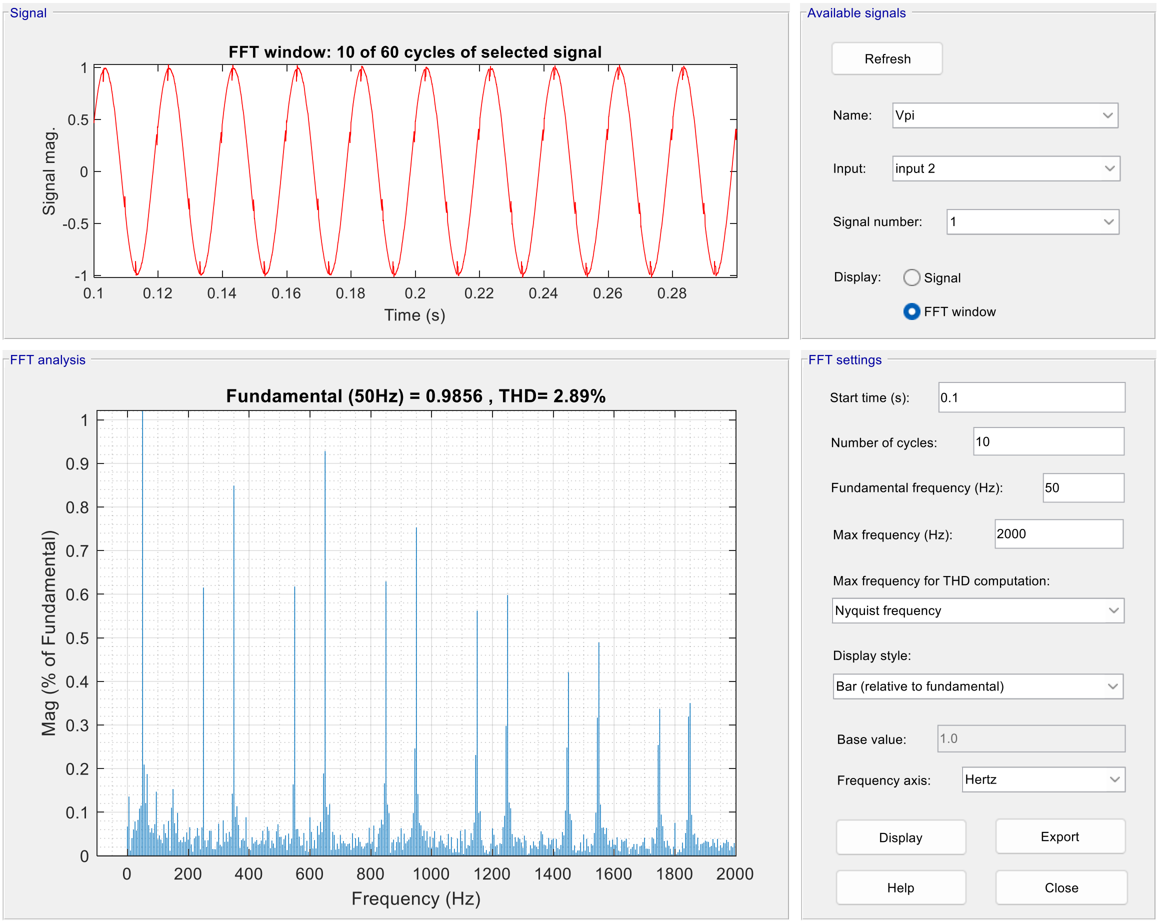



Figure 4.9. FFT analysis of the source voltage with DVR

The similarities of both my finding and (Abas, 2020), paper shows a significant reduction in THD after implementing a DVR. This study result indicates a reduction from 25.07% to 2.89%, while Abas's result showed a reduction from 18.5% to 2.69%. These demonstrates the effectiveness of dynamic voltage restorers in reducing THD.

However, there are some differences in the extent of the THD reduction achieved in both studies. This paper achieved a higher initial THD value of 25.07% compared to Abas's research with an initial THD of 18.5%. Despite this difference, both studies were able to achieve a similar magnitude of THD reduction, with your result showing a reduction of 22.18% and Abas's result showing a reduction of 15.81%.

Overall, both finding are demonstrated the effectiveness of dynamic voltage restorers in reducing THD in power quality mitigation techniques. The differences in initial THD values and the magnitude of reduction achieved highlight the potential variability in the performance of such techniques.

# CHAPTER FIVE

# 5. CONCLUSTIONS AND RECOMMENDATIONS

## 5.1.Conclusions

The paper focuses on evaluating the power quality issues and solutions at the St. George Brewery factory in BGI Ethiopia. The assessment was conducted by utilizing recorded data and conducting direct measurements through fluke 435 power quality and energy analyzer. Additionally, the analysis of the recorded data was conducted based on IEEE standards. Findings revealed that voltage sags and Total harmonic distortions were the most critical power quality issues in the factory and appropriate steps were taken to mitigate the identified problems.

During the data analysis, it was observed that a voltage sag occurred on all three phases, resulting in dropping to below 65% of rms voltage (380V). The cause of the voltage sag was a three-phase short-circuit fault that led to the tripping of protective devices. The voltage sag also resulted in equipment malfunctions and damage. To mitigate this problem, a dynamic voltage restorer was simulated in the distribution system between the power supply and the sensitive load feeder at the PCC. The dynamic voltage restorer effectively restored the voltage to the normal standard voltage level.

The assessment conducted at the factory during the given period indicated the presence of a distortion, which was recorded up to 25.07% THD at full load. This value far exceeds the IEEE limits set for THD distortion. The impact of the total harmonics distortion were studied, and the results indicated the necessity to design passive filters (multi- single-tuned) for mitigating the distortion. The measures were successful in reducing the distortion levels from 25.07% to 2.89%. This reduction in distortion level substantiates how essential filters are for eliminating the harmful effects of harmonics such as additional heating, false tripping and equipment malfunction.

## 5.2.Recommendations

Based on the findings of this thesis, it is suggested that St. George Brewery Factory should prioritize the identification of power quality problems and to design appropriate solutions, which the industry should implement and install to prevent the loss of money, enhance productivity, profitability, and avoid early equipment failure. These methods protect crucial equipment like microprocessor-based control systems, Human-Machine interface (HMI), programmable logic controls, and adjustable speed drives, eliminating the chances of any damage. Additionally, the techniques can prevent production processes shutdown, disconnections, and efficiency losses in electrical rotating machines, prevent the burnout of motors, as well as cable insulation damage. Ultimately, the implementation of these techniques can improve profitability and productivity while simultaneously enhancing the efficiency and performance of the factory's equipment.

## 5.3.Suggestion for future works

Overall, the thesis provides valuable contributions to the area of power quality improvement, and future research could build on the findings to further enhance and optimize the performance of dynamic voltage restorer with super capacitor-based energy storage systems.

- Testing the proposed dynamic voltage restorer system in a real-world scenario to verify and validate simulation results would be beneficial.
- Further analysis could be performed to compare the proposed system with other conventional mitigation techniques.
- Investigating the economic feasibility of implementing the proposed dynamic voltage restorer system compared to other conventional mitigation techniques could provide additional insights.

Overall, the thesis provides valuable contributions to the area of power quality improvement, and future research could build on the findings to further enhance and optimize the performance of dynamic voltage restorer with super capacitor-based energy storage systems.

## REFERENCE


A. H. Al-Badi, M. H.-H. (2014). Designing of filter to reduce harmonic in industrial power networks. *IEEE Int. Energy Conf.*

Abas, N. (2020). Power Quality Improvement Using Dynamic Voltage Restorer. *IEEE*.

Anu G. Pillai. (2019). Study on Power Quality Problem and its Mitigation Techniques. *IRJET*.

Aurelio G. Cerrada, A. a. (2014). "Dynamic Voltage Restorer (DVR) System for Compartion of Voktage sag, State-of -the Art Review ," . *International Journal of Computational Engineering Research , vol. 3, no. 1, May 2014*.

Carnovale, T. M. (2006). "Application of IEEE STD 519-1992 Harmonic Limits,". *IEEE*.

Chow, J. H., & Juan J. Sanchez-Gasca. (2020). "Flexible AC Transmission Systems," in Power System Modeling, Computation, and Control . *IEEE*.

Davanagere. (2016). Technical investigation of voltage sag 1Electrical and Electronics Engineering Research Centre, . *University B.D.T. College of Engineering,, India. American journal of Engineering research center*.

Eltamaly, A. S.-S. (2018). The usefulness of including DVR in distribution system for the purpose of voltage sag and swell mitigation is described. *IEEE*.

engineeringenotes.com. (2017, August ). Voltage: Variation, Imbalance and Fluctuations | Electrical Engineering.

Gupta, S. K. (2020). Design and implemetation of super capacitor based DVR circuit for power powe quality enhancement. *International journal of modern agriculture*.

Heydt, G. (1998). Simulation and Analysis of Series Voltage Boost Technology for Power Quality enhancement. *IEEE*.

IEC 60747-9, E. (2019). *Semiconductor Devices – Discrete Devices – Part 9:*.

IEEE-1100. (1992). IEEE-Std 1100-1999. *IEEE-1100*.

IGI Global. (2019). *Handbook of Research on Smart Power System Operation.* IGI Global.

Inchi, M. (2013). Modeling and analysis of multilevel inverter based dynamic voltage restorer with dc-dc converter. MSc. thesis, University of Çukurova, Adana. *IEEE*.

Kangarlu, M. H. (2010). Transformer less DVR Topology Based on Multilevel Inverter with Reduced Number of Switches. 1 st Power Electronic & Drive Systems & Technologies Conference, . *Tehran, Iran, pp.371–375.*

Lumbreras, D. G. (2020). Trends in Power Quality, Harmonic Mitigation and Standards for Light and Heavy Industries:. *Article 5792*.

M. F. McGranaghan, S. S. (2004). *electrical power systems quality, second ed.*

M. Rusli, a. M. (2015). nternational Conference on Electricity Distribution single tuned harmonic filter design as total harmonic distortion . *23 rd International Conference on Electricity Distribution," noJune, pp. 15–18*.

M.M. Abdel Aziz, G. A. (2004). "Cost and Mitigation of Voltage sag for Industrial Plants",. *IEEE*.

Mahmoud, M. (2012). Modeling and simulation of dynamic voltage restorer in power system. . *MSc. thesis, University of Azhar, Cairo*.

Meyer, C. D. (2008). (2008). Optimized Control Strategy for a Medium-Voltage DVR-Theoretical Investigations and Experimental Result. *IEEE Transactions on Power Electronics, Vol. 23, No. 6, pp. 2746-2754.*

Mohank, G. a. (2013). Performance Analysis of Multi Converter Unified Power Quality Conditioner using PI Controller. . *Australian Journal of Basic and Applied Sciences, 7(9), pp. 331-340.*

Muhammad, A. O. (2021). Dynamic voltage restorer (DVR) enhancement in power quality mitigation with an adverse impact of unsymmetrical faults. *ELSEVIER*.

N. Patel, K. G. (2017). "A Review On Power Quality Issues and Standards," . *Int. Res. J. Eng. Technol*.

Naeem Abas, S. D. (2020). "Power Quality Improvement Using Dynamic Voltage Restorer" , . *IEEE Access,*.

Namita R. Chavan1, D. M. (2020). DVR Based Mitigation of Voltage Sag. *IJIRT*.

Negendrabu, N. V. (2012). Series Compensation Technique for Voltage Sag Mitigation. *IOSR journal of Engineering*.

P. Daehler and R. Affolter. (2000). "Requirements and solutions for dynamic voltage restorer, a case study," 2000 IEEE Power Engineering Society Winter Meeting. Conference Proceedings. *IEEE*.

Padmanaban, S. (2020). *Power Quality in Modern Power Systems.* ELSEVIER.

Pal, R. D. (2015). State of The Art: Dynamic Voltage Restorer for Power Quality Improvement. *An International Journal (ECIJ), 04(02).*

R. Pal, S. G. (2016). Simulation of dynamic voltage restorer (DVR) to mitigate voltage sag during three-phase fault. *International Conference on Electrical Power and Energy Systems*.

Reddy, P. V. (2014). "power Quality Improvement using mulitiple statcoms ," . *the international journal of engineering and science , pp. 2319*.

Rosli, O. R. (2011). Dynamic Voltage Restorer Application for Power Quality improvement in Electrical Distribution System. Australian Journal of Basic and applied Sciences. *IEEE*.

Ryan, H. M. (2013). *High-Voltage Engineering and Testing, 3rd Edition.* IET.

S.Balaji. (2021). Power Quality Improvement Using Dynamic Voltage Restorer for Various Line Faults. *Turkish Journal of Computer and Mathematics Education* .

Soomro, A. H. (2021). Dynamic Voltage Restorer—A comprehensive review. *ELSEVIER*.

T. C. Sekar and B. J. Rabi. (2012). *A Rivew and study of Harmonic Mitigation Techniques.*

Tasneem Akhtar. (2018). A Review on Distribution System with Harmonic Reduction. *IRJET*.

Vol.2, N. (2012). *Improved method for characterization of ultra capacitor by constant current charging. International Journal of modeling and optimization,.*

Won, D. A. (2003). A New Definition of Voltage Sag Duration Considering the Voltage Tolerance Curve. *IEEE Power Tech Conference Proceedings, 3: 1-5.*

www.infineon.com, I. (2015). Industrial IGBT Modules Explanation. *AN2011-05*.

www.infineon.com, I. A.-0. (2015). Industrial IGBT Modules Explanation of Technical Information . *Application Note AN 2011-05 V1.2*.

www.Semikron.com. (2007). Application/DriverCalculation, Application note AN- 7004, 2007-10-31 . *Rev00 © by SEMIKRON.*

Yau, H.-T. (2014). Sources, effects, and modelling of interharmonics. *Hindawi*.

# APPENDIX

**Appendix** I. Parameter of Simulation

| Items | Value |
|---|---|
| Three phase source rated voltage | 15 KV, 50 Hz, |
| Step Down Transformer | 15 KV/0.38 KV, |
| Step Down transformer winding 1 Resistance/inductance ( $Pu$ ) | 0.002/0.08 |
| Step Down transformer winding 2 Resistance/inductance ( $Pu$ ) | 0.005/0.018 |
| DVR rated capacity | 200 KVA |
| Maximum voltage injection | 210 V |
| Sensitive load | 188.75 KVA |
| LC Filter , Inductance/capacitance | 10 $mH$ /5 $\mu F$ |
| Injection transformer voltage | 21/210 V |
| Injection transformer Rate power | 159 KVA |
| Injection transformer winding 1, Resistance/Inductance ( $Pu$ ) | 0.0038/0.013 |
| Injection transformer winding 1, Resistance/Inductance ( $Pu$ ) | 0.005/0.018 |
| PI Controller $d$ -axis PI controller | KP d=40, Ki d=154 |
| PI Controller $q$ -axis PI controller | KP q=25, Ki q =260 |
| IGBT FSW | 16 KHz |
| IGBT Vce/Ic | 600 V/200 A |
| IGBT Snubber resistance | $100\times10^3\Omega$ |
| Super capacitor , rated capacitor | $500F$ |
| Super capacitor , Voltage cell | 3 V |
| Series capacitors | 81 |
| Parallel capacitors | 6 |
| Super capacitor equivalent DC-series resistance | $2.1 \times 10^{-3}\,\Omega$ |

**Appendix** II. Industries and their loss per event

| No | Industry | Loss per event (USD) |
|---|---|---|
| 1. | Semiconductor industry | 2,500,000 |
| 2. | Credit card processing | 250,000 |
| 3. | Equipment manufacturing | 100,000 |
| 4. | Automobile industry | 75,000 |
| 5. | Chemical industry | 50,000 |
| 6. | Paper Manufacturing | 30,000 |

**Appendix** III. Shows industries & their Cost of Momentary interruption

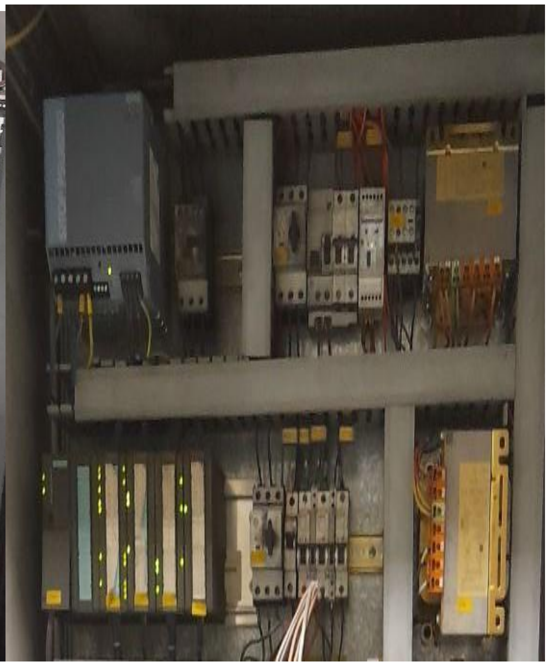
| | | Cost of Momentary interruption in (USD) | |
|---|---|---|---|
| No | Industry | Minimum | Maximum |
| 1. | Semiconductor | 20.0 | 60.0 |
| 2. | Pharmaceutical | 5.0 | 50.0 |
| 3. | Electronics | 8.0 | 12.0 |
| 4. | Communications, Information | 1.0 | 10.0 |
| 5. | Automobile manufacturing | 5.0 | 7.5 |
| 6. | Food processing | 3.0 | 5.0 |
| 7. | Glass | 4.0 | 6.0 |
| 8. | Petrochemical | 3.0 | 5.0 |
| 9. | Textile | 2.0 | 4.0 |
| 10. | Rubber & plastics | 3.0 | 4.5 |
| 11. | Metal fabrication | 2.0 | 4.0 |
| 12. | Mining | 2.0 | 4.0 |
| 13. | Hospitals, Banks, Civil services | 2.0 | 3.0 |
| 14. | Paper | 1.5 | 2.5 |
| 15. | Printing (News Paper) | 1.0 | 2.0 |
| 16. | Restaurants, bars, hotels | 0.5 | 1.0 |
| 17. | Commercial shops | 0.1 | 0.5 |

**Appendix** IV. Fluke 435 power quality and energy analyzer

**Appendix** V. Previously recorded sample data in the case study factory.

| Date | Time | Vrms ph-n AN Min | Current A Avg | Current N Avg | Active Power AN Avg | Apparent Power Total Avg | Power Factor Total Avg | Reactive Energy Total Max |
|---|---|---|---|---|---|---|---|---|
| 8/18/2022 | 9:34:00 AM.489 | 228.97 | 1215.6 | 17.1 | 269260 | 848850 | 0.94 | 4258 |
| 8/18/2022 | 9:35:00 AM.489 | 228.56 | 1316.7 | 18 | 290310 | 914850 | 0.94 | 8828 |
| 8/18/2022 | 9:36:00 AM.489 | 228.49 | 1376.4 | 18.1 | 303790 | 954720 | 0.94 | 13501 |
| 8/18/2022 | 9:37:00 AM.489 | 228.5 | 1369.2 | 18.4 | 302040 | 949020 | 0.94 | 18122 |
| 8/18/2022 | 9:38:00 AM.489 | 228.66 | 1337.1 | 15.6 | 296540 | 929190 | 0.94 | 22600 |
| 8/18/2022 | 9:39:00 AM.489 | 228.11 | 1337.1 | 15.3 | 297630 | 930390 | 0.94 | 27015 |
| 8/18/2022 | 9:40:00 AM.489 | 228.72 | 1349.9 | 15.3 | 299490 | 938190 | 0.94 | 31482 |
| 8/18/2022 | 9:41:00 AM.489 | 228.33 | 1385.7 | 13.3 | 307310 | 963600 | 0.94 | 36100 |
| 8/18/2022 | 9:42:00 AM.489 | 225.79 | 1402.5 | 13.7 | 311280 | 975420 | 0.94 | 40781 |
| 8/18/2022 | 9:43:00 AM.489 | 226.05 | 1430.1 | 13.9 | 317340 | 983010 | 0.94 | 45599 |
| 8/18/2022 | 9:44:00 AM.489 | 228.19 | 1262.2 | 13.1 | 280720 | 879810 | 0.94 | 49957 |
| 8/18/2022 | 9:45:00 AM.489 | 228.78 | 1199 | 12.5 | 267560 | 839340 | 0.94 | 54113 |
| 8/18/2022 | 9:46:00 AM.489 | 229.29 | 1022.2 | 12.4 | 226230 | 717390 | 0.93 | 57863 |
| 8/18/2022 | 9:47:00 AM.489 | 230.05 | 980.9 | 12.9 | 217740 | 691290 | 0.93 | 61554 |
| 8/18/2022 | 9:48:00 AM.489 | 228.8 | 1059.2 | 12.5 | 235830 | 743580 | 0.93 | 65365 |
| 8/18/2022 | 9:49:00 AM.489 | 228.8 | 1170 | 12.3 | 260940 | 820020 | 0.94 | 69548 |
| 8/18/2022 | 9:50:00 AM.489 | 228.63 | 1188.9 | 13.4 | 264100 | 831720 | 0.94 | 73812 |
| 8/18/2022 | 9:51:00 AM.489 | 228.52 | 1208.1 | 14.7 | 266920 | 842610 | 0.94 | 78193 |

**Appendix** VI. Nonlinear loads sample photo in the case study factory.



**Appendix** VII. Case study site Transformer two 1000 KVA and one 1500 KVA