Design And Analysis of Tlbo Based Centralized Controller for on Grid Hybrid Renewable Energy System

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Abstract—Renewable energy sources like solar photovoltaic (PV) and wind power systems play a crucial role in modern electricity generation. However, their reliance on current and forecasted weather conditions leads to inconsistent energy production and output variations. This variability places increased demands on energy transmission and distribution systems to quickly compensate and maintain stability. This paper introduces a new smart grid application for power system operation, utilizing a Static Compensator (STATCOM) device to enhance power quality, improve power flow in the distribution system, reduce unwanted harmonics, and compensate for reactive power in power sources.

A quasi-Z-Source Inverter (qZSI)-based STATCOM is integrated with a Three-Phase Four-Wire (3P4W) distribution system. The proposed compensator circuit combines a qZSI and a PV system, which facilitates switching. To control the compensator, an Adaptive Frequency Fixed (AFF) Second Order Generalized Integrator (SOGI) is implemented. While the Fuzzy Logic Controller (FLC) has traditionally been used to optimize Proportional Integral (PI) controller parameters such as Kp and Ki, this paper introduces the use of an Teache learner-based optimization (TLBO) for optimization. Experimental results demonstrate that the TLBO outperforms FLC by achieving superior dynamic performance and accuracy. Specifically, the TLBO-optimized system effectively reduces Total Harmonic Distortion (THD) of the source current from 25.5% to 1.1%, compared to 1.3% achieved with FLC. Additionally, the system efficiently supplies active power to the load, showcasing TLBO's superior control and adaptability in modern smart grid applications.

I. INTRODUCTION

1.1 Introduction

In the present day, Renewable Energy Sources (RES) are extensively employed to meet the increased power requirements of the contemporary society. The utilisation of non-renewable energy sources is steadily diminishing as a result of the consequences of global warming and the adoption of renewable energy sources (RES). The Renewable Energy Source (RES) is regarded as a crucial energy resource for meeting the electricity needs in distant and secluded regions. In the current state of economic progress, renewable energy sources (RES) offer a clean, cost-effective, and reliable energy supply to the intended system. The benefits of RES include being environmentally benign and having unlimited potential. The various categories of renewable energy sources (RES) include tidal power, solar energy, wind power, biomass energy, hydroelectric power, and geothermal energy. Additionally, photovoltaic (PV) systems offer other advantages such as noiselessness, absence of fuel expenses, strong reliability, and ease of installation.

In addition to this, a cost-efficient solution has been implemented in rural areas where the construction has been integrated with an extensive gearbox system. The primary limitation of the Renewable Energy System (RES) is mostly contingent on the topological state of specific locations, resulting in erratic outputs. Furthermore, a solitary renewable energy source (RES) is insufficient to meet the total energy requirements of the load. Therefore, a consistent power supply can be achieved by combining two or more RES into a single unit. Thus, a dependable, adaptable, and economical Energy Management System (EMS) has been developed by combining the modular power generating and storage devices known as hybrid systems. The primary obstacles encountered in the RES-based EMS are the ubiquitous presence and environmentally favourable nature of wind and solar energy. Nevertheless, the aforementioned solutions proved inadequate in delivering uninterrupted power to the system due to their erratic characteristics. The equilibrium between the photovoltaic (PV) source and the load is maintained by the battery storage in the energy management system (EMS). The PV/Wind/battery-based system fails to meet the long-term energy

demands due to its limited battery capacity. The EMS procedure is challenging because it involves the creation of constant variations in RES and varying loads.

The extensive integration of renewable energy resources (RES) presents substantial obstacles to grid frequency regulation (FR) in upholding the stability and dependability of the power system. Energy storage systems (ESSs) are seen as a potential technology for providing frequency regulation (FR) services. They help maintain stability by balancing power supply and load demand. There has been extensive research on integrating energy storage devices with renewable energy sources (RES) in order to mitigate grid frequency fluctuations. Researchers have explored different types of energy storage system (ESS) technology for frequency regulation (FR), including battery ESSs (BESSs), supercapacitors (SCs), superconducting magnetic energy storage (SMES), and flywheels. Nevertheless, a battery is defined by its low power and high energy density, which means that it has a negative effect with a rapid response at a momentary moment. Consequently, extensive research has been carried out on FR hybrid energy storage systems (HESSs), which involve combining batteries with high power density devices including SCs, SMES, and flywheels.

1.2 Literature Survey

The authors, L. de Oliveira-Assis, P. García-Triviño, E. P. P. Soares-Ramos, R. Sarrias-Mena, C. A. García-Vázquez, C. E. Ugalde-Loo, and L. M. Fernández-Ramírez, discuss the need for research and development to enhance the technology of charging stations for electric vehicles (EVs) in order to promote their widespread adoption. This research introduces a novel energy management system (EMS) for a hybrid electric vehicle (EV) charging station. The system is based on a Biogeography-Based Optimisation (BBO) algorithm and incorporates Z-source converters (ZSC) into medium voltage direct current (MVDC) grids. The EMS utilises the evolutionary Biogeography-Based Optimisation (BBO) algorithm to optimise a fitness function that defines the equivalent hydrogen consumption/generation. The charging station comprises a photovoltaic (PV) system, a local grid connection, two rapid charging units, and two energy storage systems (ESS): a battery energy storage (BES) and a complete hydrogen system with a fuel cell (FC), an electrolyser (LZ), and a hydrogen tank.

By employing the BBO algorithm, the EMS effectively regulates the energy distribution between components to maintain power equilibrium in the system. This results in decreased hydrogen consumption and enhanced hydrogen generation efficiency. The paper's primary contributions are the Energy Management System (EMS) and the charging station layout utilising ZSCs. The EMS's behaviour is showcased by connecting three electric vehicles to the charging station under varying levels of sun irradiation. Furthermore, the suggested EMS is contrasted with a less complex EMS to determine the most efficient approach for managing ESS in hybrid settings. The simulation results demonstrate that the suggested EMS provides a significant enhancement in the equivalent hydrogen consumption/generation compared to the less complex EMS. By implementing the suggested arrangement, the output voltage of the components can be increased to MVDC, while simultaneously minimising the number of power converters in comparison to other setups that lack ZSC.

S. Parthiban and V. Madhaiyan discuss the current issue of power quality and the challenges associated with the deployment of power electronic devices. The voltage stabilisation of power distribution networks coupled with Photo Voltaic (PV) is crucial for ensuring the efficient functioning of all interconnected devices in the distribution system. Ensuring the stability of voltage levels is a significant obstacle when integrating photovoltaic (PV) systems into the power grid. Traditional devices like passive filters, series and shunt filters, synchronous condensers, etc. are not enough to solve the many issues related to power quality. The series compensator is employed to enhance voltage quality, while the shunt compensator is utilised to improve current quality. Furthermore, when both of these power quality issues are addressed at the same time, the device is employed in the distribution system referred to as Unified Active Power Filter (UAPF). The UAPF is fitted with a Z-source inverter (ZSI) in both the shunt and series compensator. This study focusses on the voltage and current issues related to power quality, namely voltage sag, voltage swell, and voltage and current distortion. It also involves

simulating the UAPF device to mitigate these problems.

L. Ashok Kumar and V. Indragandhi present the Renewable energy sources, which are anticipated to be a viable substitute for traditional energy sources, might present novel issues when integrated into the power system. Nevertheless, the power provided by renewable energy sources is inherently variable as a result of environmental conditions. The injection of wind power into an electric grid impacts electricity quality due to the fluctuating nature of the wind and the use of relatively new types of wind generators. The performance of the wind turbine and power quality are determined based on measurements and norms described in the IEC-61400 standard set by the International Electro-technical Commission. The power generated by a wind turbine when it is connected to the grid system is measured in terms of power quality. This includes active power, reactive power, voltage sag, voltage swell, flicker, harmonics, and the electrical behaviour of switching operations. These measurements are conducted in accordance with national and international guidelines. The study unequivocally demonstrates the presence of a power quality issue resulting from the installation of a wind turbine connected to the grid.

The suggested scheme involves the connection of a STATIC COMPENSATOR (STATCOM) FACTS device to a battery energy storage system (BESS) at a point of common coupling. This connection aims to mitigate power quality issues. The battery energy storage technology is incorporated to bolster the actual power source during unpredictable wind power variations. The control strategy of the FACTS Device (STATCOM) is simulated using MATLAB/SIMULINK in the power system block set to enhance the power quality of the grid-connected wind energy generation system. The suggested technique aims to alleviate the main supply source from the reactive power requirements of both the load and the induction generator. Based on the findings we obtained, we have confirmed that the approach is both feasible and practical for the applications we investigated.

In their study, F. S. Ahmed, A. N. Hussain, and A. J. Ali examined the impact of using multiple sources of photovoltaic (PV) cells and batteries on the input dc link chTLBOel of a voltage source converter (VSC) for distribution STATCOM (DSTATCOM). They implemented a highly coordinated design on the input of a three-leg VSC for DSTATCOM to ensure a consistent voltage output over time, without any delays or interruptions in power. This was achieved through the control circuit and the DC to DC circuit, which boosted the output of the photovoltaic cells and performed a buck-boost operation on the battery. During periods of high solar radiation, the photovoltaic (PV) system generates electricity which is then provided to the three-leg voltage source converter (VSC) of the distribution static synchronous compensator (DSTATCOM) to compensate for power demand. Any excess power is stored in the battery for later use. The battery is discharged during nighttime or overcast days to ensure the long-term operation of the VSC DSTATCOM. Furthermore, the design incorporates a Star / Delta transformer to separate the three-leg VSC for DSTATCOM. This allows for the creation of a closed loop for zero sequence fundamental and the subsequent reduction of harmonics in the neutral current. The primary objective of employing DSTATCOM is to mitigate current source harmonics, rectify reactive currents, and neutralise ground currents at the point of common coupling (PCC). The technique employed to synchronise and manage the compensation process of DSTATCOM is known as the synchronous reference frame (SRF) algorithm.

The authors, K. Muthuvel and M. Vijayakumar, offer a description of a Quasi Z-source inverter (QZSI)-based unified power quality conditioner (UPQC) supported by solar photovoltaic (SPV) technology. The purpose of this system is to improve power quality. The Unified Power Quality Conditioner (UPQC) is comprised of converters that are interconnected both in parallel and series. Parallel and series connections of active power filters (APFs) are a versatile method of specialised power circuitry used to mitigate current and voltage instabilities. The primary purposes of QZSI are to amplify the variable direct current (DC) voltage to a desired alternating current (AC) output voltage, minimise the required components, and mitigate harmonic distortion. The compensating function of the UPQC mostly depends

on the control system utilised for generating the reference current and voltage.

The suggested system utilises the enhanced second order generalised integrator (ESOGI) to extract the reference current of QZSI-UPQC. The proposed Unified Power Quality Conditioner (UPQC) incorporates a Solar Photovoltaic (SPV) system, which includes an energy storage unit. This unit is utilised to counterbalance prolonged disturbances in current and voltage, while also meeting the active power requirements of the electrical grid. The experimental findings validate that the SPV-supported QZSI-UPQC effectively produces grid currents with a total harmonic distortion (THD) of around 1.2%, hence enhancing the power efficiency of the interconnected SPV power distribution network.

1.3 Problem Formulation

Typically, the intermittent nature of solar and wind power makes it difficult for them to fully satisfy the fluctuating requirements of the power system. In order to fulfil the energy requirements of customers located far away, independent solar and wind energy systems must possess a surplus of storage capacity. By leveraging the complementing characteristics of wind and solar electricity, it is feasible to decrease the required energy storage capacity of a system. Various types of decentralised power generation are widely recognised for microgrid applications. The interface power converter plays a crucial role in ensuring the reliability of the microgrid. Therefore, the interface power converter's efficient power regulation will provide a stable and reliable distributed power generation system. The main focus of this project is to construct an off-grid quasi-Z-source inverter, which is a novel type of interfacing inverter. Photovoltaic (PV) systems employ many power converter configurations, each with distinct benefits and drawbacks. These include the inclusion or exclusion of a transformer and the utilisation of either a two-level or multilayer inverter. Single-stage inverters are increasingly replacing conventional two-stage types because to their compact dimensions, affordable cost, and superior dependability. Conversely, the typical inverter must be larger in size to handle the significant fluctuations in PV array voltage caused by the low output voltage of the PV panels, as well as the extensive range of variation

influenced by irradiance and temperature, frequently at a ratio of 1:2. In order to connect the low voltage output of an inverter to the grid, it is necessary to use huge low-frequency transformers.

However, these transformers have various disadvantages, such as their bigger physical size, lesser efficiency, increased acoustic noise, and higher total costs. The two-stage inverter obviates the necessity of a transformer by employing a boost DC/DC converter to amplify the input voltage from a broad spectrum to the intended constant magnitude. The failing switch causes the DC/DC converter to become both the costliest and most efficient component of the system. In order to enhance safety, certain solar-powered electricity generating systems use galvanic isolation. This isolation can be implemented either in the DC/DC boost converter, which utilises a high-frequency transformer, or on the AC output side of a line frequency transformer. Implementing additional galvanic isolations like this increases the overall cost and size of the system, while also diminishing its overall effectiveness. Transformerless topologies warrant additional exploration because to their greater efficiency, smaller size, and cheaper cost for PV systems.

1.4 Objective Of Thesis

The qZSI has been utilised in photovoltaic (PV) systems due to its single-stage power converter, which enables both step-up and step-down operations. Furthermore, the inverter does not require excessive power to handle a wide variety of photovoltaic direct current voltage fluctuations. This leads to a decrease in the overall expenses of the system and a reduction in the number and expenses of components, while simultaneously enhancing reliability and stability. PV systems can get many distinct and intriguing advantages from the unique benefits provided by qZSIs. The qZSI reduces switching ripples and streamlines the PV system by extracting a consistent current from the PV panel and eliminating the requirement for extra filtering capacitors.

Additionally, it possesses a reduced rating for the component known as a capacitor, which in turn streamlines the photovoltaic system. This study employed qZSI to connect the PV-generating equipment for the isolated load situation. This study

describes the implementation of an AFF-SOGI control scheme along with a PV array and a Wind Energy Conversion System (WECS)-supported qZSI-STATCOM to improve the power quality of the distribution system. This is achieved by employing a blend of both. The inquiry seeks to accomplish these fundamental objectives. To enhance the power quality in the distribution system, the qZSI-STATCOM can be utilised with an AFF-SOGI-based control algorithm when there are DC offset in the load currents, as well as distorted and unbalanced voltages. The multi-mode feature of the qZSI-STATCOM allows for the simultaneous operation in the presence of both circumstances.

1.5 Organization of Thesis

The thesis has been structured into six chapters. After the introductory chapter, the other sections of the thesis are outlined as follows.

Chapter 2 provides a comprehensive explanation of power quality, including its various varieties and the technical difficulties associated with it.

Chapter 3 provides a comprehensive explanation of the various energy sources. This chapter provides a comprehensive description utilising block diagrams and various methodologies.

Chapter 4 provides a comprehensive explanation of system modelling. This chapter provides a comprehensive description utilising block diagrams and various methodologies.

Chapter 5 provides an exposition of the simulation outcomes obtained through the MATLAB/SIMULINK environment.

Chapter 6 presents the results derived from the research conducted in this thesis. The references utilised for the purpose of research work are also included in this chapter.

II. POWER QUALITY

2.1 Overview

The technical area has become completely reliant on the continuous availability of electrical power. Economic power is typically distributed through nationwide grids, which consist of multiple generating stations interconnected to supply electricity to various loads. The grid shall provide essential nationwide services for lighting, air conditioning, heating, residential, refrigeration, and transportation, as well as significant support for commercial, governmental, medical, financial, engineering, and communication communities. Economic power enables the efficient functioning of today's modern world.

The economical power grid, with its extensive network of transmission lines spTLBOing thousands of kilometres, faces numerous power challenges. These challenges include adverse weather conditions such as snowfall, ice, hurricanes, lightning storms, and flooding, as well as equipment failures, critical switching operations, and traffic accidents. Power conundrums that harm today's technological apparatus sometimes arise locally due to several variables, including poor distribution apparatus, high start-up loads, limited construction, and background electrical noise.

The widespread use of electronics in various applications, ranging from household devices to large-scale industrial processes, has increased the importance of power quality. Power quality, or more specifically, a disturbance in power quality, is typically defined as any alteration in power (current, frequency, or voltage) that interferes with the regular operation of electrical equipment.

The regulation of power quality and its impact on electric services, large industrial organisations, businesses, and even residential users is a matter of concern. The revision has escalated as devices have become increasingly vulnerable to even minor fluctuations in the electrical power's current, frequency, and voltage. "Power quality refers to the extent to which the delivery and utilisation of electric power affect the performance of electrical equipment."

There is no universally agreed-upon definition for power quality. The issue of electricity quality can be examined from two different perspectives related to both sides of the consumer meter, namely the Consumer and Utility. An alternative interpretation of PQ is acknowledged.

An ideal power supply would be consistently accessible, consistently operating within specified voltage and frequency limits, and provide a clean sinusoidal waveform devoid of any noise. Power

Quality refers to the capacity of utility companies to deliver uninterrupted electric power.

There are primarily seven categories of Power Quality concerns. They exist.
Transient phenomena.
Interruptions.
Voltage sag.
Voltage swell.
Waveform distortion refers to any alteration or deformation of a waveform, typically caused by factors such as interference, noise, or non-linearities in the signal path.

Fluctuations in voltage.
Frequency fluctuations.

2.1.1 Transients
The most unsettling form of power disturbances is transients, which can be classified into two subclasses.

1. Spontaneous. The number 2. Characterised by oscillations or periodic motion.

2.1.2 Characterisation
Impulsive transients refer to sudden and intense disturbances that cause a rapid increase in current and/or voltage levels, either in a positive or negative direction. These eventualities can be further categorised based on their speed of occurrence, which can be classified as slow, medium, or fast.

Impulsive transients are rapid and sudden events. Figure 2.1 illustrates a single occurrence of a positive impulsive transient caused by Electrostatic discharge (ESD).
The causes of transient impulses include inadequate grounding, lightning strikes, utility fault clearing, switching of inductive loads, and electrostatic discharge (ESD). The implications might range from the loss or alteration of information to physical damage to equipment. Among these causes, lightning is arguably the most devastating.

2.1.3 Oscillatory
An oscillatory transient refers to a rapid change in the voltage, current, or both of a signal at the positive and negative boundaries, occurring at the predicted frequency of the system.

During brief intervals, the power signal in plain spans oscillates rapidly, increasing and decreasing rapidly. Oscillatory transients typically decay to zero within a single cycle, resulting in a diminishing oscillation.

These transients occur when we deactivate a capacitive or inductive load, such as a motor or capacitor bank. Oscillatory transients are overcome when the load prevents any changes from occurring. This phenomenon occurs when a rapidly running tap is suddenly shut off, resulting in a loud banging noise in the pipes. The moving water resists changes and undergoes an oscillating transitory state.
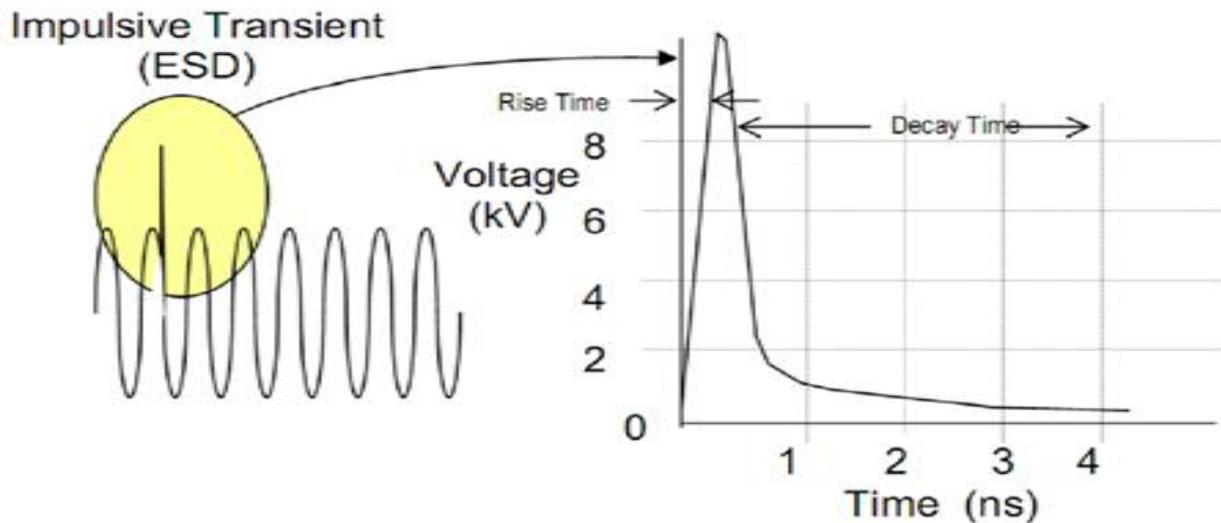

Figure 2.1 illustrates a positive impulsive transient.

For example, when a revolving motor has a leading distortion, it briefly functions as a generator while it is in operation. This results in the generation of electricity, which is then distributed through the electrical system.

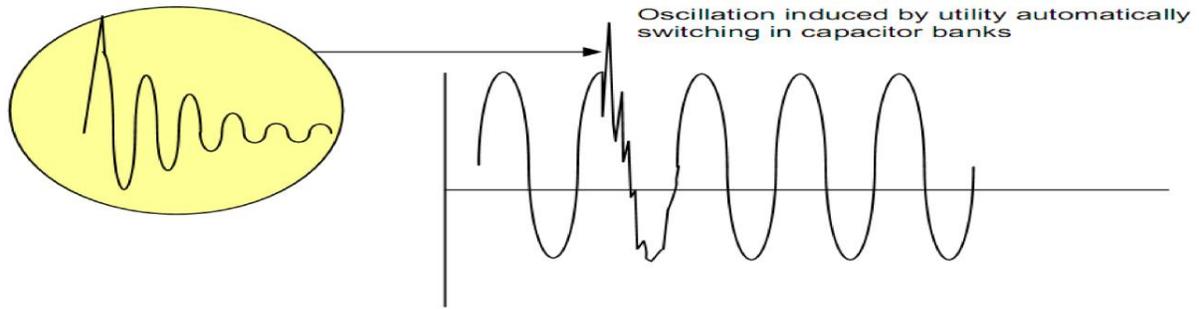Oscillation induced by utility automatically switching in capacitor banks

Figure 2.2 displays an oscillatory transient.

When power is switched on or off, a lengthy electrical network allocation can exhibit behaviour resembling that of an oscillator. This is because all networks possess multiple important properties such as inductance and allocated capacitance, which quickly energise in a decaying mTLBOer.

Oscillatory transients can often be observed on an energised circuit, typically due to utility switching operations, particularly when capacitor banks are automatically connected to the network. These transients can closely resemble electronic equipment and may create interference. Figure 2.2 depicts a unique occurrence of low frequency oscillatory transient that can be addressed by energising capacitor banks.

2.1.4 Disruptions

Interruptions (Figure 2.3) are defined as the complete cessation of load current or supply voltage. When anything continues, an interruption can be defined as transient, immediate, persistent, or temporary. The duration times for different types of interruptions are as follows:

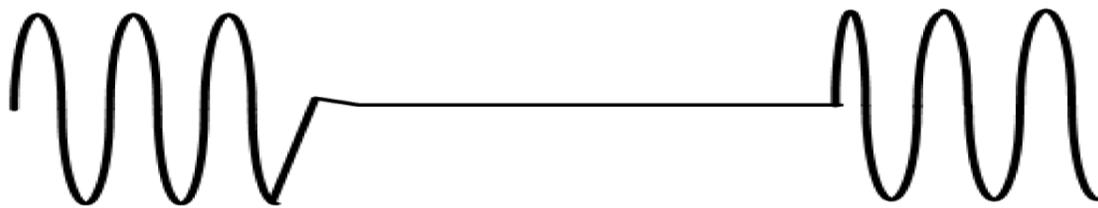|	
Momentary	thirty (30) cycles to two (2) seconds
Instantaneous	1/2(0.5) to thirty (30) cycles
Sustained	> (greater than) 2 minutes
Temporary	2 seconds to 2 minutes

Figure 2.3 illustrates a brief interruption in the flow of something.

The causes of interruptions can vary, but they are often the result of electrical supply grid damage caused by severe weather conditions (such as heavy ice or snow on power lines, strong winds, etc.), animals, lightning strikes, vehicle accidents, trees, circuit breaker tripping, or equipment failure. Although the utility basic structures are designed to automatically resolve many of these problems, they are not reliable. An example of a common cause of interruptions in electrical power networks is the malfunction of utility protective devices, such as automatic circuit re-closers.

Re-closers terminate the duration of most instabilities required for the characteristics of the fault. Re-closers are devices utilised by utility companies to detect an increase in current caused by a short circuit in the service network and then interrupt the flow of power supply. The re-closer will restore power to the line after a predetermined time interval, with the intention of dissipating the material causing the short circuit. This material can be a branch of a tree or a small deteriorating object caught between the ground and the power line. An interruption, whether it is brief, immediate, prolonged, or temporary, can result in downtime, harm, and disruption for both industrial and residential users. A small business or residential computer user may lose vital information due to power failure causing data degradation in their applications.

2.1.5 Voltage Sag

A Voltage Sag is a reduction in AC voltage below a specific frequency for a duration of 0.5 cycles to 1 minute. Sags are typically caused by system faults and often occur as a result of activating loads with high startup currents.

Figure 2.4 illustrates a decrease in voltage known as voltage sag.

Common causes of sags include the activation of high-power devices (such as when a large air conditioning unit is turned on) and the usage of remote fault clearing by utility appliances. Likewise, the activation of powerful motors in an industrial facility can result in a significant decrease in voltage (sag). A motor has the ability to draw a current that is six times greater than its normal operating current while starting up. Generating a sudden and substantial electrical load of this nature is likely to cause a significant decrease in voltage for the rest of the circuit it is connected to.

Imagine a scenario where someone activates all the water sources in your residence while you are taking a shower. The water temperature may decrease if the water pressure decreases. Indeed, a viable solution to this issue would need the addition of a dedicated water heater specifically for the shower. The correlation remains valid for circuits with significant startup loads that generate a substantial inrush current.

While adding a dedicated circuit for huge starting loads may be the most advantageous outcome, it is not always cost-effective or feasible in the long term. However, a complete system contains a multitude of substantial startup loads. Additional outcomes of high initial loads include the use of alternative power sources to prevent overloading the rest of the electrical system during motor startup. These sources can include reduced-voltage starters, as well as star-delta or autotransformer designs. A solid-state soft starter is readily available and is effective in reducing the voltage drop during motor start-up. In recent times, adjustable speed drives (ASDs) have been primarily utilised to efficiently and economically control industrial processes. These drives not only modify the speed of a motor according to the load, but also solve the challenge of starting huge motors.

Although mentioned in the Interruptions category, the infrastructure's attempts to minimise remote malfunctions may cause difficulties for end users. This issue is clearly perceived as an interruption. However, it can also designate itself as a sign of perplexing situations that are resolved quickly or that occur frequently in a short period of time. The techniques employed to mitigate interruptions can also be utilised to address voltage sags, including

system design, UPS equipment, and motor generator approaches. However, the detrimental effects caused by sags may not be immediately apparent and may only become evident over time, such as errors in industrial operations, data corruption, or damage to appliances.
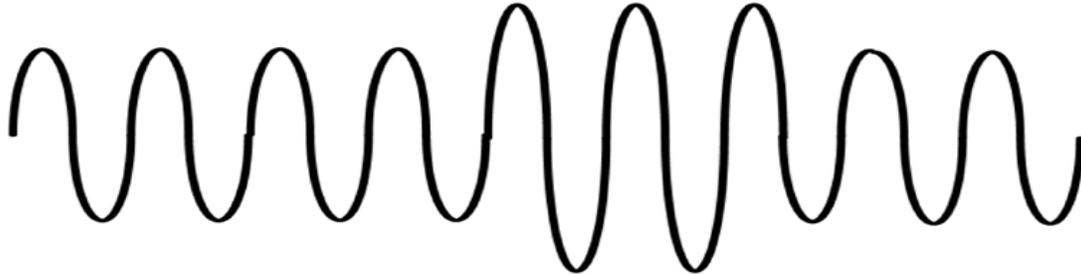
2.1.6 Voltage Swell

A swell is a phenomenon characterised by an upward deviation from the normal AC voltage level, lasting for a period of 0.5 cycles to 1 minute. Swells occur when there is a sudden and significant decrease in load on a high-resistance neutral connection, and a single-phase fault occurs on a three-phase power supply system.

Figure 2.5 illustrates a sudden increase in voltage, known as a voltage swell.

Possible consequences include the deterioration of electrical contacts, the disruption of semiconductor components in electronic devices, data mistakes, degradation of insulation, and the intermittent flickering of lights. UPS systems, power line conditioners, and resonant "control" transformers are often used solutions. The true extent of similarities and fluctuations may not become apparent until the resulting effects are observed. Utilising power conditioning and/or UPS devices that also monitor and record incoming power events will facilitate the calculation of the frequency and timing of these occurrences.

2.1.7 Waveform Distortion

Currently, there are five primary forms of waveform distortion.

DC offset refers to a constant voltage level that is added to a signal, causing it to deviate from its original zero level.

A. Harmonics

Inter harmonics refer to the frequencies that are present in a signal but do not correspond to the integer multiples of the fundamental frequency.

B. Sound pollution

Notching refers to the process of creating a V-shaped or U-shaped cut or groove in a material.

2.1.8 Direct Current (DC) Offset

DC can enter an AC distribution system as a result of rectifier failures in various AC to DC conversion methods commonly used in modern appliances. DC has the ability to manipulate the AC power supply and introduce excessive current into appliances that are currently working within their designated limits. The presence of direct current (DC) passing through transformers can lead to saturation and overheating. When a transformer saturates, it does not just become warm. It also becomes unable to carry full power to the load, which can lead to waveform distortion and extra instability in electronic load devices. Figure 2.6 illustrates the presence of a DC offset.
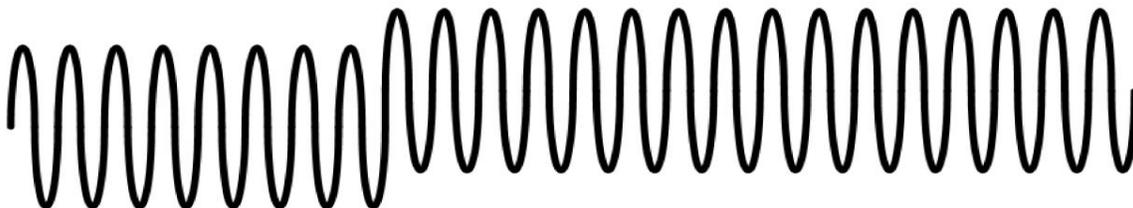

Figure 2.6 illustrates the presence of a direct current (DC) offset.

The solution to DC offset problems is to replace the defective device that is causing the problem. Utilising easily replaceable components in consumer equipment can significantly simplify the process of identifying DC offset issues produced by malfunctioning appliances, while also reducing the expenses typically associated with professional repair services.

2.1.9 Harmonics
Harmonic distortion refers to the presence of additional frequencies that are integer multiples of the fundamental frequency in a sine wave. (For example, 150Hz is the third harmonic of a 50Hz fundamental frequency, calculated as 3 multiplied by 50 equals 150). Indications of harmonic issues include malfunctioning transformers, neutral conductors, and other electrical distribution equipment, as well as circuit breakers and a lack of synchronisation in timing circuits that depend on a smooth sine wave beginning at the zero-crossover point.

Figure 2.7 displays a standard example of waveform distortion caused by harmonics.

Historically, IT appliances have faced a significant challenge in the form of harmonic distortion, primarily caused by switch-mode power supply (SMPS). Non-linear loads and other capacitive models consume power intermittently at both the positive and negative peaks of the voltage wave, rather than continuously drawing current during each entire half cycle. The transient return current, which lasts for approximately one-third of a cycle, combines with the other return currents from switch-mode power supplies (SMPS) via all three phases in the typical distribution system.

Instead of removing, the pulsed neutral currents combine, resulting in extremely high neutral currents, potentially reaching up to 1.73 times the maximum current of each phase. A clogged neutral can lead to significantly high voltages on the legs of the delivery power, resulting in severe damage to connected appliances. Simultaneously, the load on numerous Switched-Mode Power Supplies (SMPS) is concentrated at the highest points of each electromagnetic force (emf) half-cycle. This has sometimes resulted in transformer scattering and subsequent excessive heat generation. Additional factors contributing to this problem include sizable outdated uninterruptible power supply (UPS) systems, variable speed motor drives, and lighting ballasts. To address this problem, many techniques have been employed, including as the installation of K-rated transformers and harmonic filters, as well as the use of larger neutral conductors.

The technique used to reduce harmonics is referred to as harmonics mitigation technique. It is unavoidable for harmonics to be generated when an adjustable speed drive is employed. The arrangement and size of these harmonics will heavily rely on the driving configuration and impedance of the system. The available strategies for mitigating harmonics are as follows: Phase multiplication is a commonly used method in the design process to reduce the formation of harmonics, regardless of whether the drive is AC or DC. This technique involves either multiplying the phases or cancelling out the harmonics. As long as the load is balanced, it effectively reduces low order harmonics.

Passive filters: Enhancing power factor results in a reduction of high frequency harmonics. Instability

may arise when using large tuning reactors due to parallel resonance with the source impedance, which is why they are not employed. The performance of a system is influenced by the impedance of the source. Accurate measurement of this performance is challenging as it might fluctuate with changes in the system. Therefore, passive filters are unsuitable for cyclo-converters.

Active filters provide for enhanced control of the output current by improving the power factor. Active filters offer consistent performance in the face of changes in AC source impedance and respond quickly regardless of the number and size of harmonics. These filters are suitable for use with cyclo-converters. Passive filters generally have lower upfront and ongoing expenses compared to active filters. The injection has the potential to permeate into other components.

Harmonic injection is a method used to address the presence of atypical harmonics. System impedance is not considered in the design criteria due to its potential to generate low order harmonics. Harmonic mitigation techniques utilising Pulse Width Modulation (PWM) can effectively reduce harmonics to less than one percent of the fundamental frequency. PWM can be programmed to selectively eliminate specific harmonics. Furthermore, aside from the aforementioned methods, harmonics can be diminished by various circuit techniques.

2.1.10 Interharmonics
Inter harmonics, as seen in Figure 2.8, refer to a type of waveform distortion that occurs when electrical appliances, such as static induction motors and static frequency converters, introduce a signal onto the supply voltage. Cycloconverters are responsible for regulating the operation of big linear motors in industries such as mining, cement, and rolling mills. They play a significant role in addressing the challenging issue of inter-harmonic power supply. These appliances convert the input voltage into alternating current (AC) with a frequency that is either greater or lower than the frequency of the input voltage. The primary and most noticeable consequence of inter harmonics is the occurrence of visual flickering in incandescent lights and displays, which can potentially lead to communication interference and heat generation.
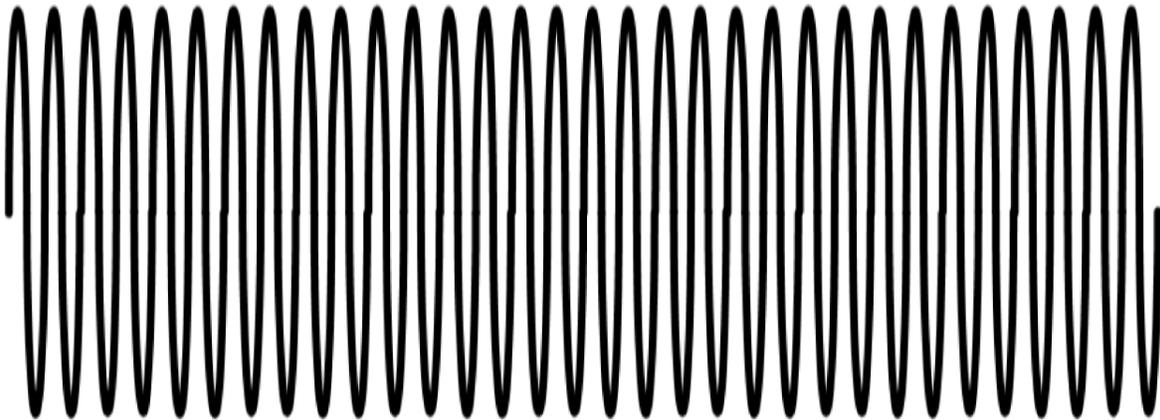

Figure 2.8 illustrates the distortion caused by inter-harmonic waveforms.

UPS systems, line conditioners and filters are effective solutions for mitigating inter harmonics.

2.1.11 Notching
refers to the process of creating a small cut or groove in a material. Notching (Fig.2.9) refers to the occasional voltage disturbances that occur during the normal functioning of electrical devices, such as light dimmers, arc welders, and variable speed drives. This puzzle can be described as a temporary impulse puzzle. However, since the notches occur periodically during each half cycle, they are regarded a distortion puzzle in the waveform. The typical consequences of notching include data loss and related issues.
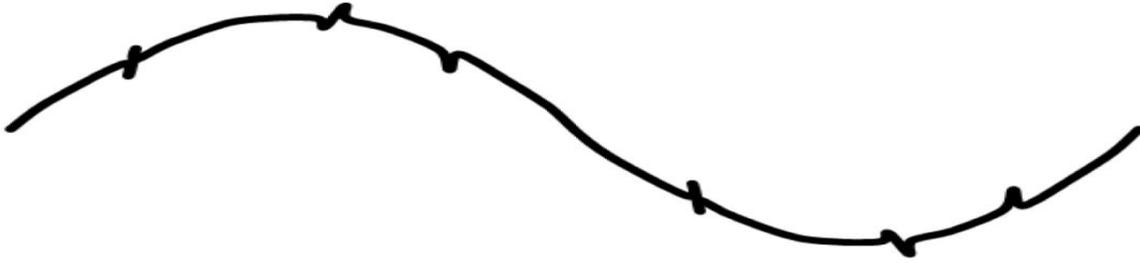
Figure 2.9 illustrates the process of notching.

One option to prevent notching is to relocate the load away from the equipment that is generating the problem, if feasible. If it is not possible to move the unit, alternative options to notching include using filter equipment and preventing data loss.

2.1.12 Noise

Noise, as seen in Figure 2.10, refers to the presence of additional current or voltage that is not required and is overlaid on the power system's current or voltage waveform. Control circuits, power electronic equipment, switching power supply, radio transmitters, and arc welders are among the sources that might generate noise. Improperly grounded networks increase the system's susceptibility to noise. Excessive noise can lead to several technical issues, including equipment malfunction, data problems, long-term component damage, distorted TV displays, and hard disc failure.
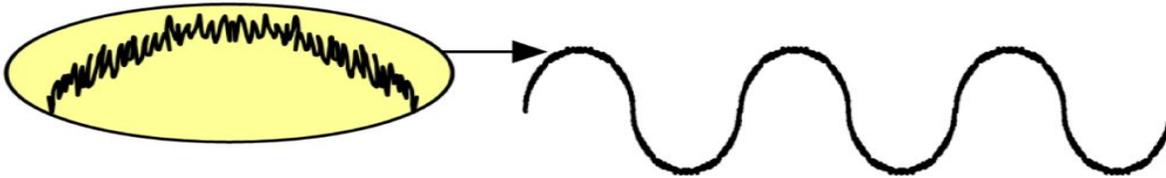
Figure 2.10 illustrates the presence of unwanted sound, sometimes referred to as noise.

There are multiple diverse strategies for managing noise, and sometimes it is necessary to employ various ways in combination to achieve the desired outcome. Several techniques include:

- Install a transformer that is both grounded and shielded to provide isolation.
- Use a UPS to separate the load from other electrical devices.
- Cable insulation
- Move the load away from the source of interference
- Implement noise filters

2.1.13 Voltage Fluctuations

Voltage fluctuations are distinct from other waveform irregularities and are classified separately.

Figure 2.11 illustrates the variations in voltage.

A voltage fluctuation refers to a consistent deviation from the normal voltage waveform or a sequence of random voltage changes that are of modest magnitude, typically ranging from 95% to 105% of the nominal value, occurring at a low frequency, usually below 25 Hz.

Voltage changes can occur when a load exhibits significant deviations in current. Arc furnaces are the primary source of voltage fluctuations in the distribution and transmission system. An indicator of this perplexing situation is the flickering of incandescent lighting. To remedy this problem, you can try removing the visible load, relocating the sensitive equipment or UPS, or installing power line conditioning devices.

2.1.14 Frequency Variations

The frequency fluctuation (Figure 2.12) is highly unusual in steady utility power systems, especially in systems that are interconnected through a power grid. Frequency variation is more common in locations where there is inadequate power infrastructure or standby generators, especially when the generator is under heavy load. The appliance is resilient to changes in frequency and is typically unaffected by minor fluctuations in the local generator frequency. Any sensitive or motor equipment that depends on a consistent and regular flow of power over a period of time would be impacted. Frequency discrepancies can cause a motor to either operate slower or faster in order to match the input power frequency. Running the motor improperly could have a negative impact on its performance, perhaps leading to increased wear and overheating. This is especially true when the motor is operated at higher speeds or when it draws excessive current.
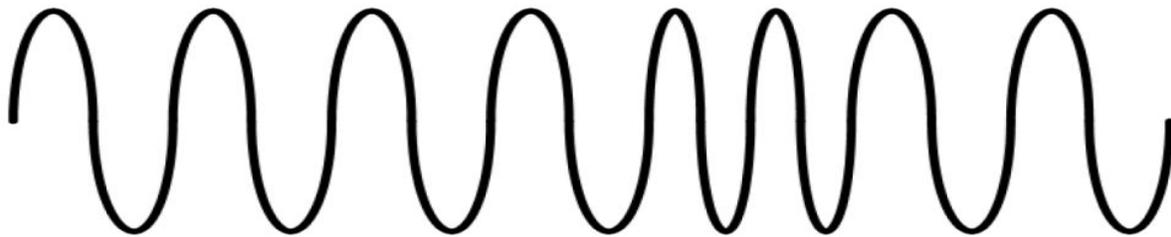

Figure 2.12 depicts the different fluctuations in frequency.

In order to resolve this perplexing situation, it is necessary to thoroughly examine and subsequently refurbish and rectify all generated power sources and other sources of power that are causing the frequency deviation.

2.2 Power Quality Problem Solutions
There are two approaches to resolving power quality issues. The explanation of power quality can be approached from either the utility's perspective or the customer's perspective. The primary way is known as load conditioning, which ensures that the appliance is less susceptible to power instability, allowing it to continue operating even under significant voltage fluctuations.

A further alternative is to establish line conditioning technologies that mitigate or suppress power supply disturbances. Active power filters provide a versatile and flexible solution to voltage quality issues. Currently, they are constructed using PWM converters and are connected to medium and low voltage distribution systems either in series or in parallel. In order to achieve load current harmonics balance, it is necessary for series active power filters to operate simultaneously with shunt passive filters.

Shunt active power filters work as series active power filters and controllable current sources function as controllable voltage sources. Both methods are best implemented using voltage source PWM inverters, with a dc bus that includes a reactive component like a capacitor. Active power filters are capable of performing many functions required to enhance power quality and compensate power systems. Their achievements are contingent upon the

power rating and the speed of response. Solutions will have a significant role in improving the quality of natural resources. Some of the effective and efficient strategies that can be identified are as follows:

2.2.1 Lightning and Surge Arresters

The Arresters are designed to provide lightning protection for transformers; however, they are not sufficiently effective in preventing voltage surges from damaging sensitive electronic control circuits.

2.2.2 Static Switches Utilising Thyristors

The static switch is a versatile device used to introduce a new component into an electrical circuit when a specific voltage level is desired. It has a rapid response time of around one cycle. In order to quickly address interruptions, sags, or voltage spikes, the static switch can be utilised to regulate one or more appliances, such as energy storage systems, filters, alternate power lines, capacitors, etc. This static switch can be utilised for several applications in power distribution. This solution requires two separate power networks, either from the service or from localised and utility power sources, similar to those used in distributed generation systems. This system has the capability to safeguard approximately 85% of voltage sags and disruptions.

2.2.3 Energy Storage Systems

Storage solutions can be employed to safeguard sensitive construction applications against shutdowns caused by temporary disruptions or transient outages. Typically, these systems consist of DC storage devices such as superconducting magnet energy storage (SMES), batteries, uninterruptible power supplies (UPS), flywheels, or DC generator storage capacitors. An inverter can quickly provide the system with the output of these appliances using a fast-acting electrical switch. Sufficient energy is supplied to the system to compensate for any energy loss caused by disruption or voltage sag. If there is a supply utility that is backed by local generation, it has the potential to be further improved.

2.2.4 Electronic Transformer with Tap Changing

An electronic load tap changer can be used to regulate voltage in a transformer. This allows for the use of a single circuit from the power supply. It has

the ability to regulate voltage reductions by up to 50% and requires a rigid system with a short circuit power to load ratio of 10:1 or higher. This could involve the utilisation of either steady increments or abrupt adjustments in voltage for intermittent alterations.

2.2.5 Harmonic Filters

Filters are employed in some situations to effectively eliminate or decrease specific harmonics. It is always more advantageous to utilise a 12-pulse or higher transformer connection rather than a filter. It is necessary to apply tuned harmonic filters in order to address and prevent potential issues. Typically, it is preferable to have numerous filters, each specifically adjusted to remove a specific harmonic. Each filter is based on a series resonance and a parallel resonance, and each filter slightly alters the resonances of additional filters.

2.2.6 Constant-Voltage Transformers

To enhance the ability to withstand transient interruptions and voltage sags in power systems, it may be beneficial to implement shielding techniques in control circuits. Constant voltage transformers (CVTs) can be utilised in circuit management to provide a consistent voltage for a duration of three cycles. Alternatively, AC contactors and relays can be equipped with electronic coil hold-in devices to prevent misoperation caused by voltage interruptions or low voltage.

2.2.7 Intelligent controllers and digital-electronic systems for load-frequency control.

The electricity supply Frequency is a fundamental factor that greatly affects power quality and can have a substantial impact on the running of machines. The power frequency precisely amplifies important components of the principal system apparatus, such as interconnected-grid control and Turbine life. A load frequency controller, designed specifically to regulate power frequency in response to varying loads, must possess sufficient speed to effectively adjust to any changes. In countries such as India and other rising nations, the usage of controllers based on electrical or mechanical devices is still prevalent. These controllers often experience predicted delays and dead time, and may also be subject to tolerances resulting from ageing and associated effects. In the

future, these controllers can be repaired by their digital-electronic equivalent.

2.3 Utilising traditional power devices to enhance power quality

To address the challenges mentioned earlier, a new concept called bespoke power appliances has been developed. bespoke power is a strategy specifically designed to cater to the needs of commercial and industrial customers.

Custom power involves the utilisation of static controllers or power electronics in the plTLBOing of medium voltage distribution systems. Its purpose is to provide high-quality and dependable power to sensitive users. Power electronic valves are responsible for the creation of specialised power applications, including active filters, converter-based devices, and static transfer switches.

Power electronics applications utilising converters can be categorised into two types: series-connected and shunt-connected devices. The shunt-connected device is commonly referred to as the Distribution Static Synchronous Compensator (DSTATCOM), while the series-connected device is known as the Static Series Compensator (SSC), commercially referred to as DVR. It has been documented that both the DSTATCOM and SSC have been employed to mitigate common power system issues such as voltage sags, dips, harmonics, and flicker imbalance.

To rectify sags of lower voltage in the load voltage magnitude, it is sufficient to inject reactive power into the system. In order to support the voltage magnitude, it is necessary to have voltage sags in addition to reactive power when injecting a higher amount of active power. Both DSTATCOM and DVR have the capability to absorb or generate reactive power. However, the insertion of active power by these devices requires an energy storage system or an external energy source.

III. PV SOURCES

3.1. Overview

This chapter introduces the paradigm, overall organisation, and management of energy sources examined in the research. This chapter provides a comprehensive introduction to renewable energy sources and their modelling. Every renewable energy source will undergo design validation in MATLAB/Simulink before being developed. The energy resources will be represented as three-phase controlled current sources. Subsequently, these sporadic renewable sources will be linked to the power grid to demonstrate that frequency fluctuations are not a concern in a grid-connected microgrid. In conclusion, this chapter emphasises the significance of voltage and frequency regulation in ensuring the stable operation of an isolated microgrid.

The system described is a solar photovoltaic energy conversion system with a rating of 3.1. French physicist Edmond Becquerel was the first to experimentally show the photovoltaic effect. At the age of 19 in 1839, he constructed the inaugural photovoltaic cell at his father's laboratory. In a publication in the 20 February 1873 edition of the scientific journal Nature, Willoughby Smith initially documented the phenomenon known as the "Effect of Light on Selenium during the passage of an Electric Current." In 1883, Charles Fritts constructed the initial solid-state photovoltaic cell by applying a thin film of gold onto the semiconductor selenium to create the junctions. However, the device's efficiency was merely approximately 1%. In 1888, Aleksandr Stoletov, a Russian physicist, constructed the inaugural cell utilising the outer photovoltaic effect, which was initially identified by Heinrich Hertz in 1887. In 1905, Albert Einstein introduced a groundbreaking quantum theory of light and provided an explanation for the photoelectric effect in a significant scientific publication. As a result of this achievement, he was awarded the Nobel Prize in Physics in 1921. In 1941, Vadim Lashkaryov made notable discoveries about p-n junctions in Cu2O and silver sulphide protocells. Russel Ohl obtained a patent for the contemporary junction semiconductor solar cell in 1946 while engaged on a sequence of advancements that ultimately resulted in the invention of the transistor. The inaugural operational photovoltaic cell was officially showcased on 25 April 1954 at Bell Laboratories. A solar cell, also known as a photovoltaic cell or "solar battery," is an electrical device that directly converts the energy of light into electricity using the photovoltaic effect, a physical and chemical phenomena. A photoelectric

cell is a type of device that exhibits changes in its electrical properties, such as current, voltage, or resistance, when it is exposed to light. Solar cells serve as the fundamental components of photovoltaic modules, commonly referred to as solar panels. Solar cells are referred to as photovoltaic, regardless of whether the source of light is natural sunlight or artificial light. They serve as a photo detector, such as infrared detectors, which detect light or other electromagnetic radiation in the vicinity of the visual range, or measure light intensity.

3.1.1. Photovoltaic panel

The operating principle is described in section 3.1.1. Photovoltaic panels are composed of solar cells. The majority of them are composed of silicon, while alternative materials are sometimes utilised. Solar cells utilise the photoelectric effect, which is the capacity of certain semiconductors to directly transform electromagnetic radiation into electric current. The incident radiation generates charged particles which can be readily separated to produce an electrical current through the design of the solar cell's structure.

A solar cell is essentially a p-n junction comprised of two distinct layers of silicon that have been doped with a small amount of impurity atoms. The n-layer contains atoms with an additional valence electron, referred to as donors, while the p-layer contains atoms with one fewer valence electron, known as acceptors. Upon the joining of the two layers, the free electrons from the n-layer diffuse into the p-side near the interface, resulting in the creation of a positively charged area due to the presence of donors. Similarly, the unoccupied spaces in the p-layer are spread out in the n-side, resulting in an area that is negatively charged due to the presence of acceptors.

This generates an electric field between the two sides, which acts as a potential barrier to prevent further flow. The equilibrium is established at the junction when the movement of electrons and holes is hindered by the potential barrier, preventing them from crossing it. The electric field exerts a force on the electrons and holes, causing them to move in opposite directions. As a result, the current can only flow in one direction: electrons can go from the p-side to the n-side, while the holes move in the opposite direction Figure 3.1 depicts a representation of the p-n junction, highlighting the impact of the electric field described. Electrodes are incorporated on both ends to gather the electrons and holes, facilitating the flow of current. For the n-layer that is exposed to solar irradiance, the contacts consist of several metallic strips known as fingers.
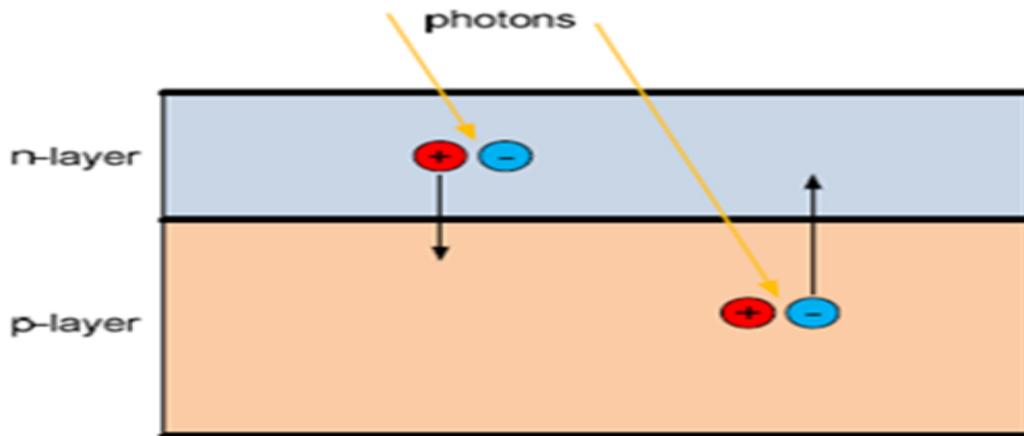

Figure 3.1 displays a solar cell.

These contacts are designed to enable the passage of light to the solar cell. Thus far, the composition of the solar cell has been elucidated, and now we shall proceed to explain its operational concept. The solar radiation photons illuminate the cell. Three distinct scenarios can occur: a portion of the photons are reflected off the upper surface of the cell and metal fingers. Unreflected entities permeate the substrate. Some of them, often those with lower energy, traverse the cell without producing any discernible

impact. Electron-hole pairs can only be created by individuals whose energy level exceeds the band gap of silicon. These pairs are formed on both sides of the p-n junction. The minority charges, specifically electrons in the p-side and holes in the n-side, are dispersed towards the junction and propelled in opposite directions by the electric field.

Electrons move towards the n-side while holes move towards the p-side. This movement generates a current within the cell, which is then collected by the metal contacts on both sides. One can observe this in

Figure 3.1. The light-generated current of a solar cell is directly proportional to the level of irradiation. A higher level of irradiation means that there are more photons with sufficient energy to make additional electron-hole pairs, resulting in an increased current output from the solar cell.

3.1.2 Equivalent Circuit of A Solar Cell

The solar cell can be represented by the electrical model shown in Fig.3.2. Its current voltage characteristic is expressed by the following Eqn.(3.1).

$$I = I_L - I_O \left(e^{\frac{q(v - IR_S)}{AKT}} - 1 \right) - \frac{V - IR_S}{R_{SH}} \qquad \dots (3.1)$$

The solar cell output current is represented by I, while the solar cell output voltage is represented by V. I_0 refers to the dark saturation current, q represents the charge of an electron, A is the diode quality factor, k is the BoltzmTLBO constant, T represents the absolute temperature, and RS and RSH are the series and shunt resistances of the solar cell. RS represents the opposition to the flow of electric current caused by the connections and the main semiconductor material of the solar cell. Explaining

the origin of the shunt resistance RSH is a challenging task. The presence of impurities along the margins of the cell creates a short-circuit path around the p-n junction, which is caused by the non-ideal character of the junction. In an optimal scenario, the value of RS would be 0 and the value of RSH would be infinite. Nevertheless, achieving this ideal environment is unattainable, thus manufacturers strive to mitigate the impact of both resistances in order to enhance their products.
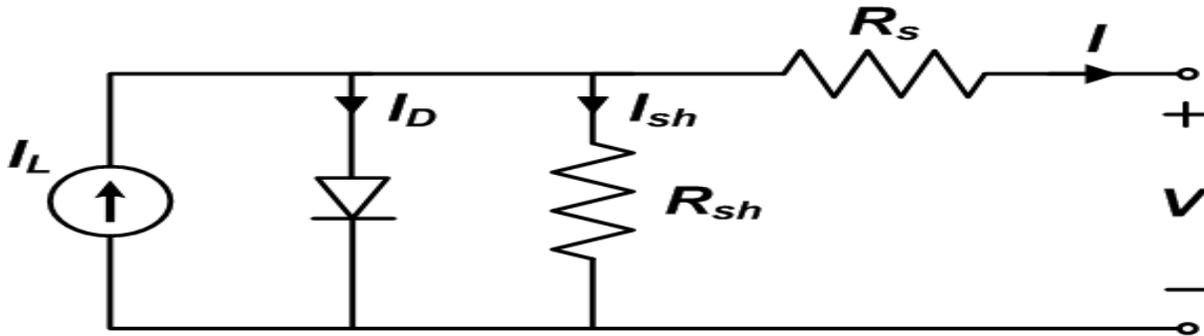

Fig.3.2 Equivalent circuit of a solar cell.

Occasionally, in order to streamline the model, the impact of the shunt resistance is disregarded, meaning that RSH is assumed to be infinite. As a result, the final term in Equation (3.1) is omitted. A photovoltaic (PV) panel consists of multiple solar cells that are interconnected in both series and parallel configurations. This arrangement ensures that

the output current and voltage of the PV panel meet the necessary criteria for the grid or equipment. The output current-voltage characteristic of a PV panel is given by Equation (3.2), considering the simplification mentioned before. In this equation, np represents the number of solar cells in parallel, and ns represents the number of solar cells in series.

$$I = n_p I_L - n_p I_O \left(e^{\frac{q(v - IR_S)}{AKT n_s}} - 1 \right) \qquad \dots (3.2)$$

3.1.3 Determination of Open Circuit, Short Circuit Current, and Maximum Power Point

There are two significant aspects of the current-voltage characteristic that need to be highlighted: the open circuit voltage (VOC) and the short circuit current (ISC). Power output is zero at both sites. The value of VOC can be estimated using Equation (3.1)

$$V_{OC} = \frac{AKT}{q} \ln\left(\frac{I_L}{I_O} + 1\right) \qquad \dots (3.3)$$

under the condition that the output current of the cell is zero (I=0) and the shunt resistance (RSH) is disregarded. It is denoted by the equation (3.3). The short circuit current, ISC, is the current when the voltage, V, is zero. It is nearly equal to the current created by the light, IL, as indicated in Equation (3.4).

$$I_{SC} = I_L \qquad \dots (3.4)$$

The solar cell generates its maximum power at a certain point on its current-voltage characteristic where the product of current (I) and voltage (V) is at its highest. The specific point referred to as the Maximum Power Point (MPP) is distinct and may be observed in
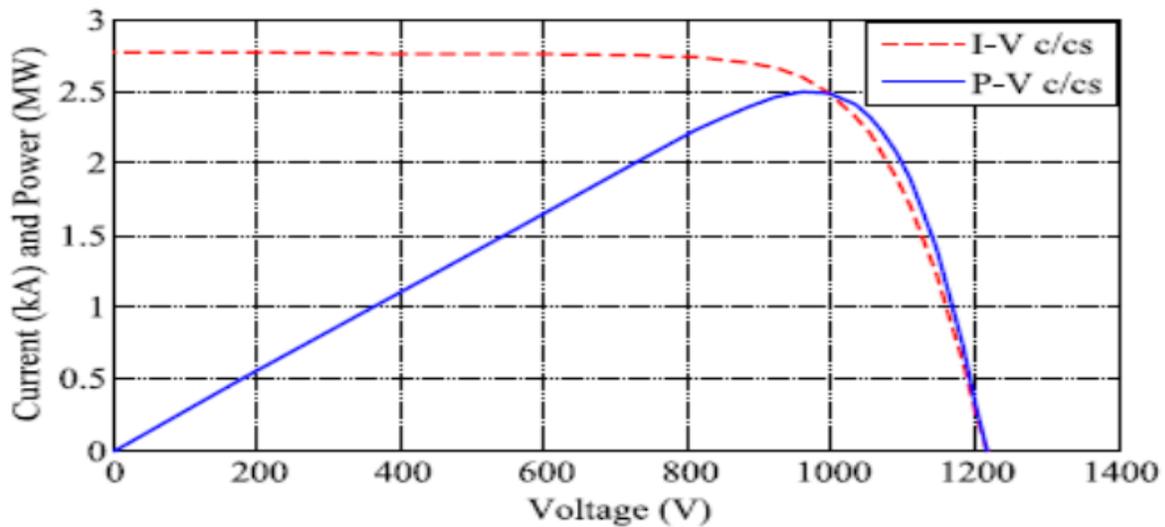
Figure 3.3, which displays the preceding points.

3.1.4 Fill Factor

The fill factor (FF) can be defined by utilising the MPP current (IMPP) and voltage (VMPP), as well as the open circuit voltage (VOC) and the short circuit current (ISC):

$$FF = \frac{I_{MPP}V_{MPP}}{I_{SC}V_{OC}} \qquad \dots (3.5)$$

The metric is commonly utilised to assess the overall quality of solar cells. The ratio being referred to is the quotient of the actual maximum power (IMPPVMPP) divided by the theoretical maximum power (ISCVOC), which is unattainable in reality. The MPP voltage and current are consistently lower than the open circuit voltage and short circuit current, respectively, due to the presence of series and shunt resistances and the diode illustrated in Figure 3.2. Commercial solar cells often have a fill factor exceeding 0.70.

3.1.5 Impact of Temperature and Irradiance

Two crucial variables that must be considered are the irradiation and the temperature. They have a significant impact on the properties of solar modules. Consequently, the Maximum Power Point (MPP) fluctuates throughout the day, necessitating continuous monitoring to maintain optimal power extraction from the solar panel. Figure 3.4 illustrates the impact of irradiance on the voltage-current (V-I) and voltage-power (V-P) characteristics. The curves are displayed in per unit, meaning that the voltage and current values are normalised using the VOC and ISC respectively. This normalisation allows for a

clearer understanding of how irradiance affects the V-I and V-P curves.

As stated before, the amount of current produced by the photoelectric effect is directly related to the level of irradiance. Therefore, an increase in irradiation results in a greater amount of current being generated. Furthermore, the short circuit current exhibits a direct correlation with the photo produced current, thereby demonstrating a direct correlation with the irradiance. When the operating point deviates from the short circuit condition, where no power is produced, the photo generated current becomes the dominant factor in the PV current, as indicated by equations (3.1) and (3.2). Due to this factor, the voltage-current relationship changes depending on the level of irradiation. On the other hand, the impact on the open circuit voltage is generally insignificant, since the generated current from the light follows a logarithmic relationship, as demonstrated in Equation (2.4).
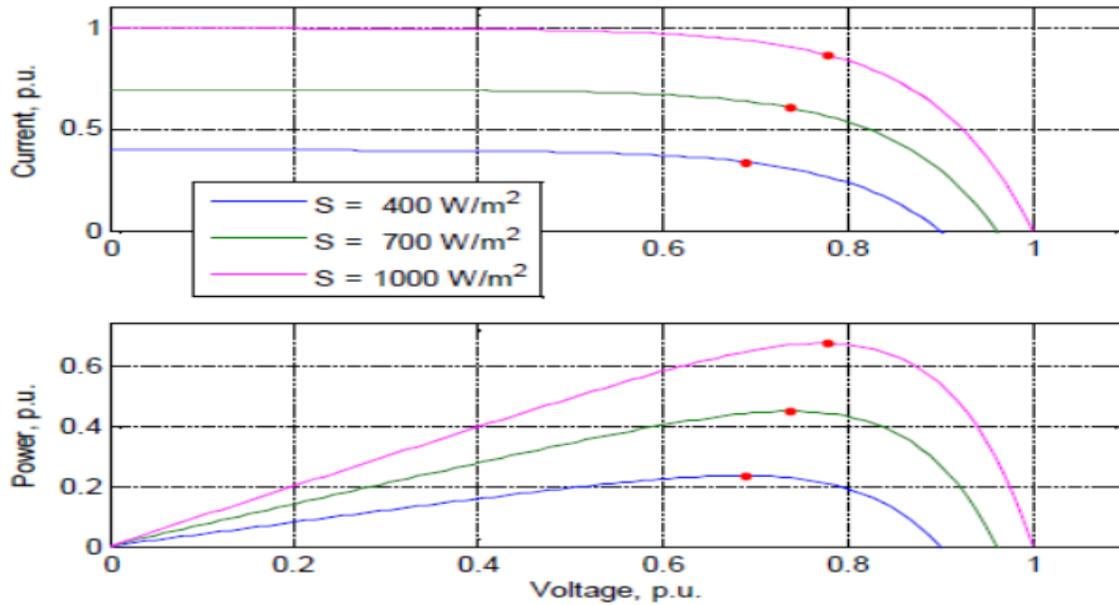
Figure 4.4 displays the voltage-current (V-I) and voltage-power (V-P) curves with a constant temperature of 25°C.

Figure 3.4 illustrates that the magnitude of the current change is larger than that of the voltage change. Typically, the impact of irradiation on voltage is disregarded in practical applications. Both the current and voltage exhibit a positive correlation with irradiation, meaning that they both grow as the irradiation level rises. Consequently, the power generated likewise shows a positive relationship with irradiation, with higher levels of irradiation resulting in more power generation. The temperature primarily influences the voltage. The open circuit voltage has a linear relationship with the temperature, as expressed by the following equation:

$$V_{OC}(T) = V_{OC}^{STC} + \frac{K_{V\%}}{100}(T - 273.15) \qquad \dots (3.6)$$

Based on Equation (3.6), the impact of temperature on VOC (voltage open circuit) is negative due to the negative value of KV (temperature coefficient of voltage). In other words, as the temperature increases, the voltage lowers. The current exhibits a slight increase in response to temperature, but, this increase is insufficient to offset the loss in voltage resulting from a given temperature elevation. This is the reason why the power also diminishes. PV panel manufacturers include temperature coefficients in their data sheets to indicate how variations in temperature affect the open circuit voltage, short circuit current, and maximum power output. Due to the negligible impact of temperature on current, it is typically disregarded. Figure 3.5 illustrates the variations in voltage-current and voltage-power

characteristics in response to changes in temperature. The curves are once again expressed in per unit, just
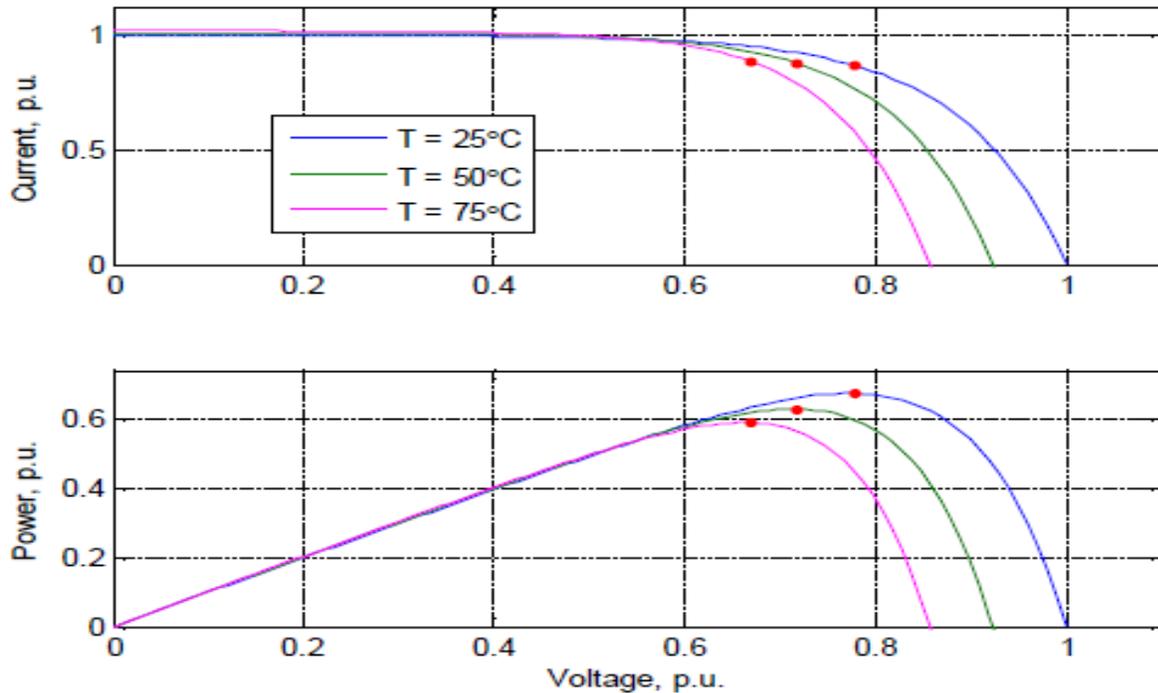
like in the preceding scenario.

Figure 3.5 displays the V-I and V-P curves under constant irradiation of 1 kW/m2 and three distinct temperatures.

As was mentioned before, the temperature and the irradiation depend on the atmospheric conditions, which are not constant during the year and not even during a single day; they can vary rapidly due to fast changing conditions such as clouds. This causes the MPP to move constantly, depending on the irradiation and temperature conditions. If the operating point is not close to the MPP, great power losses occur. Hence it is essential to track the MPP in any conditions to assure that the maximum available power is obtained from the PV panel. In a modern solar power converter, this task is entrusted to the MPPT algorithms.

The wind-diesel energy conversion system has a power output of 3.2 watts. Recently, the wind energy system has been witnessing a significant surge in its growth rate, offering a novel technological energy option. Wind energy technologies are widely distributed, abundantly accessible, and environmentally sustainable. The utilisation of wind-diesel hybrid systems has gained global popularity due to the unpredictable nature of wind availability, which is contingent upon geographical and climatic factors. Hybrid operation enhances the dependability of a self-contained system, diminishes the manufacturing expenses, and guarantees the accessibility of electricity.

This system is commonly utilised as a prospective electricity supply for communities and facilities that are not connected to the main power grid. This chapter presents the basic principles of wind energy conversion systems (WECS), the mathematical modelling of wind power extraction, and the interface between electrical generators and power electronic converters. An optimisation technique called maximum power point tracking is utilised to enhance the performance of the wind turbine. Additionally, the machine side converter controller enables control over the speed of the turbine. This chapter provides an explanation of the modelling process for the diesel generator and control system used in the diesel energy conversion system (DECS).

Wind energy has been harnessed for centuries to grind grains, extract water, and navigate the oceans. The utilisation of windmills for the production of electricity commenced in the late 19th century, coinciding with the creation of a 12kW direct current windmill generator. In the past twenty years, several wind power technologies have been created, resulting in enhanced conversion efficiency and decreased prices for wind energy generation. Wind turbines have undergone a significant growth in size, growing from a few kilowatts to several megawatts each. Aside from being installed on land, there has been a push to place giant wind turbines in offshore regions to maximise energy production and minimise their impact on land use and landscape.

In recent years, wind energy has exhibited the most rapid growth among all forms of power generation. This progress has been driven by the concerns of national policy makers regarding climate change, energy diversification, and supply security. When it comes to shifting to low-carbon energy sources, wind-generated electricity is considered more feasible compared to other complex sectors like surface and air transport and household heating. Therefore, the use of affordable and dependable low-carbon electricity generation sources, along with steps to control energy consumption, is increasingly becoming a significant goal of energy policy in numerous countries.

The volatility of wind energy undermines the dependability of a power grid. Despite the numerous disadvantages of diesel generating systems, such as high maintenance requirements, expensive fuel supply, noise pollution, and the emission of dangerous gases, they are frequently included into isolated systems to ensure reliability and maximise profitability.

3.2. Components of Wind Energy Conversion System
The major components of wind energy conversion systems are:

3.2.1 Wind energy technology
It has had remarkable advancements in the past 30 years, characterised by larger rotor diameters and the implementation of advanced power electronics that enable variable rotor speed operation. The following sections will examine the primary elements of wind energy conversion systems:

The wind turbine is a device used to convert wind energy into electrical energy. The wind turbine is a crucial component in wind energy conversion systems. Wind turbines generate electricity by harnessing the kinetic energy of the wind to power an electrical generator. The blades of the wind turbine experience the flow of wind, which creates an upward push and applies a rotational force. The rotating blades cause the rotation of a shaft located within the nacelle, which is then transmitted to a gearbox. The gearbox amplifies the rotational velocity to a level suitable for the generator, which employs magnetic fields to transform the rotational energy into electrical energy. The power generated is directed to a transformer or power electronic converter, which transforms the electricity from the generator by controlling the voltage.

3.2.2 An electrical generator
Advancements in wind power conversion technology have resulted in the creation of several wind turbine configurations that utilise a range of electric generators. Wind generators are categorised into two main classes based on their construction and working principle: induction generators (IGs) and synchronous generators (SGs). Both induction and synchronous generators are equipped with wound rotors that receive power through slip rings and brushes or through a brushless electromagnetic exciter. Currently, SGs are widely employed in WECS and can be categorised into two types: (i) wound rotor synchronous generator (WRSG) and (ii) permanent magnet synchronous generator (PMSG). Of these two types, Permanent Magnet Synchronous Generators (PMSGs) are regarded as a favourable choice for operating wind turbines directly, without the need for gearboxes. PMSG has several benefits, including increased efficiency, superior thermal properties, a robust magnetic field structure, a high power-to-weight ratio, and enhanced dynamic stability.

The Permanent Magnet Synchronous Generator is a type of generator using permanent magnets that are used to produce synchronous electrical power.

Permanent magnet synchronous machines offer superior efficiency in low-speed applications. The utilisation of a Permanent Magnet Synchronous Generator (PMSG) in a Wind Energy Conversion System (WECS) yields a reduced system size and increased power density, resulting in optimal overall efficiency. A standard configuration of PMSG consists of a stator and rotor. Permanent magnets are utilised to enable brushless operation and generate magnetic flux. By eliminating the rotor windings, it becomes feasible to attain a high power density by reducing the weight and size of the machine.

The state space model represents the mechanical and electrical system of the machine. To achieve a sinusoidal electromotive force, the stator flux generated by permanent magnets is deliberately selected to be sinusoidal as well. The presence of a significant air gap in the Permanent Magnet

Synchronous Generator (PMSG) implies that the machine is considered to have a linear magnetic circuit, and neither the stator nor the rotor core experiences saturation.

The power electronic converter interface is referred to as 3.2.2. The power electronic interface enables control over the wind energy conversion system (WECS) by regulating the speed and torque. A back-to-back converter, which is a bi-directional converter unit, is commonly used in this type of system. The rectifier-inverter pair is mostly utilised in wind energy systems, with one converter functioning as a rectifier and the other as an inverter. Both converters are bi-directional, meaning they may convert power in either direction of power flow throughout the power conversion process. The VSC on the generator side controls the converter using pulse width modulation (PWM) method.
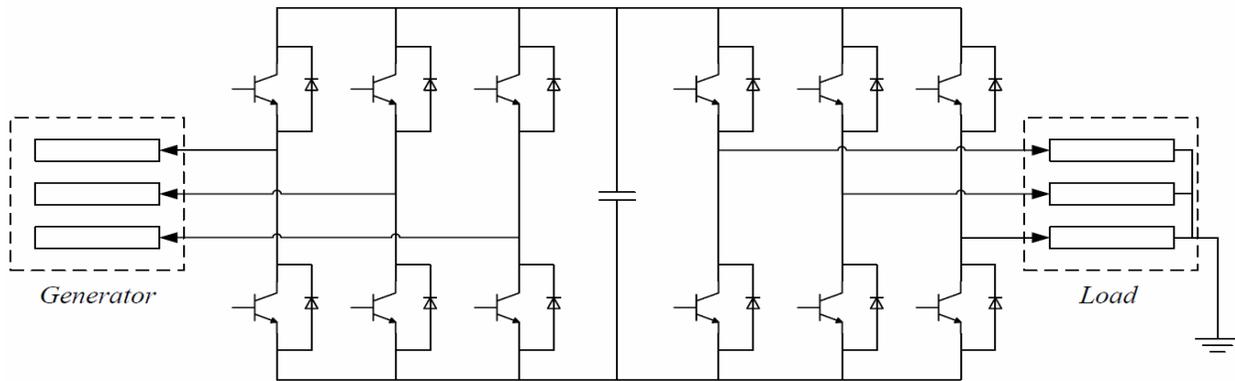
Figure 3.6 illustrates a configuration of back-to-back Voltage Source Converters (VSCs).

A DC-link capacitor is attached between the pair to enable control access. Usually, the DC-link voltage magnitude is maintained at a level higher than the line-to-line voltage on the load side. One major benefit of utilising this configuration is its long-standing status as a well-established technology, which has been successfully implemented in machine drive applications for numerous years. Furthermore, the separation of voltage source converters (VSCs) using a capacitor enables independent regulation of the two converters.

3.3 Diesel Generator
Diesel power generators are widely regarded as the most dependable source of emergency backup power.

Due to the necessity for quick reaction time, high load bearing capacity, reliable fuel supply, and consistent availability, diesel generators are widely favoured and deemed essential in modern building codes and standards. Diesel generators provide the distinctive capability of promptly responding to power failures by absorbing the entire electrical demand in a little ten seconds.

A diesel generator typically comprises a diesel engine equipped with a governor control system and a synchronous machine. A diesel engine model primarily comprises a controller that monitors the steady-state error in speed and an actuator equipped with gain K, time constant Ti, and an integrator to

regulate the fuel rack position. Diesel engines are widely recognised for being nonlinear devices, meaning that their behaviour is not directly proportional to changes in input parameters. Additionally, the characteristics of diesel engines can vary depending on factors such as power output, speed, and ambient temperature. The presence of non-linear, time-varying, dead time between the fuel injection and the generation of mechanical torque, Tmech, significantly complicates the regulation of diesel engines. Diesel engines often utilise a PI controller to regulate their speed and minimise any steady-state inaccuracy.

The synchronous machine is a type of electrical machine. A synchronous generator comprises two components: the field and the armature. The field is situated on the rotating part of the machine, whereas the armature is situated on the stationary part. The field winding conducts direct current (DC) to generate a magnetic field that rotates along with the rotor shaft. The revolving magnetic field induces three voltages in the stator conductors. The electrical system of a diesel generator is described using a state space model. Every phase is comprised of a voltage source connected in series with RL impedance, which represents the internal impedance of the machine. This model incorporates the dynamics of the stator, field, and damper windings. The diagram below displays the comparable circuit in the d-q rotor reference frame.
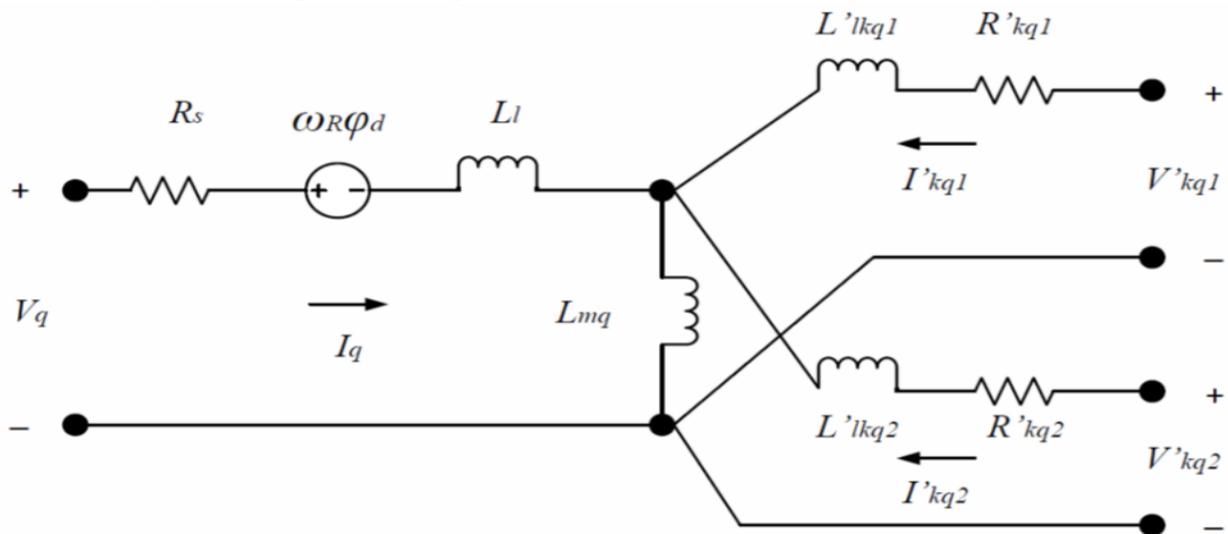
Figure 3.7 depicts the equivalent circuit of the electrical system of a synchronous machine in the q-axis
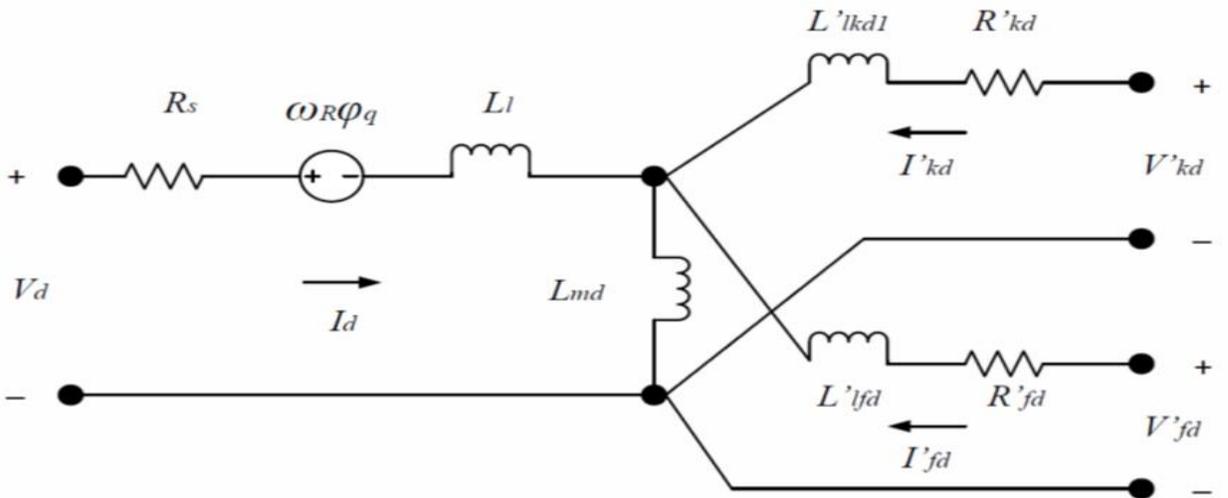
Figure 3.8 depicts the equivalent circuit of the electrical system of a synchronous machine in the d-axis frame.

The excitation system is referred to as 3.3.2. An excitation system is necessary to provide a variable direct current to the primary generator field winding. On smaller set sizes, the exciter might be a direct current (DC) generator. Regulating the terminal voltage is achievable when working in generator mode. The excitation system utilised in this study is a direct current (DC) exciter, and it is presumed that there is no saturation present within the system. The primary elements of an excitation system consist of a voltage regulator and an exciter circuit.

The governor control system is a component of a machine or engine that regulates its speed or output. The speed of a diesel engine can be regulated by manipulating the injection of diesel fuel into the cylinders through the use of injectors. The equipment responsible for performing this operation in diesel generators is commonly referred to as a governor. Irrespective of any fluctuations in demand, it is the governor's responsibility to maintain a consistent speed of operation for the engine. A Diesel Engine Control System (DECS) utilises a diesel engine as the primary source of power, which is connected to the generator shaft. The purpose of the speed limiting governor is to regulate the engine's speed within a specific range. In this study, a constant speed governor is selected to be integrated with the hybrid system.

3.4 Energy Storage Systems
In DC microgrid applications, energy storage systems (ESSs) are utilised to balance the power difference between the generation and the load by either delivering or absorbing energy. This function is crucial for DC microgrids that rely on renewable energy resources because of the unpredictability and stochastic nature of these sources. Additionally, it facilitates the independent operation of microgrids by enabling the storage and subsequent supply of renewable energy to meet local load demands as required. The literature discusses many storage system technologies suitable for DC microgrid applications, including electric double-layer capacitors, batteries, flywheels, and superconducting magnetic energy storage.

3.4.1 Electric Double-Layer Capacitors

Electric double-layer capacitors (EDLCs) are alternatively referred to as super capacitors or ultra capacitors. An EDLC (Electric Double-Layer Capacitor) is constructed in a mTLBOer resembling a battery, wherein two electrodes are placed within an electrolyte, separated by a dielectric separator. The two electrodes possess numerous micropores on their surfaces, resulting in a significant surface area that facilitates the accumulation of charges. Electrostatic energy is stored in the dielectric substance. EDLCs provide quicker responses, need less maintenance, and have longer life cycles in comparison to battery storage. Nevertheless, their capacity for storing energy is restricted, rendering them ideal solely for temporary storage. They are commonly employed in power bridging applications, with durations ranging from seconds to a few minutes, to compensate for the failure of the primary power source. A one farad capacitance ELDC is used in combination with a battery storage system to provide transient compensation. The ELDC is regulated by a bidirectional chopper to ensure a consistent DC voltage when the desired power is set by a central controller. The battery energy storage system was utilised to regulate DC voltage by ensuring a balance between power generation and load. The simulation results demonstrated the ability of the ELDC and battery system to effectively regulate the DC voltage during transient events. Nevertheless, the rationale of employing two energy storage systems to fulfil the same purpose is left unexplained.

This paper presents an Energy-Limited Direct Current (ELDC) storage system designed for a residential DC microgrid that includes dispatchable distributed power units. It was utilised to regulate the DC voltage of the microgrid during isolated operation and to limit the voltage in grid-connected mode when it surpasses predetermined upper and lower thresholds. The paper introduces a direct current (DC) microgrid that incorporates an extended low-frequency DC (ELDC) system with battery energy storage. The presented system utilises storage device converters with varying time constants to effectively manage rapid variations in the DC voltage using the ELDC, while slower transients are handled by the battery.

3.4.2 Batteries

Battery energy storage systems (BESSs) are currently the most prevalent energy storage technology because of its superior energy density, extended lifespan, and affordable price. Lead-acid batteries are frequently utilised in the construction of Battery Energy Storage Systems (BESSs) for microgrid applications due to their high economic energy density. Valve-regulated lead-acid batteries are hermetically sealed batteries that offer greater reliability compared to flooded lead-acid batteries due to their low maintenance requirements. The authors employed a Battery Energy Storage System (BESS) to maintain a constant voltage in a DC microgrid during regular operation and in the event of an AC line fault. A lithium-ion battery model was employed, where the state of charge (SOC) is calculated by integrating the power from charging and discharging. A Battery Energy Storage System (BESS) can be used to address the power mismatch that arises between variable generation and loads during islanding and fault scenarios. The researchers employed the generic battery model that was introduced. Lead-acid batteries are frequently utilised in photovoltaic (PV) renewable systems. In order to address the unpredictability of PV generation, a battery storage system was utilised in the reported study. Specifically, a valve-regulated lead-acid battery was incorporated into the experimental setup to validate the control technique.

Flywheels are mechanical devices used to store rotational energy. Flywheel storage systems utilise the principle that energy can be stored within the rotating mass of a flywheel, which is connected to an electrical machine. Energy is transmitted to the flywheel when the machine is used in motor mode to accelerate the flywheel shaft. Energy can be returned to the electrical system through regenerative braking, which decelerates the spinning of the shaft. Flywheels serve as energy storage devices with notable capacity, exceptional efficiency, and rapid operation. Nevertheless, flywheels have limited energy storage capabilities and can only release energy for brief intervals. A flywheel storage technology is being discussed for its application in a DC microgrid. The flywheel system was utilised to regulate the DC voltage by effectively managing the power discrepancy between the generation and the load through its capacity to supply or absorb power. The system described employs a low-cost squirrel-cage induction machine, but necessitates an AC-to-DC converter in order to establish a connection with a DC microgrid. The researchers utilised a hybrid flywheel/battery energy storage technology in a DC microgrid powered by wind production. A permanent magnet synchronous machine was utilised as a flywheel and linked to the system via a bidirectional AC-to-DC converter. A Battery Energy Storage System (BESS) is utilised in combination with the flywheel due to the flywheel's inability to regulate the DC voltage while in speed control mode. The flywheel needs to be driven to a high speed before it can be converted to voltage control mode.

3.4.3 Superconducting Magnetic Energy Storage (SMES)

Superconducting magnetic energy storage (SMES) involves the storing of energy within a magnetic field generated by the flow of electric current through an inductor. The inductor is constructed using a superconducting material and is maintained at an extremely low temperature to preserve its superconducting characteristics. The transfer of energy to the SMES storage occurs by applying a positive voltage across the inductor, and it is then returned to the electrical system by applying a reverse voltage. The cost of SMES storage is high and it has a short bridging time of one to two minutes. Additionally, it possesses exceptional efficiency and rapid response times, enabling it to supply grid frequency assistance. SMES is utilised to address low-voltage ride-through and power fluctuation issues in wind doubly-fed induction generators connected to a DC microgrid. Nevertheless, the simulation results do not provide any indication of the impact of this technique on the DC bus voltage.

IV. PROPOSED SYSTEM

Due to its affordability and versatile functioning, power generators such as wind turbines and photovoltaic systems are utilised to efficiently meet the power demand, surpassing other sources of energy. As a result, the wind turbine is depended upon to supply both linear and non-linear demands.

Compensation circuits are utilised to enhance the power quality inside the distribution network. In order to address the power quality problems at the origin, a STATCOM compensator utilising a qZSI is constructed in tandem with the distribution network. The qZSI and PV system have been integrated into a single unit in the intended compensator circuit, which employs STATCOM for switching. The STATCOM model based on qZSI, which is depicted in Figure 4.1, is presented.

The AFF-SOGI control technique instructs the compensator to maintain the voltage and frequency of the wind energy system within acceptable limits. This also aids in reducing the intensity of the harmonics that exist in the 3P4W distribution system. The fuzzy-tuned proportional-integral (PI) controller is employed to optimise the parameters of the frequency controller. This method regulates the power supply to the load by removing harmonics and offsetting the reactive power that exists in the power sources. Figure 4.2 depicts the flowchart illustrating the process of selecting the operating mode for PV-qZSI-STATCOM. This photovoltaic-assisted quadrature zero sequence injection static synchronous compensator (PV-assisted qZSI-STATCOM) consists of four distinct modes implemented through

coordinated control. Mode 1 represents the production of PV power, Mode 2 represents battery backup, Mode 3 represents continuous supply, and Mode 4 represents flywheel energy storage. These modes indicate whether the power electronic switches (S1-S7) are in a closed or open state.

The control system transitions into a specific mode: 1 When the electricity generated by the photovoltaic (PV) system exceeds the power used by the load (PLoad). In this mode, the switches are set as follows: S1, S2, and S3 are turned on, S4 is turned on only if the State of Charge (SOC) of the battery is less than or equal to 50%, S5 is turned off, and S6 and S7 are turned on. When the power generated by the photovoltaic (PV) system decreases to less than 10% of the rated power (PPV), the control system transitions to mode 2. When Vsabc is equal to zero, the mode 3 setting is triggered, and the switch positions are configured as follows: S1, S2, and S3 are turned on, S4 is turned on if PPV is less than 10%, S5 is turned off, and S6 and S7 are turned on. Once the control system verifies that the power generated by the wind energy system, Pwind, exceeds the power consumed by the load, PLoad, it will switch to mode 4. System parameters are as shown in table 1.
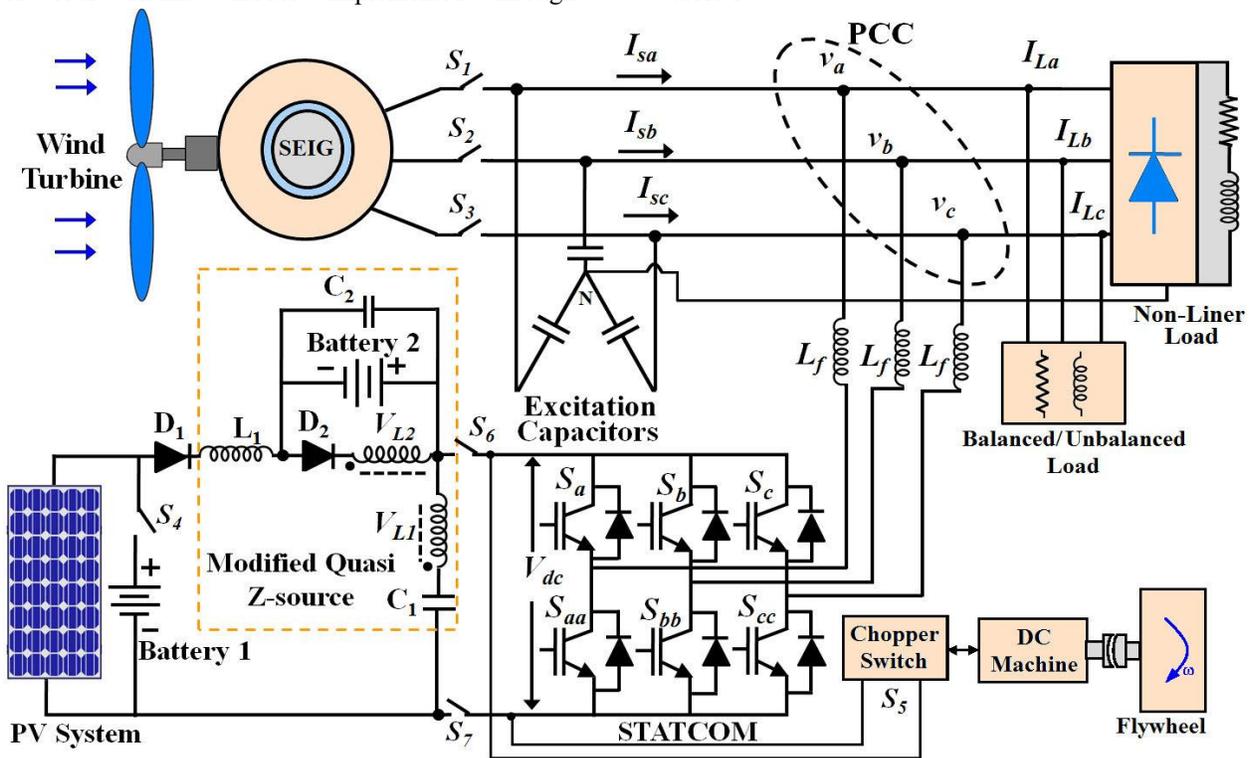

Figure 4.1 shows the integration of a qZSI-STATCOM with a wind energy conversion system.

Table-1 System parameters used

Symbol	Value	Description
V_{ph}	230V	System Voltage (Phase)
f	50Hz	System Frequency
L	26 mH	Filter Inductance
R	1.5Ω	Resistance
Ah	500Ah	battery capacity
PV_w	600 W	Power output of PV array
V_{PV}	72V	PV Nominal voltage
V_L / V_{Ph}	400 V/ 230 V	SEIG Voltage
P	4 kW	SEIG Power rating
N	1410 rpm	SEIG speed
kW	10 kW	Flywheel rated power
N_f	1500 rpm	Flywheel speed
D_f	500 mm	Diameter of Flywheel

The qZSI-STATCOM control can effectively address harmonics and adjust for reactive power consumption caused by linked loads. This control system significantly improves the overall reliability of the power grid. Furthermore, the objective is to ensure that the grid currents exhibit pure sinusoidal waveforms despite distorted load currents and imbalanced voltages. The AFF-SOGI can be utilised to estimate sinusoidal reference grid currents, irrespective of distorted load currents and imbalanced grid voltages. Figure 4.3 illustrates the AFF-SOGI control system used for qZSI-STATCOM. AFF-SOGI only considers the fundamental frequency currents. ZCD is for Zero Crossing Detector, S/H stands for Sample and Hold circuit, and Abs stands for Absolute.
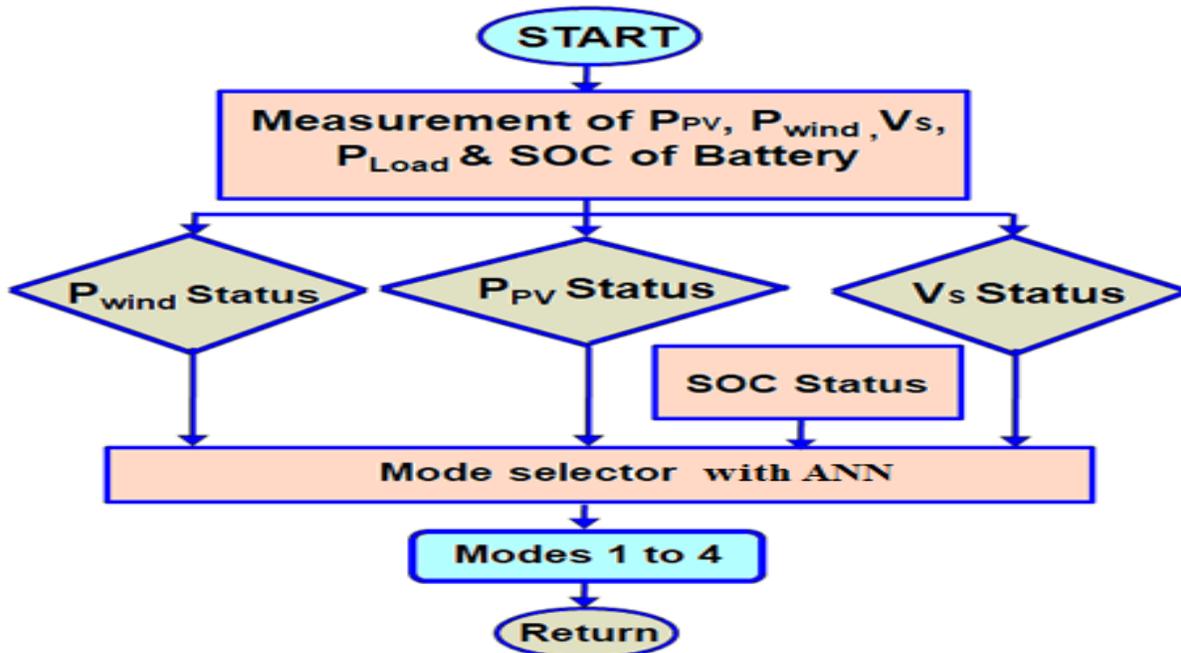
Figure 4.2 displays the flowchart that is used to determine the operating mode for the PV-qZSI-STATCOM.

Figure 4.3 illustrates the AFF-SOGI control system used for the qZSI-STATCOM. This is achieved by preventing the other frequency component from producing the currents in question, hence preventing those currents from entering the grid. Instead, only the currents generated by the other frequency component are allowed. Consequently, the system only draws active power from the source. Furthermore, the controller utilises unit voltage vectors that are calculated based on the positive sequence voltages of the grid. This ensures that any distortions or imbalances in the grid voltages do not affect the reference currents. This technique, derived from a SOGI algorithm utilising a fixed frequency, enables the isolation of the primary electric current by substituting the damping factor and resonant frequency with fractional order counterparts of these parameters. The performance of the AFF-SOGI has been greatly enhanced with the integration of a DC offset rejection loop. This loop ensures that the fundamental current estimation is no longer affected by any direct current offsets that may be present in the load current. Figure 4.4 illustrates the schematic of the AFF-SOGI, providing a visual representation of how its internal components are organised.

Figure 4.4 illustrates the internal composition of AFF-SOGI.

A Zero-Crossing Detector (ZCD) is employed to ascertain if a signal has transitioned from positive to negative or vice versa. The grid voltage phase and frequency are conveyed by unit vectors, allowing synchronisation using these vectors. In order to prevent vectors from being distorted, it is important that both distortion and unbalanced voltages are pure sinusoids with a unit amplitude.
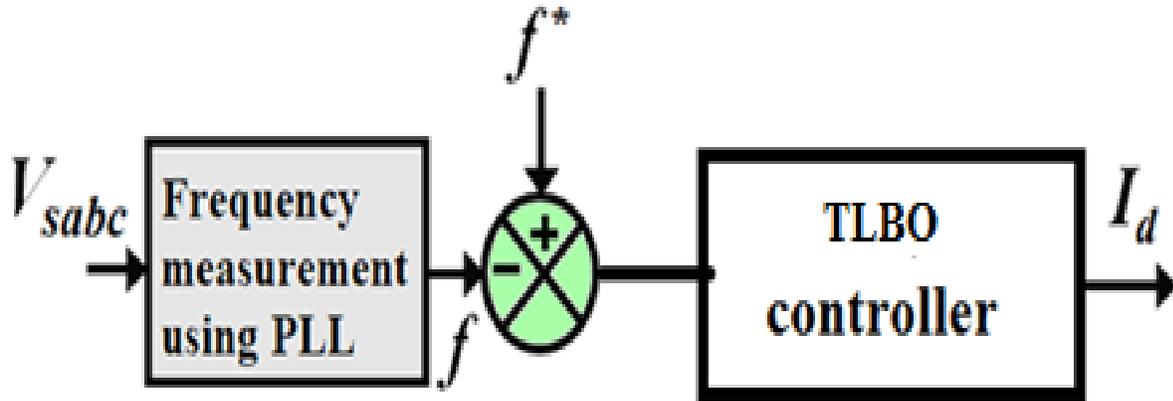
Figure 4.5 displays a frequency controller with TLBO
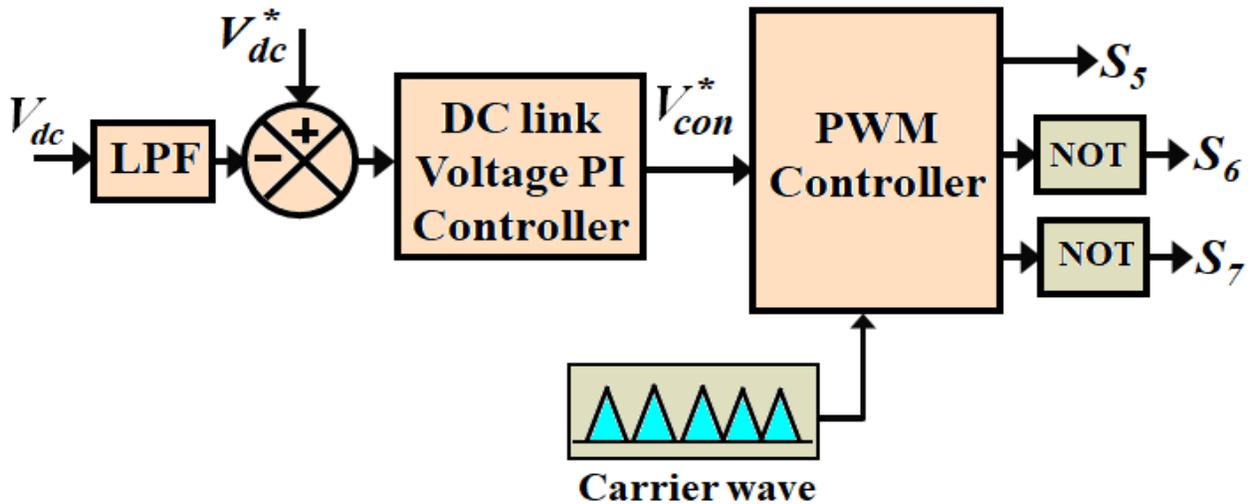
Figure 4.6 illustrates a controller for the DC link voltage.

The unit vectors are derived from positive sequence voltages for this purpose. The system's frequency is determined by employing a Phase Locked Loop (PLL) that takes three-phase terminal voltages as input. A TLBO based controller is employed to compare the estimated frequency with the reference frequency and regulate the frequency error. The compensator circuitry generates the output of the frequency PI controller in the form of the active current it draws. In the context of the frequency PI controller, Kpd and Kid correspond to the proportional and integral gains, respectively. The TLBO based controller is used to adjust the gain characteristics of the PI controller. Figure 4.5 displays the TLBO based controller. The load requirements of a three-phase system are uniformly distributed as a result of the average active currents. Grid currents remain balanced regardless of voltage imbalances or uneven load demands. Figure 4.6 depicts the DC-link voltage controller of qZSISTATCOM.

V. SIMULATION RESULTS

Scenario 1: Equally distributed non-linear loads under a consistent wind speed
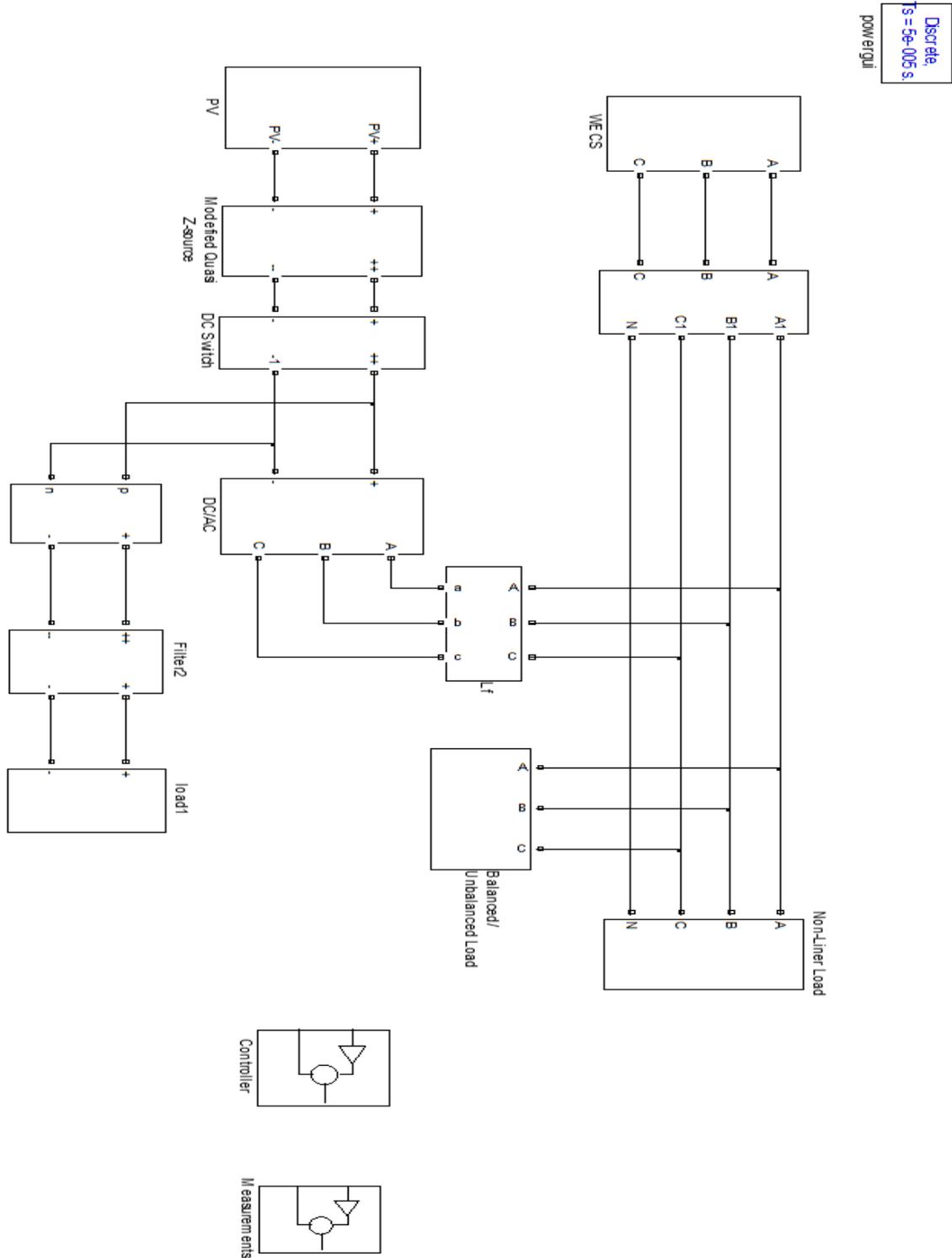
Figure 5.1 displays the simulation diagram of the proposed system.
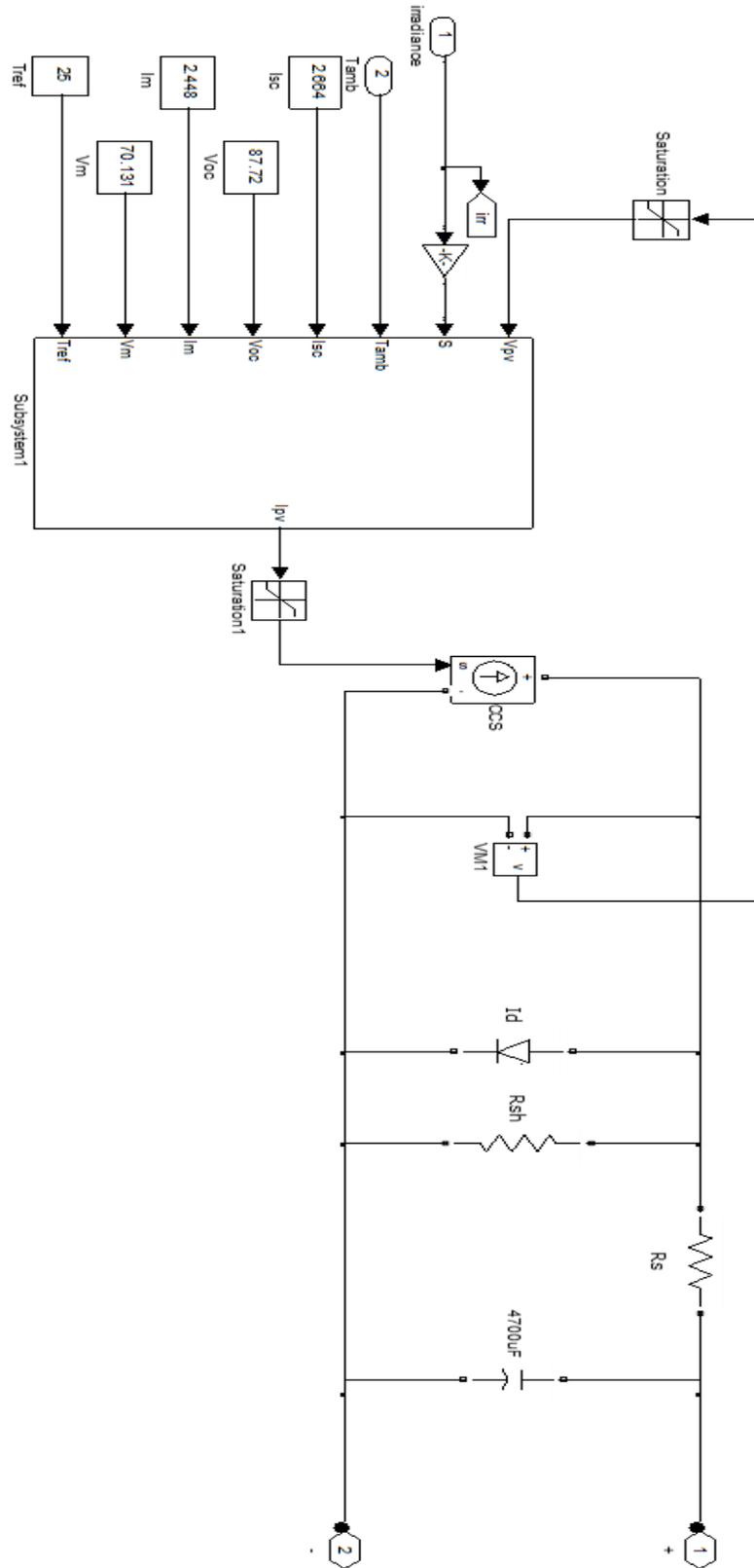
Fig.5.2 PV system
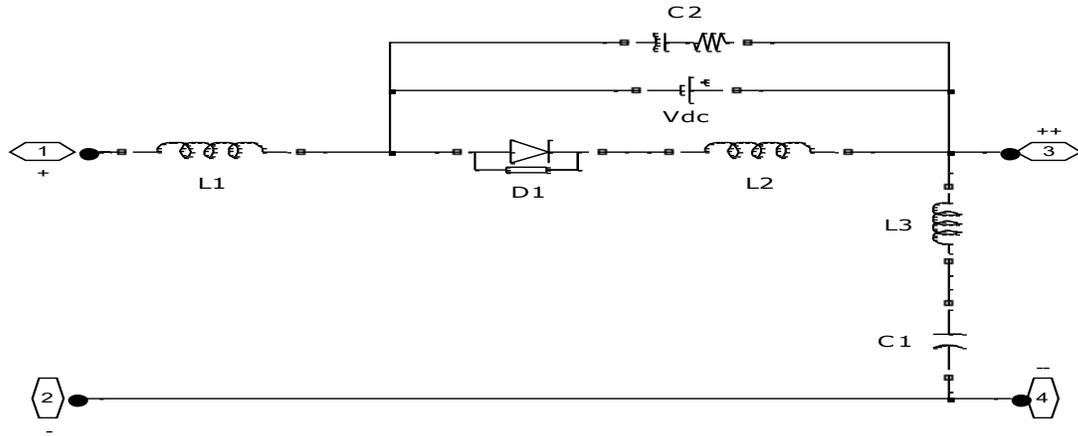
Fig.5.3 Z source Converter
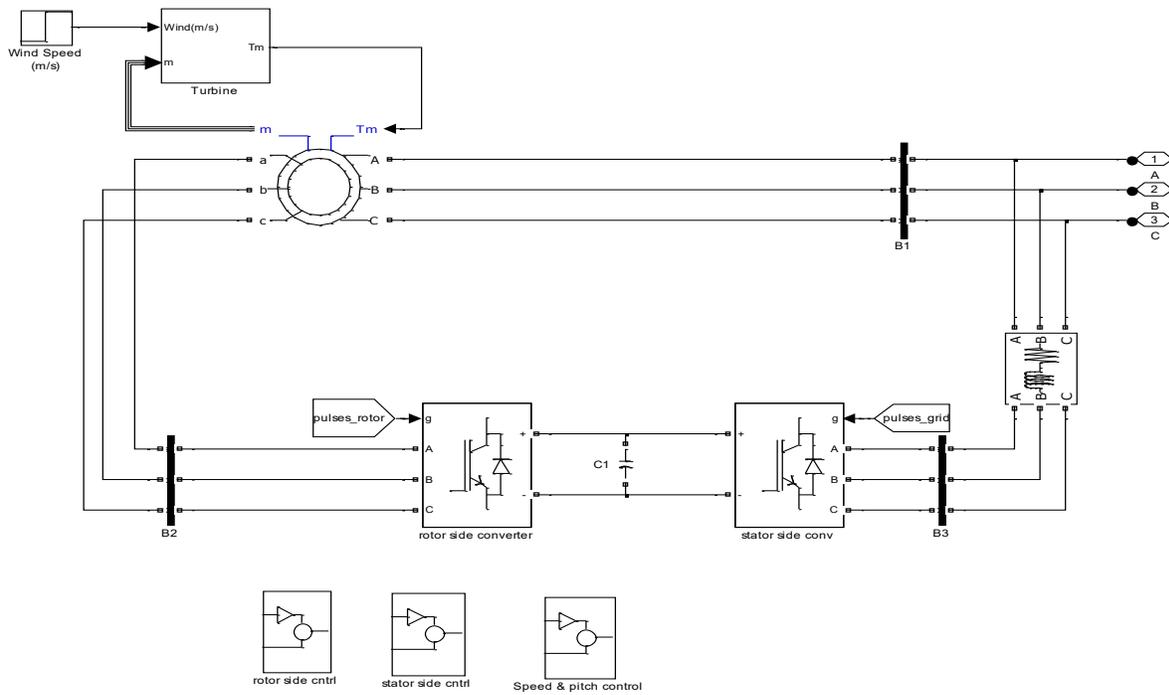
Fig.5.4 Wind power Generation system
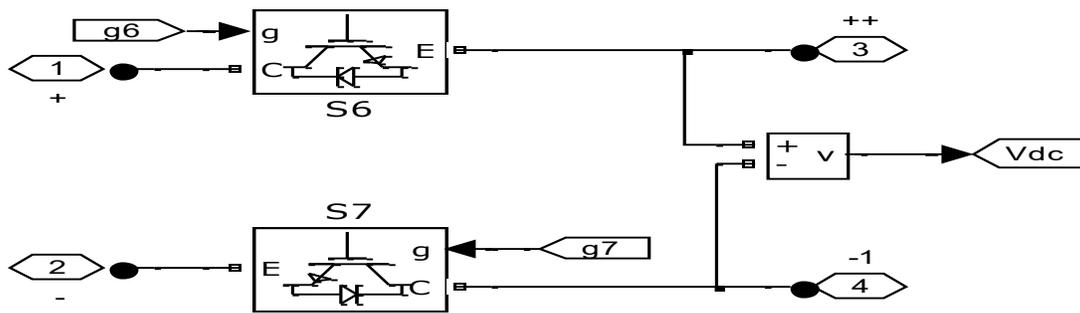
Fig. 5.5 DC switch

Fig. 5.6 Controller
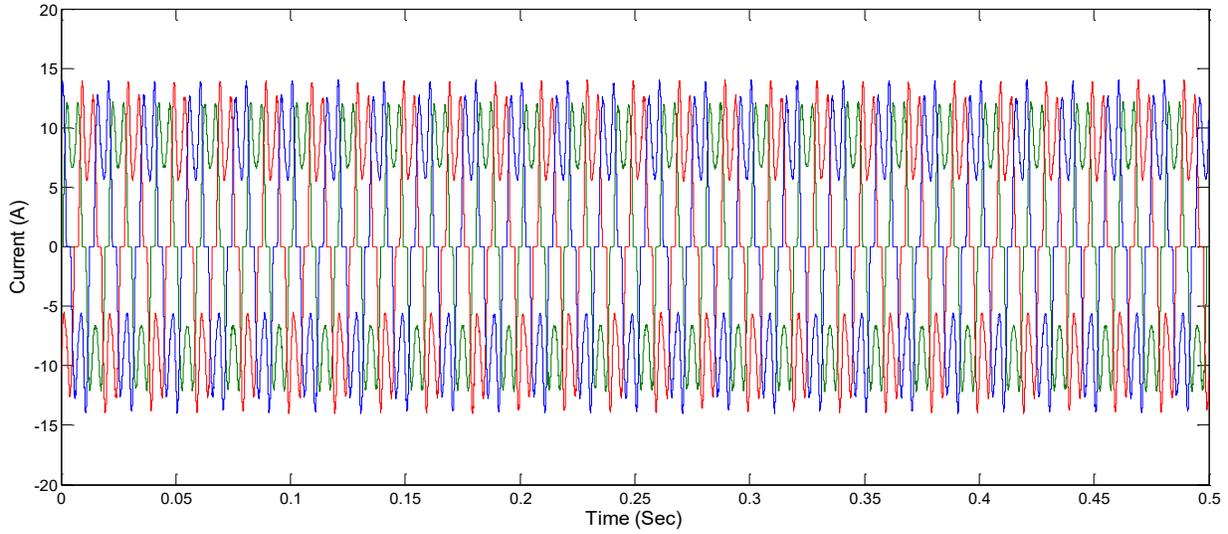
Figure 5.7 displays the currents of nonlinear loads in the proposed system.
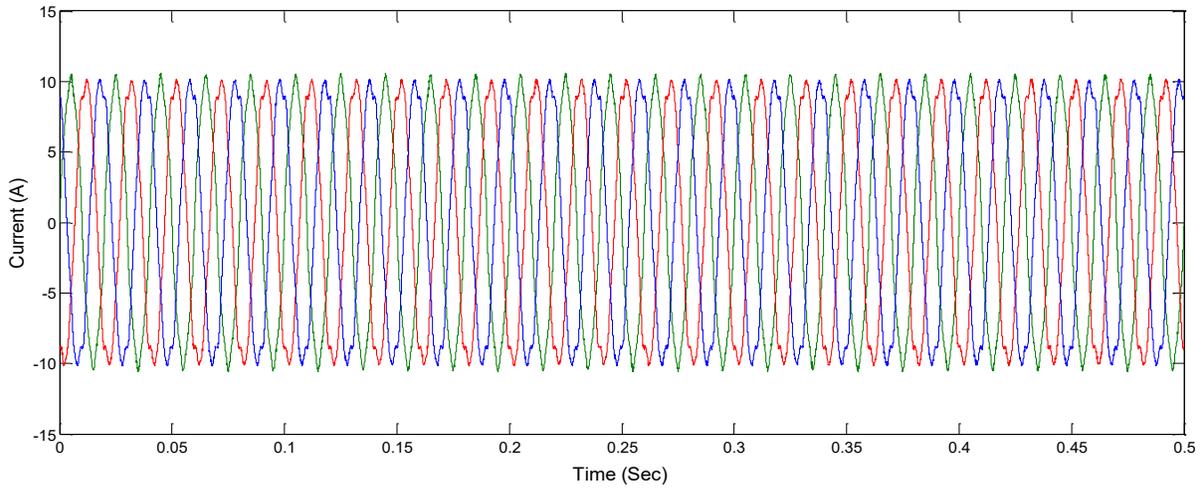
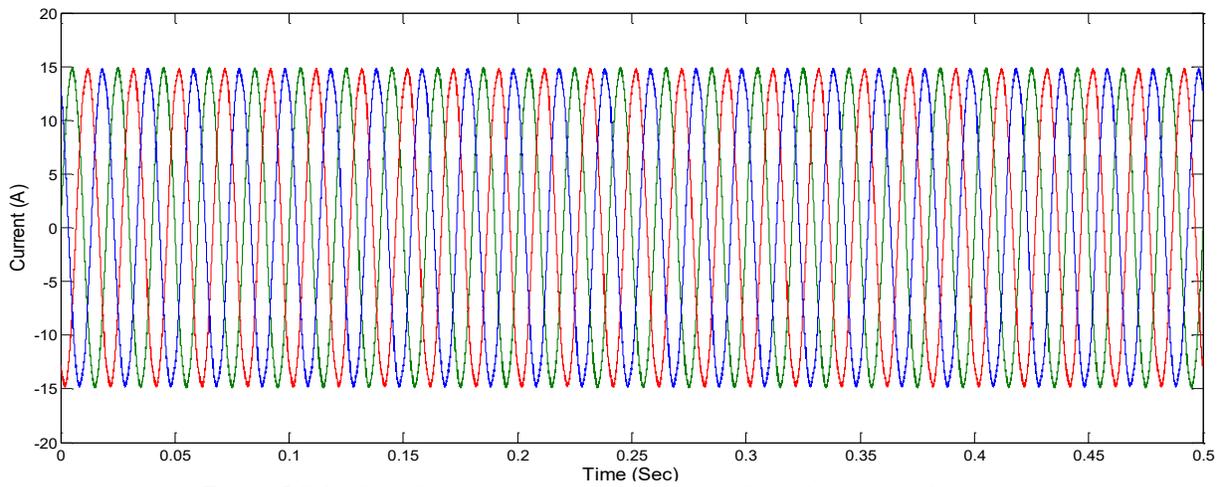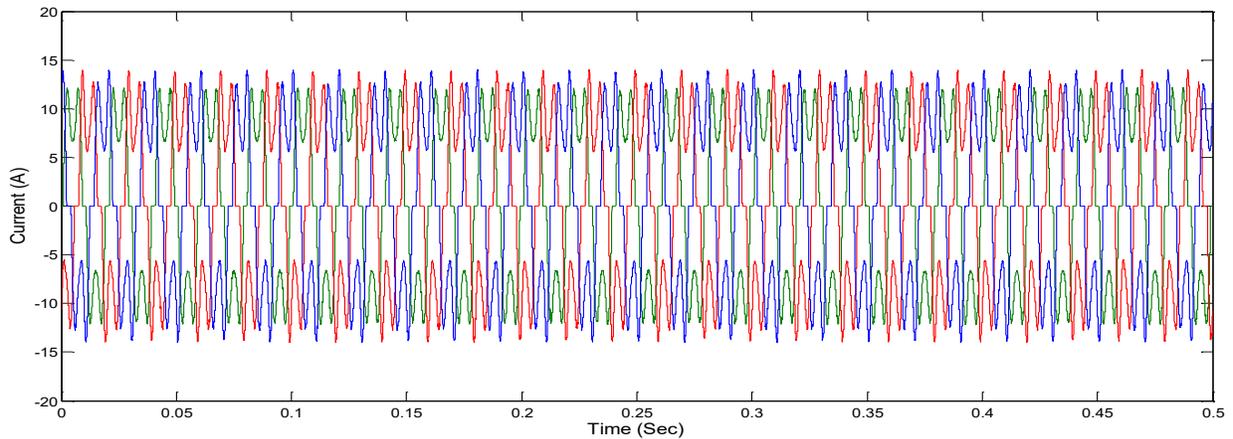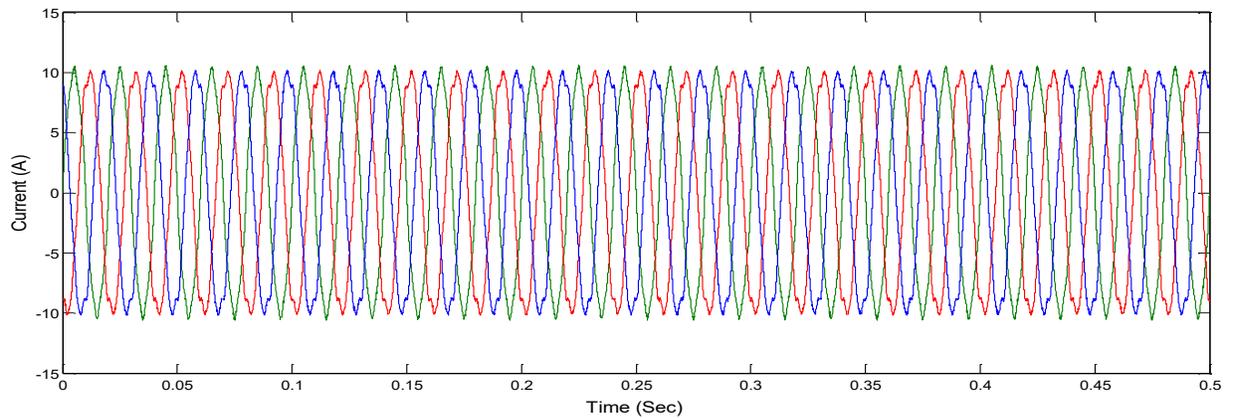Figure 5.8 displays the currents of a balanced load in the proposed system.

Figure 5.9 displays the source currents originating from the proposed system.
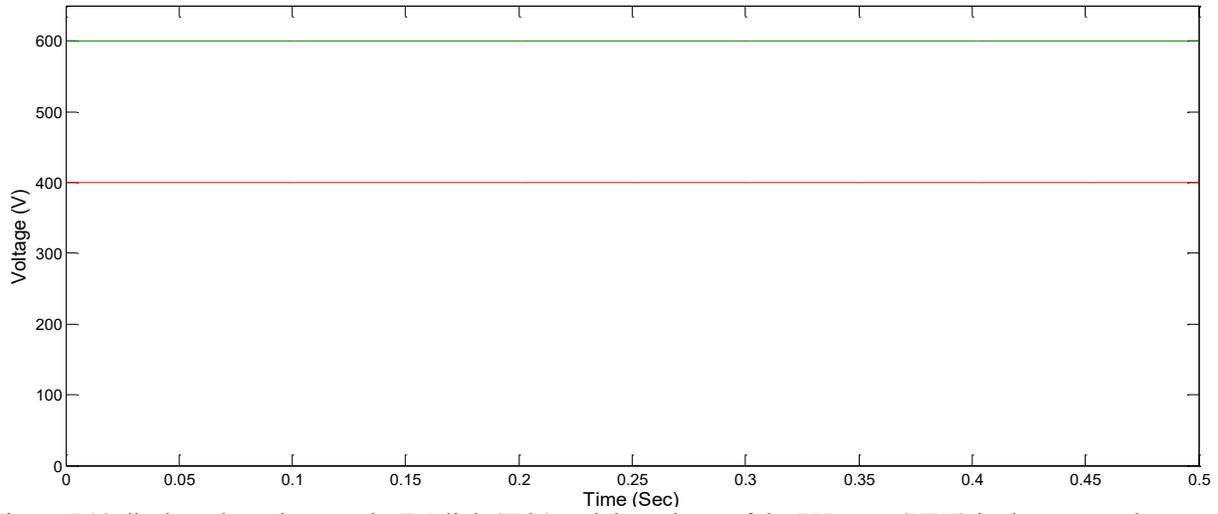
Figure 5.10 displays the voltage at the DC link (Vdc) and the voltage of the PV array (VPV) in the proposed system.
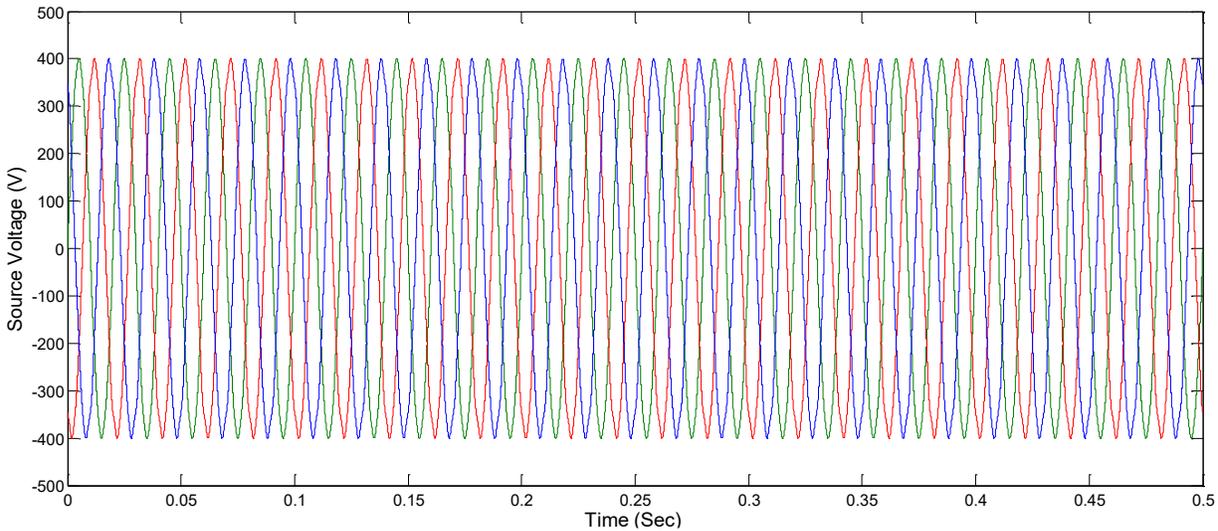
Figure 5.11 displays the source voltages of the proposed systme.
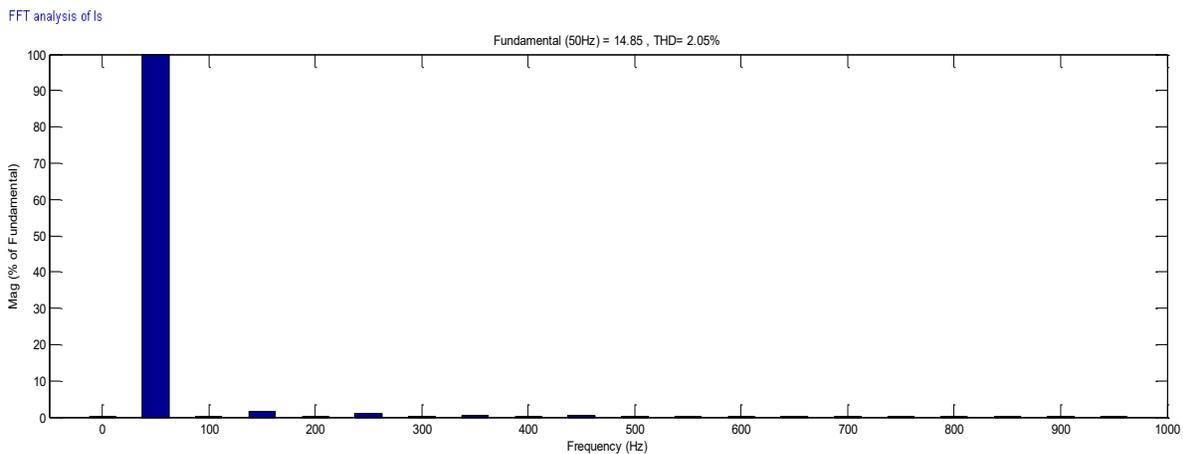
Fig.5.12 FFT analysis of Source current with TLBO Controller
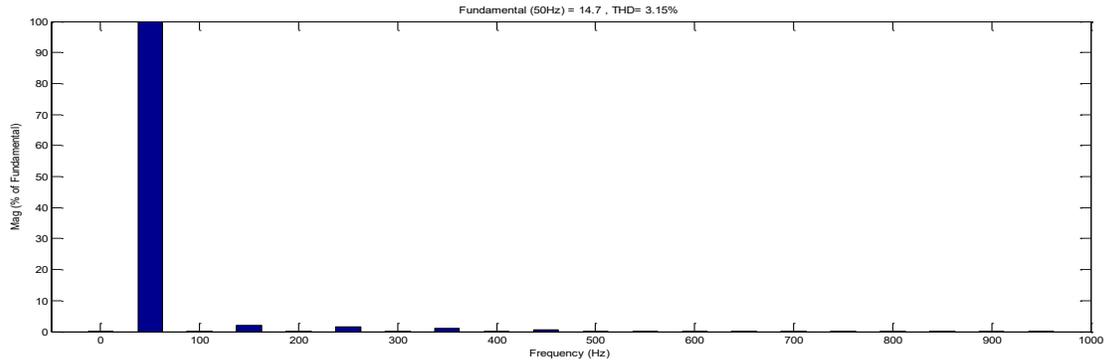
Fig.5.13 FFT analysis of Source current with fuzzy Controller

PV-STATCOM is assessed when the wind speed is constant and the non-linear loads are equalised. The compensatory experimental findings for Case 1 are displayed in Fig. 5.2, 5.3, and 5.4. The compensator circuit can be used to maintain a constant voltage and current, notwithstanding the impact of the non-linear balanced load. The experimental findings for the DC link voltage, PV array voltage, and source voltage and current are depicted in Figures 5.5 and 5.6.

Figure 5.14 displays the currents of nonlinear loads in the extension system.

Figure 5.15 displays the currents of a balanced load in the extension system.
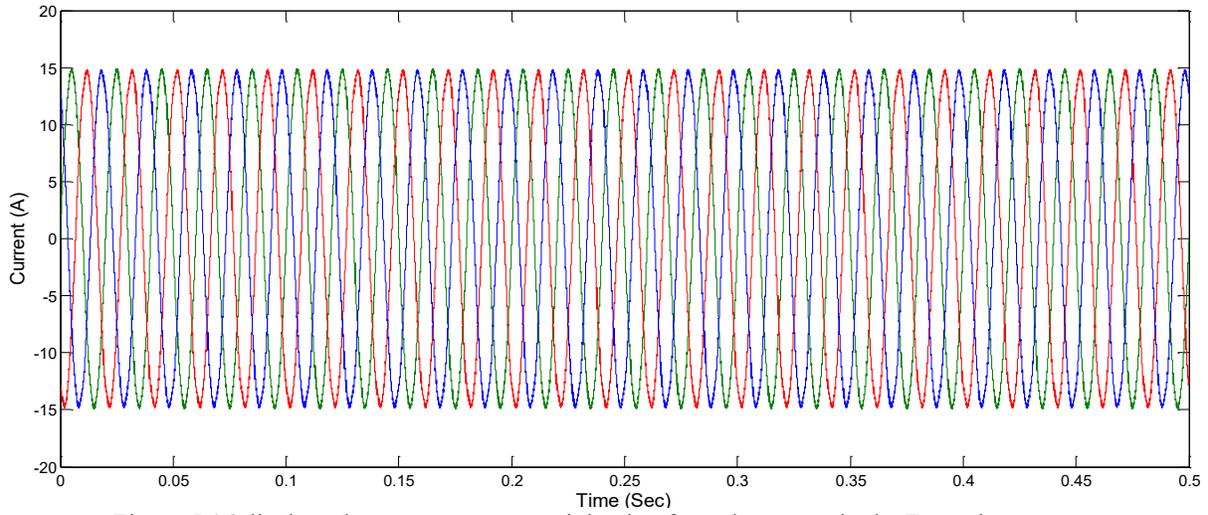
Figure 5.16 displays the source currents originating from the source in the Extension system.
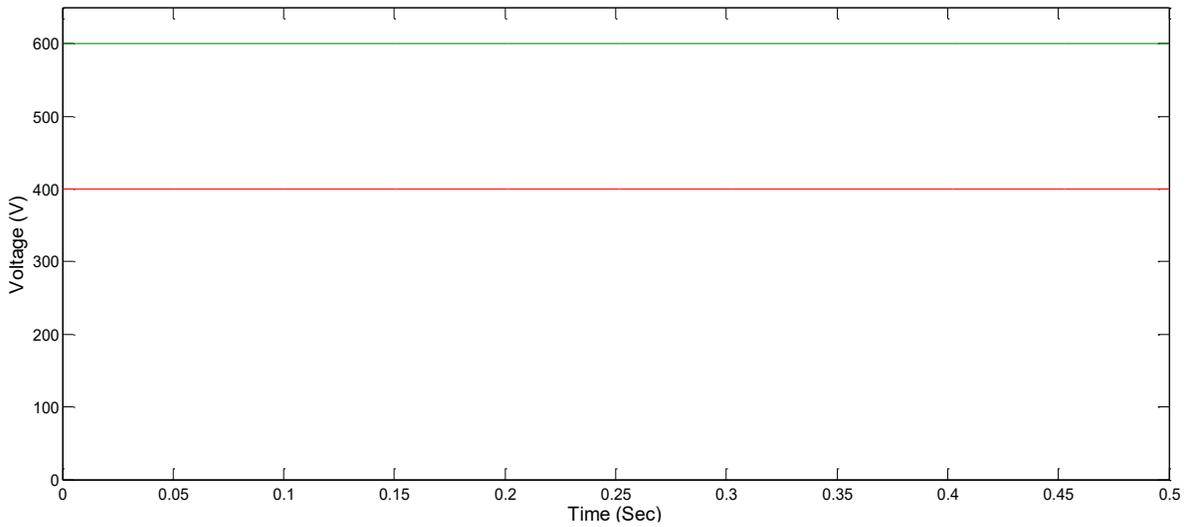

Figure 5.17 displays the voltage at the DC link (Vdc) and the voltage of the PV array (VPV) in the extension system.
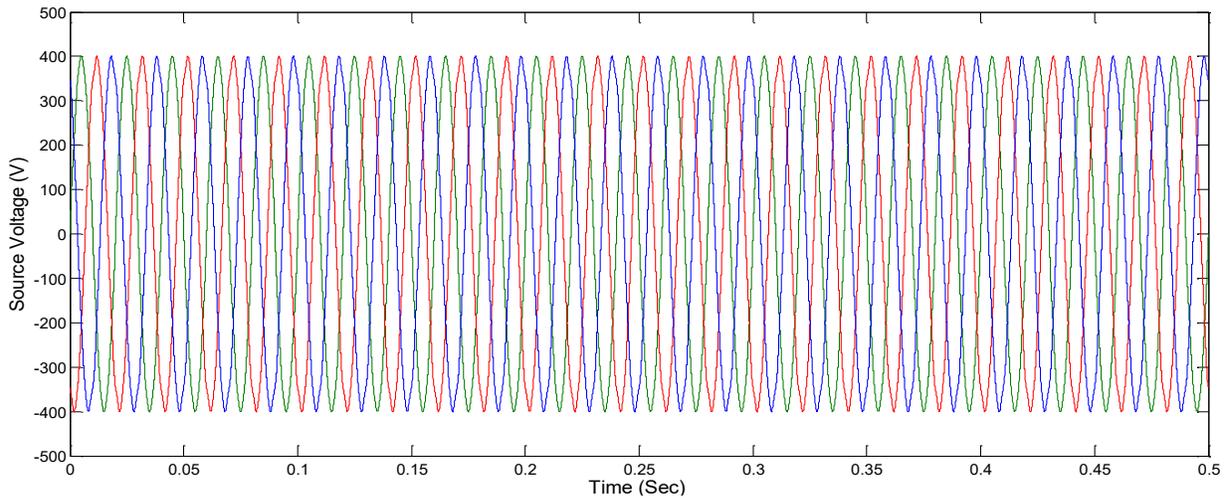

Figure 5.18 displays the voltages of the source in the Extension system. Scenario 2: Imbalanced load currents affected by changing wind speed.
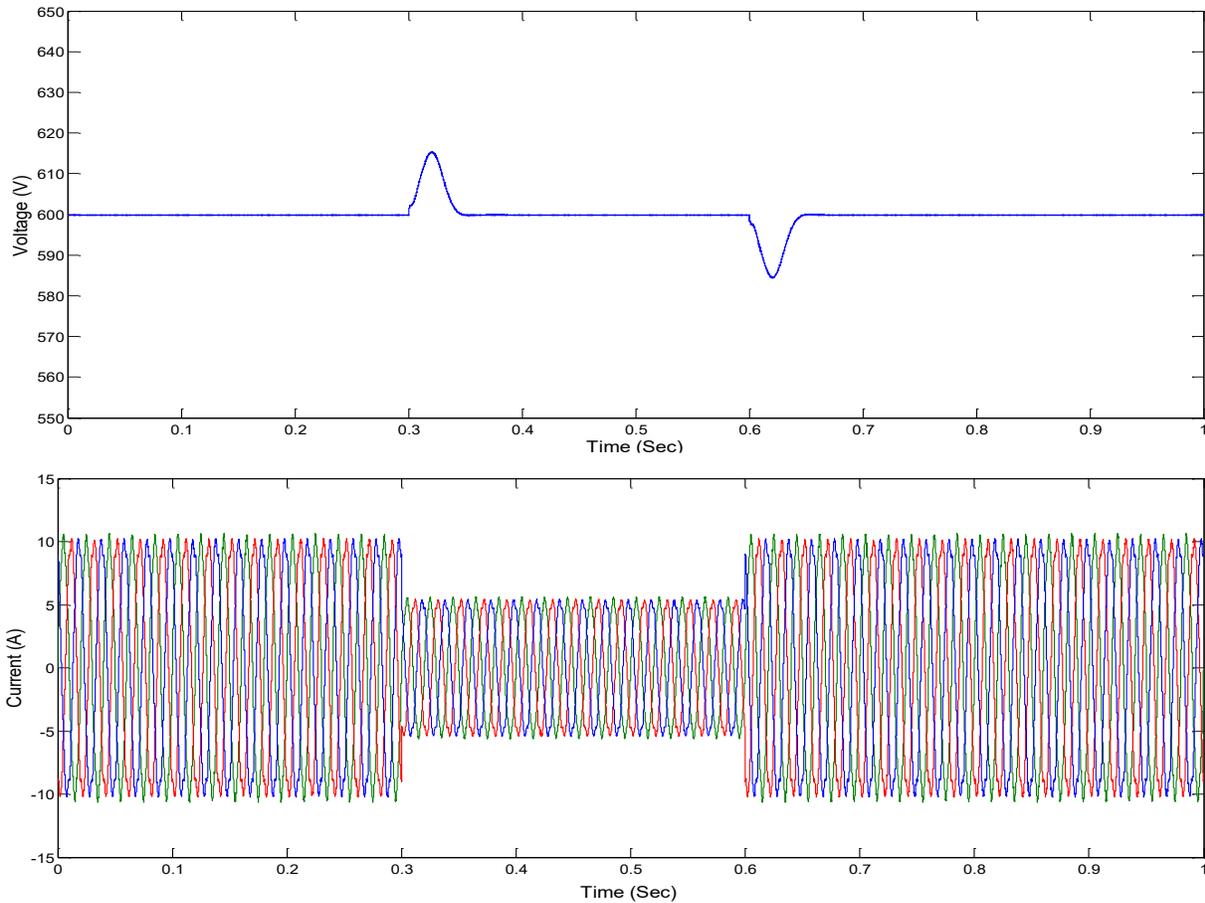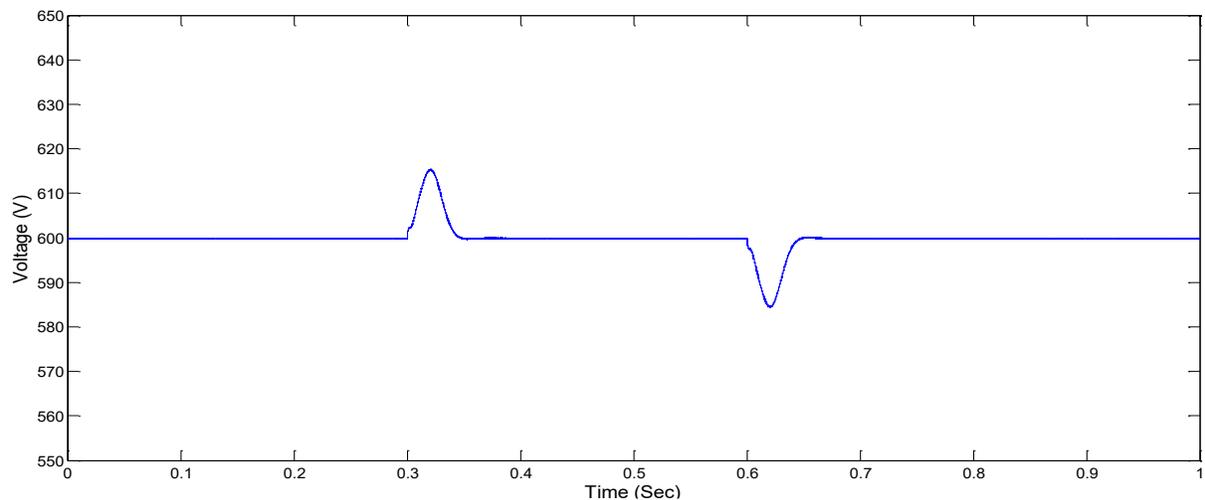
Figure 5.19 illustrates the direct current (DC) link voltage when there are sudden fluctuations in the load. (Suggested system)

The application of step loads yields the results depicted in Figure 5.12. When a nonlinear load is deactivated, the power that was previously supplied is transferred to the DC link until a new reference for the supply current is calculated based on the new load current. Consequently, the voltage of the DC link surpasses the designated value. Upon switching the nonlinear load, the DC link voltage experiences a decrease of around 50 volts. The DC link voltage is regulated after a few power cycles in both situations.
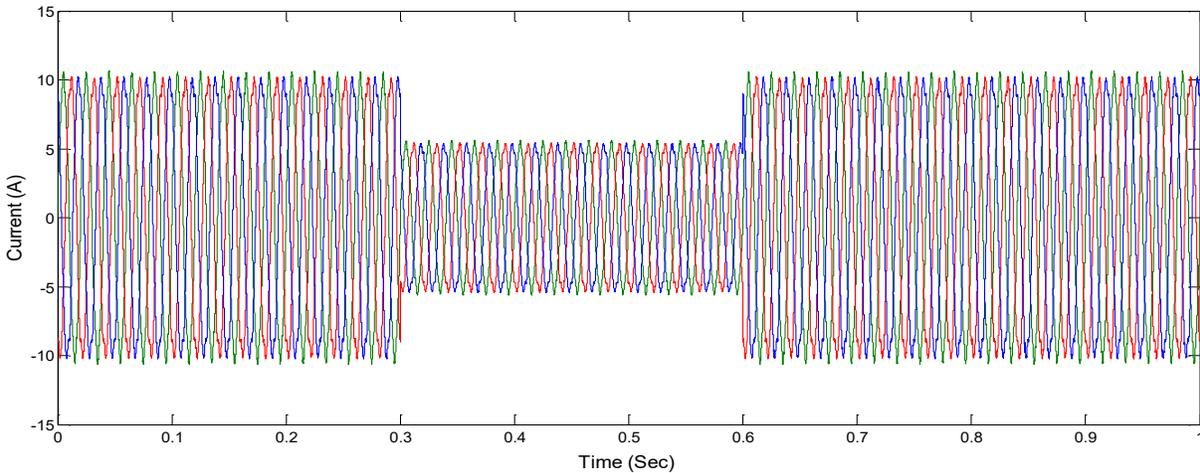
Figure 5.13 displays the direct current (DC) link voltage when there are sudden fluctuations in the load. The extension system

VI. CONCLUSION

Incorporating a Three-Phase Four-Wire (3P4W) distribution system with a STATCOM based on quasi-Z-Source Inverters (qZSIs) is a new way to improve grid power system operation. Solar photovoltaic (PV) and other renewable energy sources allow the system to effectively counteract variations in power output caused by weather. The compensator is effectively controlled using the suggested control approach, which makes use of an Adaptive Frequency Fixed (AFF) Second Order Generalised Integrator (SOGI).

The traditional Fuzzy Logic Controller (FLC) is outperformed by an Teache learner-based optimization (TLBO) when it comes to optimising the parameters of the Proportional Integral (PI) controller. Total Harmonic Distortion (THD) was significantly reduced from 25.5% to 1.1% in the experimental results, compared to 1.3% using FLC, highlighting the TLBO's improved performance. Dynamic reaction, control precision, and adaptability are all enhanced in the TLBO-optimized system. These results demonstrate the promise of teacher learner-based optimization (TLBO) based control for smart grid applications, which could lead to better energy management in future power systems by improving power quality, stability, and active power delivery.

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