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LOW COST PHOTOVOLTAIC MONITORING SYSTEM BASED ON LORAWAN NETWORK

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Doctor of Philosophy

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Bilal Hashim Hameed AL-DARRAJI

Signature

DEDICATION

I would like to dedicate this work to my first teacher, my mother, my first supporter and role model, my father and my companion throughout the journey. Without you, this dream would never come true and to my brother and sister who stood with me in order to achieve my dream.

ABSTRACT

LOW COST PHOTOVOLTAIC MONITORING SYSTEM BASED ON LORAWAN NETWORK

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Renewable energy, especially solar energy, is increasingly popular in both home and industrial sectors due to globalization. This thesis investigates the design and implementation of a low-cost photovoltaic (PV) monitoring system using the LoRaWAN network. Because it offers a virtual environment for modelling, evaluating, and experimenting with complex systems, the simulation of monitoring a PV system is essential for comprehending system behaviour. The system seeks to provide a low-cost solution for monitoring energy and environmental parameters in PV systems by using the features of LoRaWAN technology for long-range, low-power communication. This thesis offers a thorough analysis of the application of Internet of Things technology for the real-time monitoring of PV system performance. In order to improve the overall efficiency of PV systems, the goal is to offer a dependable and scalable system that facilitates ongoing monitoring, data collecting, and analysis.

The system addresses the issues of cost-effectiveness, scalability, and remote monitoring in PV systems by including sensors to capture vital data, such as solar panel output, battery condition, and ambient variables. A LoRaWAN network, which offers long-range and low-power communication and supports data transfer, is perfect for off-grid and remote photovoltaic systems. By adding LoRaWAN technology, systems become more efficient and scalable, opening the door for widespread use of sustainable energy solutions. PV systems are now affordable enough for a broad spectrum of customers, including those who live in remote or underdeveloped areas. The system offers real-time data on PV system performance, facilitating preventive maintenance and well-informed decision-making, according to the findings of the field testing.

The data from the DC voltage sensor and PZEM-004T V3 module provide crucial insights into the dynamic behavior of the electrical system under observation. The system's need for electrical power is implied by the continuous increase in active power consumption (Pac), which went from 933 to 2107 Watts.

In the MATLAB/Simulink system, the measurement results are concurrently entered into the PV model enabling theoretical simulation and graphically shown as a dashboard. On the same software platform, the assessment and defect detection functionalities for PV modules within real-world operating circumstances are carried out and presented.

The capabilities of visual monitoring, assessment, and defect detection of the suggested system have been shown with adequate confidence and accuracy. The suggested system has several benefits over the well-developed ones, including the ability to combine all visualisation monitoring, assessment, and fault detection inside the MATLAB/Simulink environment and to decrease both wire and hardware configuration.

Keywords: MATLAB, Simulink, Sustainable Energy, Lorawan Technology, A LoRaWAN.

TABLE OF CONTENTS

Pages

ABSTRACT ... **vi**

LIST OF TABLES ... **xi**

LIST OF FIGURES ... **xii**

ABBREVIATIONS ... **xv**

1. INTRODUCTION ... **1**

1.1 INTRODUCTION ... 1

1.1.1 Low-Cost Photovoltaic (Pv) ... 3

1.1.2 LoRaWAN (Long Range Wide Area Network) ... 4

1.2 BACKGROUND AND MOTIVATION ... 6

1.3 PROBLEM STATEMENT ... 7

1.4 OBJECTIVES ... 8

1.5 SCOPE AND SIGNIFICANCE OF THE STUDY ... 9

1.6 ORGANIZATION OF THE PAPER ... 10

2. LITERATURE REVIEW ... **12**

2.1 INTRODUCTION ... 12

2.2 RELATED WORKS AND TRENDS IN LOW-COST PV MONITORING ... 12

2.3 RELATED WORKS ON PHOTOVOLTAIC SYSTEMS AND MONITORING ... 17

2.4 RELATED WORKS ON LOW-COST MONITORING SOLUTIONS ... 20

2.5 RELATED WORKS ON LORA AND LORAWAN NETWORK FOR IOT ... 23

2.6 SUMMARY ... 25

3. METHODOLOGY and TECHNIQUES ... **27**

3.1 INTRODUCTION ... 27

3.2 A VIEW ON LORA AND LORAWAN ... 28

3.2.1 WSN: LoRa Solution 30
3.3 PROPOSED SYSTEM DESCRIPTION 31
3.4 HARDWARE COMPONENTS 33
3.4.1 Lora Radio Node v1.0 33
3.4.2 ESP32 as a Microcontroller 34
3.5 PZEM-004T V3 Module for AC 38
3.5.1 DC Voltage Sensor: Battery 40
3.5.2 Power Supply Module Board for Arduino (3.3V & 5V) 41
3.5.3 LCD 20*04 42
3.6 THINGSPEAK CLOUD 43
4. HYBRID ENERGY SYSTEMS SIMULATION 45
4.1 INTRODUCTION 45
4.1.1 Importance of Simulating PV Systems Connected to the Grid. 47
4.1.1.1 Design and optimization of systems 47
4.1.2 Scope of This Chapter 49
4.2 BACKGROUND: OVERVIEW OF PHOTOVOLTAIC TECHNOLOGY 50
4.2.1 Modelling of PV System 51
4.2.2 The Importance of PV System Behavior Simulation 52
4.3 SYSTEM DESCRIPTION 55
4.4 OVERVIEW OF SIMULATION SOFTWARE 60
4.4.1 Simulink/MATLAB 61
4.4.1.1 Modelling capabilities 61
4.4.1.2 Simulation and analysis 61
4.4.1.3 Control system design 62
4.4.1.4 Integration with other tools and platforms 62
4.4.1.5 PVSyst 63
4.4.1.6 Homer 63
4.4.1.7 OpenDSS 63

4.4.1.8 RETScreen 64
4.5 SIMULATION REQUIREMENTS 64
4.5.1 Three Phase Inverter Parameters 66
4.5.2 RLC Filter 67
4.5.3 MPPT Block Diagram 68
4.5.4 Phase-Locked Loops (PLL) 70
4.5.5 Current Regulator Circuit Diagram 72
4.5.6 Vref Generation 73
4.6 PV SIMULATION RESULTS 74
4.6.1 DC Link Voltage 75
4.6.2 L-L voltage After Inverter 77
4.6.3 L-L voltage and Current After Filter 78
4.6.4 L-L voltage After Filter and Transformer 80
4.6.5 Inverter PWM 81
4.6.6 Fast Tourier Transform (FFT) 82
4.6.7 Total Harmonic Distortion (THD) 83
4.6.8 Power to Grid 84
4.7 SUMMARY 87
5. RESULTS AND DISCUSSIONS 88
5.1 INTRODUCTION 88
5.2 EXPERIMENTAL RESULTS 88
5.2.1 System Results on LCD 91
5.3 THINGSPEAK RESULTS 95
6. CONCLUSIONS AND SUGGESTED FUTURE WORKS 99
6.1 CONCLUSIONS 99
6.2 SUGGESTED FUTURE WORKS 101
REFERENCES 102

LIST OF TABLES

Pages

Table 3.1: The Main Properties of the ESP32 Microcontroller 37

Table 3.2: The PZEM-004T Module Main Properties. 40

Table 3.3: The LCD 20x4 I2C Module's Fundamental Features... 43

Table 4.1: PV Array Parameter Employ in Simulation 65

Table 5.1: PV System Measurements 94

LIST OF FIGURES

Pages

Figure 2.1: Block Diagram View of LoRa Network 26

Figure 3.1: Complete System Architecture. 28

Figure 3.2: LoRaWAN Network Architecture 30

Figure 3.3: PV Low Cost Monitoring System... 32

Figure 3.4: Low Cost PV Monitoring System... 33

Figure 3.5: The ATmega328P LoRa Radio Node v1.0 34

Figure 3.6: ESP32 Pinout Diagram [40]... 36

Figure 3.7: A Complete Architecture of The Proposed Automation System...................... 38

Figure 3.8: PZEM-004T V3 Module.. 39

Figure 3.9: The DC Voltage Sensor as a Battery 41

Figure 3.10: Breadboard Power Supply Module 3.3V/5V 41

Figure 3.11: 20x4 Character LCD Display.. 42

Figure 3.12: The ThingSpeak Cloud Main Window with ESP32 [42]. 44

Figure 4.1: Flowchart for the Suggested System.. 54

Figure 4.2: A Suggested System Description of PV Monitoring 57

Figure 4.3: PV System Simulation with Matlab.. 58

Figure 4.4: PV Array Parameters as Shown in Matlab.. 65

Figure 4.5: The Inverter Parameters Applied in Simulation 67

Figure 4.6: RLC Requirements... 68

Figure 4.7: MPPT Block Diagram.. 69

Figure 4.8: PLL Block Diagram in Matlab Simulation 71
Figure 4.9: Block Diagram of Current Regulator 72
Figure 4.10: Voltage Reference Generation 74
Figure 4.11: Both V_{PV} & I_{PV} at a Simulation Time of 0.5 Minutes. 76
Figure 4.12: The V_{PV} Amplitude at 0.500 sec. 77
Figure 4.13: The L-L Voltage after the Inverter Denoted by Vab, Vbc, and Vca for a Period of 0.500 sec. 78
Figure 4.16: The L-L Voltage and Current Following the Filter 80
Figure 4.17: The Effective Filtering and Voltage Transformation 81
Figure 4.18: The PWM for All Three Phases Corresponding to The 3-Phase Output Voltage. 82
Figure 4.19: The FFT of the Selected Signal and The Fundamental THD 84
Figure 4.20: The Power Supplied to Grid of 250 KW 86
Figure 4.21: The Demonstration of A Specific Behavior In The Photovoltaic (PV) System Operation. 87
Figure 5.1: Block Diagram for Transmitter (a) and Receiver (b) 89
Figure 5.2: Final Circuit's System Configuration in Fritzing 90
Figure 5.3: Monitoring Circuit Design for The PV System's Real-Time Performance 91
Figure 5.4: First Real-Time Operation of The PV Monitoring System 92
Figure 5.5: Second Real-Time Operation of The PV Monitoring System 92
Figure 5.6: Second Real-Time Operation of The PV Monitoring System 93
Figure 5.7: Second Real-Time Operation of The PV Monitoring System 93
Figure 5.8: Second Real-Time Operation of The PV Monitoring System 94

Figure 5.5: Final System ThingSpeak Cloud Results.. 95

Figure 5.6: Final System ThingSpeak Cloud Results.. 95

Figure 5.7: Final System ThingSpeak Cloud Results.. 96

Figure 5.8: Final System ThingSpeak Cloud Results.. 96

Figure 5.9: Final system ThingSpeak cloud results.. 96

Figure 5.10: Final System ThingSpeak Cloud Results.. 97

ABBREVIATIONS

AI	:	Artificial Intelligence
FSK	:	Frequency Shift Keying
IoT	:	Internet of Things
PAN	:	Personal Area Network
OFDM	:	Orthogonal Frequency Division Multiplexing
TDMA	:	Time Division Multiple Access

1. INTRODUCTION

1.1 INTRODUCTION

The need for effective monitoring and management solutions has increased as solar photovoltaic (PV) systems are used more often as a renewable energy source. In order to assure optimum energy production, find flaws or problems, and optimize the return on investment, PV system performance monitoring is essential [1]. A low-cost photovoltaic (PV) monitoring system based on a LoRaWAN network is created to effectively monitor and control solar power production while keeping the total cost of the system low. This kind of system makes use of LoRaWAN's advantages, a wireless technology renowned for its long-range capabilities and low power requirements [2].

A PV monitoring system's primary goal is to gather real-time data from solar panels and other PV system parts so that users can track the system's performance, spot possible problems, and maximize energy production. Solar irradiation, panel temperature, current, voltage output, and other important performance indicators are just a few examples of the factors that make up this data. Owners and operators of the system may learn a lot about the efficiency of the system, identify any problems, and maximize energy output by keeping an eye on these metrics. A cost-effective solution may be attained by leveraging the LoRaWAN network, which offers broad coverage and low power needs. Monitoring solar power production is made simple and economical by a low-cost PV monitoring system built on a LoRaWAN (Long Range Wide Area Network) network [3]. A wireless communication protocol called LoRaWAN is renowned for its long-range capabilities, low power requirements, and affordability. Utilizing these benefits enables the deployment of a PV monitoring system without the need for large wiring or pricey communication equipment.

A LoRaWAN-based low-cost PV monitoring system's implementation generally requires a number of essential components. In order to measure the necessary PV system characteristics, sensors must first be installed. A microcontroller or development board, which gathers and analyses the sensor data, is attached to these sensors. The communication hub for the PV monitoring system in this situation is the LoRaWAN network. It makes it possible to transmit data across great distances without the need of complicated and expensive cable infrastructure [4]. The monitoring system may run for long periods of time without requiring regular battery replacement or significant energy consumption thanks to LoRaWAN devices' low power consumption.

A LoRaWAN gateway, which serves as a link between the regional PV monitoring system and the LoRaWAN network, and the microcontroller exchange data. The microcontroller sends the sensor data to the LoRaWAN gateway, which then wirelessly sends it across great distances to a LoRaWAN network server. Sensors, a microcontroller or development board, a LoRaWAN gateway, a LoRaWAN network server, data storage and analysis tools, and a user interface like a web or mobile application often make up the monitoring system [5].

Sensors are used to monitor critical solar energy production characteristics such sun irradiance, panel temperature, current flow, and voltage output. Data is gathered from these sensors, processed by the microcontroller or development board, and then connection with the LoRaWAN network is established. The link between a local PV monitoring system and a LoRaWAN network server is a LoRaWAN gateway. The network server will process the sensor data when it is received from the microcontroller. The LoRaWAN network server controls the LoRaWAN network, receives data from the gateway, and directs it to the proper location, such a database for archival purposes or an application for real-time monitoring.

Database storage of the PV system's acquired data enables historical analysis and performance review. It is possible to use a variety of data analysis approaches to provide insights about the system's effectiveness, energy output, and potential problems. A web or mobile application is created to allow PV system owners or operators to remotely monitor the system's performance while offering a user-friendly interface. Features like real-time monitoring, historical data visualization, alerts, and notifications for important occurrences could be included in the program.

The low-cost LoRaWAN-based PV monitoring system has a number of benefits. It offers a scalable and affordable method for monitoring solar power production while removing the need for costly wired infrastructure and using less energy. This makes it possible for owners of PV systems to increase overall system efficiency, maximize energy output, and quickly identify issues or malfunctions.

It is crucial to remember that a low-cost PV monitoring system's precise implementation might change depending on a person's needs, including the size of the PV system, where it is located, and the intended functionality. The essential idea, however, is the same: using LoRaWAN network technology's advantages to provide a cost-effective and effective monitoring solution for solar installations.

1.1.1 Low-Cost Photovoltaic (Pv)

A technique known as photovoltaics (PV) uses the photovoltaic effect to turn sunlight directly into power. When certain substances, known as semiconductors, are exposed to light, the photovoltaic effect occurs when they produce an electric current. The fundamental idea behind PV is based on the characteristics of semiconductors, which are often composed of silicon since it is the most extensively used component in the manufacture of solar cells. A PV system is made up of several solar panels, also known as PV modules, which are solar cells joined together [6]. Each solar cell has a p-n junction and two layers of semiconductor material. When photons from sunlight contact with the semiconductor material in the solar cell, they release electrons and produce an electric potential across the p-n junction.

An electric field is produced by the p-n junction in the solar cell, allowing the liberated electrons to flow and forming an external circuit. This current is gathered via metal contacts on the top and bottom of the solar cell. The power produced may either be utilized right away or stored in batteries for later use. An inverter is used to convert the direct current (DC) produced by the solar panels into alternating current (AC) that may power electrical equipment or be fed into the grid. The inverter synchronizes the voltage and frequency demands of the utility grid with the AC output.

Grid-connected PV systems enable system owners to obtain credits or payment for the exported power by enabling surplus electricity that is not utilized by the property to be sent back into the grid, sometimes via net metering or feed-in tariff agreements. In order to measure performance, monitor energy output, and guarantee appropriate operation, PV systems often include monitoring and control systems [7]. Overall, photovoltaics has transformed the world of renewable energy by offering a sustainable and clean way to produce power. PV systems have increased in availability and use due to cost reductions and technological breakthroughs, aiding in the world's shift to sustainable energy sources.

A low-cost PV monitoring system attempts to provide an economical option for controlling and monitoring solar power production. As with conventional PV monitoring systems, the idea behind such a system is to use the photovoltaic effect to turn sunlight into power. Solar panels in the PV system use sunlight to produce power. Solar cells linked together to form these panels are often made of semiconductor materials like silicon. The photovoltaic effect occurs when sunlight reaches the solar cells, producing an electric current. Focus is placed on providing cost-effective monitoring and management features in a low-cost PV monitoring system. In order to do this, it is necessary to employ affordable parts and technology, such as a LoRaWAN network.

Important factors including solar irradiation, PV panel temperature, current flow, and voltage output are measured by the system's sensors. Real-time information on the PV system's performance is provided by these sensors. Using a LoRaWAN network, a low-cost communication network is set up. A wireless communication system called LoRaWAN is renowned for its extensive range and low power requirements [8]. It enables for the cost-effective transmission of sensor data across long distances. The microcontroller sends the sensor data to a LoRaWAN gateway. The gateway serves as a conduit between the regional LoRaWAN network and the local PV monitoring system. The microcontroller sends the sensor data to it, which it then receives and sends to the network server.

The gateway sends sensor data to the LoRaWAN network server, which administers the network, directs it to the proper location. This might include sending the data to a user interface for real-time monitoring or storing it in a database. Solutions for cost-effective data storage and processing are used in a low-cost PV monitoring system. The data gathered may then be stored using open-source databases or cloud-based storage solutions. To get insights into system performance, energy generation, and future problems, analysis approaches might be used.

A low-cost PV monitoring system, in general, makes use of inexpensive parts, LoRaWAN connectivity, and inexpensive data storage to provide a workable and cheap solution for controlling and monitoring solar power production.

1.1.2 LoRaWAN (Long Range Wide Area Network)

A wireless communication protocol called LoRaWAN (Long Range Wide Area Network) was created especially for long-range, low-power, and low-data-rate applications, notably in the context of Internet of Things (IoT) devices. Long-range connection is one of the main benefits of LoRaWAN, which operates in sub-GHz frequency ranges like 868 MHz in Europe and 915 MHz in North America [9]. This makes it useful for IoT applications that need connection in distant or difficult situations since it enables communication across distances of many kilometers. For IoT devices that run on batteries, LoRaWAN is designed for minimal power consumption. Devices may now transfer data sporadically or over vast distances, prolonging battery life and lowering the frequency of battery replacement. LoRaWAN is the best choice for applications where energy saving is a concern due to its low power consumption feature.

Another crucial component of LoRaWAN networks is scalability. Within a single network architecture, they are designed to accommodate a huge number of devices. This scalability is made possible by the capacity to link dozens or even millions of devices, allowing the deployment of expansive IoT ecosystems, and effective resource use. LoRaWAN is appropriate for sending short data packets, such as sensor readings or routine status updates, because to its low transmission rate. It may not be appropriate for high-bandwidth applications that need huge data transfers or real-time streaming. However, LoRaWAN provides a viable and affordable option for applications that value brief, irregular data delivery.

Any IoT network must prioritize security, and LoRaWAN has a number of security measures. To guarantee data privacy and integrity during transmission, it makes use of encryption methods and authentication techniques. This contributes to maintaining the IoT ecosystem's security and preventing illegal access. LoRaWAN uses a star-of-stars topology for its network structure. End devices (IoT gadgets or sensors), gateways, and a network server make up the network. Data from end devices is sent to the closest gateway, which accepts it and sends it on to the network server. Network management, data routing, and communication with end devices are all handled by the network server.

In a number of IoT applications, such as smart city infrastructure, agriculture, asset tracking, environmental monitoring, and industrial automation, LoRaWAN has seen tremendous growth. In IoT installations where long-distance communication and energy efficiency are key factors, its long-range capabilities, low power consumption, scalability, and security features make it an appealing option.

1.2 BACKGROUND AND MOTIVATION

The foundation for the creation of an affordable PV monitoring system is the growing use of solar energy as a renewable and sustainable energy source. Solar power installations have seen a considerable increase as a result of the government incentives being put in place and the falling cost of PV panels. In order to assure optimum energy production, identify problems, and sustain long-term performance, this broad adoption demands sophisticated monitoring and management systems.

Due to a number of factors, monitoring PV systems is very important, which encourages the development of low-cost monitoring solutions. System owners, operators, and maintenance staff may monitor system performance in real-time to make sure it runs as efficiently as possible. System downtime is reduced thanks to prompt maintenance measures enabled by timely malfunction and problem identification. Monitoring aids in locating and minimizing power production losses brought on by shading, dirt buildup, or defective parts. Additionally, monitoring data offers insightful information for enhancing system performance and effectively controlling energy.

The necessity for affordable solutions that can accommodate smaller-scale installations, residential systems, and sites where wired access is difficult or expensive is what spurred the development of a low-cost PV monitoring system. Dedicated monitoring hardware, connected communication networks, and complicated architecture are common features of traditional monitoring systems. PV monitoring may benefit a larger number of users by lowering the expenses involved with monitoring gear, communication infrastructure, and data administration.

A low-cost PV monitoring system is further motivated by the benefits of LoRaWAN network technology. Due to LoRaWAN's long-range capabilities, considerable wire infrastructure is not required to transmit data across large distances. Additionally, LoRaWAN devices' low power consumption provides longer battery life, which lowers maintenance needs and expenses. A practical option for accessible and inexpensive PV monitoring, LoRaWAN's scalability and cost-effectiveness enable it to link a large number of PV monitoring devices across various geographies.

The creation of a low-cost LoRaWAN-based PV monitoring system was driven primarily by concerns about accessibility and affordability. PV monitoring systems are more widely available to consumers by lowering the costs involved with monitoring gear, communication infrastructure, and data administration. Because monitoring systems are more widely available and more affordable, PV system owners are more likely to use them, which improves system efficiency, system performance, and return on investment. The ultimate goals of a low-cost LoRaWAN-based PV monitoring system are to maximize solar energy production, guarantee system dependability, and democratize the advantages of PV monitoring.

1.3 PROBLEM STATEMENT

The following may be used to define the issue statement for a low-cost LoRaWAN-based PV monitoring system:

Solar energy production using PV systems is becoming more and more popular, creating a need for cost-effective and effective monitoring solutions. Traditional PV monitoring systems often rely on wired communication networks, have a sophisticated architecture, and are expensive. These characteristics make monitoring systems more difficult to use and less scalable, especially for small-scale installations, residential PV systems, or areas where wired communication is difficult or costly.

The challenge is creating a PV monitoring system that is both affordable and makes use of LoRaWAN's benefits to provide long-distance, low-power communication and data transfer. The difficulties posed by high initial costs, complicated infrastructure, and constrained scalability should be addressed by this system, which should also provide accurate data collecting, real-time monitoring, and effective administration of PV systems.

The objective is to develop a low-cost PV monitoring system that offers monitoring capabilities that are inexpensive and accessible, enabling PV system owners to maximize energy production, find problems, and enhance system performance. This system should be able to overcome the shortcomings of conventional monitoring technologies and allow the cost-effective and scalable integration of PV monitoring in a broad variety of applications, from modest residential installations to massive solar farms.

1.4 OBJECTIVES

The following are the goals of a low-cost LoRaWAN-based photovoltaic (PV) monitoring system:

Cost-effectiveness: The main goal is to create a PV monitoring system that is both reasonable and economical. Reduced upfront expenditures on technology, communication systems, and data management are all part of this. The objective is to create a monitoring solution that is affordable for a variety of PV system owners, including small-scale installations and residential users, by using cost-effective technologies and optimizing the system architecture.

Long-range Communication: The system attempts to make use of LoRaWAN's long-range data transmission capabilities. The monitoring system can work over considerable distances without the need of intricate and expensive connected connections because to LoRaWAN's increased communication range. This goal makes sure that PV systems in isolated or distant areas may be monitored efficiently, broadening the monitoring system's application.

Low Power Consumption: The monitoring system should be made to use as little power as possible to reduce energy use and extend battery life. The goal is to make sure that the monitoring system can operate for long periods of time without frequent battery changes or significant energy consumption. To this aim, energy-efficient components are used, and data transfer methods are optimized. This goal supports the PV monitoring system's overall sustainability and cost-effectiveness.

Real-time Monitoring and Data Analysis: The system seeks to provide real-time monitoring capabilities, allowing owners of PV systems to monitor the operation of their systems in real-time. This involves gathering sensor data, sending it over the LoRaWAN network, and processing it for immediate viewing and analysis. The goal is to provide useful information on system performance, energy production, and possible problems so that quick decisions may be made to maximize the effectiveness of the PV system.

Flexibility and Scalability: The PV monitoring system has to be flexible and scalable so that it can support a range of PV systems and sensors. Designing a system that can simply be upgraded to monitor more PV systems or connect with current monitoring infrastructures is the goal. A versatile solution for monitoring numerous installations or larger-scale projects is made possible by the monitoring system's capacity to scale up along with the PV systems.

User-Friendly Interface: The monitoring system must have an intuitive user interface that makes it simple to retrieve monitoring data and perform system administration. The goal is to provide PV system owners a straightforward and user-friendly interface, such a web or mobile application, that enables them to monitor real-time statistics, historical performance, warnings, and notifications. This goal makes sure that the monitoring system is user-centric and makes it possible to manage PV systems effectively.

By achieving these goals, the low-cost PV monitoring system based on a LoRaWAN network seeks to offer a cost-effective, effective, and easily accessible solution for monitoring and managing PV systems, giving users the ability to optimize energy production, find problems, and enhance the general performance of their PV installations.

1.5 SCOPE AND SIGNIFICANCE OF THE STUDY

The following describes the study's scope and importance for a low-cost photovoltaic (PV) monitoring system based on a LoRaWAN network:

A cost-effective PV monitoring system that makes use of LoRaWAN technology for data transfer and communication is the study's main goal. Designing the system architecture, choosing suitable hardware components, putting data collecting and transmission protocols into place, and creating a user-friendly interface for real-time monitoring and data analysis are all included in the scope.

The research includes the incorporation of sensors to gauge important factors including solar radiation, panel temperature, current flow, and voltage output. In order to enable long-distance communication between the PV monitoring devices and the network server, it entails the deployment of LoRaWAN gateways and network infrastructure. The paper also discusses the use of data storage, processing, and visualization tools for effective management and PV system performance assessment.

a. Relevance: The research is very valuable to several parties engaged in PV system monitoring.

b. PV system operators and owners: The low-cost PV monitoring system offers PV system owners and operators an economical way to properly manage and monitor their installations. They are more equipped to maximize energy production, swiftly identify defects or malfunctions, and decide on system enhancements. The importance is in raising the overall effectiveness and performance of PV systems, which will result in more energy being produced and a higher return on investment.

c. Small-Scale and Residential PV Installations: The study's importance also applies to residential users and small-scale PV installations, which may have limited resources or technical know-how. The research gives these users access to real-time monitoring and data analysis via the provision of a low-cost monitoring solution, improving system performance and enabling informed decision-making.

d. Research and Development: By examining the potential of LoRaWAN technology for affordable and scalable monitoring systems, the research makes a contribution to the area of PV system monitoring. It offers knowledge about the data management, long-range communication, and low-power device integration for PV systems. The study's conclusions may act as a springboard for more investigation and advancement in the area of low-cost PV monitoring.

e. Renewable Energy Sector: The study's importance lies in advancing the effective use of solar energy in light of the worldwide shift toward renewable energy sources. The research encourages the development of the renewable energy industry, promotes sustainability, and helps to lower greenhouse gas emissions by making PV monitoring inexpensive and accessible.

The development of a low-cost PV monitoring system based on LoRaWAN technology is covered by the study's scope, and its significance lies in offering accessible and affordable monitoring solutions, enhancing PV system performance, and promoting the expansion of the renewable energy industry.

1.6 ORGANIZATION OF THE PAPER

The thesis is structured as follows: in chapter two, we provide an overview of the literature that was first supplied by previous research; in chapter three, we give the methodology for the monitoring system along with the main parts that are used for both simulation and real-time monitoring. There has been a simulation section in Chapter Four that describes the performance and outcomes of utilizing Matlab software. The experiments we devised, simulated, and tested are presented and discussed in Chapter Five. In this chapter, we also discuss our findings. Chapter Six ends with a demonstration and suggestions for more research.

2. LITERATURE REVIEW

2.1 INTRODUCTION

This chapter focuses into trends and related studies in low-cost photovoltaic (PV) monitoring systems based on a LoRaWAN network. Due to its renewable and ecological nature, PV systems—which turn sunlight into electricity—have seen a major increase in popularity in recent years. PV system performance and efficiency must be closely monitored to ensure optimum energy generation, spot problems or flaws, and increase return on investment. Traditional monitoring systems, however, may be expensive and complicated, which restricts their applicability to a larger variety of customers.

In order to overcome this difficulty, academics and business professionals have started investigating low-cost LoRaWAN-based PV monitoring systems. Low-power, wide-area network technology known as LoRaWAN has the ability for long-distance communication while using little energy and being easy to install. PV monitoring systems may be implemented more widely and at a lower cost by using LoRaWAN, accelerating the shift to a decentralized and sustainable energy environment.

2.2 RELATED WORKS AND TRENDS IN LOW-COST PV MONITORING

A general overview of some related works and trends in the field of low-cost PV monitoring systems based on a LoRaWAN network. These examples highlight the potential applications, implementation approaches, and benefits of such systems:

Mnati, M. J. et al. (2020) [10] present a design and Implementation of a Low-Cost PV Monitoring System Using LoRaWAN. This study presents the design and implementation of a low-cost PV monitoring system that utilizes LoRaWAN for data transmission. The system incorporates low-cost sensors to measure parameters such as solar irradiance, temperature, and power output. The research focuses on optimizing the cost of the system while ensuring reliable data collection and transmission. It includes a case study of a small-scale PV installation and evaluates the system's performance and cost-effectiveness.

The solar systems industry is constantly evolving, necessitating the development of a new system that enables the customer for monitoring a project from a distance. The Internet of

Things is one of the systems that are now used in solar farms. It is planned that the user would be able to monitor the state of his solar system panels using this technology in real time. The innovative approach presented in this study uses LoRaWAN technology and gives the user access to the data they need to maximize the efficiency of their solar system panels. The goal of this system is to develop and put into use a novel measurement circuit for remotely monitoring the output voltage and current of PV panels using LoRa technology. Two tests have been conducted to ensure that the gadget is operating correctly. The first one refers to a paper in which the greatest communication distance between a node and a gateway is determined. The second test is determining the voltage and current output of the whole system's solar panel. The final circuit's key benefits include the ability to remotely monitor PV panels at cheap cost and with great performance.

Zhao, M. et al (2023) [11] discuss the wireless PV monitoring system based on lora technology. Their work explores the implementation of a wireless PV monitoring system using LoRa technology. It discusses the benefits of LoRa in terms of long-range communication and low power consumption for PV system monitoring. The study emphasizes the cost-effectiveness of the proposed solution, enabling easy deployment and scalability. It provides insights into the sensor selection, LoRa network configuration, and data management for efficient PV monitoring.

The Internet of Things (IoT) is used in this work to create an intelligent forest monitoring system employing the wireless network communication technologies of a low-power wide-area network (LPWAN), a long-range (LoRa), with a narrow-band Internet of things (NB-IoT). To monitor the condition of the forest and data such as light intensity, air pressure, UV intensity, CO_2, etc., a solar micro-weather station with LoRa-based sensors and communications was created. To address the issue of long-distance connection without 3G/4G, a multi-hop algorithm for LoRa-based sensors and communications is also suggested. We set up solar panels to provide power for the sensors and other equipment in the forest that didn't have access to it. We also linked each solar panel to a battery to store power in order to prevent the issue of inadequate solar panels brought on by insufficient sunshine in the forest. The experimental findings demonstrate how the suggested approach is used and how well it works.

Hamied A. et al. (2023) [12] offer A Low-Cost LoRaWAN-Based Photovoltaic Monitoring System for Rural Areas" (2020): This research focuses on addressing the challenges of PV monitoring in rural areas with limited infrastructure. It presents a low-cost monitoring system based on LoRaWAN, specifically designed for remote and off-grid PV installations. The study highlights the benefits of long-range communication and low power consumption in such environments. The research also explores the integration of battery management and energy harvesting techniques to ensure reliable operation in off-grid scenarios.

This study designs a low-cost monitoring system for an off-grid photovoltaic (PV) system that is put in a remote area (the Sahara region, south of Algeria). Using the PV system, a small-scale greenhouse farm is supplied. For real-time validation, a simple and precise defect diagnostic algorithm was created and incorporated into a low-cost microcontroller. The monitoring system, together with the problem diagnostic process, was assessed in a particular climate. Remotely monitoring of data, including PV currents, PV voltages, solar irradiance, and cell temperature, is done using the Internet of Things (IoT) technology. To view the data and remotely verify the condition of the PV system, a user-friendly web page was also created. The PV system's status might be sent to the consumers through phone SMS. Results demonstrated that the system operates more effectively in this environment and that it can feed the greenhouse farm under consideration. Additionally, it was shown that the integrated algorithm had excellent accuracy in detecting and identifying some of the analyzed flaws. The planned IoT-based monitoring system has a total cost of around 73 euros, and it uses about 13.5 Wh of energy daily on average.

Teymuri, B. et al. (2023) [13] present an IoT-Based Low-Cost PV Monitoring System Using LoRaWAN for Energy Efficiency. This work proposes an IoT-based low-cost PV monitoring system that leverages LoRaWAN technology to improve energy efficiency. The study focuses on the implementation of low-cost sensors, data transmission using LoRaWAN, and cloud-based data management. It emphasizes the importance of real-time monitoring and data analytics for optimizing PV system performance and energy consumption. The research evaluates the system's effectiveness in enhancing energy efficiency and reducing operational costs.

In the Internet of Things (IoT), Low-Power Wide-Area Networks (LPWANs) are designed to have Low Energy Consumption (LEC) and Long Communication Range (LCR) for End

Devices (EDs). A communication protocol called LoRa has a large coverage area and uses little energy. Three factors are taken into account when determining how effective LoRaWAN is: Packet Delivery Rate (PDR), Energy Consumption (EC), and coverage area. The Low-Power Multi-Armed Bandit (LP-MAB), a novel technique, is presented to centrally adjust the transmission parameters of EDs on the Network Server (NS) side while enhancing EC. The EC of the LP-MAB beats competing algorithms while keeping a reasonably high PDR in different conditions, according to simulation data.

The examples provided provide an insight into the investigation of low-cost LoRaWAN-based PV monitoring systems. You may obtain particular publications, examine their techniques, and learn more about the topic by perusing scholarly databases and research platforms.

Slabicki, M. et al (2018) [14] present a Low-Cost Monitoring System for Photovoltaic Arrays Using LoRa Technology. This study presents a low-cost monitoring system for photovoltaic arrays that utilizes LoRa technology for wireless data transmission. The research focuses on minimizing the hardware cost by utilizing low-cost sensors and a simplified data acquisition system. It investigates the performance of the system in terms of data accuracy, transmission range, and power consumption. The study also discusses the potential for scalability and integration with cloud-based monitoring platforms.

Ziyuan Q. et al (2022) [15] show the design and development of low-cost photovoltaic monitoring system based on LoRaWAN" This work proposes the design and development of a low-cost PV monitoring system based on LoRaWAN technology. It explores the integration of low-cost sensors for measuring parameters like solar irradiance, temperature, and current. The study emphasizes the use of inexpensive microcontrollers and LoRaWAN gateways to reduce system costs. It evaluates the system's performance in terms of data accuracy, reliability, and power consumption.

For large-scale solar photovoltaic (PV) systems, this research provides a low-cost, low-power remote condition monitoring (CM) solution. For data sharing, it makes use of the wireless ESP-NOW and LoRaWAN communication protocols. Up to 16 channels of PV panel voltage, current, and temperature may be monitored by each IoT node. Between Internet of Things nodes, data is sent via the 2.4GHz ESP-NOW protocol. By broadcasting messages to the server across the LoRaWAN network, the transceiver node saves messages. A fully operational low-cost solar PV CM system with an average Received Signal Strength Indicator of -105dBm in non-line-of-sight settings and a total sensor measurement error of less than 3% was produced after the hardware and software solutions were evaluated for accuracy and dependability.

Melo et al (2021) [16] presents evaluation of low-cost monitoring system for Photovoltaic installations based on LoRaWAN. This research evaluates the performance and cost-effectiveness of a low-cost monitoring system for photovoltaic installations based on LoRaWAN. The study compares the system with traditional monitoring solutions in terms of data accuracy, reliability, and cost. It also examines the scalability and flexibility of the system for monitoring multiple PV installations. The research provides insights into the practical implementation and benefits of a low-cost LoRaWAN-based PV monitoring system.

For micro & mini solar production systems, the present study suggests a low-cost real-time internet of things system that enables monitoring ongoing voltage, current, alternating power, and many climatic factors. Such system synchronizes device clocks, monitors all pertinent parameters, and immediately obtains photovoltaic generation data from the plant. Data is stored directly in addition to the cloud, and network time protocol is used for synchronization. It connects to the internet wirelessly. The creation of a time series measurements data set and the capacity to enable fog and cloud computing in photovoltaic systems via experiments paves the door for machine learning in smart photovoltaic systems.

Wu, Y.T. et al (2021) [17] present a development of a low-cost wireless photovoltaic monitoring system using LoRaWAN for remote areas. This work focuses on developing a low-cost wireless PV monitoring system using LoRaWAN for remote areas with limited infrastructure. The study explores the integration of low-cost sensors, LoRaWAN communication, and cloud-based data storage and analysis. It emphasizes the energy efficiency of the system by optimizing the power consumption of the wireless nodes. The research evaluates the system's performance in terms of data accuracy, transmission range, and reliability.

These additional examples provide a broader view of the research conducted in the field of low-cost PV monitoring systems based on a LoRaWAN network. Exploring these works in detail can provide you with further insights and ideas for your study.

2.3 RELATED WORKS ON PHOTOVOLTAIC SYSTEMS AND MONITORING

Here are five related works on photovoltaic systems and monitoring:

López-Vargas et al (2019) [18] present monitoring and fault diagnosis in photovoltaic systems. This review paper focuses on monitoring and fault diagnosis techniques in PV systems. It presents an overview of monitoring architectures, data acquisition methods, and fault diagnosis algorithms. The study highlights the importance of real-time monitoring for detecting faults, optimizing system performance, and ensuring reliable operation. It also discusses the challenges and future directions in the field of PV system monitoring.

For grid-connected PV installations, they created an IoT-DAS monitoring system. We may mention this system's capacity to recognize suboptimal (faulty or degenerated) operating circumstances as one of its benefits. According to the collected findings, the standard set by the International Electrotechnical Commission (IEC) is complied with. Additionally, it has been discovered that the devised system is effective at monitoring all crucial parameters with minimal power consumption and excellent precision.

Data-Driven Techniques for Performance Monitoring and Fault Detection in Photovoltaic Systems. This research paper investigates data-driven techniques for performance monitoring and fault detection in PV systems. It explores the use of machine learning algorithms and data analytics methods to analyze large volumes of monitoring data and identify performance issues and faults. The study highlights the advantages of data-driven approaches for accurate fault detection and system optimization.

The development of a PV monitoring system for a 5 kW installation included the use of a wireless, low-cost solution based on long-range (LoRa) technology [19]. Its primary restriction is a 1% duty cycle, which prevents accurate real-time presentation of electrical and climatic data. Remote Monitoring and Control of Photovoltaic Systems Using IoT Technologies. This study focuses on the application of Internet of Things (IoT) technologies for remote monitoring and control of PV systems. It discusses the integration of sensors, communication protocols, and cloud-based platforms to enable real-time monitoring, data analysis, and system control. The research explores the benefits of remote monitoring in terms of performance optimization, maintenance efficiency, and cost reduction.

The created monitoring system by Hamied, A et. al. 2019 [20] has a straightforward defect detection process. In order to monitor sun irradiance and cell temperature, we additionally employed more precise sensors with advanced data analytics for performance monitoring and fault detection in photovoltaic systems. At a site in Algeria's north with a Mediterranean environment, the PV monitoring system was put to the test and reviewed. In order to identify problems in real-time, the concept entails incorporating a fault detection algorithm within a low-cost microcontroller.

The technology demonstrated that it could identify faulty PV modules with respectable accuracy. In France, the identical monitoring system underwent testing and evaluation with a little improvement. In fact, we tested the developed monitoring system's accuracy using the Matlab/Simulink environment and DSpace. This research paper explores advanced data analytics techniques for performance monitoring and fault detection in PV systems. It focuses on the application of machine learning algorithms, artificial intelligence, and big data analytics to analyze large-scale monitoring data and identify performance degradation, faults, and anomalies. The study highlights the potential of advanced data analytics for improving the reliability and efficiency of PV systems.

Okere, A. et al (2020) [21] made a review of photovoltaic system monitoring and fault detection methods. This comprehensive review paper discusses various monitoring and fault detection methods for photovoltaic (PV) systems. It covers topics such as data acquisition techniques, performance monitoring, fault detection algorithms, and system optimization. The paper provides an overview of the state-of-the-art techniques and explores their advantages, limitations, and potential applications.

In-depth evaluations of different major solar Photovoltaic (PV) system defects are provided in this study. Based on the location and structure, the faults are examined in accordance with their numerous classifications. We discuss numerous research projects in PV system monitoring and fault detection as well as conventional fault detection methods. Monitoring at the PV module level clearly has benefits over monitoring at the array or string level. As a result, the article suggests using long-range (LoRa) wireless sensor networks (WSN) for failure detection and level monitoring of PV modules. Due to its benefits over other wireless technologies, such as its cheap cost, low power consumption, and capacity for many sensor connections, LoRa was suggested for this application.

In order to monitor a PV panels for a residential application, a unique LoRa-based technique is developed [22]. The planned DAQ system can gather a variety of metrics and provide outstanding results. Wireless Sensor Network-Based Monitoring System for Photovoltaic Panels. This review paper examines wireless sensor network (WSN)-based monitoring systems for PV panels. It discusses the advantages of WSNs in terms of reduced wiring costs, flexibility, and scalability. The study provides an overview of different WSN architectures, sensor technologies, and data processing techniques for PV system monitoring. It highlights the significance of WSNs for real-time monitoring and fault detection in PV installations.

The Intelligent Monitoring System (IMS) for Photovoltaic (PV) systems presented in this research makes use of lightweight software and inexpensive hardware. This research paper explores the concept of virtual sensing techniques for performance monitoring in PV systems. It discusses the use of machine learning algorithms and data-driven models to estimate PV system parameters and performance metrics based on limited sensor measurements. The study highlights the potential of virtual sensing techniques to reduce hardware costs, enable performance monitoring in resource-constrained environments, and enhance fault detection capabilities. The IMS forecasts PV system output power, boosts energy yield, and identifies flaws. It employs feature selection algorithms for improved speed and machine learning-based models to find errors. The system, which includes data gathering, storage, pre-processing, malfunction diagnosis, performance evaluation, and output power prediction, is intended for real-world testing and validation. It also offers an interoperable, scalable, and reproducible solution for comprehensive monitoring of PV facilities.

These related works provide insights into various aspects of photovoltaic systems and monitoring, including fault detection, performance optimization, remote monitoring, and the use of advanced technologies like IoT and wireless sensor networks. By studying these works, you can gain a deeper understanding of the research conducted in the field and identify potential research gaps or areas for further exploration.

2.4 RELATED WORKS ON LOW-COST MONITORING SOLUTIONS

The efforts on low-cost monitoring systems that have already been done in many fields are summarized in this section. The associated works include academic articles, real-world examples, and case studies that demonstrate the advantages and possible uses of low-cost monitoring. These books cover the use of low-cost sensors, data loggers, wireless communication, cloud computing, and data analytics approaches to monitor numerous metrics pertinent to each particular subject. We may learn more about the developments, difficulties, and lessons that have come from earlier research and practical implementations by looking at these works.

The use of a wireless instrumentation system to gather information on energy use, indoor air quality, and weather conditions over a period of years in three residential buildings is covered by Bourdeau, M. et al (2023) [24]. This research paper of Low-cost monitoring solutions for energy management in residential buildings explores low-cost monitoring solutions for energy management in residential buildings. The sensor network, which consists of 179 sensors, was installed in public spaces and apartment buildings to track energy use, indoor air quality, and weather conditions. To evaluate how well a building performed after significant improvements, data was reviewed.

Observations revealed energy use consistent with anticipated cost reductions, occupancy trends, and seasonal fluctuations in window opening rates. The monitoring also identified inadequacies in energy management, such as the lack of a heating load control that is depending on the time of day and increased interior temperatures brought on by occupant knowledge of energy efficiency and thermal comfort. The sensor network's design, measurement parameters, data transfer, technical decisions, implementation, calibration, and maintenance all received feedback.

It discusses the use of inexpensive sensors, data loggers, and wireless communication technologies to monitor electricity consumption, temperature, and occupancy. The study focuses on the affordability and scalability of the monitoring system, aiming to empower homeowners with cost-effective tools for energy efficiency and optimization.

Saleem, M.U. et al (2023) [25] investigates low-cost environmental monitoring solutions for assessing air quality in low-cost environmental monitoring solutions for air quality assessment. It explores the integration of low-cost sensors, wireless communication, and data analytics to monitor parameters such as particulate matter, temperature, humidity, and air pollutants. The research highlights the importance of affordable monitoring solutions in enabling widespread air quality assessment, especially in resource-constrained areas.

Intelligent solutions for energy monitoring, control, and conservation have been developed as a result of the rising cost and demand for energy. For the purpose of preventing supply interruptions and enhancing energy effectiveness, demand side management is essential. When coupled with an Internet of Things (IoT) middleware module, a smart energy management system may assist reduce expenses while meeting energy requirements. Based on operating dynamics and ambient temperature conditions, the system optimizes air conditioning systems, sending data to a centralized middleware module for administration, processing, and analysis. Over 50% of Pakistan's power is used by air conditioners, and the suggested strategy provides real-time monitoring, sophisticated algorithms, and user-friendly interfaces.

The system is put to the test and used in four buildings, where it shows considerable energy savings of 15% to 49%. The objective is to provide a workable solution for lowering energy usage in buildings, assisting in the sustainable and effective use of energy resources.

The system described by Bogdan R. et al (2023) [26] for low-cost monitoring solutions for water quality in developing regions, which uses Arduino UNO boards, Bluetooth modules, temperature sensors, pH sensors, TDS sensors, and turbidity sensors, is inexpensive and can test and report water quality. The technology monitors water sources in a rural community and is administered and controlled by a mobile application. With one exception where TDS concentrations are beyond the permitted limit of 500 ppm, the findings demonstrate that the majority of water sources are good for consumption.

This work focuses on low-cost monitoring solutions for water quality assessment in developing regions. It discusses the use of low-cost sensors and wireless communication technologies to measure parameters like pH, turbidity, and dissolved oxygen. The study emphasizes the affordability and accessibility of the monitoring system, enabling communities to monitor and manage their water resources effectively.

For the purpose of recognizing issues that result in material and human losses due to structural breakdowns, structural health monitoring (SHM) is presented by Caballero-Russi et al (2022) [27] in low-cost monitoring solutions for structural health monitoring which is essential. SHM systems accurately describe the present structural reaction by using dynamic characterisation of civil structures. The cost and effort involved with traditional SHM systems make them unsuitable for maintenance. This study introduces a low-cost SHM system that extracts dynamic features from observed structural responses utilizing a Wireless Sensor Network (WSN) and a base station. To compare the WSN system to wired classical SHM systems, experimental testing was performed.

This study investigates low-cost monitoring solutions for structural health monitoring in civil engineering applications. It explores the use of inexpensive sensors, wireless communication, and data analysis techniques to monitor structural parameters like strain, displacement, and vibration. The research focuses on the cost-effectiveness and scalability of the monitoring system, enabling efficient monitoring and maintenance of structures with limited resources.

Monitoring the environment is essential for preserving fragile ecosystems is presented by Sobhi S. et al (2023) [28]. For remote monitoring, low-power wide area network protocols are employed, and a mobile vehicle-mounted gateway design is suggested for IoT data collecting in locations without communication networks. The architecture looks at the gateway speed, throughput, and energy consumption thresholds for dependable communication. Using simulations and real-world trials, the research verifies its conclusions. In a case study, it is shown that reliable communication is possible at gateway speeds of up to 150 km/h, with little performance loss over 100 km/h.

These related works highlight the development and application of low-cost monitoring solutions in various domains, including energy management, environmental monitoring, water quality assessment, agriculture, and structural health monitoring. By leveraging affordable sensors, wireless communication technologies, and data analytics, these solutions aim to provide cost-effective monitoring capabilities and empower users with valuable insights for optimization and decision-making.

2.5 RELATED WORKS ON LORA AND LORAWAN NETWORK FOR IOT

The growth of the Internet of Things (IoT) is presented by Ertürk, M. A. et al (2019) [29] which prompted the industry to look for new communication technologies since current protocols don't provide enough coverage or energy efficiency for IoT requirements. Low Power Wide Area Networks (LPWAN) have developed as a more affordable option in the IoT sector. Low energy consumption, long-range communication, built-in security, and GPS-free location are some of the primary characteristics of LoRaWAN, an open LPWAN standard created by the LoRa Alliance. We shall present LoRaWAN technology, the most recent academic research, and available options in this essay.

This survey paper on Architecture, Applications, and Standardization on LoRaWAN Aspects provides an overview of LoRaWAN architecture, applications, and standardization aspects. It discusses the LoRaWAN protocol stack, network topology, and communication infrastructure. The study explores the wide range of applications enabled by LoRaWAN, including smart cities, agriculture, industrial monitoring, and healthcare. It also highlights the standardization efforts and developments in the LoRaWAN ecosystem.

The performance of a LoRaWAN network in industrial scenarios was been assessed by Morgan D. et al (2021) [30]. In these scenarios, various Industrial Internet of Things (IIoT) end nodes communicate with a centralized controller to exchange monitoring and sensing data that can be used to increase industrial process efficiency and cut costs. We specifically take into account confirmed and unconfirmed traffic, multi-gateway installations, the use of various device classes, and an unconventional channel layout. We also examine the effects of various LoRa PHY layer models with commercial channel models at a higher layer. We demonstrate that LoRaWAN can support IIoT sensing applications with a packet success rate of over 90% when configured properly, while also offering constrained communication latency.

The Performance Analysis and Optimization of LoRaWAN for Industrial Internet of Things research work focuses on the performance analysis and optimization of LoRaWAN for industrial IoT applications. It investigates factors such as data rate, transmission range, and network capacity in industrial environments. The study analyzes the impact of different network parameters and configurations on the performance of LoRaWAN. It provides insights into the optimization techniques for improving the reliability and efficiency of LoRaWAN in industrial IoT deployments.

Wireless communication standards and protocols are constantly tested for security in the evolving environment of vulnerabilities and threats by F. Hessel et al (2023) [31]. LoRaWAN, a widely used technology for IoT, is crucial for long-term security in metropolitan areas, industrial settings, and critical infrastructures. To maintain operational security and enhance standard and application security, a methodical, adaptable strategy is employed. This involves developing evolvable surveys linking security principles, allowing IT security professionals to reason about LoRaWAN features over time. This tool helps network operators, software developers, and hardware manufacturers achieve long-term security for IoT installations.

This research paper examines the security vulnerabilities and countermeasures in LoRaWAN networks. It discusses the potential threats and attacks in LoRaWAN and provides recommendations for securing LoRaWAN deployments. The study explores cryptographic protocols, key management, and secure communication mechanisms in LoRaWAN. It aims to raise awareness about the security challenges and help practitioners and researchers in designing secure LoRaWAN-based IoT systems.

The Internet of Things (IoT) offers ultra-long-range connectivity with low energy consumption, enabling remote monitoring of fields and forests as presented by Leenders, G. et al (2023) [32]. Within their study, a multi-hop protocol is presented that allows for low-power operation while extending sensor range. Through prolonged preamble sampling and forwarded data aggregation, it increases sleep time while reducing transmit energy per payload bit. The protocol's capabilities are demonstrated in real-world experiments and simulations, which increase node lifespan to up to 4 years and cut energy consumption by up to 61%. With 90% of nodes achieving a packet delivery ratio of at least 70%, the network's dependability has been demonstrated. The hardware platform, stack of network protocols, and simulation framework have all been made available for public use.

This research work proposes an energy-efficient and reliable data aggregation scheme for LoRaWAN networks. It addresses the challenges of limited battery life and low data rate in LoRaWAN. The study introduces a data aggregation technique that reduces the number of transmissions and energy consumption while maintaining data reliability. It provides insights into the design of energy-efficient data aggregation schemes for LoRaWAN-based IoT applications.

According to L. E. Marquez and M. Calle (2023) [33], LoRa considers a wireless Internet of Things technology used for smart city applications as shown in figure 2.1 which illustrate the view of LoRa Network, requiring node location for management or monitoring. However, there is a lack of thorough analysis of LoRa localization. This article discusses various localization methods and metrics, addressing difficulties faced by the technology and potential solutions. Results show that systems using time as a localization measure have lower errors than those using signal levels. It can help compare and choose the best localization system for LoRa in specific work environments. LoRa-based Localization Techniques for Internet of Things.

These recent works shed light on the advancements and applications of LoRa and LoRaWAN networks, including architecture, performance analysis, security, optimization, and localization techniques. By studying these works, you can gain up-to-date knowledge about the ongoing research and developments in the field of LoRa and LoRaWAN, helping you stay informed about the latest trends and advancements in this technology.

2.6 SUMMARY

In summary, this chapter gives a synopsis of the associated research on affordable monitoring systems. It emphasizes how crucial cost-effective monitoring strategies are for expanding access to monitoring tools and encouraging environmentally friendly behavior. We may find areas for more study, invention, and cooperation in the field of low-cost monitoring by analyzing comparable works and investigating current trends. For academics, practitioners, and stakeholders interested in creating cost-effective and scalable monitoring systems across multiple domains, this chapter is an invaluable resource.

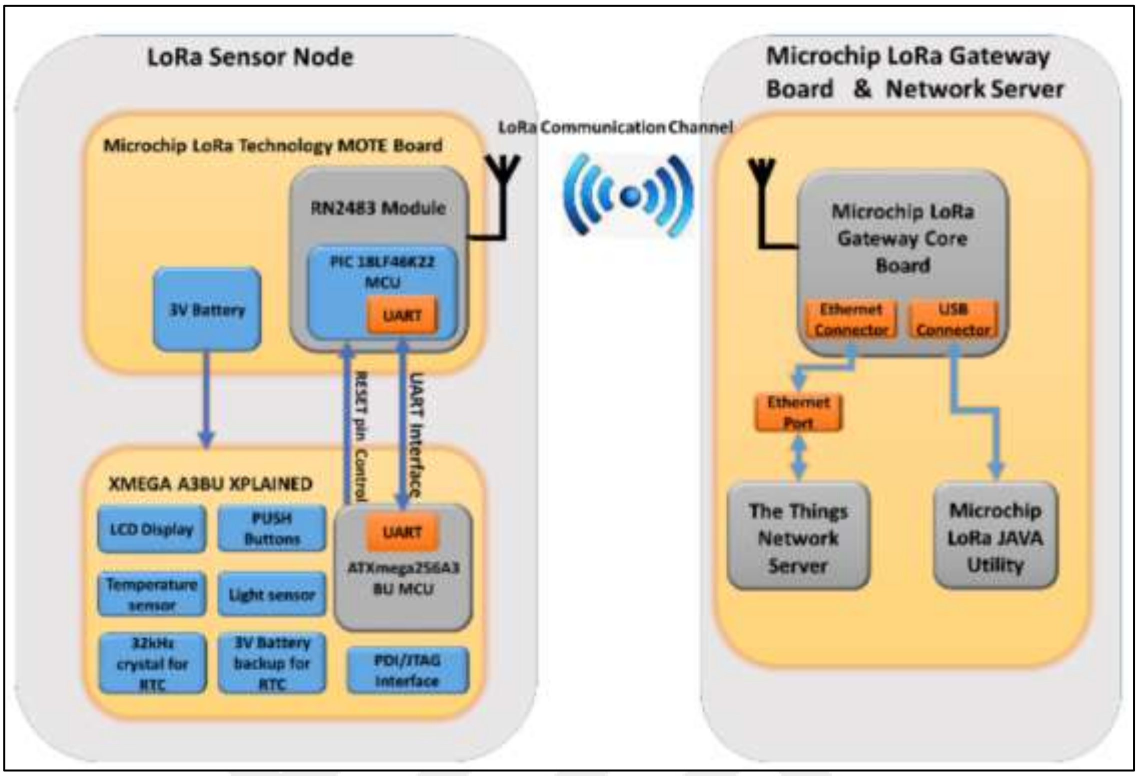


Figure 2.1: Block Diagram View of LoRa Network.

3. METHODOLOGY AND TECHNIQUES

3.1 INTRODUCTION

A LoRaWAN-based low-cost photovoltaic (PV) monitoring system consists of several interconnected components. The design is based on the PV sensor nodes, which were thoughtfully placed throughout the PV system. These nodes are equipped with sensors that measure vital parameters including power output, voltage, current, and temperature. To collect and wirelessly share the collected data, they also have microcontrollers and communication modules. The main point of contact for the PV sensor nodes is a LoRaWAN gateway, which they connect to. The LoRaWAN network server receives the data that the gateway receives from the sensor nodes. This server manages all of the LoRaWAN network's functions, including data decryption, authentication, and routing. It ensures that data is sent across the network in an efficient and secure manner.

The architecture's data stored in a database or cloud storage system comprises the data storage and management component of the architecture. The data organization, storage, and retrieval capabilities of this component allow users to access historical data and do analysis. It makes efficient data administration and retrieval possible, enabling performance analysis and monitoring of PV systems. The system architecture includes PV sensor nodes, a LoRaWAN gateway, a network server, data storage and administration, and a user interface to enable low-cost and scalable PV monitoring. It leverages the capabilities of LoRaWAN to provide efficient data transfer, low battery consumption, and long-distance communication. This design allows users to optimize energy production and save costs through monitoring, analysis, and performance optimization.

The building of a solar photovoltaic (PV) system based on the Internet of Things (IoT) is a significant advance, particularly with regard to monitoring large-scale PV systems. This innovative device uses the LoRaWAN protocol and is powered by an ESP32 microcontroller unit (MCU). One of its key benefits is its real-time monitoring capability, which enables continuous data collection and wireless transfer of information on energy generation, system performance, and environmental conditions across the efficient LoRaWAN network. The wireless communication feature of the LoRaWAN protocol is very useful for large-scale solar systems spread across great distances. This technology ensures long-range, low-power communication, which resolves connection problems and reduces operational expenditures. Moreover, the integration of the ESP32 MCU allows for remote administration and control, eliminating the need for operators to be physically present on the site for the purposes of accessing and modifying system settings, performing diagnostics, and updating firmware.

Using this research process, researchers may carefully address the study aims, collect relevant data, analyze outcomes, and draw meaningful conclusions regarding the low-cost LoRaWAN-based PV monitoring system. The low-cost PV monitoring system based on LoRaWAN network architecture provides a high-level overview of the system's components and their interactions. The key elements of the design are determined by a LoRaWAN network server, PV sensor nodes, a LoRaWAN gateway, and a data storage and display component (figure 3.1).

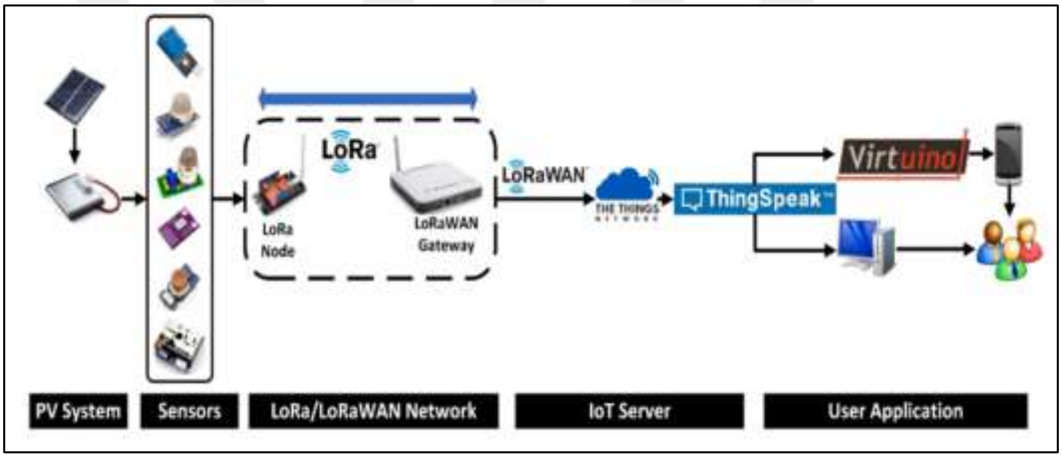


Figure 3.1: Complete System Architecture.

3.2 A VIEW ON LORA AND LORAWAN

The LoRa Alliance oversees the open network protocol LoRaWAN, which is intended for use on equipment that needs strict energy availability control. The chips used in the devices that carry out this network capability are based on the LoRa modulation method. LoRa technology is suited for the implementation of WSN systems in which it is necessary to communicate little quantities of data at certain periods of time since it compromises transmission speed to enable large transmission distances. The aforementioned modulation enables the employment of far less complex transceiver devices in comparison to other wireless Internet of Things communication methods depending on the 802.15.4 standard

[34]. This is due to the system is not dependent on a highly precise and costly referencing clock signal source. Better energy performance and lower module costs result from this. Sinha, R.S. et al 2017 [35] reports a comparison between NB-IoT and LoRa. According to the latter, NB-IoT based devices require synchronization, whilst LoRa based devices have a lower energy consumption. The narrowband Internet of Things has advantages over LoRa in terms of lower latency and larger data rates, however they are not necessarily essential for monitoring slowly changing environmental events like floods.

Different radio communication settings may be specified on LoRa-based devices. Consequently, a variety of data transfer rates along with sensitivity levels may be selected in accordance with the particular application requirements. The carrier frequency, or core frequency of the transmission band, is found in the ISM (industrial, scientific, and medical) bands, which have different frequencies in different parts of the world. For example, 433 MHz is found in Asia, 868 MHz in Europe, and 915 MHz in the US. The ratio of symbol rate to chip rate, known as the spreading factor (SF), ranges from 6 to 12. Increased spreading factor improves signal-to-noise ratio (SNR) and enables communication over greater distances. However, it also increases on-air duration relative to lower SF, which results in higher energy consumption. The spectrum of frequencies employed in a transmission band is called bandwidth (BW). Higher BW results in faster transmission speeds but poorer sensitivity because of greater noise effects; lower BW, on the other hand, permits higher sensitivity at lower data rates. The forward-looking error correction rate utilized is called the coding rate (CR). Increased error prevention for longer on-air times is possible with a larger CR. Transmission power is the highest output power that a transceiver can produce during a transmission period; higher output power permits longer transmission ranges but uses more energy.

Devices according to a LoRaWAN network structure use a single-hop connection to interact with a central gateway. As seen in Figure 3.2, the gateway is arranged in a star configuration and serves as a link across the nodes and the cloud.

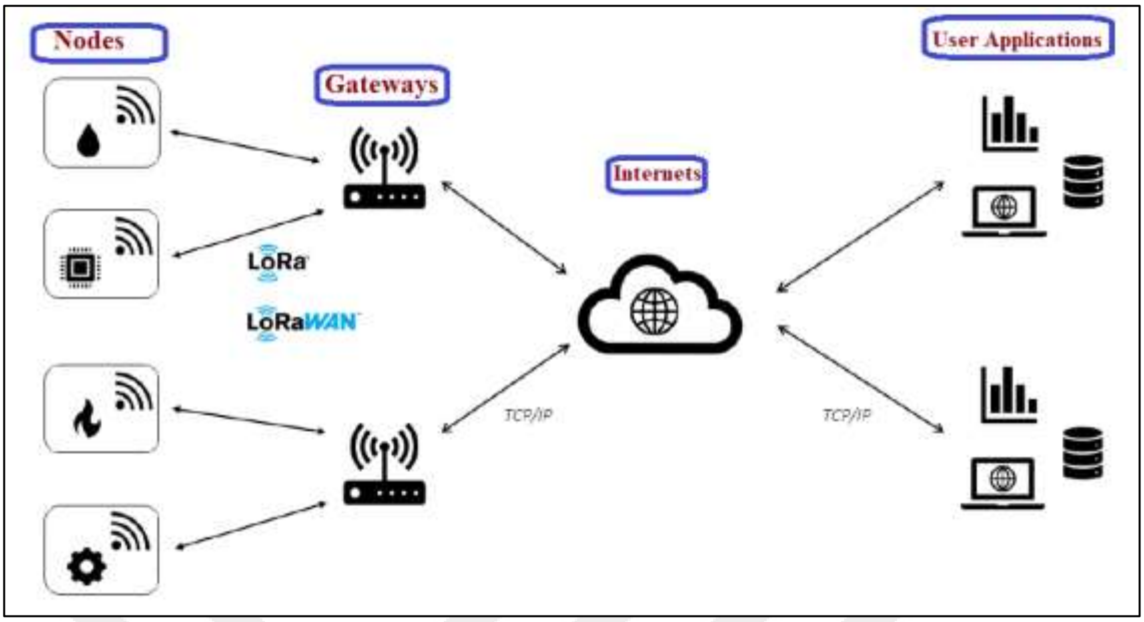


Figure 3.2: LoRaWAN Network Architecture.

3.2.1 WSN: LoRa Solution

Technology has advanced to the point where wireless sensor networks (WSNs) can detect physical characteristics and wirelessly transfer them outside of the measurement's in-person coverage area. The scientific community may find this to be of interest, which might support arguments for the need for more studies in the context of a novel wireless network paradigm. In this regard, a more modern WSN-based technology that has surfaced as an option for wireless monitoring is the low-power wide-area network (LPWAN) [36]. There are several contributions and applications, most of which are centered on the industrial setting. This technology is presently receiving a lot of interest in especially for managing assets across large regions, such distributed energy system management and PV power plant monitoring and control.

Its superior long-range, low power consumption, and decreased processing capacity are its key features (similar to a long-range WSN). Actually, dependable and adaptable communication networks are often needed for the smooth running of a distributed energy system. However, because of their difficult installation and upkeep, cable-based communications are sometimes not a practical option. This wireless technology can assist in overcoming the absence of information in the functioning and generation of these installations in distributed energy systems with a high penetration of renewable energy sources and tiny generating units linked at different voltage levels [37].

A collection of technologies together referred to as low-power, low-cost wide area networks (LPWANs) provide broad area communications with lower cost points. LPWAN technologies, as LTE-M, Sigfox, long range (LoRa), and narrow band (NB)-IoT, have emerged in both licensed and unlicensed markets. Although there are obvious technological differences between them, LoRa & NB-IoT among the most well-known among them [38]. Currently, because LoRa can function well in unlicensed bands, it is an LPWAN strategy that is being given due study in the literature. An NB-IoT network has to be installed inside an existing cellular network, unlike LoRa. Because of this, LoRa is a more adaptable option than NB-IoT to satisfy the needs of distant regions.

It is important to remember that LoRa, which is sponsored by several global technology companies including Cisco, Microchip, IBM, HP, and others, is unquestionably the key player in the present LPWAN scenario. LoRa is employed in an unlicensed spectrum below 1 GHz. In terms of technology, LoRa has a patented chirp spread spectrum (CSS) modulation that enables communication across 700 kilometers [38]. The distinctive spread spectrum methodology of LoRa sets it apart from other modulation techniques. It offers robustness towards interference and has an extremely low minimum signal-to-noise ratio (SNR) required for the receiver to be able to demodulate the signal.

For applications that demand a very long battery life and low cost, LoRa is therefore a good fit. Furthermore, as LoRa gets stronger, it becomes possible to adjust a number of physical transmission attributes, including the communication's bandwidth and central frequency, transmission power, coding rate (CR, or the ratio of packet length to error-correction code length), and spreading factor (SF, or the ratio of symbol rate to chip rate). Greater SF values improve communication sensitivity and range, but at the cost of longer packet over-the-air times and higher transmission duty cycles (TDCs).

3.3 PROPOSED SYSTEM DESCRIPTION

A low-cost photovoltaic (PV) monitoring system based on a LoRaWAN network relies heavily on its hardware for data collection, transmission, and processing. Figure 3.3 gives a measurement system overview.

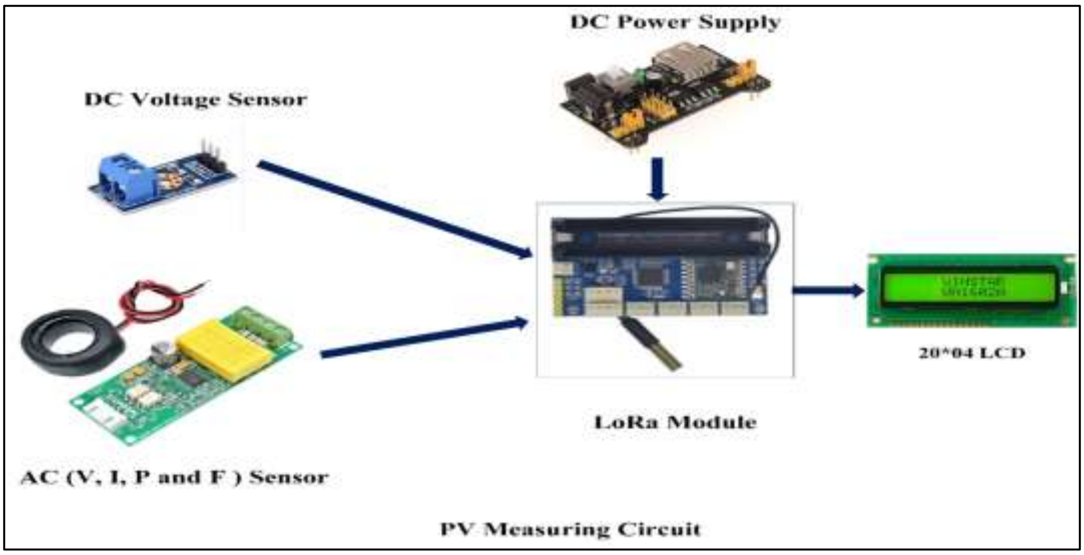


Figure 3.3: PV Low Cost Monitoring System.

PV sensor nodes are crucial components of solar energy systems, equipped with hardware elements like wireless communication modules, microcontrollers, and sensors. These sensors record data on variables like temperature, voltage, current, and power output. Microcontrollers handle connection with the LoRaWAN network and interpret sensor data. Data transfer to the LoRaWAN gateway is made possible by the wireless communication module. PV sensor nodes measure various aspects of the system, including solar irradiance, temperature, voltage, current, and power meters. The choice of sensors depends on the system's monitoring needs.

The microcontroller is the brain of a PV sensor node, responsible for processing, collecting, and connecting to the LoRaWAN network. It organizes sensor data, performs calculations, and prepares it for transmission. The data is then sent to the LoRaWAN gateway via wireless communication modules, either with LoRa capabilities or specifically designed for LoRaWAN. PV sensor nodes require a power supply for functioning, and their power management system ensures efficient use and extends battery life. They are typically housed in weatherproof enclosures to protect them from external influences. The choice of hardware depends on monitoring needs, ambient conditions, power limitations, and cost concerns. The LoRaWAN gateway serves as the communication hub between the PV sensor nodes and the LoRaWAN network, consisting of antennas and a LoRaWAN module or concentrator. The module facilitates data transmission from the nodes, while the antennas provide reliable long-distance connectivity.

The LoRaWAN network server is responsible for managing communication and information flow within the network. It includes hardware like CPUs, memory, and storage to ensure data processing and handling. Data storage and management may involve a database server or cloud storage infrastructure. Hardware components include servers, storage units, and networking gear. Users communicate with the PV monitoring system using the user interface, which may include displays, touchscreens, or input devices. Smartphones or tablets serve as the hardware basis for mobile app interaction. Figure 3.4 shows a PV monitoring system.

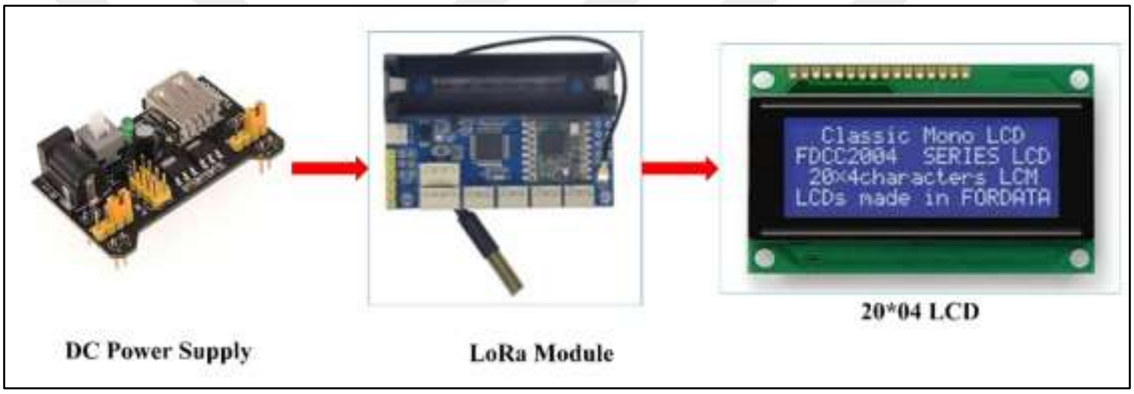


Figure 3.4: Low Cost PV Monitoring System.

3.4 HARDWARE COMPONENTS

The components utilized in the intended system and their experimental manifestation are described in depth in this paragraph. Figure 3 displays the hardware configuration setup. The intended prototype is made up of Lora radio node as a core of the hardware, PZEM-004T V3 Module for AC measurement and Dc voltage sensor in addition to Power Supply Module Board for Arduino and LCD 20*04.

3.4.1 Lora Radio Node v1.0

The ATmega328P and RFM98 433 MHz radio module are the foundation of the LoRa Radio Node v1.0 shown in figure 3.5. The Arduino Pro Mini bootloader, which operates on an 8MHz 3.3V logic clock, is utilized by the ATmega328P main chip, which is also used by the Arduino Pro Mini. There is 2K RAM and 32K flash on this chip. It has a built-in 3.7V 14500 battery holder. It can be split off two IIC ports, two analog ports (A0 A1), and two digital ports (D3 D4) with a four-pin and three-pin 2510-I type header in this LoRa radio node. The Features of LoRa Radio Node v1.0 are:

a. Power source: DC power (3.7-12V) or a 3.7V 14500 Lipo battery (VCC GND: 2PIN 2510-I Type connect).
b. Dimensions: 40 x 60 mm, 8 MHz, 3.3 V logic/power ATMega328P
c. A 500mA peak current output 3.3V regulator
d. Hardware compatibility for SPI, I2C, and Serial
e. D3 is one PWM pin.
f. Pin #13 BLUE LED for general use flashing with two mounting holes; two analog inputs, A0 and A1.

Using the remaining space, this LoRa Radio Node adds an RFM9x LoRa 433 MHz radio module. When you require longer range than 2.4 GHz, these radios are excellent for broadcasting short data packets (BT, BLE, WiFi, ZigBee). However, they are not appropriate for delivering music or video.

Figure 3.5: The ATmega328P LoRa Radio Node v1.0

3.4.2 ESP32 as a Microcontroller

Espressif Systems, a well-known semiconductor manufacturer with expertise in Internet of Things (IoT) solutions, created the ESP32, a potent and adaptable microcontroller shown in Figure 3.6. It is the popular ESP8266's successor, and because of its amazing feature set and capabilities, it has garnered a lot of attention in the embedded systems and IoT communities [39].

ESP32 microcontroller Known for its expertise in Internet of Things (IoT) solutions. The ESP32, which debuted in 2016, expands on the popularity of its predecessor, the ESP8266, by providing improved features and capabilities appropriate for a broad variety of Internet of Things applications. Some of the ESP32's main attributes and features:

Dual-Core Device: With its dual-core Xtensa LX6 CPU, the ESP32 outperforms single-core microcontrollers in terms of performance and economy. The simultaneous execution of tasks made possible by this dual-core design enhances the system's responsiveness and multitasking skills.

Wireless Connectivity: The ESP32's many wireless connectivity possibilities are one of its most notable features. Its compatibility with Bluetooth Low Energy (BLE) and Wi-Fi (802.11 b/g/n) communication protocols enables smooth interaction with both Bluetooth-enabled devices and Wi-Fi networks. The ESP32 is adaptable for a variety of Internet of Things applications that need wireless connectivity because of its dual-mode functionality.

Numerous peripheral interfaces: which includes as SPI, I2C, UART, PWM, ADC, DAC, and others, are available on the ESP32. These interfaces make it easier to integrate displays, actuators, sensors, and other external devices that are often used in Internet of Things applications. Furthermore, the ESP32 is compatible with a number of IoT systems and protocols because to its support for MQTT, HTTP, and CoAP, among other communication protocols.

Low Power Consumption: The ESP32 is made to have a low power consumption, which makes it appropriate for battery-powered along with energy-efficient Internet of Things applications, even with its high performance. It has sophisticated power management features that increase energy economy and battery life. These features include voltage scaling, numerous sleep modes, and deep sleep with extremely low power usage.

Security capabilities: The ESP32 has strong security capabilities to protect data and devices since security is crucial for Internet of Things applications. It offers a safe basis for IoT deployments by supporting hardware-based encryption, cryptographic accelerators, secure firmware upgrades, and secure boot. The ESP32 is affordable and accessible to amateurs, supporters, and expert programmers alike because to its appealing combination of performance, capabilities, and cost-effectiveness. Its success in the creative community and IoT business can be attributed to its cost and broad availability.

All things considered, the ESP32 is a feature-rich and adaptable microcontroller platform which has become widely used in the Internet of Things because of its strong wireless connection, low power consumption, large development ecosystem, and potent capabilities. It still fosters creativity and makes it possible to create cutting-edge IoT solutions for a variety of businesses.

Due to its many features and capabilities, the ESP32 microcontroller is a popular choice for embedded systems and Internet of Things applications. Table 3.1 displays the main features of the ESP32.

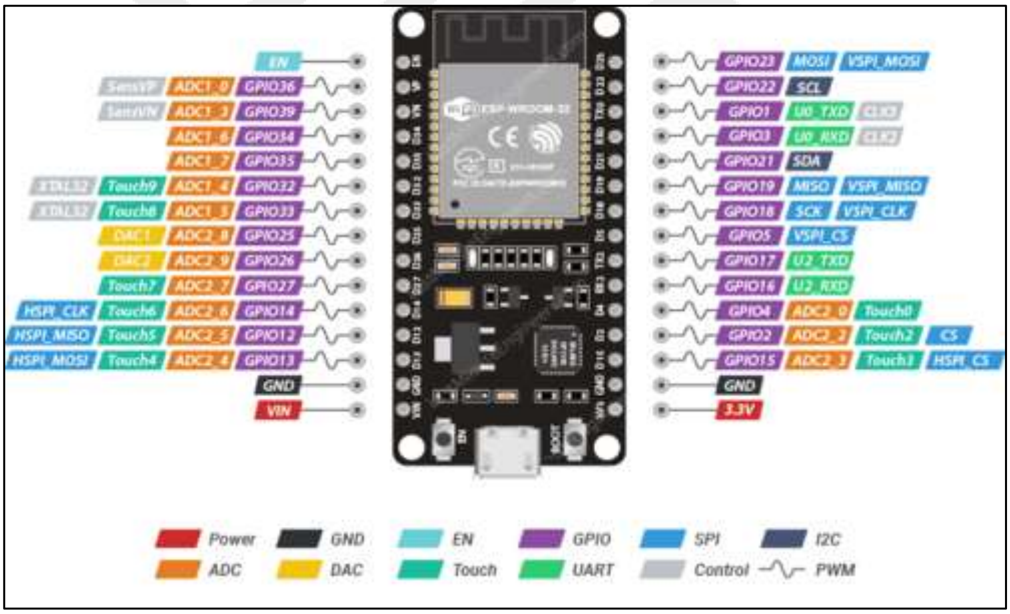


Figure 3.6: ESP32 Pinout Diagram [40].

Table 3.1: The Main Properties of the ESP32 Microcontroller.

Feature	Description
Dual-Core Processor	Two Xtensa LX6 CPUs running at up to 240 MHz
Wireless Connectivity	Wi-Fi 802.11 b/g/n and Bluetooth v4.2 / v5.0 BLE
Memory	Up to 520KB of SRAM
Modes of Low-Power	Supporting many low-power modes
Communication Protocols	SPI, I2C, UART, CAN, and more
Security Features	Hardware-based cryptographic accelerators, secure boot, flash encryption, secure flash partitions
General Purpose I/O (GPIO)	Large number of GPIO pins
Analog-to-Digital Converter (ADC)	Allows analog sensor data to be converted into digital values
Digital-to-Analog Converter (DAC)	Supports generating analog output signals
PWM	Allows precise control of analog-like output signals
Capacitive Touch Sensing	Built-in support for capacitive touch sensing
Software Development Tools	Arduino IDE, ESP-IDF (Espressif IoT Development Framework), MicroPython, JavaScript (Espruino)
Integrated Peripherals	Timers, RTC (Real-Time Clock), and watchdog timers

The suggested system is mostly split into two sections. The system uses a wireless network to link users' mobile phones to an ESP32 module at the sender end, which is the initial component. Next, a LoRa module is linked to the ESP32 module in order to transfer data. The second component is the receiving end, which combines an ESP32 and a LoRa module. This section involves connected connections to the ESP32 module and many sensors. The household appliances are linked to the receiver side. Figure 3.7 A & B show the suggested system's architecture conceptually.

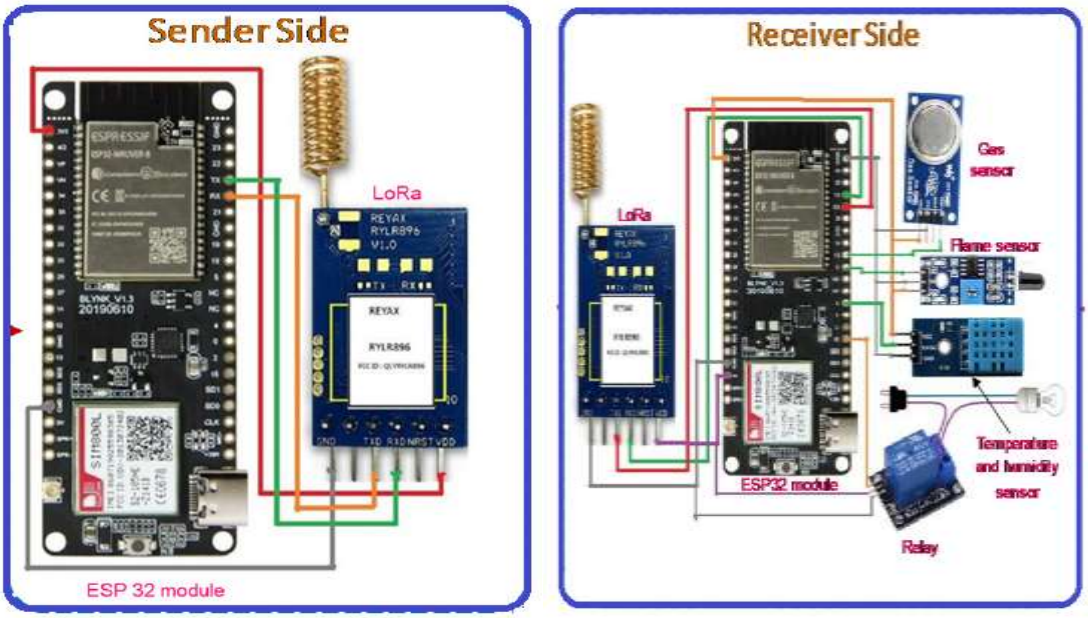


Figure 3.7: A Complete Architecture of The Proposed Automation System.

3.5 PZEM-004T V3 Module for AC

An electrical parameter measurement tool that is frequently used for tracking and measuring different parameters in AC circuits is the PZEM-004T V3 module shown in figure 3.8. Measurements of voltage, current, frequency, active power, and energy consumption may all be made using this flexible module. Below is a summary of the main attributes and functions often linked with the PZEM-004T V3 module [41]:

a. AC voltage measurement is the purpose of the PZEM-004T V3 module. It is capable of giving precise measurements of the voltage in the linked circuit.
b. Current Measurement: The AC current passing through the circuit may be measured using this module. Users are able to keep an eye on the current usage in real time.
c. Measurement of Frequency: The module has the ability to measure the frequency of the AC signal in addition to voltage and current. Measuring frequency is essential for determining how stable the power source is.
d. Measurement of Active Power: The PZEM-004T V3 module has the ability to ascertain the circuit's active power. The real power that the linked load is supplying or consuming is represented by its active power.

The PZEM-004T V3 module is extensively utilized in applications including power distribution panels, home automation, energy monitoring systems, and industrial control systems because of its adaptability. It is imperative that you consult the manufacturer's documentation while utilizing the PZEM-004T V3 module to obtain precise information on its wiring, calibration, and communication protocols. Additionally, programming and setting up the module in accordance with the application's specifications is usually required for integration with microcontrollers or other data logging systems.

Figure 3.8: PZEM-004T V3 Module.

The specification of PZEM-004T V3 module can be illustrated within table 3.2 which gives a comprehensive detail for

Table 3.2: The PZEM-004T Module Main Properties.

Feature	Description
Measurement Range	AC Voltage: 80V to 260V
	AC Current: 0A to 100A
Power Measurement	Real-time power measurement
Energy Measurement	Cumulative energy consumption (in kWh)
Data Communication	TTL Serial Interface or Modbus-RTU Protocol
Current Sensing Method	Non-invasive current measurement using CT
LCD Display	Integrated LCD display for real-time readings
Accuracy	High accuracy for precise measurements
Compact Size	Compact and easy to install
Application	Ideal for DIY projects, energy monitoring, and industrial setups
Safety Precautions	Requires adherence to safety measures when working with electrical circuits

3.5.1 DC Voltage Sensor: Battery

The DC voltage sensor operates based on magnetic modulation that is intended for use in DC voltage measurement and monitoring applications. This sensor produces an output signal (DC voltage or current) that is proportionate to the DC voltage input. They may be used in power supply management, DC motor drivers, battery chargers, and other systems. They are also appropriate for measurements and long-term monitoring of DC voltages.

A unique voltage sensor for bidirectional voltage tracking is a DC voltage sensor with a supply voltage of DC 12V/15V/24V shown in figure 3.9. The input voltage measurement range is ±50mV, ±50V, ±200V, ±500V, and ±1000V. A DC 2.5±2.5V, 5±5V, 12±8mA, or 10±10mA output signal is possible.

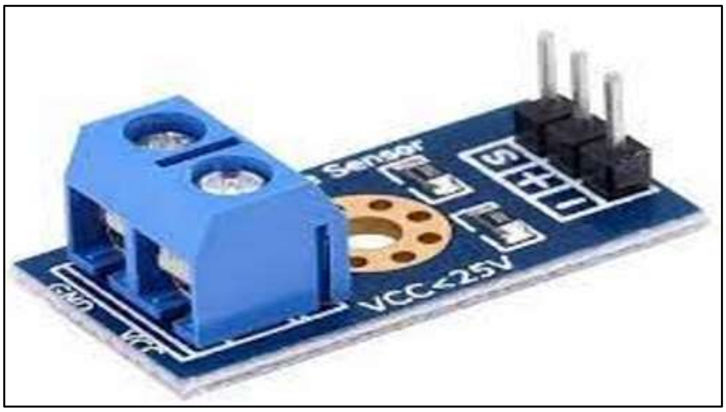


Figure 3.9: The DC Voltage Sensor as a Battery.

3.5.2 Power Supply Module Board for Arduino (3.3V & 5V)

The MB102 Breadboard Power Supply Module with 3.3V/5V output shown in figure 3.10 is a highly functional and user-friendly breadboard component that can be integrated into any project connected to breadboarding that requires either 3.3V or 5V of power. Because of its simplicity of use, customers may connect any DC power supply unit with a barrel jack that offers a power output of 6.5–12 VDC. The board features two separate power output channels for breadboards. It is possible to individually set up these power channels for 3.3V, 0V, and 5V activities.

Additionally, a push switch on the module allows you to turn the complete power supply module on and off. A USB input with two 5V, two 3.3V, and four GND pinouts for additional power pin needs is an extra feature. The user will be informed of the input power availability status via the power LED.

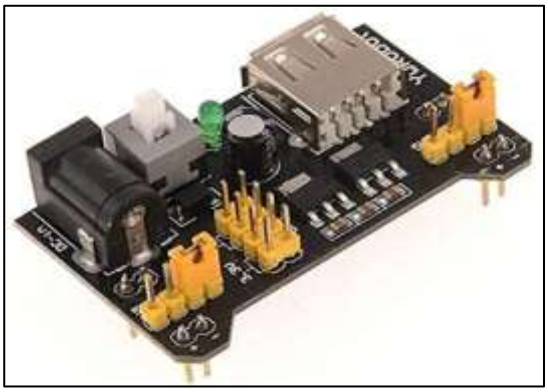


Figure 3.10: Breadboard Power Supply Module 3.3V/5V.

3.5.3 LCD 20*04

A typical type of numeric display seen in many different electronic devices, including consumer electronics, digital instrumentation, and applications based on microcontrollers, is the 20x4 LCD as shown in figure 3.11. The dimensions and arrangement of the display are indicated by the notation "20x4", which signifies that each of its four lines can show 20 characters. Across four panels of 20 characters each, the 20x4 LCD shows a total of 80 characters. Alphabetic letters, symbols, and user-defined characters can all be shown at each character location.

Usually, it can handle a conventional character set that includes special characters, digits, symbols, and both capital and lowercase letters. The specific character set may change depending on the LCD controller being used. On 20x4 LCDs, EL (Electroluminescent) or LED backlights are usually featured. It is possible to change the illumination to improve legibility under different lighting circumstances. Usually, an integrated controller processor built around the Hitachi HD44780 or a similar controller is in charge of the 20x4 LCD. Character creation, display functioning, and host device connectivity are all controlled by the controller.

Figure 3.11: 20x4 Character LCD Display

The most important characteristics and functions of the LCD 20x4 I2C module is listed in Table 3.3.

Table 3.3: The LCD 20x4 I2C Module's Fundamental Features.

Feature	Description
Display Size	20x4 character LCD display
I2C Interface	Simplified communication with only two wires (SDA and SCL)
Backlight Control	Controllable backlight for adjusting display brightness
HD44780-Compatible	Compatible with HD44780 controller, supporting popular microcontrollers
Wide Voltage Range	Operates within 3.3V to 5V voltage range
Contrast Adjustment	Some modules may offer contrast adjustment for better readability
User-Definable Characters	Support for creating custom characters or symbols
Application Versatility	Suitable for various projects, including data loggers, temperature monitors, IoT devices, and more
Ease of Use	Simplified programming and integration with available libraries and code examples
Visual Output	Provides clear and easy-to-read display for presenting information to users

3.6 THINGSPEAK CLOUD

MathWorks' ThingSpeak is a powerful and adaptable cloud service and Internet of Things (IoT) platform. This platform offers a complete solution for gathering, processing, and displaying data from sensors and Internet of Things devices. With ThingSpeak's intuitive UI and robust capabilities, creating, deploying, and managing Internet of Things apps is a breeze for users. It gives users the ability to log, visualize, and analyze data in real-time and derive meaningful insights from their Internet of Things data. Furthermore, ThingSpeak easily connects with MATLAB, enabling users to take advantage of MATLAB's sophisticated analytics and data processing features for in-depth IoT data analysis and visualization. ThingSpeak serves a broad spectrum of Internet of Things projects and applications by supporting multiple hardware platforms, communication protocols, and third-party services.

ThingSpeak is a dependable platform for Internet of Things (IoT) and cloud service supplied by MathWorks, a top supplier of engineering and scientific software. It acts as a link between the physical world of sensors and actuators and the digital world of data processing and visualization. Users may construct cutting-edge IoT projects and apps because of the platform's capacity to acquire, analyze, and display data from a variety of IoT devices and sensors. Figure 3.12 depicts ThingSpeak's primary window. Its broad feature set, scalability, and dependability make it a solid option for deploying IoT solutions in a variety of industries.

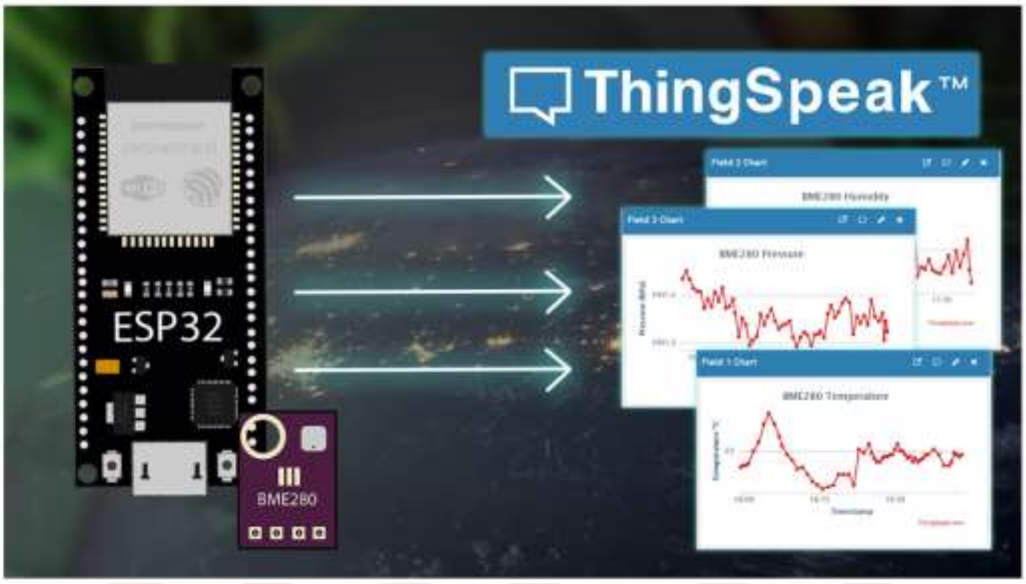


Figure 3.12: The ThingSpeak Cloud Main Window with ESP32 [42].

The flexibility of ThingSpeak expands beyond its fundamental capabilities, since it can be coupled with various IoT platforms, solutions, and tools to construct entire IoT applications. Applications for it can be found in many different areas, including industrial automation, environmental monitoring, home automation, agricultural, and smart city projects.

4. HYBRID ENERGY SYSTEMS SIMULATION

4.1 INTRODUCTION

Photovoltaic (PV) systems are a major participant in the renewable energy space as we search for more sustainable energy sources. PV systems provide a clean, plentiful, and endless source of energy by capturing solar radiation and turning it into electrical power. PV systems are essential to the renewable energy landscape as efforts are made to wean ourselves off fossil fuels and lessen the effects of climate change. The solar panels that make up photovoltaic systems are made of many solar cells. Through the process of photovoltaics, these cells, which are usually composed of silicon or other semiconducting materials, collect sunlight and produce direct current (DC) power. Afterwards, inverters are used to transform this DC power into alternating current (AC) electricity, which makes it compatible with grid.

Photovoltaic (PV) systems are becoming a major component of the renewable energy scene as a result of the continuous search for sustainable energy solutions. PV technology provides a clean, sustainable, and limitless source of electricity by capturing the plentiful energy from sunshine and turning it into electrical power.

PV systems are essential to the world's transition to renewable energy for a number of reasons.

a. Clean Energy Generation: Photovoltaic (PV) systems generate power without releasing greenhouse gases and other pollutants, which helps to improve air quality and combat climate change. This is in contrast to fossil fuels.

b. Plenty of Resource: Solar energy is a dependable and easily obtainable source of power since sunlight is plentiful and unrestricted throughout the majority of the earth.

c. Energy Independence: Communities and people may increase energy reliability and resilience by utilizing solar energy to lessen their reliance on imported fossil fuels and centralized power systems.

d. Economic Benefits: The fast falling costs of photovoltaic technology, together with a number of benefits and subsidies, have increased solar energy's competitiveness with traditional power generating methods. This has contributed to the development of jobs and economic development within the renewable energy industry**.**

PV systems are becoming increasingly popular because to their many advantages and contributions to the worldwide search for sustainable energy sources:

a. Environmental Sustainability: PV systems generate power without releasing any harmful pollutants or greenhouse gases into the atmosphere, therefore reducing the negative effects of climate change and encouraging environmental stewardship.

b. Energy Security and Independence: PV systems improve energy security by lowering dependency on limited and politically unstable fossil fuel supplies by utilizing the sun's nearly infinite energy. Furthermore, localized PV systems promote energy independence and resilience by enabling people and groups to produce their own clean electricity.

c. Economic Viability: As a result of scientific breakthroughs and economies of scale, the costs of photovoltaic technology are falling quickly, making solar energy a more affordable alternative to traditional fossil fuel-based power generation. PV installations also boost local economies by attracting investments, creating jobs, and fostering technical innovation.

The goal of this chapter is to explore the topic of grid-connected PV systems with an emphasis on simulation. It offers a thorough introduction to photovoltaic systems, highlighting their importance within the larger framework of renewable energy as well as the shift to a low-carbon future. Researchers and engineers may improve the design and operation of grid-connected PV systems, learn a great deal about their performance, and eventually advance the field of renewable energy technology by modeling the behavior of these systems.

The goal of this chapter is to offer a thorough examination of modeling approaches and procedures for grid-connected PV systems. The chapter aims to clarify the fundamental ideas guiding the behavior of grid-connected PV systems, pinpoint important variables impacting their performance, and suggest methods for improving their effectiveness, dependability, and integration with the electrical grid through in-depth analysis and case studies.

Rationale for Simulation Studies

Accurate simulation and modeling of PV systems are becoming more and more necessary as PV technology develops and spreads. Simulation studies provide important new information on the performance traits, dynamic behavior, and operational difficulties of grid-connected photovoltaic systems. Researchers and engineers can improve system performance overall, assess the effectiveness of different control tactics, and optimize system design by simulating real-world situations and scenarios in a controlled setting.

4.1.1 Importance of Simulating PV Systems Connected to the Grid.

The simulation of grid-connected photovoltaic (PV) systems is essential for the field of engineering and research on renewable energy. The importance of simulation in this situation is shown by the following few main points:

4.1.1.1 Design and optimization of systems

PV systems may be designed and optimized by engineers using simulation prior to deployment, taking into account variables like array arrangement, panel orientation, tilt angle, and inverter size. To optimize energy output and return on investment, researchers can determine the most economical and efficient system configurations by experimenting with different design scenarios in a virtual environment.

4.1.1.2 Performance prediction

PV system performance can be predicted under various environmental conditions, such as changes in temperature, shade, and solar irradiation, thanks to accurate modeling. Through the examination of performance indicators including energy production, capacity factor, and levelized cost of electricity (LCOE), researchers may determine if photovoltaic (PV) systems are appropriate for a given region and determine their long-term financial sustainability.

4.1.1.3 Grid Integration and stability

Grid stability, voltage control, and power quality are all impacted by the dynamic interactions that grid-connected PV systems have with the power grid. Researchers may examine how PV integration affects grid metrics including voltage profiles, frequency aberrations, and power flow distribution by using simulation. This makes it possible to create and evaluate control techniques that are friendly to the grid in order to lessen possible problems like voltage fluctuations and grid instability.

4.1.1.4 Control strategy development

For grid-connected PV systems, simulation is a useful tool for designing and testing control techniques like as voltage regulation, anti-islanding protection, and maximum power point tracking (MPPT). Researchers may evaluate how well different control algorithms and scenarios optimize system performance, improve grid stability, and guarantee grid code and regulatory compliance by modeling them.

4.1.1.5 Risk mitigation

PV system simulation before deployment aids in identifying possible risks and difficulties, including as equipment malfunctions, system breakdowns, and gradual performance deterioration. Researchers may create backup plans, reliability evaluations, and maintenance plans to reduce downtime, increase system uptime, and guarantee long-term resilience and reliability by modeling worst-case scenarios with failure modes.

4.1.1.6 Cost reduction and accelerated innovation

The innovation cycle is sped up by simulation, which makes it possible to test novel PV technologies and system configurations virtually, quickly prototype ideas, and revise designs iteratively. Through silico simulation of several design iterations and performance scenarios, researchers may quickly find the best solutions, save development costs, and accelerate the release of state-of-the-art technology from the lab to the market.

An essential part of expanding the boundaries of renewable energy research and technical practice is the simulation of grid-connected photovoltaic systems. In order to fulfill the increasing demand for clean and sustainable energy around the globe, simulation helps with the design, development, and deployment of efficient, dependable, and grid-friendly PV systems by offering insights into system behavior, performance characteristics, and integration problems.

This chapter's main goal is to use simulation tools to explore the complex dynamics of grid-connected photovoltaic (PV) systems. This chapter looks at how PV systems behave, function, and interact with the electrical grid in a virtual setting in order to:

a. Provide Insight: Provide information on the operational traits, difficulties, and prospects related to grid-connected photovoltaic systems.

b. Promote Understanding: Strengthen comprehension of the fundamental ideas guiding PV system performance in a range of environmental and grid parameter circumstances.

c. Optimize Design: Make it possible for PV systems to be designed and optimized for optimal energy yield, efficiency, and grid compatibility.

d. Develop methods: In the context of PV integration, develop and assess control methods to improve grid stability, power quality, and system dependability.

4.1.2 Scope of This Chapter

An overview of popular simulation tools and approaches, such as MATLAB/Simulink, PVSyst, and Homer, as well as mathematical and numerical modeling, are used to study grid-connected photovoltaic systems. Comprehensive description of the created simulation model, including grid connection components, PV panel, inverter, and control algorithm modeling. The simulation model's correctness, scalability, and validation against actual data and empirical findings will be emphasized.

Results of the simulation are shown for a range of scenarios, which include variations in grid characteristics, environmental factors, system configurations, and geographic locations. The effects of shade, temperature, solar irradiance, and grid disturbances on PV system performance and grid interaction will be demonstrated through case studies. analysis and interpretation of simulation data with an emphasis on system behavior, important performance indicators, and the efficacy of control schemes. There will be a discussion on how to improve grid integration, optimize system design, and deal with obstacles in the PV deployment process.

The importance of modeling grid-connected photovoltaic (PV) systems in the context of engineering practice and research on renewable energy is briefly discussed in the introduction. It emphasizes the critical role that photovoltaic (PV) technology will play in the shift to a sustainable energy future and stresses the need of using simulation approaches to comprehend and optimize grid-connected PV systems.

4.2 BACKGROUND: OVERVIEW OF PHOTOVOLTAIC TECHNOLOGY

As an environmentally friendly and sustainable method of producing power, photovoltaic (PV) technology is at the forefront of renewable energy solutions. Fundamentally, photovoltaic technology is based on the direct conversion of sunlight into electrical power. Photons interact with semiconductor materials like silicon within solar cells, the fundamental units of photovoltaic panels, causing this effect. The most noticeable part of a standard PV system is its solar panels, but there are other important parts as well. These panels, which are sometimes referred to as photovoltaic modules, are made up of a matrix of linked solar cells. There are several varieties of solar cells, each with unique properties and efficiency levels, such as monocrystalline, polycrystalline, and thin-film solar cells.

During operation, the solar cells collect sunlight, which excites electrons and forms pairs of electrons and holes. This produces a direct current (DC) electrical flow, which is then transformed into an alternating current (AC) by means of an inverter to ensure grid compatibility. Further balance among system components, such junction boxes, wiring, and mounting structures, guarantee the PV system's safe operation.

PV technology's efficiency that is, the proportion of electrical energy production to solar energy input is a crucial component. Temperature, shading, cell design, and semiconductor material quality are some of the variables that affect efficiency. Performance indicators that reveal a PV system's overall efficacy and dependability include capacity factor, energy yield, and fill factor. Significant advances in manufacturing processes, durability, and efficiency have resulted from advancements in photovoltaic technology. New technologies have the potential to significantly improve performance and lower prices, such as tandem solar cells and perovskite solar cells. Market trends point to a substantial rise in PV adoption, which is being fueled by falling costs, pro-sun laws, and rising public awareness of solar energy's environmental advantages. PV systems are used in many different industries. They are used in off-grid and hybrid systems for remote or decentralized energy access, as well as in grid-connected installations for residential, commercial, and utility-scale projects. PV systems not only help the environment but also advance social and economic progress by increasing energy independence, generating jobs, and facilitating access to energy.

4.2.1 Modelling of PV System

A conventional photovoltaic (PV) system is made up of a number of essential parts, each of which is vital to the process of turning sunlight into electrical energy that may be used or integrated into the grid.

a. Solar Panels (PV Modules): The main part of a PV system is made up of solar panels, sometimes called photovoltaic modules. These panels are composed of Si or other semiconductor-based linked solar cells. Through the process of photovoltaics, solar panels use sunlight to create direct current (DC) power.

b. Inverters: For the solar panels to produce DC power and produce (AC) electricity, inverters are necessary parts. The most common type of electrical power utilized in residences, workplaces, and industries is AC electricity, which is grid-compatible. Inverters do more than just convert DC to AC; they also regulate voltage, synchronize with the grid, plus offer safety measures.

c. Grid Connection: Interfacing the PV system with the electrical grid is made possible by the grid connection component. Grid-connected PV systems enable the export of excess solar power to the grid and the use of grid power in situations where solar power is insufficient. In order to enable net energy measurement or feed-in tariffs, grid connection usually entails the setting up of a bidirectional meter, that monitors the power received from and generated to the grid.

Typically, a photovoltaic system consists of these three main parts, which facilitate the conversion of solar energy into electrical power and its integration with the current electrical infrastructure. In addition, the proper balance of system elements such as junction boxes, wiring, mounting structures, and monitoring systems is required to guarantee the effective and secure operation of the PV systems.

4.2.2 The Importance of PV System Behavior Simulation

As a virtual environment for modeling, analyzing, and experimenting with complex systems, simulation is essential to understanding system behavior. Through simulation, engineers and researchers may test different hypotheses, see how systems react, and pinpoint crucial variables that have an impact on performance. It makes experimentation more economical and productive while obviating the requirement for physical prototypes and field testing. In addition, simulation makes it possible to assess speculative situations and validate theoretical models prior to implementation, which improves comprehension of system dynamics and makes well-informed decisions easier to make during system design, optimization, and troubleshooting.

The solar power system is the most rapidly expanding energy technology in the world. Its advantages include using the sun, which is the most abundant renewable energy source on Earth, low maintenance costs, and the ability to be installed on a small or large scale. These factors have led to the popularity of PV systems among the renewable energy sources employed in smart grids. Singh and Ramakrishna have discussed PV monitoring systems in great detail. The system is utilized to give data on the energy potential based on measured solar irradiance and ambient temperature, as well as data on actual energy generated, energy loss, and fault analysis of various potential problems. Data from the monitoring system may be utilized to anticipate climate changes early on and as a warning system.

The components of a PV monitoring system typically include a PV system, smart sensors for parameter detection, a data transmission channel for data transfer from sensors, data storage for data storage of the gathered data, and a graphical user interface (GUI) to facilitate monitoring and analysis. Solar irradiation, ambient temperature, PV voltage and current, and other factors based on the kind of PV system grid-connected or stand-alone are the parameters taken into consideration. Typically, a computer-based data collection system is utilized to gather all data and display it using a graphical user interface (GUI), such LabView software. (20) recommended employing a wireless PV monitoring system, in which the characteristics of the PV system, including the temperature of the cell, irradiance, and current and voltage, were gathered using a DAQ board based on a microcontroller and sent to a computer via Bluetooth module.

The MATLAB/Simulink environment was used to show the data, which were then fed into the PV model for simulation purposes. A high security wireless home monitoring and management system was suggested by researchers. They concentrated on the safe access gateway to guarantee that data could be successfully and discreetly transferred between C-mobile and smart home management devices, such as smart phones used as monitoring and control devices.

The benefits of putting the system into place include the ability to offer hourly specific features of load demand, which allows for the definition of consumption patterns to improve visibility and load comprehension. Customers can use this information to determine which electrical equipment has to be turned off in order to lower their power costs. Additionally, it helps with improved energy management. The energy data may be used by consumers to control their power consumption performance. For economic and environmental reasons, they become more conscious of energy consumption and efficiency. Users may more effectively control their energy consumption and plan for future situations by detecting peak energy demand. Numerous additional factors, like event monitoring, building optimization, and user preferences, may be taken into account when using IoT devices for energy usage monitoring and management.

The flowchart in Figure 4.1 provides a summary of monitoring system that revealed. However, as the red area in Figure 4.1 illustrates, the scope of the research is restricted to data transmission and reception between ThingSpeak, MATLAB/Simulink, and mobile apps.

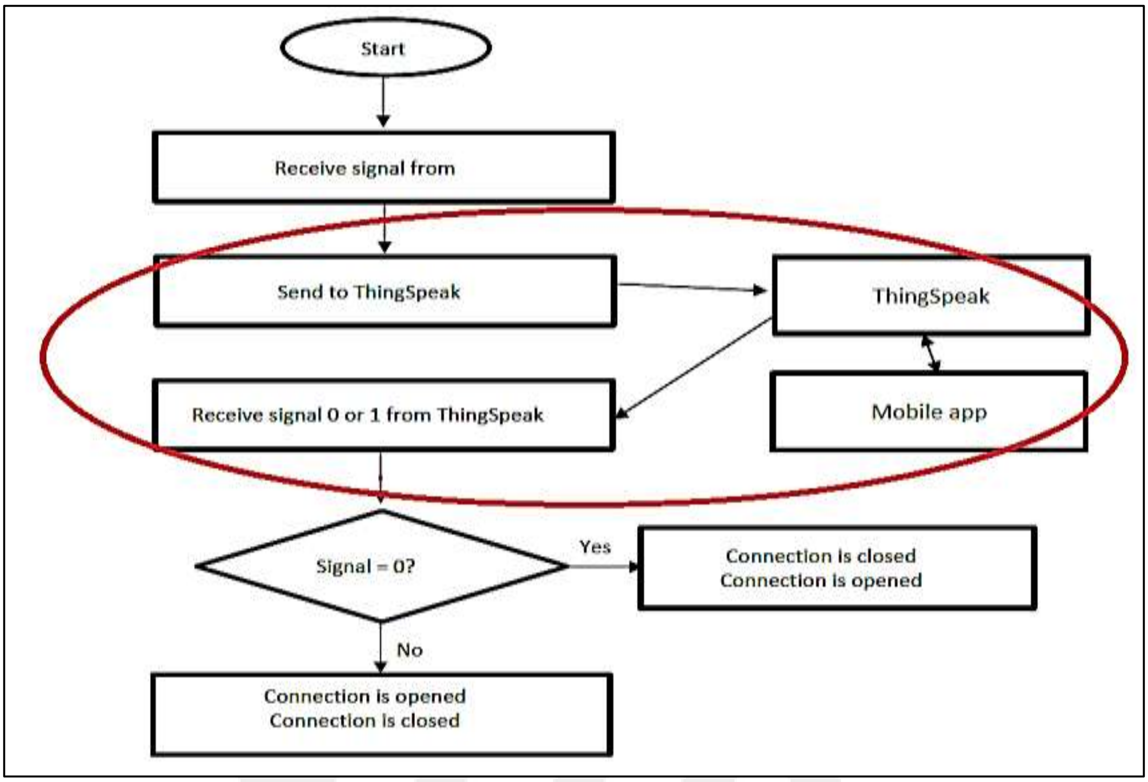


Figure 4.1: Flowchart for the Suggested System.

The controller's design of the monitoring system is where the algorithm starts. First, the main goal of the controller is stated, whether it to optimize PV panel power production, manage voltage, or perform some other essential task for system functioning. After that, an appropriate control strategy is chosen in accordance with the goals and needs of the system. Incremental conductance and Perturb and Observe (P&O) are common techniques. After a strategy is selected, MATLAB/Simulink is used to create the control algorithm. This entails putting the selected approach into practice, such as the P&O algorithm, which continually modifies the PV system's operating point and tracks the maximum power point (MPP) by observing the ensuing power change.

The algorithm then deals with the monitoring system's design. Essential parameters, such as PV panel voltage, current, power output, battery state of charge (SoC), etc., are identified in order to monitor the health and performance of the PV system. The system dynamics and the required degree of detail for analysis are taken into account when defining the monitoring frequency and recording intervals. Next, using MATLAB/Simulink blocks, the system architecture for monitoring is created. In order to measure the specified parameters, this entails choosing the proper sensors or virtual sensors and implementing data logging systems to collect and store pertinent data.

Following their independent design, the controller and monitoring systems are combined into a single Simulink model. The controller will be able to obtain real-time data from the monitoring system through this interface, enabling them to make well-informed choices. To transmit data seamlessly, communication channels are built between the controller and monitoring components. If needed, bespoke communication protocols or the relevant Simulink blocks are used.

4.3 SYSTEM DESCRIPTION

The proposed system is an IoT-based PV application energy monitoring and control system designed to monitor various parameters of a photovoltaic (PV) system and control its operation remotely. The system computes several key parameters, including instantaneous power consumption, DC link voltage, line-to-line (L-L) voltage after the inverter, L-L voltage and current after the filter, and L-L voltage after the filter and transformer. These parameters provide valuable insights into the performance and health of the PV system.

The system's block diagram (4.2) shows how several parts work together to accomplish its operation.

a. PV System: This refers to the photovoltaic system as a whole, which includes the solar panels, transformer, inverter, filter, and filter. Sunlight is converted by solar panels into electrical energy, which is further prepared for consumption or storage by the other components through processing and conditioning.

b. Sensors: Throughout the PV system, sensors are devices that are used to detect different characteristics including voltage, current, and power. To monitor the electrical properties of the system, for example, voltage and current sensors may be placed at various locations, and additional sensors may be used to assess environmental variables like temperature or irradiance. These sensors supply the real-time data required for system monitoring and control.

c. Microcontroller (MCU): Acting as the system's brain, the microcontroller is in charge of analyzing sensor input, carrying out calculations, and directing system activities. It gathers sensor data, computes variables like voltage levels and instantaneous power usage, and runs control algorithms using pre-programmed logic. The MCU makes sure the PV system runs securely and effectively.

d. Wi-Fi Module: This module allows the PV system to communicate wirelessly with other devices, including cloud platforms or the MATLAB app. Data transmission over the internet is made possible by its connection to the nearby Wi-Fi network. With the help of the Wi-Fi module, users may remotely monitor and operate the PV system, accessing real-time data and making changes from any location with an internet connection.

e. Cloud Platform (ThingSpeak): ThingSpeak is an Internet of Things platform that runs on the cloud and is intended for gathering, processing, and displaying data from linked devices. ThingSpeak acts as a bridge in this system, connecting the MATLAB app and the PV system. The PV system uses the Wi-Fi module to send the calculated parameter values to ThingSpeak, where the data is stored and available to the MATLAB app for additional analysis and visualization.

f. MATLAB App: For remote PV system monitoring and control, the MATLAB app offers an intuitive user interface. ThingSpeak provides users with access to real-time data generated by the PV system, which may be shown as tables, charts, or graphs. With the app, users can keep an eye on system performance, look for irregularities, and change system settings as needed, all from the convenience of a computer or mobile device.

The overall visibility and control over the PV system's performance is improved by this Internet of Things (IoT)-based PV application energy monitoring and control system. Users may maximize the advantages of solar energy use by remotely monitoring performance, detecting abnormalities, and optimizing energy efficiency by utilizing cloud-based platforms and IoT technologies.

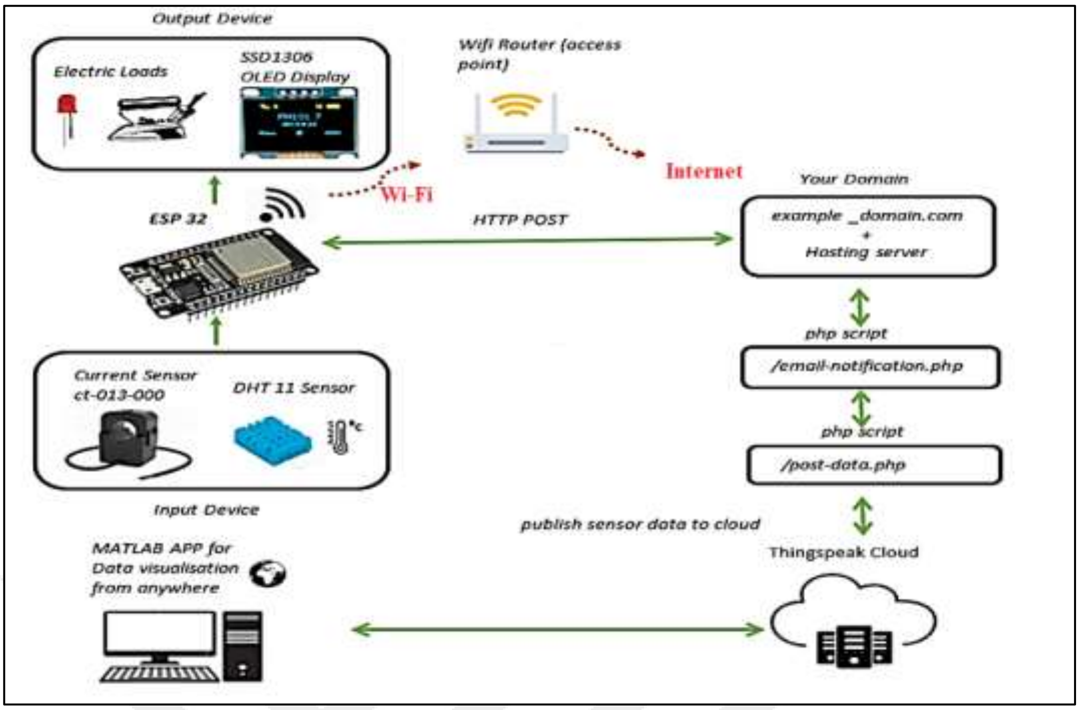


Figure 4.2: A Suggested System Description of PV Monitoring.

The 250 kW PV system under simulation shown in figure 4.3 is a large solar energy producing plant intended to transform sunlight into electrical power. It is made up of a number of solar panels connected to other parts including monitoring tools and inverters. Together, these parts enable the effective capture of solar energy and its conversion into useful power.

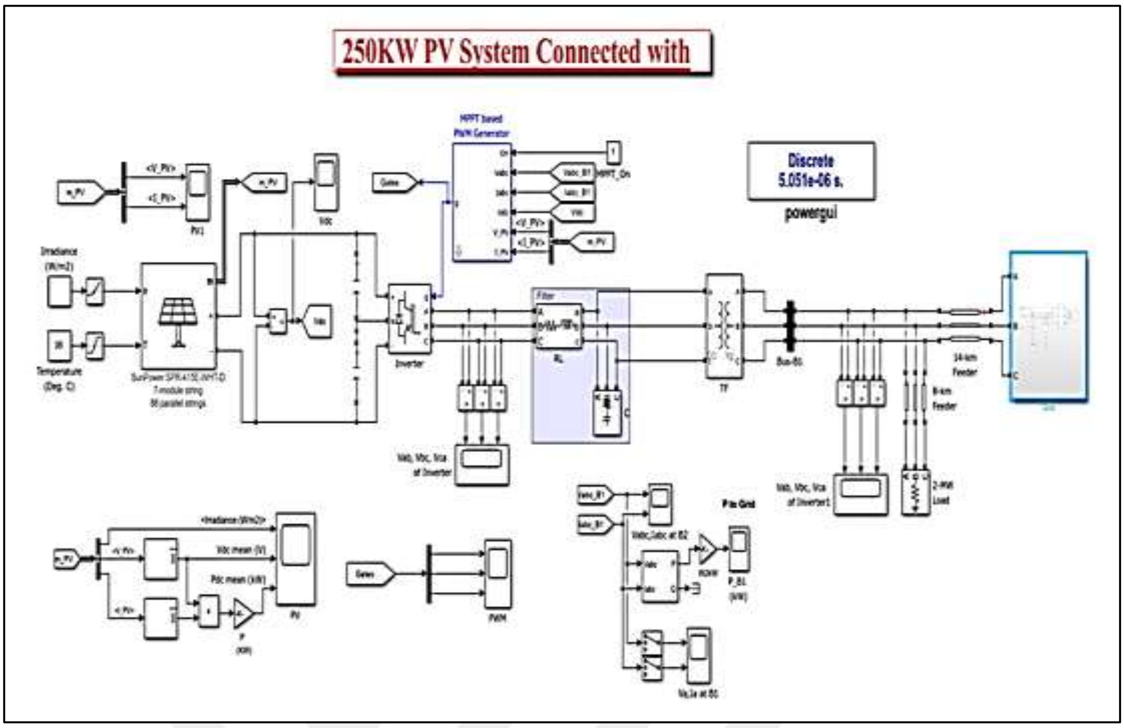


Figure 4.3: PV System Simulation with Matlab.

The PV system's total capacity is shown in the graphic, which also shows its 250 kW peak power production. The maximum electrical power that the system is capable of producing in optimal circumstances is indicated by this value. It could also display the system's actual physical design and setup, including how the inverters, solar panels, and other parts are arranged.

The parameter being monitored is shown in the figure, which includes:

a. Vdc, or DC Voltage, is a quantity that shows the PV system's direct current (DC) voltage output. It shows the voltage level at the system's DC side, usually prior to the inversion process.

b. Idc (DC Current): The PV system's direct current (DC) current is represented by this parameter. It provides the DC side of the system's current level, which is essential for tracking power generation and system health.

c. Power: Power measurements, which show the PV system's electrical power output, are probably included in the figure. This parameter, which gives information on the effectiveness and performance of the system, is obtained from the product of Vdc and Idc.

A 250 KW PV system is simulated with Matlab, a figure with its parameters is shown, how can we describe it and mentioned it

Need for simulation in understanding system behaviour.

Simulation plays a crucial role in understanding the behaviour of grid-connected photovoltaic (PV) systems for several reasons:

a. Complex Interactions

Grid-connected PV systems involve complex interactions between various components, including solar panels, inverters, grid connection equipment, and the electrical grid itself. Simulation allows researchers to model these interactions comprehensively, considering factors such as solar irradiance, temperature variations, shading, and grid conditions.

b. Dynamic Nature

PV systems exhibit dynamic behaviour due to fluctuations in solar irradiance, weather conditions, and electricity demand. Simulation enables the modelling of these dynamic processes over time, allowing researchers to analyse system performance under different scenarios and operating conditions.

c. Optimization

Simulation provides a platform for optimizing the design, operation, and control of grid-connected PV systems. By iteratively simulating various system configurations, control strategies, and component choices, researchers can identify the most efficient and cost-effective solutions to maximize energy yield and grid integration.

d. Risk Mitigation

Simulating PV systems allows researchers to identify potential risks and challenges before deployment. By simulating failure modes, extreme weather events, and other adverse conditions, researchers can develop contingency plans, reliability assessments, and risk mitigation strategies to enhance system resilience and reliability.

e. Cost-Effectiveness

Conducting real-world experiments and testing on PV systems can be costly and time-consuming. Simulation offers a cost-effective alternative, allowing researchers to explore a wide range of scenarios virtually without the need for physical prototypes or extensive field testing.

f. Policy and Regulation

Simulation can aid in evaluating the impact of policy interventions, grid codes, and regulations on the operation and integration of grid-connected PV systems. By simulating compliance with regulatory requirements and assessing the effectiveness of policy incentives, researchers can inform decision-making and policy formulation processes.

g. Education and Training

Simulation serves as a valuable educational tool for training engineers, technicians, and policymakers involved in the design, installation, and operation of grid-connected PV systems. Virtual simulations provide hands-on experience in a safe and controlled environment, facilitating learning and skill development.

In summary, simulation is essential for gaining insights into the behavior, performance, and integration of grid-connected PV systems. By leveraging simulation tools and methodologies, researchers can optimize system design, mitigate risks, inform policy decisions, and advance the adoption of renewable energy technologies for a sustainable future.

4.4 OVERVIEW OF SIMULATION SOFTWARE

Three Methods and Tools for Simulation: An overview of popular simulation programs for photovoltaic systems, such as Homer, PVSyst, MATLAB/Simulink, and others.

An overview of some popular photovoltaic (PV) system simulation programs is provided here:

4.4.1 Simulink/MATLAB

One of the most potent computational tools available for modeling, simulation, and analysis in many engineering specialties, including PV systems, is MATLAB/Simulink. Simulink provides engineers and researchers with an intuitive graphical user interface (GUI) for creating dynamic system models using block diagrams. Simulink's simulation capabilities, when paired with MATLAB's vast mathematical function and toolbox library, enable detailed modeling of PV components, control algorithms, and grid interactions. A popular computational tool in many engineering fields, including the modeling and analysis of photovoltaic (PV) systems, is MATLAB/Simulink. This is a more thorough synopsis of MATLAB/Simulink and its capabilities for modeling PV systems:

4.4.1.1 Modelling capabilities

a. Simulink makes it simple for engineers and researchers to create intricate PV system models by offering a graphical user interface (GUI) for creating dynamic system models using block diagrams.

b. Maximum power point trackers (MPPT), inverters, solar panels, and grid connection equipment can all be fully modeled using MATLAB's vast mathematical function library, toolboxes, and Simulink's simulation capabilities.

c. Simulink allows for both continuous-time and discrete-time modeling, which makes it possible to simulate the transient responses and dynamic behaviors of PV systems under various operating conditions.

4.4.1.2 Simulation and analysis

a. For simulating PV system behavior over time, Simulink provides a variety of solvers and simulation choices. To evaluate system performance in various settings, users can do frequency-domain, transient, and steady-state analyses.

b. The ability to script in MATLAB facilitates automated parameter sweeps, sensitivity

c. analysis, and optimization studies to investigate how control tactics, environmental factors,

d. and design parameters affect PV system performance.

e. Users may display time-domain and frequency-domain responses, assess simulation

f. findings, and compare simulated data with empirical or experimental observations thanks to

g. Simulink's built-in visualization capabilities.

4.4.1.3 Control system design

a. Simulink offers tools for creating and putting into practice voltage regulation, anti-islanding protection, and MPPT algorithms, among other control algorithms for PV systems.

b. Block diagrams, state-space representations, and transfer function models can all be used to build control systems. These systems can then be implemented in real-time simulations to assess how well they regulate PV system functioning and maintain grid stability.

c. PV system control design and tuning can benefit from a variety of control design approaches, including robust control, state feedback, and PID control, which are all available in MATLAB's Control System Toolbox.

4.4.1.4 Integration with other tools and platforms

a. Simulink and MATLAB/Simulink easily interface with other MATLAB toolboxes and outside software programs, giving users access to more features for PV system analysis and optimization.

b. The scripting language and APIs provided by MATLAB allow for the exchange of data and workflow automation in the modeling and analysis of PV systems by enabling interoperability with databases, simulation environments, and external data sources.

c. Hardware-in-the-loop (HIL) simulation and rapid prototyping are made possible by Simulink Real-Time and Simulink Desktop Real-Time, which let users interface

Simulink models with actual hardware for testing and validation. In summary, MATLAB/Simulink offers a comprehensive platform for modelling, simulating, and analyzing PV systems, providing engineers and researchers with the tools and capabilities needed to design, optimize, and control grid-connected PV installations effectively.

4.4.1.5 PVSyst

a. PVSYSt is a specialist software program made only for PV system analysis and simulation.

b. With PVSyst, users can simulate how well PV systems would work depending on factors like location, solar irradiance statistics, system setup, and component specs.

c. For evaluating the financial sustainability of PV projects, the software offers comprehensive simulation results that include energy production estimates, performance ratios, and financial analysis.

4.4.1.6 Homer

a. PV, wind, hydro, and battery storage are examples of hybrid renewable energy systems that may be designed and optimized using the modeling program Homer.

b. Users can simulate intricate energy systems with several generation sources, storage choices, and demand patterns using Homer.

c. The software offers optimization algorithms to find the best possible system configuration based on user-specified goals like environmental impact, dependability, and cost reduction.

4.4.1.7 OpenDSS

a. An open-source simulation program called OpenDSS (Open Distribution System Simulator) is used to model and analyze distribution systems, including PV integration.

b. To evaluate the effect of PV integration on distribution system performance, users can model PV systems, distribution transformers, inverters, and other grid components using OpenDSS.

c. To assess grid stability, voltage regulation, and power quality, the software offers time-domain simulations, load flow analysis, and voltage profile computations.

4.4.1.8 RETScreen

a. Natural Resources Canada created the free software program RETScreen to assess the viability of energy-efficiency and renewable energy projects.

b. PV system simulation modules in RETScreen enable users to simulate energy production, financial analysis, and environmental effects of PV projects.

c. Pre-configured templates, data sets, and analysis tools are provided by the software to expedite the PV system project evaluation process.

4.5 SIMULATION REQUIREMENTS

To meet the demands of academics, engineers, and decision-makers involved in the planning, development, and implementation of solar energy projects, these simulation tools provide a wide range of features and functionalities for modeling, simulating, and assessing PV systems. Simulink and MATLAB/Simulink easily interface with other MATLAB toolboxes and outside software programs, giving users access to more features for PV system analysis and optimization. The scripting language and APIs provided by MATLAB allow for the exchange of data and workflow automation in the modeling and analysis of PV systems by enabling interoperability with databases, simulation environments, and external data sources. Hardware-in-the-loop (HIL) simulation and rapid prototyping are made possible by Simulink Real-Time and Simulink Desktop Real-Time, which let users interface Simulink models with actual hardware for testing and validation.

The electrical output of solar panels in renewable energy systems must be predicted and optimized using an accurate PV array model with the right parameters. Table 4.1 lists a few of these simulation-related parameters. Also, it may be seen that these parameters can explained in the Matlab box as shown in figure 4.4 with specified values.

Table 4.1: PV Array Parameter Employ in Simulation.

PV parameter	value
Maximum power (W)	414.94
Cells per module (Ncell)	128
Open cct voltage Voc (V)	85.3
Voltage at max power point Vmp (V)	72.9
Current at max power point Imp (A)	5.69
Temp coeff. Of Voc (%/deg.C)	-0.299
Cells per module (Ncell)	60
Short – cct current Isc (A)	4.82
Current at max power point Imp (A)	4.85
Temp coeff. Of Isc (%/deg.C)	0.03070

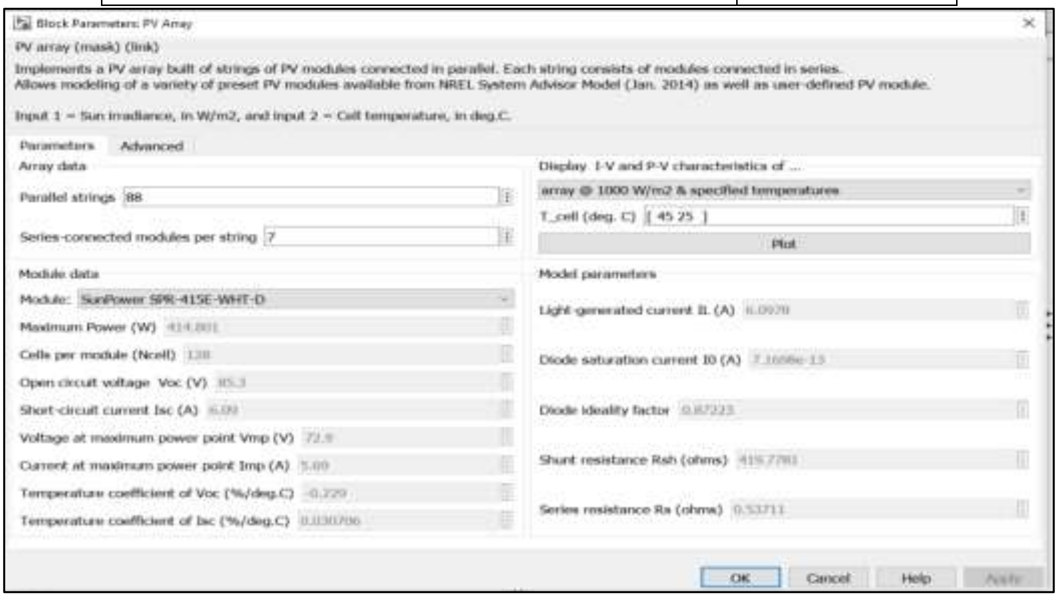


Figure 4.4: PV Array Parameters as Shown in Matlab.

4.5.1 Three Phase Inverter Parameters

Three-phase inverters are often utilized in many different applications, such as power electronics, motor drives, and renewable energy systems. Three-phase AC output voltages are produced by three-phase inverters. Important characteristics include the output waveform's frequency and voltage magnitude. The output voltage is usually sinusoidal, commonly at a frequency of 50 Hz or 60 Hz, which corresponds to the grid frequency. On the other hand, the modulation strategy controls how the inverter switches are set up to produce the intended output waveform. Space Vector Modulation (SVM), Sinusoidal Pulse Width Modulation (SPWM), and Pulse Width Modulation (PWM) are common modulation methods. These methods have an impact on the inverter's efficiency as well as the output waveform quality.

A DC power source, such as a battery or a rectifier linked to an AC power source, is often where three-phase inverters get the DC input voltage they need. The voltage level at the inverter's input, or DC link voltage, is a key factor in determining the output voltage's magnitude. A three-phase inverter's maximum power rating tells you how much power it can put into the load. It is dependent on a number of variables, including thermal management, cooling capacity, and the rating of the power semiconductor devices (such as MOSFETs and IGBTs). The percentage representation of the ratio of input power to output power is known as inverter efficiency. Reduced power loss during the conversion process results in higher efficiency, which improves energy conversion and reduced operating costs.

The Inverter parameters can be shown in the figure 4.5 with values applied to the simulation. Current three-phase inverters come with sophisticated communication interfaces and control algorithms that enable remote monitoring and management. Modbus, Ethernet, and CAN bus are examples of common communication protocols that enable integration with SCADA (Supervisory Control and Data Acquisition) and supervisory control systems.

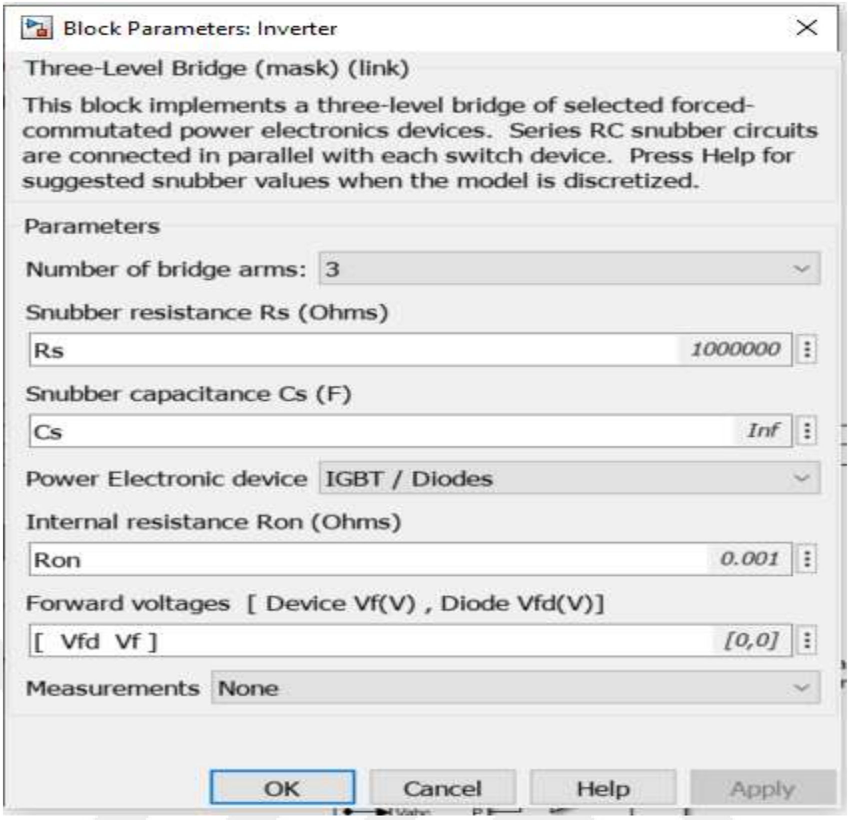


Figure 4.5: The Inverter Parameters Applied in Simulation.

Four IGBT switches and a resistor make up the inverter block, and both the voltage and current are monitored. IGBT 1 and IGBT 4 conduct throughout the first half of the cycle, while the other two are in an off state. In the latter part of the cycle, IGBT 2 and IGBT 3 will be conducted. It functions similarly to a diode bridge rectifier, except instead of having diode bridges, it has switches that need a gating pulse to activate.

4.5.2 RLC Filter

An electrical signal's particular frequency components can be passed through or attenuated by using resistors (R), inductors (L), and capacitors (C) in different combinations to create a passive RLC filter.

RLC filters come in several varieties, such as band-pass, low-pass, high-pass, and band-stop (notch) filters. Every kind is intended to either pass through or weaken specific input signal frequency bands.

An RLC filter's frequency response explains the filter's behavior with respect to frequency. It displays the amplitude and phase changes of the filter's output in relation to various input frequencies.

When using a low-pass filter, frequencies above the cutoff are muted while frequencies below it are passed through with little loss. In a high-pass filter, on the other hand, frequencies below the cutoff are muted while frequencies beyond it are passed through with little loss.

RLC filters are vital parts of electronic circuits because they provide flexible frequency filtering that is needed for a variety of applications. So, for dealing with analog and mixed-signal systems, it is essential to comprehend their operating principles and design concerns. RLC values can be chosen such that shown in figure 4.6 such that when designing RLC filters, the proper values for R, L, and C must be chosen in order to provide the required frequency response properties, such as bandwidth, selectivity, and cutoff frequency.

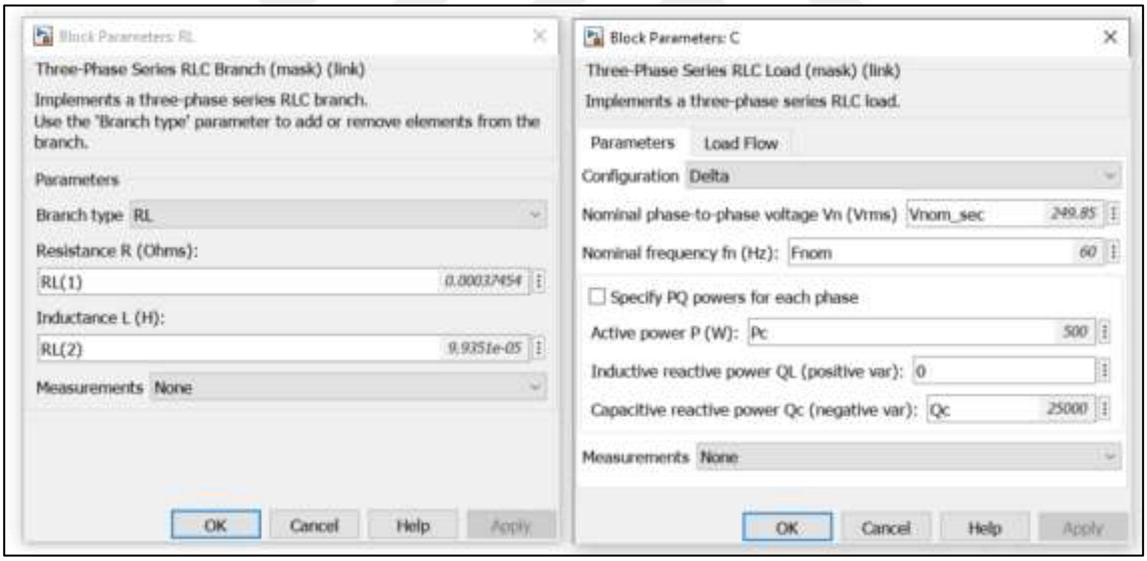


Figure 4.6: RLC Requirements.

4.5.3 MPPT Block Diagram

In photovoltaic (PV) systems, the Maximum Power Point Tracking (MPPT) technology is used to optimize the power production from solar panels by continually adjusting the panels' operating point to their maximum power point (MPP). The point at which a solar panel produces its highest amount of electricity production for a particular temperature and sunshine intensity is known as the maximum power point, or MPP. It happens at a certain voltage and current combination called the MPP voltage and MPP current.

The voltage-current characteristics of solar panels are nonlinear, and their output power fluctuates in response to temperature and irradiance variations. Reduced power output and efficiency would result from the PV system's inability to operate at the MPP under different environmental circumstances in the absence of MPPT.

With the use of MPPT block diagram as shown in figure 4.7, the PV system can continually monitor changes in the surrounding environment and modify the solar panels' operating point to maintain maximum power production.

In PV inverters or charge controllers, MPPT algorithms are commonly implemented through the use of microcontrollers or digital signal processors (DSPs). These algorithms compute the power-voltage characteristic, track the MPP by adjusting the operating point, and continually check the solar panels' output. Analog-to-digital converters (ADCs) are a tool that MPPT controllers may utilize to assess voltage and current. They can also employ digital signal processing techniques to apply the MPPT algorithm.

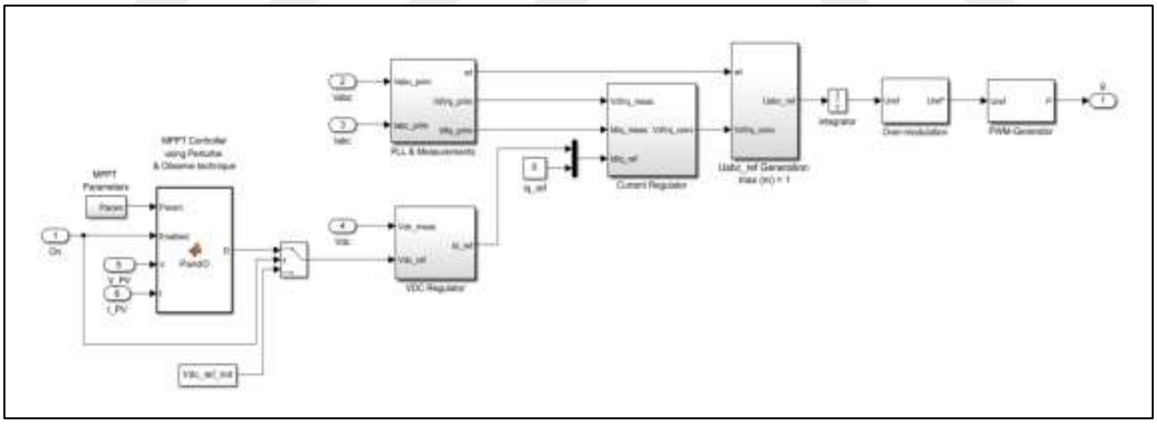


Figure 4.7: MPPT Block Diagram.

By optimizing solar panel energy harvesting, MPPT raises system efficiency and boosts energy production. It enhances PV systems' overall performance, particularly in environments with variable temperature and irradiance. By maximizing the use of available sunshine, MPPT makes it possible to create solar energy systems that are both more affordable and efficient. Maximizing the power production of solar panels and enhancing the efficiency and reliability of photovoltaic systems need the use of MPPT technology. It helps solar energy systems function as best they can under a variety of environmental circumstances, which promotes the broad use of solar energy as an alternative source of energy.

4.5.4 Phase-Locked Loops (PLL)

Phase-Locked Loops, or PLLs, are a popular type of control system that produces an output signal that has a phase that is correlated with the phase of an input signal. Fundamentally, a PLL compares the phase of a locally produced signal (feedback signal) with an input signal (reference signal). Phase-locking is achieved by matching the reference signal's frequency and phase with those of the feedback signal.

The main components of PLL that used in simulation shown in figure 4.8 are:

a. Phase detectors (PDs) provide error signals that are proportionate to the phase difference that exists among the reference and feedback signals.

b. The frequency of an output signal generated by a voltage-controlled oscillator (VCO) is set by the input control voltage. A PLL modifies the VCO frequency in response to the error signal received from the phase detector.

c. Low-Pass Filter (LPF): This device filters phase detector output to eliminate harmonics and high-frequency noise, giving the VCO a smooth control voltage.

d. Divider (Frequency Divider): Splits the VCO output signal's frequency into smaller feedback signals that may be compared to the reference signal.

The input frequency range that the PLL can pick up and lock onto an input signal is known as the capture range. The phase detector's bandwidth and the loop filter's properties dictate this. The input frequency range that the PLL can retain lock across after capturing the input signal is known as the lock range. The loop filter's properties and the VCO's maximum frequency deviation capacity dictate this.

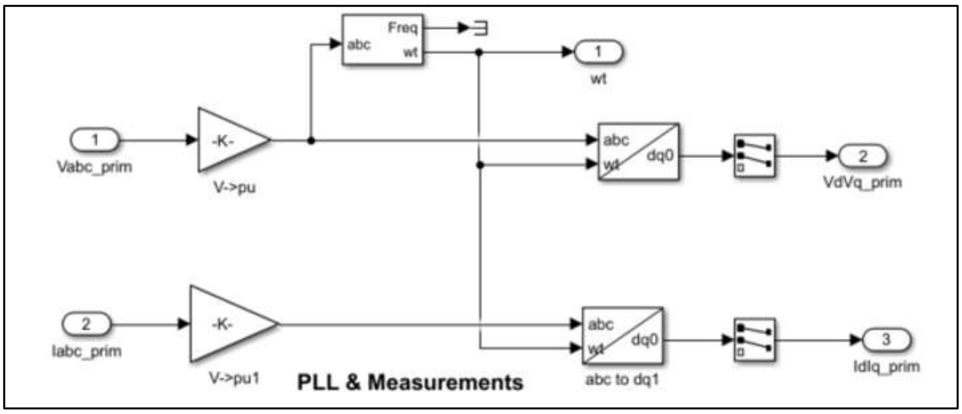


Figure 4.8: PLL Block Diagram in Matlab Simulation.

PLLs are utilized in many different contexts, such as:

a. Frequency synthesis is the process of creating accurate and consistent clock signals for digital devices including data capture, communication, and microprocessor systems.

b. Frequency demonstration is the process of taking data out of modulated signals, such phase- and frequency-shift keyed (PSK) and frequency-shift keyed (FSK) signals.

c. Phase and Frequency Synchronization: Coordinating the phase and frequency of signals in instruments, radar, and communication systems.

d. Clock and Data Recovery (CDR): In high-speed communication systems like gigabit Ethernet and optical communication, CDR is the process of recovering the clock signal from serial data streams.

e. Digital PLL (DPLL): Provides flexibility and programmability by digitally implementing PLL functions using digital signal processing methods. Fractional-N PLL: By permitting fractional frequency division in the feedback loop, this PLL improves spurious performance and frequency resolution.

Loop stability, phase noise, spontaneous performance, and setting time requirements are all carefully taken into account during PLL design. A key factor in influencing the dynamic responsiveness, stability margins, and timing of acquisition of the PLL is the loop filter design.

PLLs are flexible control systems that are extensively employed in many different applications to synchronize phase and frequency, demodulate modulated signals, and provide steady clock signals. Engineers in the communications, signal processing, and instrumentation domains need to understand the fundamentals and workings of PLLs.

4.5.5 Current Regulator Circuit Diagram

A circuit that sustains a constant output current regardless of changes in input voltage or load resistance is known as a current regulator. The fundamental schematic design of a circuit for a current regulator shown in figure 4.9 that uses a power transistor and an operational amplifier (op-amp).

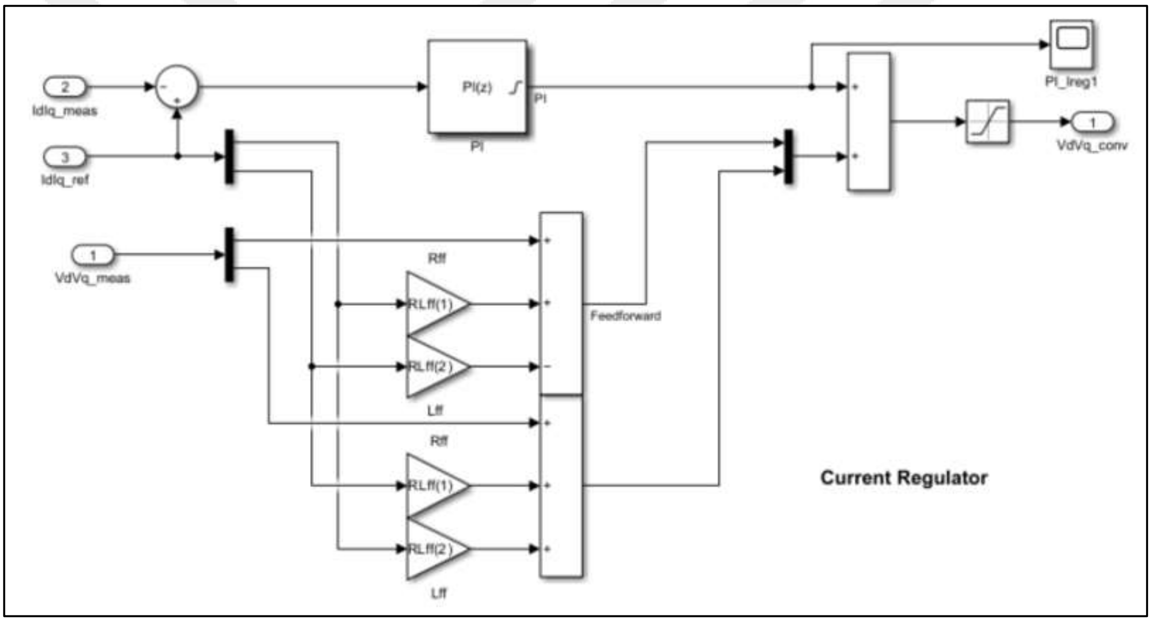


Figure 4.9: Block Diagram of Current Regulator.

Current regulators are essential in various electronic systems for maintaining a constant output current. They are used in LED drivers to ensure uniform brightness and color consistency, while in battery charging systems to prevent overcharging and damage to the battery. In motor control circuits, they help achieve precise speed and torque control, enhancing system reliability. In audio amplifiers, they bias output transistors and stabilize the amplifier's operating point, improving linearity and reducing distortion. Current regulators can be integrated into voltage regulator circuits to improve load regulation and transient response, offering superior stability and accuracy. In solar energy systems, they ensure efficient energy delivery from solar panels, optimizing power transfer and energy conversion, improving system efficiency and performance. Overall, current regulators play a crucial role in various electronic systems.

Current Regulators' Advantages:

a. Stability: Under a range of operating situations, electronic systems operate consistently thanks to current regulators, which produce steady and predictable output currents.

b. Protection: Current regulators shield delicate electronic components from harm caused by overcurrent situations by regulating the output current to a safe level.

c. Efficiency: By providing the necessary current to the load without experiencing unnecessary losses, current regulators reduce dissipation of power and energy waste, enhancing the overall efficiency of the system.

d. Accuracy: Current regulators provide accurate control over the output current, enabling accurate control and regulation of current in a variety of applications, including those that call for a high degree of precision and accuracy.

e. Flexibility: Current regulators are appropriate for a variety of electronic systems and may be readily modified and designed to match particular application needs.

4.5.6 Vref Generation

Generating voltage reference (Vref) is an essential component of many electronic systems because it offers an accurate and steady reference voltage for a range of uses, including voltage control, sensor calibration, biasing circuits, and analog-to-digital conversion. The process of producing a voltage source that is accurate and stable despite changes in supply voltage, temperature, and other external conditions is known as voltage reference generation as shown in figure 4.10. For other electronics in the system, the reference voltage acts as a calibration or point of comparison.

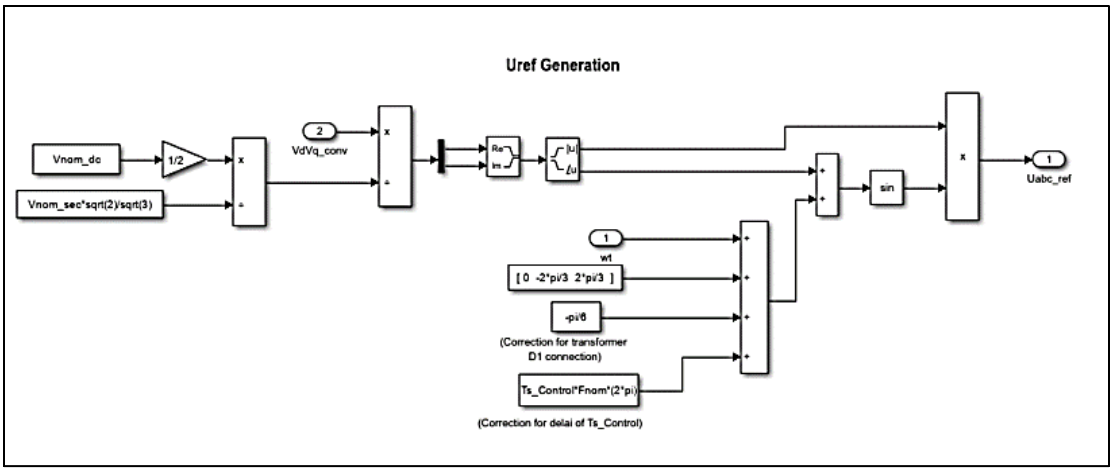


Figure 4.10: Voltage Reference Generation

The reference voltage (Vref) is a crucial component in electronic systems, ensuring accuracy, stability, and reliability. It should have high accuracy, remain constant under varying conditions, have a low temperature coefficient, exhibit low noise, and consume minimal power. Vref is used in various applications such as analog-to-digital converters, DACs, sensor interfaces, voltage regulators, precision instrumentation, data acquisition systems, and communication systems. Its advantages include providing a stable and accurate voltage reference for analog and mixed-signal circuits, enabling precise measurements and conversions, and reducing dependency on external voltage sources and environmental conditions. Therefore, choosing the right voltage reference and designing the circuitry carefully are essential for optimal system performance.

4.6 PV SIMULATION RESULTS

PV array implementation made of parallel-connected strings of PV modules. Modules comprise each string and are linked in a sequential order. application of a model of battery and specification of the effects of age and temperature on Lithium-Ion batteries. The PV simulation research aims to evaluate a photovoltaic (PV) system's behavior and performance in a range of environmental scenarios and system configurations. The objective is to get an understanding of how many elements, including temperature, solar irradiation, panel orientation, and shading, affect the PV system's efficiency and ability to produce energy through simulations.

i. Analyze the PV system's setup and design for efficacy and dependability.

ii. Determine the main variables affecting system performance and energy generation.
iii. In order to improve energy yield and efficiency, optimize system parameters.
iv. Give decision-makers information to help with the design, installation, and operation of PV systems.
v. Examine simulated data to verify theoretical models and assumptions.
vi. Examine possible avenues for innovation and advancement in PV applications and technology.

In general, the examination of simulation outcomes seeks to expand understanding.

4.6.1 DC Link Voltage

In a photovoltaic (PV) system, the voltage ranges at the DC bus or intermediate DC circuit—where the electricity produced by the solar panels is gathered and sent to the inverter for conversion into AC power—is referred to as the DC link voltage. The voltage level that is maintained between the DC bus's positive and negative ends in a photovoltaic system is known as the DC link voltage. It shows the variance in electrical potential that is available for the photovoltaic cells and the inverter to conduct direct current (DC). Since the DC link voltage directly affects the effectiveness and performance of the power conversion process, it is essential to the PV system's functioning. It establishes the most power that the solar panels may deliver to the inverter and subsequently to the grid or load.

The photovoltaic voltage (V_{PV}) and the photovoltaic current (I_{PV}) are the electrical output of a solar panel or a series of solar panels in a photovoltaic system is characterized by these characteristics, which are important variables. Figure 4.11 demonstrates both voltage and current at a simulation time of 0.5 minutes.

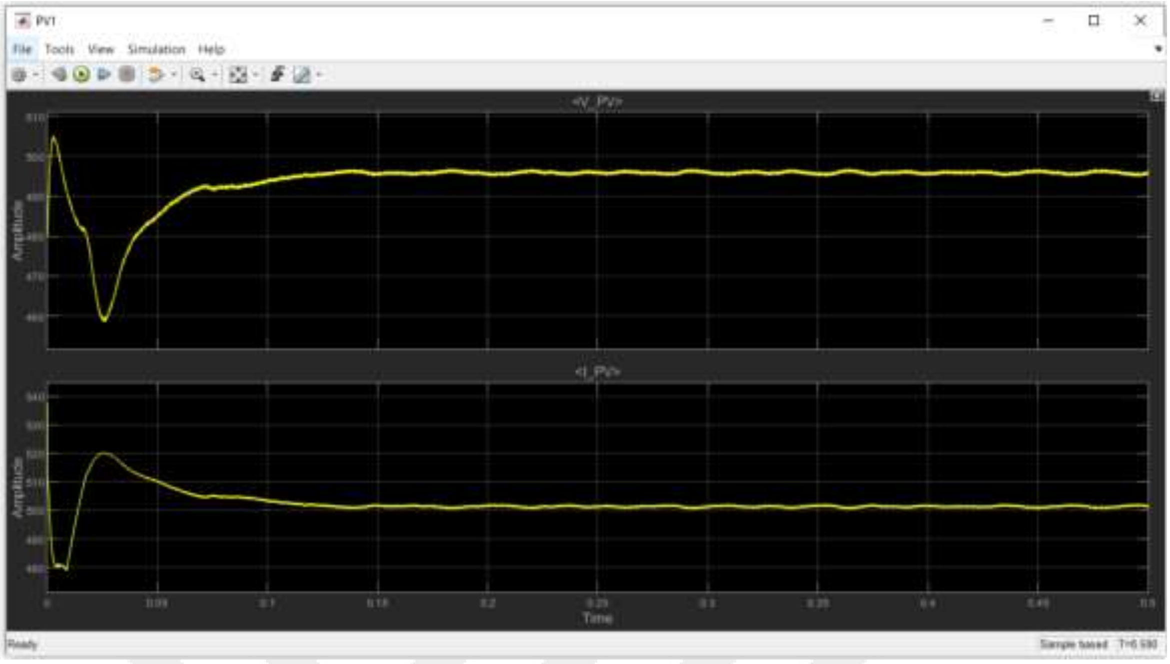


Figure 4.11: Both V_{PV} & I_{PV} at a Simulation Time of 0.5 Minutes.

V_{PV} is the voltage output of a solar panel or a series of solar panels under particular operating circumstances. It is the DC voltage that the solar cells produce when they are exposed to sunlight and is dependent on a number of variables, including temperature, shading, solar irradiation, and PV system setup. Because V_{PV} must be within the equipment's allowed input voltage range, it is an essential characteristic for establishing whether solar panels are compatible with inverters and other system components. Figure 4.12 specifies the V_{PV} amplitude for 495 V steady state

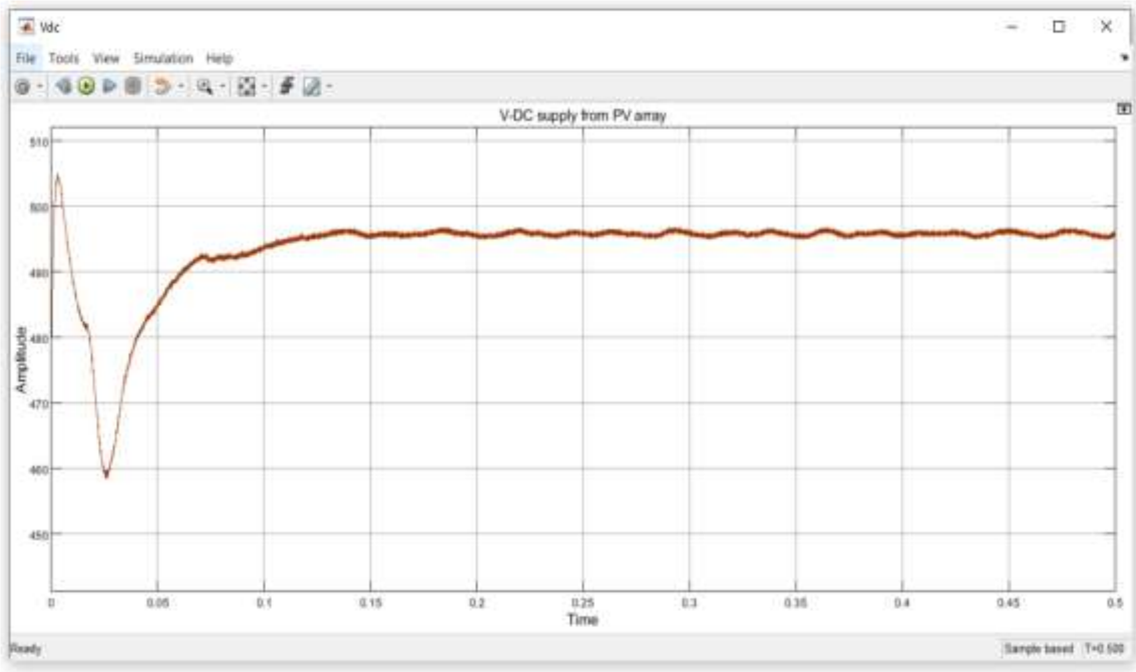


Figure 4.12: The V_{PV} Amplitude at 0.500 Sec.

4.6.2 L-L voltage After Inverter

The line-to-line voltage of the AC output generated by the inverter in a photovoltaic (PV) system is referred to as the "L-L voltage after Inverter". Once the inverter transforms the DC power produced by the solar panels into AC power, the AC voltage output is commonly monitored between two phases in a three-phase system. This measurement shows the AC output's L-L voltage. The single-phase or three-phase PV system layout, the load requirements, and the inverter's design and specifications are some of the elements that affect the L-L voltage after the inverter. Within a three-phase PV system, the voltage between any two of the three phase wires (e.g., R-Y, Y-B, B-R) is referred to as the L-L voltage.

In order to avoid overvoltage or under voltage situations that might harm equipment or present safety risks, it is essential to make sure that the L-L voltage after the inverter conforms with safety requirements and grid rules. One important metric in photovoltaic systems is the L-L voltage after the inverter, which indicates the AC output voltage that may be connected to the grid or distributed to electrical loads. In order to guarantee the PV system's dependable and effective functioning as well as its integration with the electrical infrastructure, this voltage must be monitored and controlled.

Figure 4.13 shows the L-L voltage after the inverter denoted by Vab, Vbc, and Vca with a maximum of 500 V for a period of 0.500 sec. The design and requirements of the inverter, the PV system's configuration (e.g., single- or three-phase), and the needs of the electrical system to which it is linked all affect the three-phase L-L voltage following the inverter. The PV system's design characteristics and the inverter's specs dictate the voltage level of a single phase L-L voltage after the inverter. To guarantee steady and dependable operation of the electrical system, the voltage level is usually controlled within predetermined bounds. In order to evaluate the PV system's health and performance, it is important to track the three-phase L-L voltage after the inverter. Control algorithms can be used to maximize the performance of the inverter and guarantee the electrical system's reliability and effectiveness.

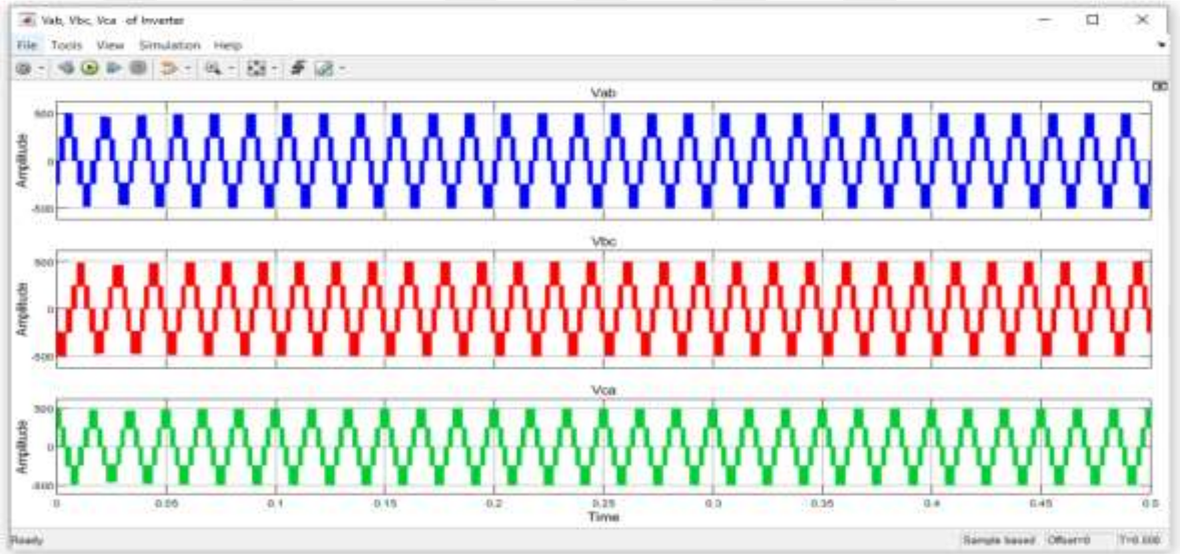


Figure 4.13: The L-L Voltage after the Inverter Denoted by Vab, Vbc, and Vca for a Period of 0.500 sec.

4.6.3 L-L voltage and Current After Filter

In a photovoltaic (PV) system, the voltage and current levels between any two of the three phase connections and the associated current flowing through them after going through a filtering circuit are referred to as the line-to-line (L-L) voltage and current after the filter. The inverter's AC output may go through a filter circuit after it to lower harmonics and enhance the quality of the AC electricity. By reducing harmonic distortion and electromagnetic interference, the filter guarantees that the AC output satisfies grid requirements and doesn't damage delicate electrical equipment. The filter circuit's design and properties, such as its type (passive or active), setup, and tuning parameters, affect the L-L voltage and current after the filter. To reduce undesirable frequency components and smooth out the AC waveform, the filter circuit may include resistors, capacitors, and inductors placed in particular designs.

It is crucial to monitor the voltage and current levels following the filter in order to evaluate the filter's efficacy and guarantee that grid requirements are being followed. Control algorithms can be used to optimize the filter's performance and modify its settings in response to system conditions and real-time data. For the PV system to operate safely and dependably as well as to be integrated into the electrical grid, it is imperative that the L-L voltage and current following the filter shown in figure 4.16 are stable and of high quality. Voltage swings, overcurrent situations, and other such risks must be avoided by adhering to safety and legal requirements.

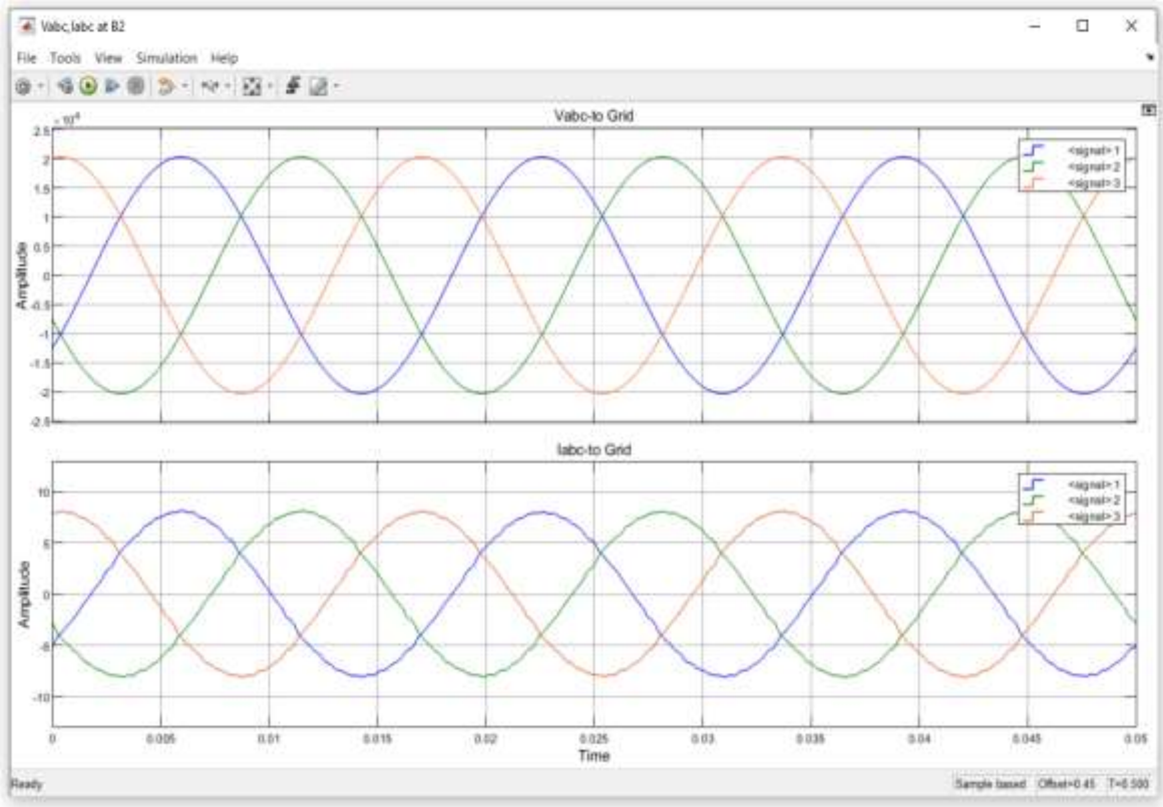


Figure 4.16: The L-L Voltage and Current Following the Filter.

4.6.4 L-L voltage After Filter and Transformer

The line-to-line (L-L) voltage after the filter and transformer in a photovoltaic (PV) system refers to the voltage level between two AC output conductors after passing through a filtering circuit and a transformer. The filter circuit reduces harmonics and improves the quality of the AC power, while the transformer adjusts the voltage level to match the electrical grid or connected loads. The L-L voltage depends on the design and characteristics of both the filter circuit and transformer, including their types, configurations, and specifications.

Both the filter circuit and transformer stabilize the voltage waveform, ensuring it meets grid requirements and does not cause disturbances or damage to electrical equipment. Proper design and tuning of the filter and transformer are essential for effective filtering and voltage transformation without introducing excessive voltage drops or impedance mismatches as shown in figure 4.17. Monitoring and control of the L-L voltage after the filter and transformer are crucial for assessing the effectiveness of filtering and transformation processes and ensuring compliance with grid standards.

Safety considerations are essential for the safe and reliable operation of the PV system and its integration with the electrical grid or loads. Compliance with safety and regulatory standards is necessary to prevent voltage fluctuations, overcurrent conditions, and other potential hazards.

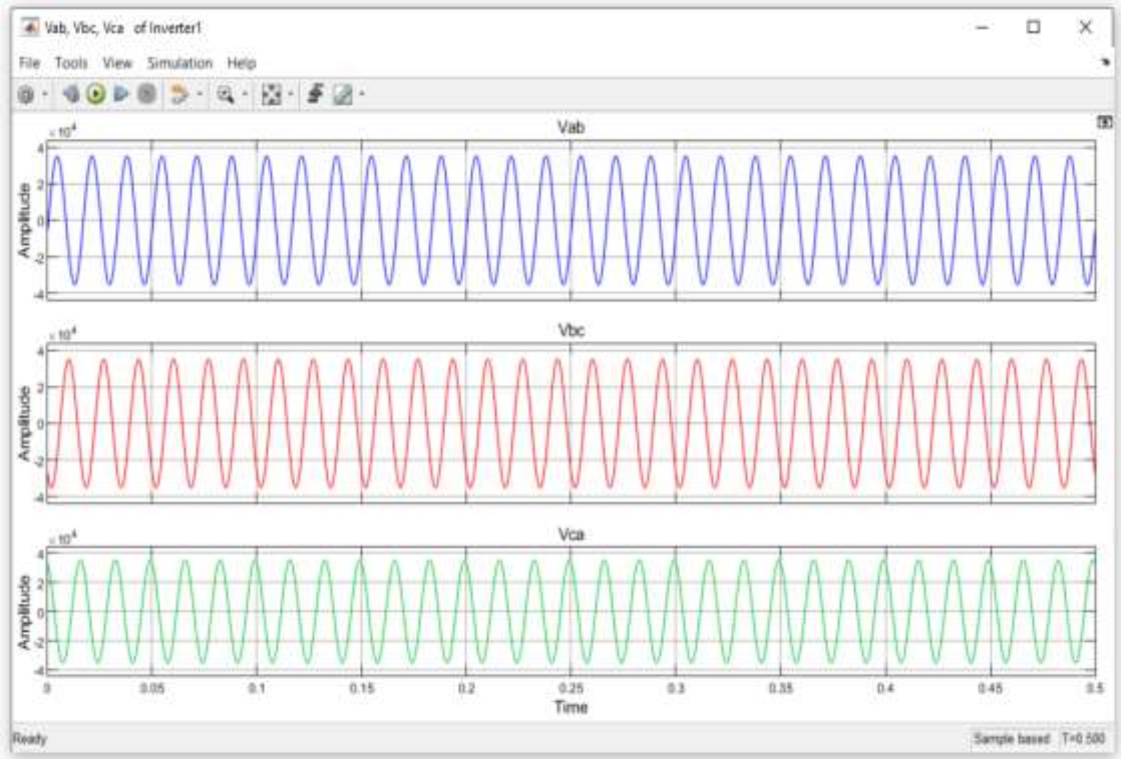


Figure 4.17: The Effective Filtering and Voltage Transformation.

4.6.5 Inverter PWM

The process of controlling the output voltage and frequency of inverters—which transform DC power from sources like photovoltaic (PV) panels or batteries into AC power appropriate for use in electrical systems—is known as inverter pulse width modulation, or PWM. It entails quickly flipping the inverter's power components, such MOSFETs or IGBTs, from the completely on to the totally off state. The output waveform's effective voltage and frequency may be adjusted by adjusting the pulse width, or on-time.

The inverter in a photovoltaic system receives the DC power from the solar panels and transforms it into AC power. Using control algorithms, the PWM control circuit of the inverter modifies the switching signals' duty cycle as well as feedback signals.

At high frequencies (usually several kHz to many tens of kHz), the PWM signals regulate the transistors in the inverter, causing them to turn on and off. The output waveform's AC frequency is substantially lower than the switching frequency. The output AC waveform's average voltage and frequency may be tuned to the demands of the loads attached or the electrical grid by varying the PWM duty cycle of signals.

Figure 4.18 shows the PWM for all three phases corresponding to the 3-phase output voltage. PWM control is a high-efficiency method for converting DC power to AC power with minimal losses. It offers flexibility in output voltage and frequency, low harmonic distortion, and fast response to changes in load conditions. Implemented using microcontroller-based or DSP control circuits, it generates PWM signals based on input from sensors, control algorithms, and user commands. Various modulation techniques, such as sinusoidal, space vector, and carrier-based PWM, can be used. PWM is widely used in grid-tied PV systems, off-grid solar inverters, and motor drives.

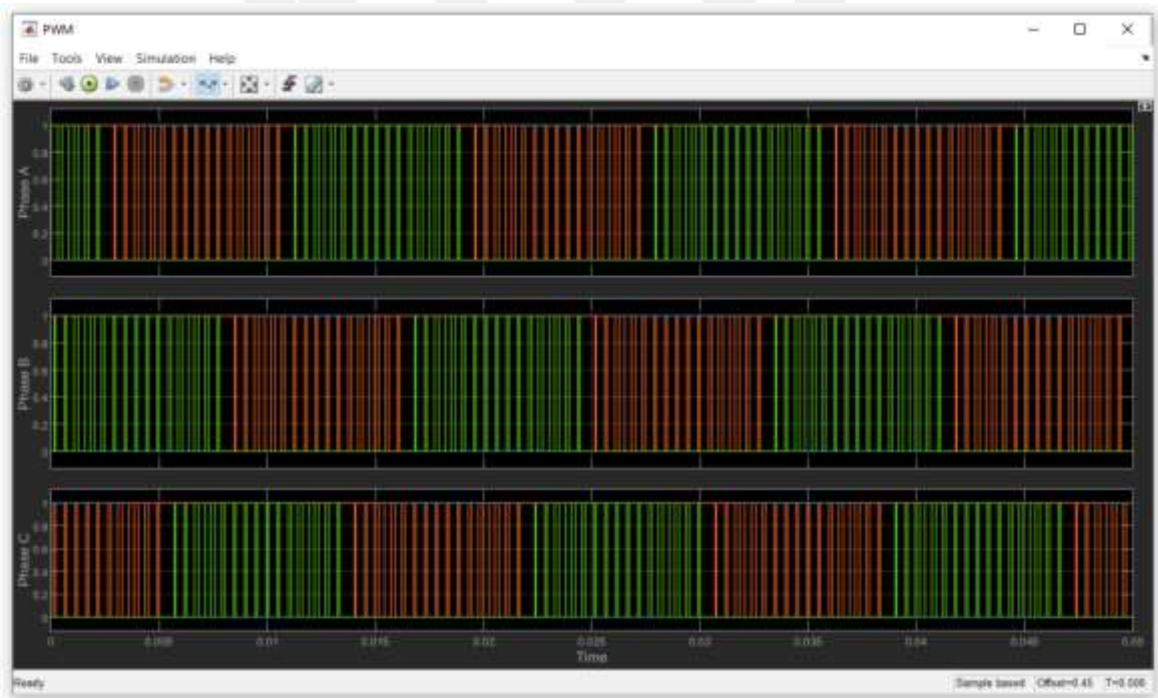


Figure 4.18: The PWM for All Three Phases Corresponding to The 3-Phase Output Voltage.

4.6.6 Fast Tourier Transform (FFT)

The FFT, or fast Fourier transform, is used to effectively convert signals from the temporal or spatial domain to the frequency domain and vice versa. The Discrete Fourier Transform

(DFT) of a series of data points can be calculated using the Fast Fourier Transform (FFT) method. It breaks down a signal into its constituent frequency components, exposing the phase and amplitude of each frequency.

FFT is frequently used to evaluate and work with signals in the frequency domain in a variety of applications, including communications, picture processing, audio processing, and signal processing.
Operation: The FFT method efficiently computes the relevant frequency components in 0 (N log N) time complexity given a sequence of N data points representing a signal in the temporal or spatial domain.

The Fourier transform (FFT) generates a set of complex values that indicate the phase and amplitude of every frequency component in the input. The FFT algorithm takes use of the periodicity and symmetry qualities of sinusoidal functions to improve computing efficiency by breaking down the DFT computation into smaller sub-problems through a series of recursive divide-and-conquer stages.

4.6.7 Total Harmonic Distortion (THD)

Total Harmonic Distortion, or THD, is a measurement of how much a signal has been distorted in relation to its primary frequency component. In relation to the energy of the fundamental frequency, it estimates the total energy of harmonic components. THD is frequently represented as a percentage in electrical engineering and is computed using the following formula:

$$\mathrm{THD} = \frac{\sqrt{H_2^2 - H_3^2 + \cdots + H_n^2}}{H_1} \times 100\% \qquad (4.1)$$

Where $H1$ is the fundamental frequency component amplitude, and H_2,H_3, …,Hn are the amplitudes of the harmonic frequency components.

When evaluating the performance of electrical power, audio transmissions, and electronic equipment, THD is a crucial metric to consider. Better signal fidelity and less distortion are indicated by lower THD levels.

Figure 4.19 displays the FFT of the selected signal and the fundamental THD that measures the distortion in a signal with respect to its fundamental frequency component, FFT is used to examine a signal's frequency content. To reliably evaluate signal quality and extract harmonic components, FFT is frequently used in the computation of THD.

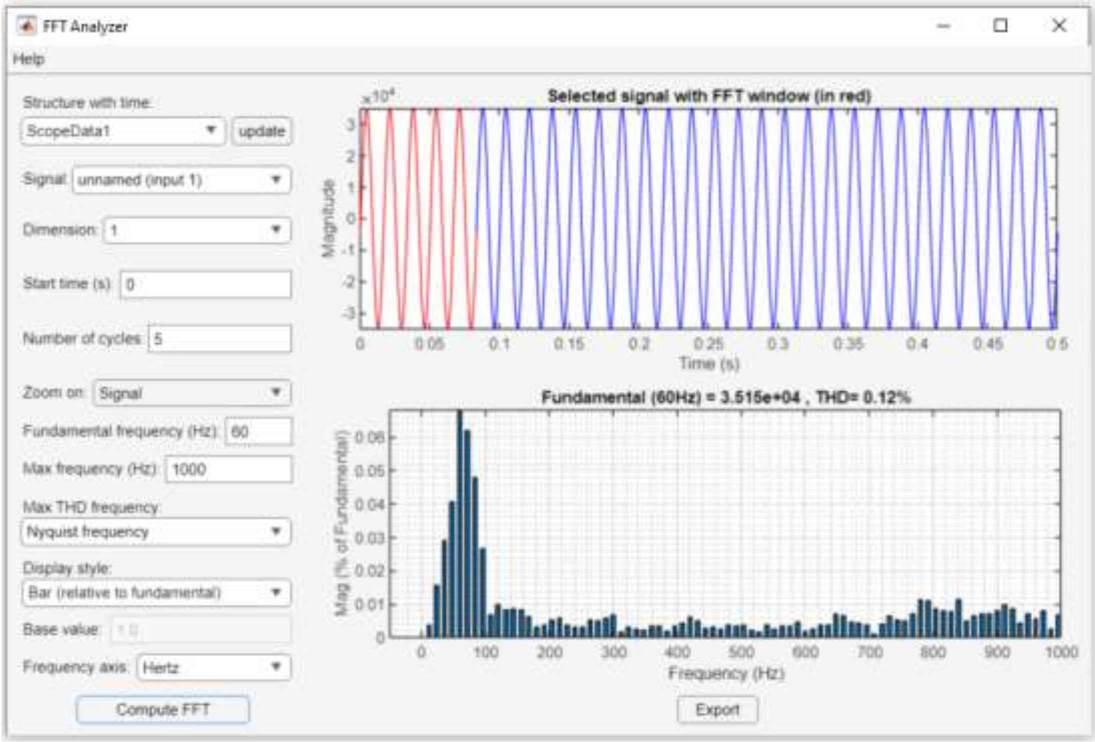


Figure 4.19: The FFT of the Selected Signal and The Fundamental THD.

4.6.8 Power to Grid

The process of delivering electrical power produced by a renewable energy source, like a photovoltaic (PV) system, into the utility grid is referred to as "power to grid." Renewable energy sources, like solar panels in a photovoltaic system, produce electricity by converting natural resources, like sunshine, into electrical power. Sunlight is transformed into direct current (DC) electricity in solar panel technology.

Inverter Conversion: In order for the DC electricity produced by the renewable energy source to work with the utility grid, it must be converted into AC electricity. An inverter is used to accomplish this conversion, turning DC electricity into AC power.

After the DC electricity is transformed into AC power, it is phased and frequency synchronized with the utility grid. The point of common coupling (PCC), which is usually located at the point where the PV system and the grid link, is then used to feed the AC power into the grid infrastructure. The electrical grid network distributes the AC power produced by renewable energy sources so that homes, companies, and other grid-connected electricity customers can use it. There is less need for power produced from traditional fossil fuel sources when it comes from renewable energy sources, which augment the grid's overall power supply.

The power supplied to the grid as shown in figure 4.20 starts at zero, indicating that the power generation system, possibly a photovoltaic (PV) system, is not yet generating electricity. The power output gradually increases to a maximum capacity of around 250 kW as the sun rises or cloud cover decreases. A sudden rise of more than 250 kW could occur due to a sudden change in environmental conditions or operational parameters affecting the PV system. After the sudden rise, the power supplied to the grid becomes constant, indicating that the PV system has reached its maximum power output capacity, limited by factors such as the size of the PV array, the efficiency of the PV panels, and the capacity of the inverter. This behavior reflects the dynamic response of a PV system to changing environmental conditions, with the power output increasing gradually with sunlight intensity, experiencing a sudden surge due to transient factors, and eventually stabilizing at its maximum capacity.

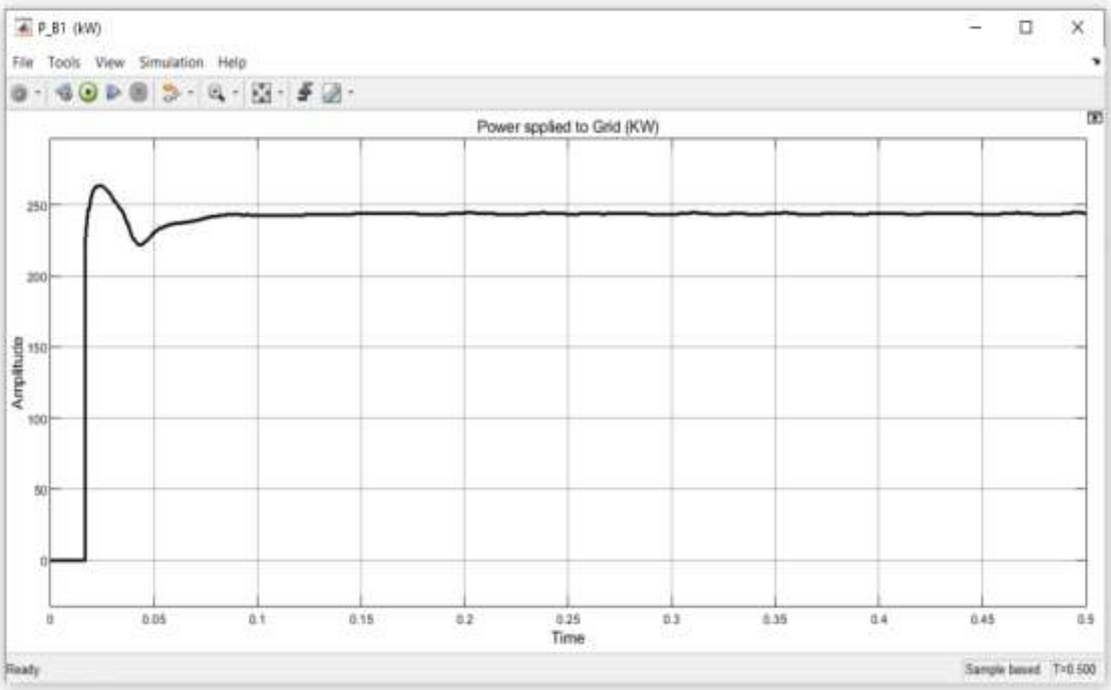


Figure 4.20: The Power Supplied to Grid of 250 KW.

Finally, a scenario described the demonstration of a specific behavior in the operation of a photovoltaic (PV) system shown in figure 4.21. The PV system initially generates electricity at a constant irradiance of 1000 W/m², with a DC voltage of 250 V. As sunlight intensity remains constant, the output voltage gradually increases to 500 V. The power output starts at 0, indicating it is not yet generating significant power. However, as the voltage increases and sunlight remains constant, the power output rises rapidly. After 0.01 seconds, the power output reaches 250 kW, indicating the PV system has reached its maximum power point (MPP). The constant irradiance of 1000 W/m² and the constant DC voltage of 500 V contribute to maintaining the power output at a stable level of 250 kW. This behavior reflects the dynamic response of a PV system to changes in irradiance and DC voltage, with the power output increasing rapidly to its maximum level as the system operates at its maximum power point.

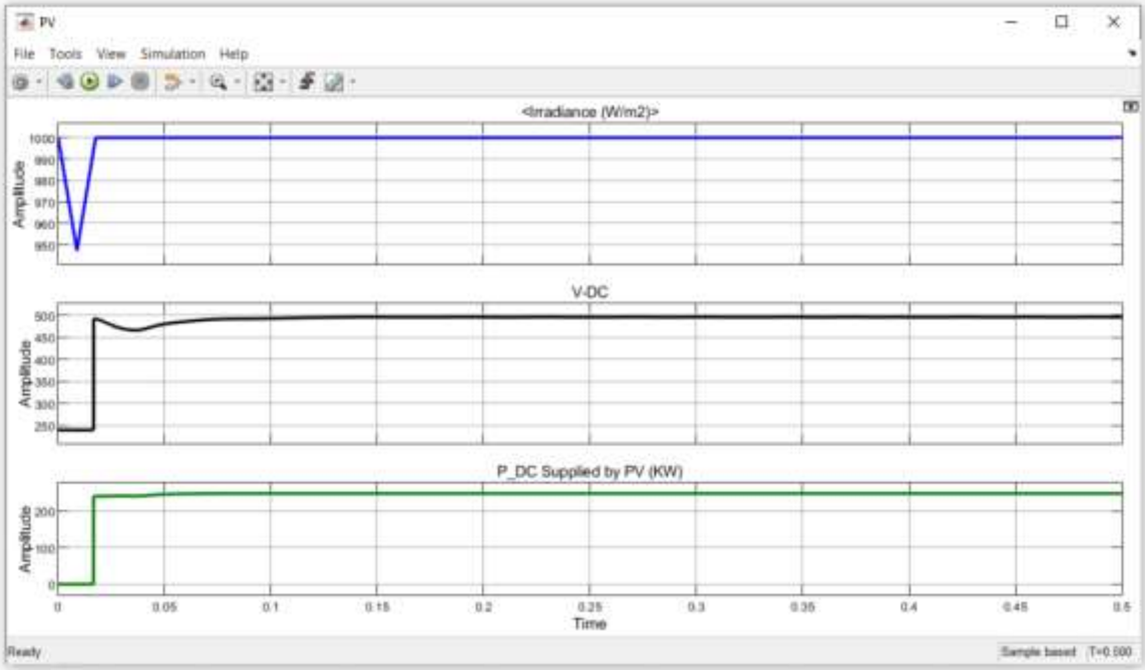


Figure 4.21: The Demonstration of A Specific Behavior In The Photovoltaic (PV) System Operation.

4.7 SUMMARY

This chapter discusses the operation, behavior, and control of a photovoltaic (PV) system, which converts solar energy into electrical power using panels. Key components include solar panels, inverters, filters, transformers, and monitoring/control systems. The system's behavior is influenced by factors like sunlight intensity, shading, and system design. Power output varies with irradiance, temperature, and system configuration. PWM techniques control inverter output voltage and frequency, while FFT analyzes frequency content. Total Harmonic Distortion (THD) measures signal distortion. PV systems supply power to the grid through inverters, converting DC power to AC power. Net metering arrangements allow consumers to receive credits for surplus power fed back into the grid. Understanding system dynamics is crucial for efficient operation.

5. RESULTS AND DISCUSSIONS

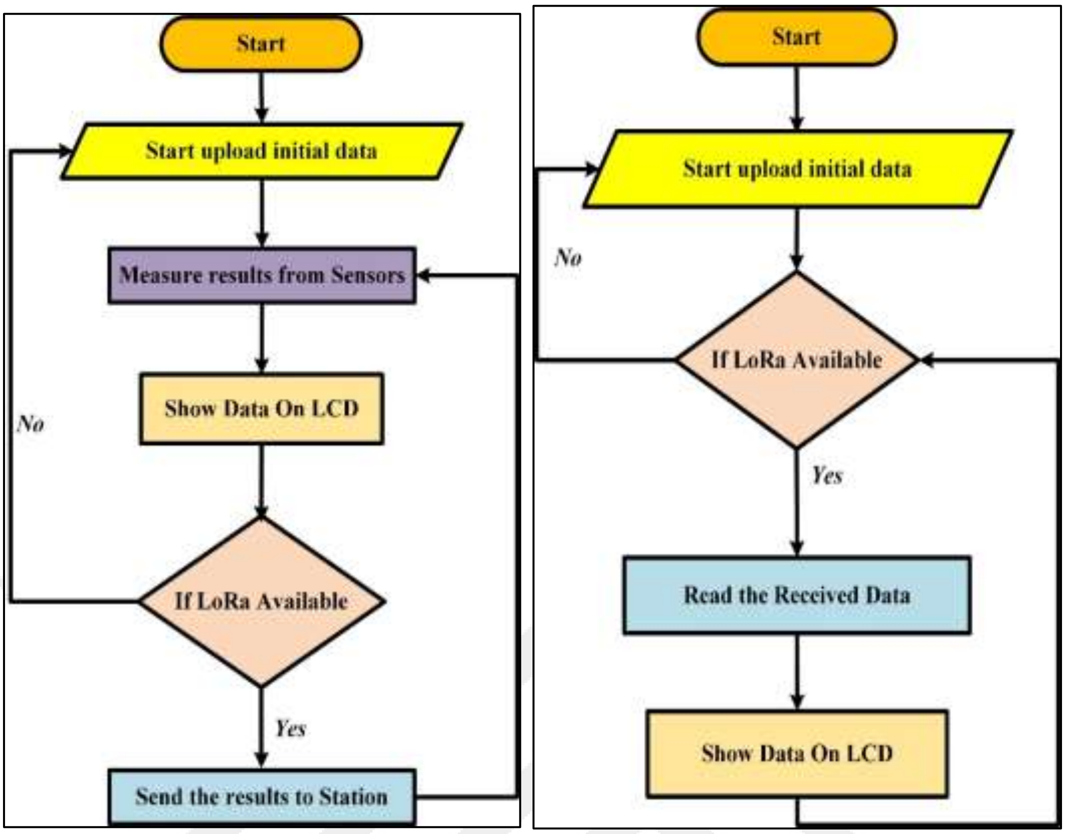
5.1 INTRODUCTION

The chapter of Experimental Configuration with Results provides an important overview of the research project or study's practical features when it comes to monitoring the performance in real time of a photovoltaic (PV) system employing Internet of Things technology. The configuration, parts, and methods used to carry out tests meant to track a PV system's performance in real time are the main topics of this chapter.

All of the electronic parts (sensors and microcontrollers) used in our project were described in the chapter before this one. The project's final system was developed and put into operation using these components. The main objective of this system is to use Internet of Things technology to monitor PV system performance in real-time.

5.2 EXPERIMENTAL RESULTS

A block diagram of the data monitoring process is shown in Figure 5.1. The procedure starts with the LCD display and Wi-Fi module ESP-8266 initialization, assuming the Wi-Fi module is connected to the router. The parameters under observation are recorded as strings and exhibited on the LCD display. Figure 5.1 shows a block schematic of the transmitter and receiver procedure for data monitoring. Initialization, data uploading, sensor measurement, data verification, and LoRa transmission are the first steps in the transmitter procedure (a). On the receiving end (b), a LoRa is examined following the upload of the received data. The parameters of the monitored data will be displayed on the LCD screen and saved as strings.



(a) (b)

Figure 5.1: Block Diagram for Transmitter (a) and Receiver (b)

The "Start" icon initiates the application and uploads first data to ensure precise monitoring. The photovoltaic system's sensors are then used to read data, measuring solar voltage, current, power, and frequency, among other factors. The LCD display of the results enables prompt on-site monitoring and analysis. The data is sent to the ThingSpeak cloud platform, which allows for remote access, monitoring, and storage, if Wi-Fi is accessible. The scalability and accessibility of real-time monitoring systems are improved by this step. The procedure of the software guarantees precise tracking and effective system functioning.

The architecture of the suggested system is dependable and functions effectively to display gathered data in real time. Five examples collectively show variations in voltage levels, current demands, and power usage, illustrating the dynamic behaviour of the system. These features need to be watched in order to assess the system's performance, spot possible problems, and ensure that it operates within the parameters that have been set.

Power Pac (W) for Active: It shows how much power the system's load actually consumes or generates. It is measured in watts (W). Pac depicts the real power that is converted to useful work or dissipated as heat. Active power monitoring is necessary to assess how well the system is utilizing its electrical energy.

Current Iac: Iac is a representation of the pace at which electric charge moves through the system. To ensure that the electrical components and conductors can handle the load without going above their rated capacity, it is imperative to monitor the current.

V(Battery), which is expressed in volts (V), quantifies the electrical potential difference in the battery. It is essential for figuring out the condition and charge level of the battery. By keeping an eye on battery voltage, you can make sure the energy storage device works within the suggested voltage range.

AC Voltage Vac: In order to ensure that the electrical appliances and equipment connected to the system receive the voltage they require to operate correctly; it is imperative to monitor the AC voltage. Variations in the reference voltage may impact the functionality of linked devices.

The free program Fritzing was used to construct Figure 5.2, which shows the system configuration of the completed circuit. Anyone may use it to develop, test, and work together on other people's electrical notions to create a schematic and, at the end, a finished product that can be wired into wire diagrams. It's even better to create your own PCB design files [25].

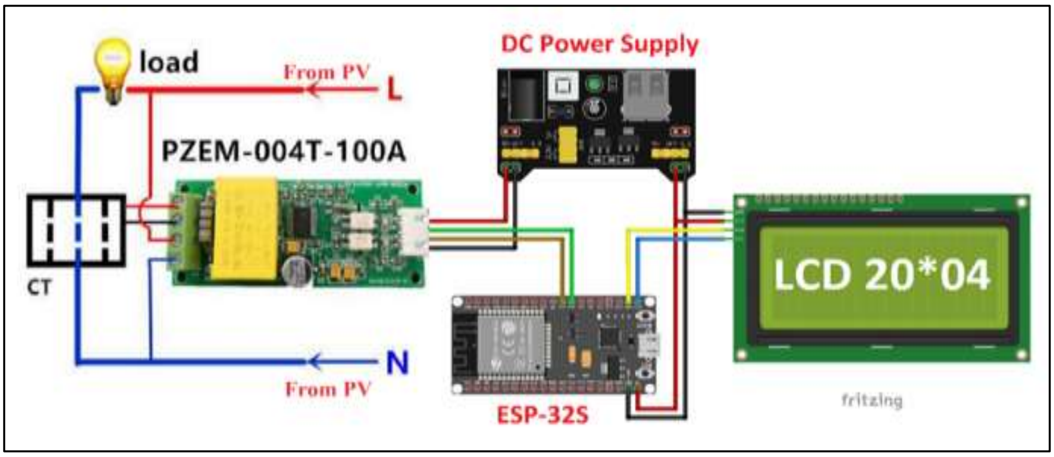


Figure 5.2: Final Circuit's System Configuration in Fritzing.

The final, workable monitoring circuit design for the PV system's real-time performance is displayed in Figure 5.3. This circuit explains the parts, configuration, and testing process used to track the real-time performance of the photovoltaic system.

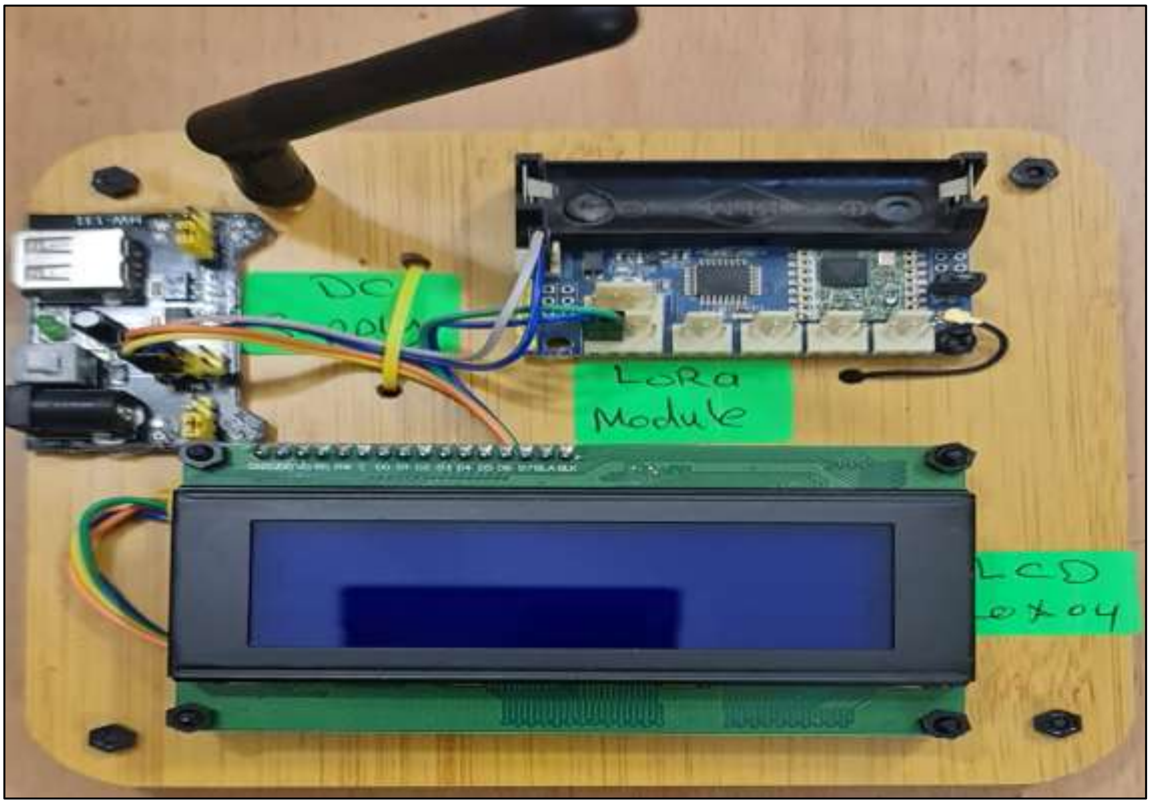


Figure 5.3: Monitoring Circuit Design for The PV System's Real-Time Performance.

5.2.1 System Results on LCD

Figure 5.4 shows a detailed image of the PV single-phase system monitoring system's real-time functioning in response to load fluctuations on the LCD. A visual snapshot of several parameters, such as power output, voltage, and current, as well as how the system responds to different loads, are provided via the LCD's value representation. For assessing a system's performance and stability in a range of operating scenarios, these data are crucial. The results shown on the LCD serve as a real-time monitoring tool for on-site assessment and offer helpful information for enhancing the PV systems under different load circumstances. This graphic aids in confirming the PV system's resilience under a variety of load profiles and provides further insight into how the monitoring system responds to variations in demand. It also helps to improve operational strategies.

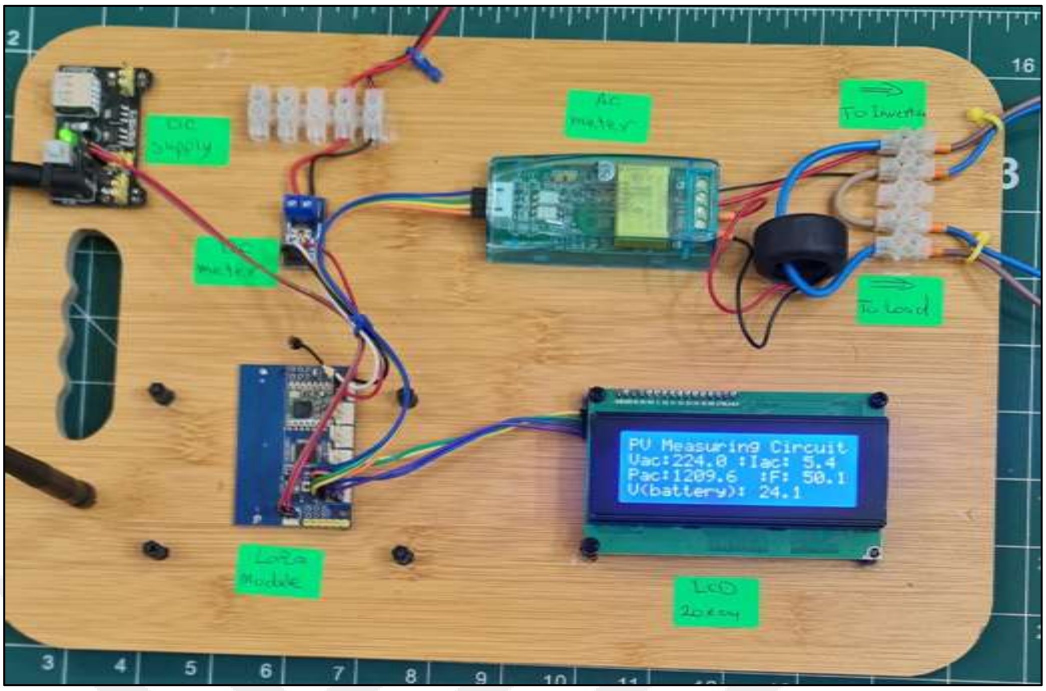


Figure 5.4: First Real-Time Operation of The PV Monitoring System.

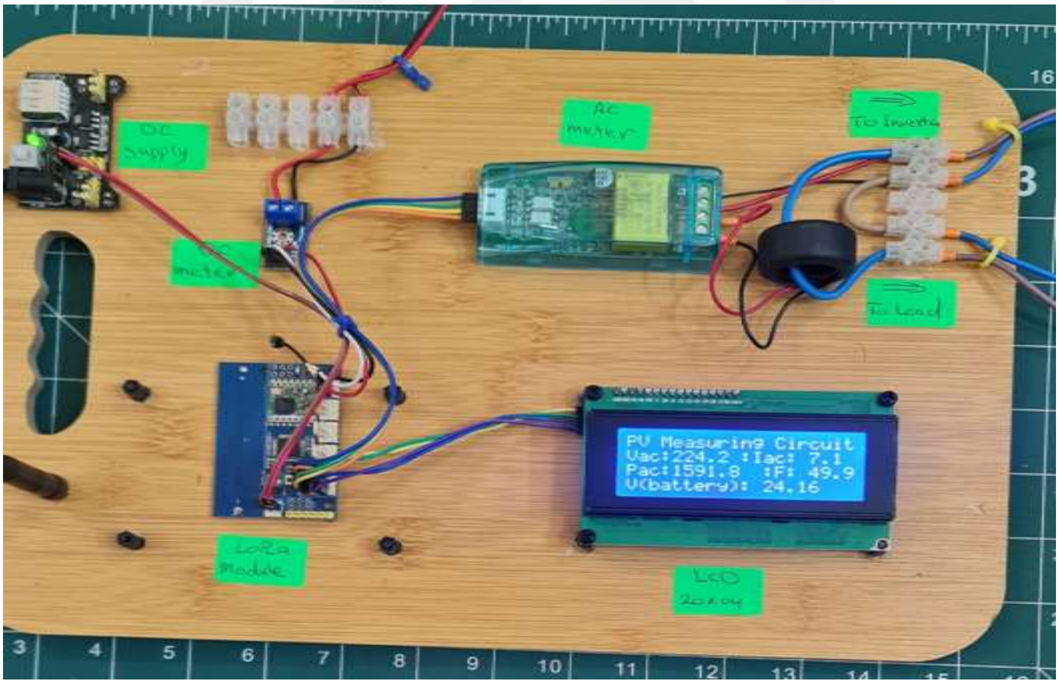


Figure 5.5: Second Real-Time Operation of The PV Monitoring System.

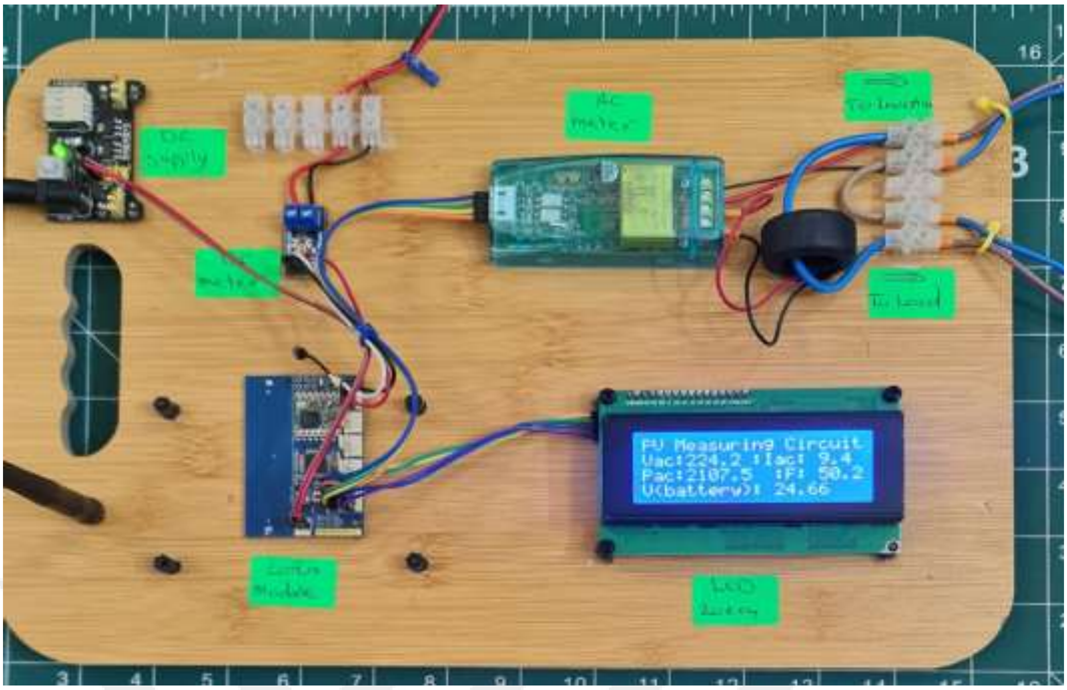


Figure 5.6: Second Real-Time Operation of The PV Monitoring System.

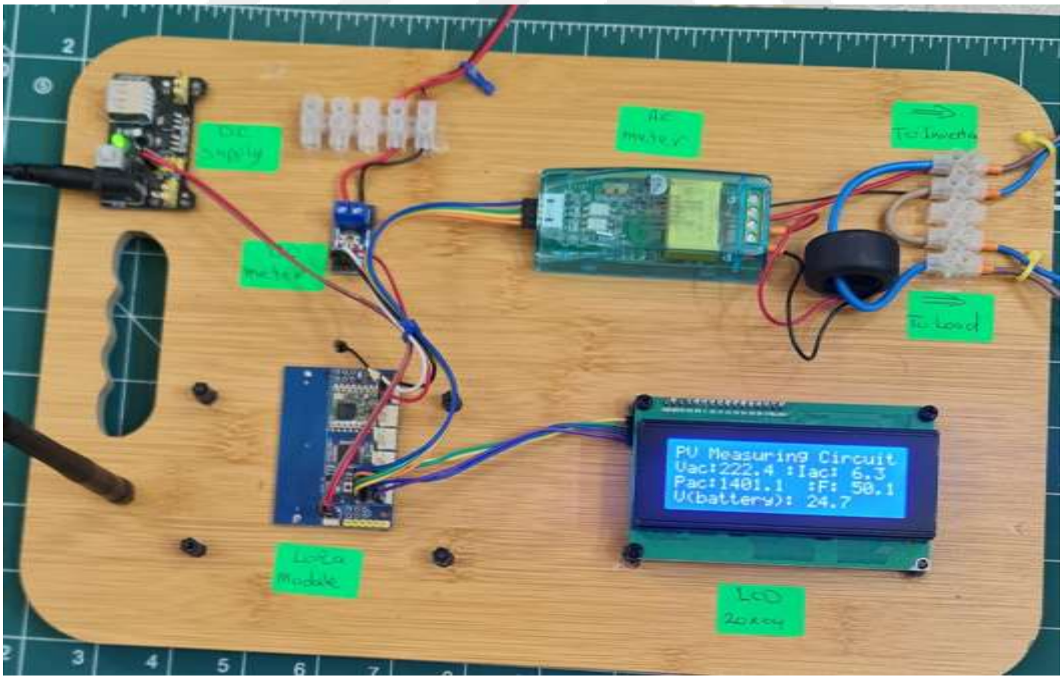


Figure 5.7: Second Real-Time Operation of The PV Monitoring System.

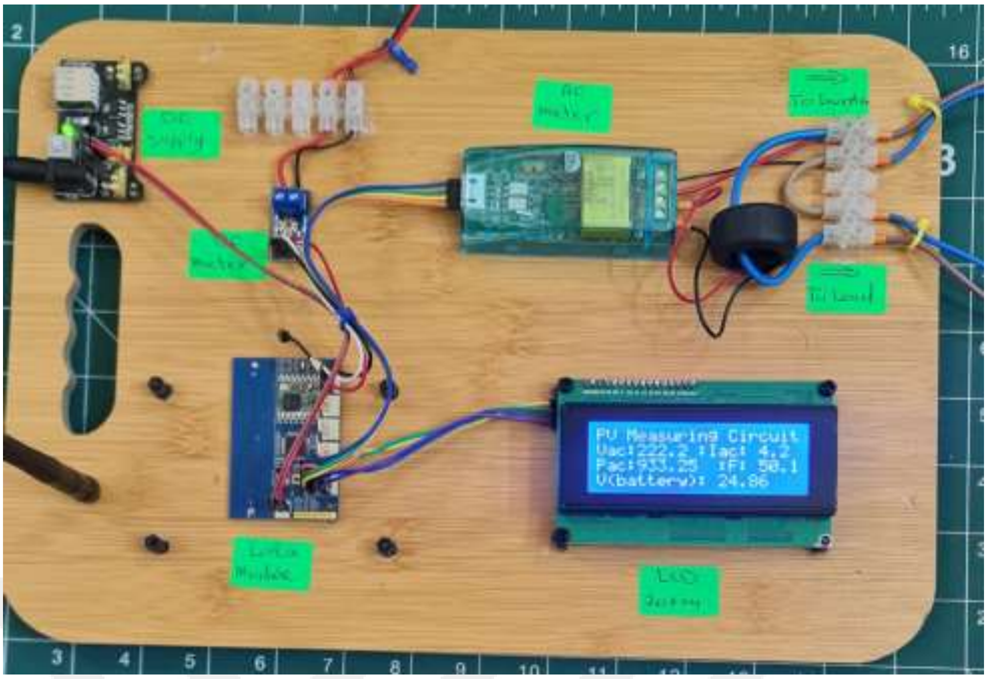


Figure 5.8: Second Real-Time Operation of The PV Monitoring System.

The results shown on the LCD serve as a real-time monitoring tool for on-site assessment and offer helpful information for enhancing the PV systems under different load circumstances. This depiction aids in understanding how the monitoring system reacts to changes in demand and helps to guarantee that the PV system is robust across a variety of load profiles. It also aids in enhancing operational plans. Results were displayed for five phases in Table 5.1.

Table 5.1: PV System Measurements.

scenario	Pac (W)	Iac (A)	$V_{(Battery)}$ (V)	Vac (V)
1	933	4.2	24.8	222.2
2	1209	5.4	24.1	224
3	1401	6.3	24.7	222.4
4	1591	7.1	24.16	224.2
5	2107	9.4	24.66	224.2

Experiments were carried out, and data were collected at a distance of 1 km in five distinct situations. The system collected data at various times. Figure 5.4 had been show the average active power, current, battery voltage, and AC voltage derived from five data points obtained during an hour.

5.3 THINGSPEAK RESULTS

A thorough compilation of data from the ThingSpeak cloud platform is shown in Figure 5.5, providing a full overview of the operation of the PV single-phase system monitoring system under various load conditions. Critical parameters including power output, voltage, and current are shown by ThingSpeak together with additional information that enables remote access and monitoring.

Figure 5.5: Final System ThingSpeak Cloud Results.

Figure 5.6: Final System ThingSpeak Cloud Results.

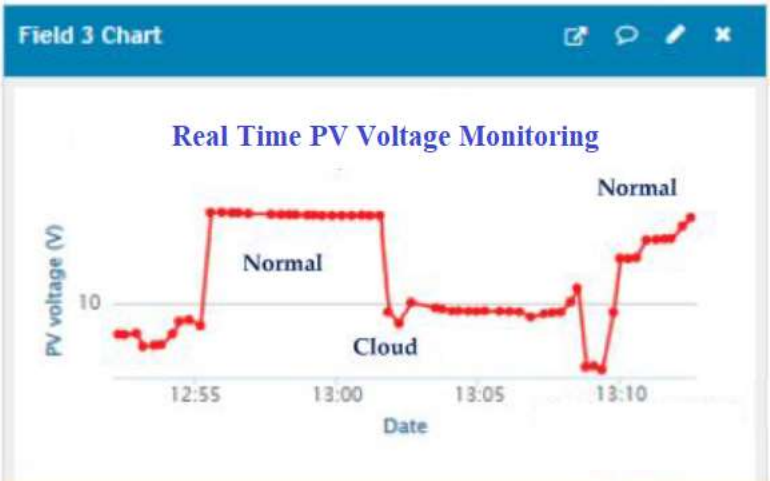


Figure 5.7: Final System ThingSpeak Cloud Results.

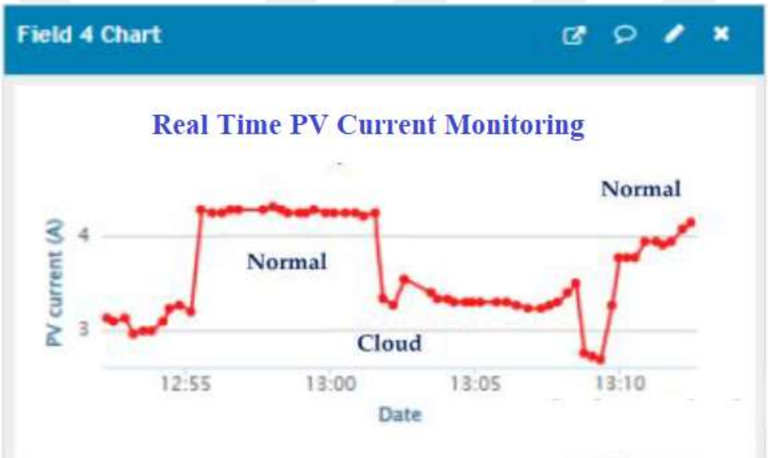


Figure 5.8: Final System ThingSpeak Cloud Results.

Figure 5.9: Final System ThingSpeak Cloud Results.

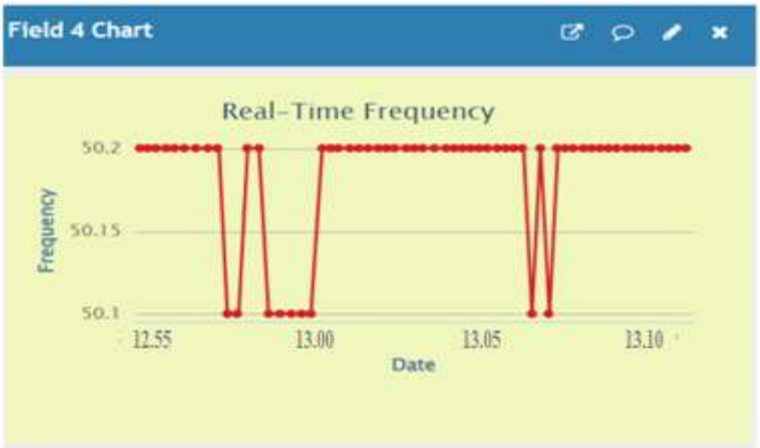


Figure 5.10: Final System ThingSpeak Cloud Results.

There are several advantages for researchers, employees, and participants in photovoltaic (PV) system management when ThingSpeak is integrated into monitoring systems. Through the use of ThingSpeak's cloud-based data presentation, stakeholders may assess the behavior of the system in real time under a range of load conditions. For PV systems to operate at their best and be reliable, this real-time monitoring feature is priceless. The integration with ThingSpeak greatly improves the monitoring system's scalability and accessibility. With the help of this cloud-based platform, stakeholders can manage and analyse massive amounts of data produced by PV systems with ease. It also makes data processing, long-term performance evaluation, and storage easier.

In addition to facilitating decision-making in real time, the data saved on the ThingSpeak cloud offers insightful information on how the PV system reacts to varying loads over time. This more thorough comprehension of system behaviour is essential for streamlining operations and enhancing the overall reliability and effectiveness of the system.

In conclusion, ThingSpeak integration improves data processing, scalability, and accessibility of monitoring systems, empowering stakeholders to make well-informed decisions, maximize system performance, and promote ongoing PV system operation improvement.

As can be seen in Figure 12, the findings displayed on the ThingSpeak cloud platform offer a comprehensive understanding of the operation and performance of the monitoring system connected to the PV single-phase system under various load circumstances. These results provide helpful information for remote access and monitoring, allowing for real-time analysis and decision-making for system operators and stakeholders.

One significant characteristic displayed on the ThingSpeak platform is the power output of the PV single-phase system. This indicator, which displays the amount of power generated by the solar panels, is crucial for assessing the system's overall efficacy and performance. By monitoring the power output over time, operators may see trends, anomalies, and potential issues that could affect the system's functionality, such as soiling, shading, or equipment failures.

In addition, important information about the electrical characteristics of the PV system is displayed by ThingSpeak's voltage and current statistics. Voltage measurements indicate the electrical potential difference between different locations in the system, whereas current data shows the flow of electric charge through the system. Operators may ensure that the system operates within safe and optimal parameters by monitoring voltage and current levels. This helps prevent issues with overloading or underperformance that might harm the equipment or waste energy.

6. CONCLUSIONS AND SUGGESTED FUTURE WORKS

A major advancement in the capabilities of renewable energy systems represented by PV systems has been made with the use of IoT technology for real-time performance monitoring of PV systems. The potential for improved data collecting, analysis, and accessibility has been established by the successful installation of an integrated monitoring framework incorporating IoT devices, cloud connection, and geographically tailored smartphone applications. The system's capacity to remotely and locally monitor important metrics in real time gives stakeholders a useful tool for decision-making and maximizes the performance of solar systems.

6.1 CONCLUSIONS

Furthermore, the monitoring system's outputs demonstrate how flexible the PV system is under various load scenarios, providing insight into its resilience and reactivity. In addition to increasing user accessibility, the MIT Inventor-developed spatially sensitive cloud application has established a standard for user-friendly and entertaining interfaces in the field of renewable energy monitoring.

The use of Internet of Things technology to monitor solar system performance in real time is a significant breakthrough in the field of renewable energy systems. Operators may remotely monitor and assess critical parameters including power production, voltage, and current by utilizing Internet of Things technologies. Real-time insights into the functionality and performance of PV systems are made possible by this. This level of monitoring and analysis enables operators to maximize system performance, identify inefficiencies or irregularities, and make well-informed decisions about maintenance and operation. Proactive maintenance and troubleshooting are also made feasible by IoT-enabled monitoring, which enhances system reliability, efficiency, and uptime overall.

ThingSpeak offers remote access, real-time monitoring, and data analysis, allowing operators to optimize energy production, enhance system performance, and increase reliability. Sustainable development and renewable energy technologies are so advanced as a result. The outcomes displayed on the ThingSpeak cloud platform provide a comprehensive and educational view of the functioning of the monitoring system linked to the PV single-phase system. Because ThingSpeak incorporates key elements like power output, voltage, and current, operators can monitor and access the system remotely. This enhances reliability and optimizes system performance while also optimizing energy yield.

The PZEM-004T V3 module's measurements offer insightful information about the dynamic behaviour of the electrical system under observation. The system's continuous growth in active power consumption (Pac), which went from 933 Watts to 2107 Watts, shows that its need for electricity is rising. The direct correlation between power demand and the rate of electric charge flow in the circuit is demonstrated by the rise in AC current that coincides with this increase. The battery voltage stability shows a well-maintained state of charge and overall health for the energy storage system, even in the face of variations in power demand and current. The alternating current voltage stays within a defined range, highlighting the system's ability to supply connected devices with a constant voltage supply and guaranteeing optimal performance.

This Matlab simulation examines the behavior and operation of a photovoltaic (PV) system, which uses panels to transform solar energy into electrical power. Solar panels, inverters, filters, transformers, and monitoring/control systems are some of the essential parts. Sunlight intensity, shade, and system design are some of the aspects that affect the system's behavior. Temperature, irradiance, and system setup all affect power output. While FFT evaluates frequency content, PWM approaches regulate the voltage and frequency of the inverter output. Signal distortion is quantified by Total Harmonic Distortion (THD). PV systems need inverters to convert DC electricity into AC power, which is then sent to the grid. Customers that use net metering setups can get credits for any excess energy they feed back into the system. It is essential to comprehend system dynamics for effective functioning.

The results that were collected demonstrate the effectiveness of the intended system, especially in the areas of data collecting and real-time monitoring, particularly in the areas of fault isolation and detection. A webpage was created and made active in order to gather data from a distance. Five different reading types were examined on a PV module, plus a short circuit within a PV module. Considering the final application effectively conforms with the pertinent technical requirements, the Internet of Things is a viable foundation for developing an affordable smart monitoring system.

6.2 SUGGESTED FUTURE WORKS

Future studies should take into account the following aspects to better improve the effects of real-time monitoring of performance in PV systems utilizing IoT technology:

Advanced Data Analytics: Apply more complex data analytics methods for anomaly identification and predictive analysis in the tracked data, including machine learning algorithms. This might enhance the system's capacity to anticipate possible problems and maximize efficiency.

a. Cybersecurity Measures: To secure data transfer and defend IoT devices from potential cyber-attacks, research and implement improved cybersecurity measures. Data security and integrity are becoming more and more important as IoT applications grow.
b. Scalability and Interoperability: Investigate methods to improve the monitoring system's scalability and interoperability, allowing for smooth integration with additional smart grid components and supporting the expansion of PV installations.
c. Investigate how to improve data gathering and monitoring capabilities by integrating ThingSpeak with IoT devices and remote sensing technologies. For better system performance analysis, look into the use of drones, satellites, and Internet of Things (IoT) sensors to gather additional environmental data, such as weather, sun irradiance, and panel temperature.

Researchers and practitioners may further enhance the capabilities of monitoring systems linked with ThingSpeak by investigating these paths for future research and development. This will ultimately lead to more sustainable, dependable, and efficient operation of PV systems.

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