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**A SMART MONITORING NETWORK FOR
HYBRID ENERGY SYSTEM BY USING IOT**

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Doctor of Philosophy

Supervisor

Assoc. Prof. Dr. Sefer KURNAZ

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Anmar Yahya Taher AL-MIHYAWI

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

A SMART MONITORING NETWORK FOR HYBRID ENERGY SYSTEM BY USING IOT

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This thesis addresses the design, development, and implementation of a smart monitoring network for hybrid renewable energy systems using Internet of Things (IoT) technologies. The research aims to improve the efficiency, reliability, and performance of renewable energy integration through real-time monitoring and control.

The aim of this thesis is to explore the creation and use of a hybrid renewable energy system that blends wind turbine and photovoltaic (PV) technologies in order to meet the increasing need for environmentally friendly energy sources. The study used a multidisciplinary methodology that incorporates engineering, renewable energy, and information technology components to develop, simulate, and assess the hybrid system's performance. The introduction gives background information, emphasizes the urgent need for integration of renewable energy sources, and outlines the goals of the study. In order to build the foundation for the next research projects, a comprehensive overview of the literature is provided, including previous research on smart monitoring networks, hybrid energy systems, and Internet of Things-based energy management solutions.

Parameter extraction, MATLAB implementation strategies, and performance analysis procedures are covered in depth in the chapters that describe the modelling and simulation of PV and wind turbine systems. The design and integration of sensors, converters, and control systems to build a network for real-time monitoring of the hybrid energy system is demonstrated in the hardware development chapter. The system's performance is thoroughly examined in the results chapters, which make use of visualizations from cloud platforms,

smartphone application interfaces, and real-time monitoring data. The chapters offer insights into operational dynamics, system efficiency, and patterns of energy generation through in-depth analysis and visualization. In the practical implementation phase, hardware components are deployed to collect real-time data from the hybrid energy system. IoT-based communication protocols enable remote monitoring and control, facilitating optimization of energy generation, storage, and utilization. The research demonstrates the scalability and reliability of the monitoring network in improving the performance of hybrid renewable energy systems.

In summary, by providing an extensive foundation to the design, implementation, and assessment of hybrid energy systems, this thesis adds to the rapidly expanding subject of renewable energy. The goal of the research is to promote an environmentally friendly and more resilient energy future by expediting the implementation of sustainable energy solutions by bridging the theory-practice divide.

Keywords: IOT, Smart Monitoring, Hybrid Energy, MATLAB, Internet of Things.

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ABBREVIATIONS

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



1. INTRODUCTION

1.1 INTRODUCTION

Hybrid energy systems are now widely used as a result of rising energy demand and the need for reliable, efficient power sources. To provide a dependable and ecologically friendly power supply, these systems integrate numerous renewable energy sources, such as solar, wind, and biomass, with traditional energy sources [1]. The monitoring and management of these sophisticated hybrid energy systems, however, present major difficulties. Due to a number of reasons, including the rising global energy demand and the growing understanding of the need of dependable and efficient power sources, hybrid energy systems have seen a significant increase in usage in recent years. Traditional dependence on fossil fuels has resulted in environmental issues including climate change and air pollution, which has prompted the investigation and use of renewable energy sources [2].

The growing need for energy is one of the main factors influencing the introduction of hybrid energy systems. The need for energy is rising as the world's population, industry, and living conditions rise. To satisfy these rising energy needs, hybrid systems provide a scalable and adaptable option, especially in places with sparse or unreliable grid infrastructure [3]. A solution is provided by hybrid energy systems, which combine several energy sources to provide a more dependable and sustainable power source. These systems often mix traditional energy sources like diesel generators or grid connection with renewable energy sources like solar, wind, hydro, or biomass. Hybrid systems may reduce the erratic and variable nature of renewable energy sources and increase the overall system dependability by diversifying the energy mix [4].

The majority of developing nations have pushed for laws and programs to attain sustainability by lowering their reliance on fossil fuels and emissions. These programs seek to slow global warming and create a decarbonized energy system [5]. Indeed, the use of renewable energy sources and energy efficiency are seen as crucial factors in achieving carbon reductions and meeting the goals of the Paris Agreement [6]. The fast cost reduction of renewable technologies, particularly photovoltaic (PV) installations, the price of solar PV modules was cut by over 85% from 2010 to 2019 [7] as well as this general condition have encouraged the deployment and investment of renewable solutions. For instance, in 2017,

the renewable energy market added 167 GW of new generating capacity worldwide. This is an increase of 8.3% over the prior year and maintains annual growth rates that have been between 8 and 9% since 2010 [8].

Hybrid systems also aid in lowering greenhouse gas emissions and minimizing the negative effects of energy generation on the environment. Renewable energy sources operate with little to no carbon emissions, which contributes to sustainability objectives and the fight against climate change. Additionally, hybrid energy systems have a lot to offer in terms of efficacy and cost-savings. They may maximize energy output and maximize the usage of the available resources by merging various energy sources. For instance, the hybrid system may use a conventional energy source to fulfill load needs during times of peak demand, while it can store or export extra renewable energy during times of high production. So that, the widespread adoption of hybrid energy systems has been fueled by the rising demand for energy and the necessity for dependable, efficient power sources. By combining renewable and conventional energy sources, these systems provide a viable solution that also has the added advantages of resilience, scalability, and environmental benefits. Hybrid energy systems are anticipated to be essential in the global energy transition to a more sustainable future as technology develops and prices continue to fall.

The development of the Internet of Things (IoT) presents opportunities to overcome these issues. IoT technology makes it possible for numerous devices and sensors to link and communicate with one another, enabling real-time monitoring, data collecting, and intelligent control of the hybrid energy system's component parts. A smart monitoring network may be created by using IoT to improve the functionality, effectiveness, and dependability of hybrid energy systems [9]. A number of difficulties related to hybrid energy systems may be addressed thanks to the Internet of Things' (IoT) growth. An internet-enabled network of linked sensors, actuators, and devices is referred to as the Internet of Things (IoT). IoT integration into hybrid energy systems may provide a number of advantages.

IoT also makes it possible to remotely operate and maintain hybrid energy systems. From a single place, operators may access and manage system settings, keep an eye on performance, and spot errors or anomalies. By enabling speedier problem resolution and reducing the need for physical intervention, this remote management capability ensures a constant and

uninterrupted power supply. Real-time monitoring and control is a major benefit. IoT makes it possible to gather data on energy production, storage capacity, grid connection, weather, and equipment performance in real-time [10]. With the use of this data, operators may plan ahead and streamline system operations, increasing efficiency and dependability.

By maximizing the usage of existing energy sources depending on demand and availability, IoT also allows intelligent energy management. Intelligent algorithms are able to forecast peak demand times, evaluate trends in energy usage, and improve energy distribution. IoT also makes it possible for demand response programs, where energy usage may be dynamically changed in reaction to grid circumstances, price signals, or the availability of renewable energy sources. Advanced analytics methods may also be used to handle and evaluate data produced by IoT. Predictive analytics and machine learning algorithms can spot patterns and trends, allowing for proactive maintenance and defect finding. Downtime is avoided, maintenance expenses are decreased, and the lifetime of system components is increased by proactively addressing possible concerns.

IoT integration enables smooth communication between smart grids and hybrid energy systems. Bidirectional energy flow is made possible, allowing extra energy to be used immediately or saved for later [11]. Demand-side management, grid balancing, and efficient integration of distributed energy resources may all be made possible by IoT, leading to a more dependable and effective power system. Briefly, there are many chances to optimize energy production, boost system performance, and improve overall energy management when IoT is integrated into hybrid energy systems. The advantages that IoT delivers to hybrid energy systems include real-time monitoring, remote management, predictive maintenance, energy optimization, and interaction with smart grids, to name just a few. These advantages help create a smarter, more sustainable, and efficient energy infrastructure.

Hybrid energy systems, which integrate energy storage technologies with a variety of renewable sources including solar and wind, offer a substantial potential for enhancing energy resilience and reducing carbon emissions. Nevertheless, the effective surveillance and regulation of these intricate systems present significant challenges, particularly in remote or off-grid environments characterized by inadequate connectivity and infrastructure (see Figure 1.1) [12].

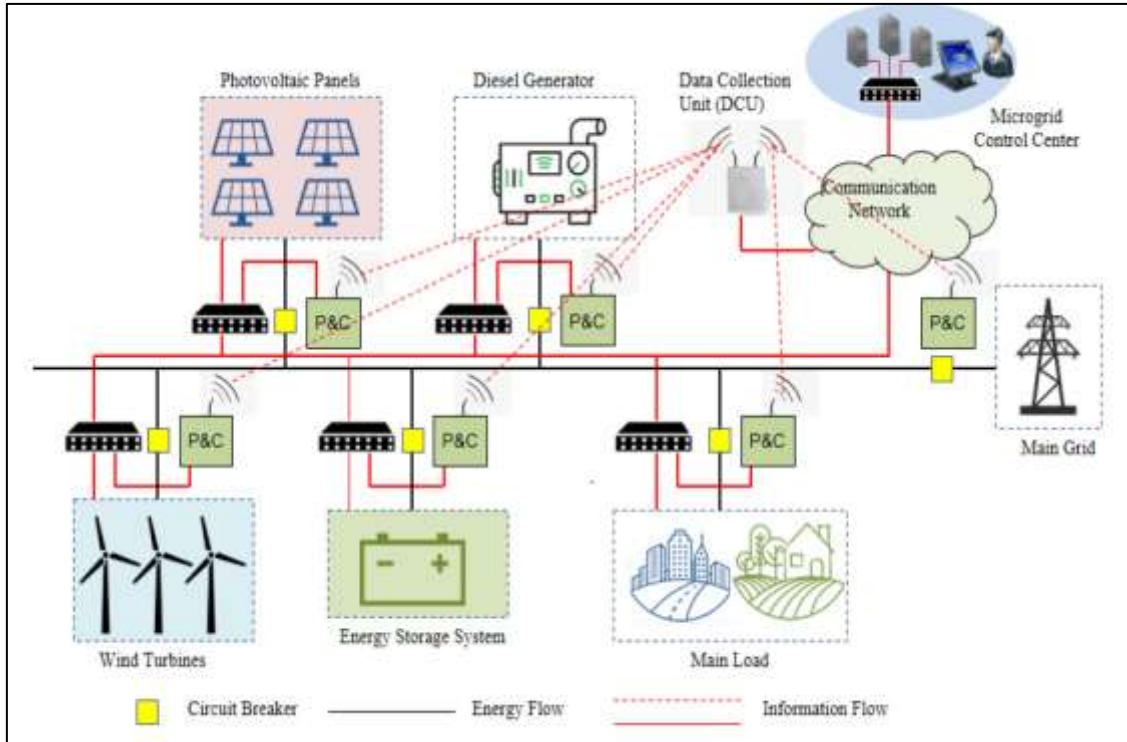


Figure 1.1: A Schematic Representation of HRES Grid Integration. [12]

Now, an IoT-based smart monitoring network for a hybrid energy system is to suggest and show off. This suggested system seeks to provide thorough monitoring and control capabilities to enhance the performance of the hybrid energy system, identify defects or irregularities, and facilitate proactive maintenance and effective energy management.

Advanced monitoring and control approaches, as well as ICT solutions, require reliable communication infrastructures. Proper communication systems need sophisticated and costly installation, making them a vital part of such applications.

Installing wired systems, such as optical fiber in large areas (not more than hundreds of meters) or small areas represented by ethernet networks (e.g., less than 100 meters), can be costly, especially in old buildings or complex scenarios like smart campuses with buildings separated by dozens or hundreds of meters.

Wireless networks are becoming popular, especially in large-area or hybrid situations. Local Area Network (LAN) technologies, such as IEEE802.11 (WiFi), are commonly utilized within buildings to use pre-existing infrastructure. However, wireless systems like WiFi have limitations in coverage capability, both indoors and outside. Power Line

Communication (PLC) can only be effectively deployed on a certain segment of the electrical network, making it only suitable for simple user systems. For large systems, like a campus, a mixed situation with many buildings and exterior locations is more plausible, requiring a Wide Area Network (WAN) solution. Low Power Wide Area Network (LPWAN) solutions are gaining popularity due to their extensive coverage, simplicity, and low power consumption. LoRaWAN technology has excellent coverage in both outdoor and hybrid areas, making it an attractive alternative.

The availability of appropriate communication infrastructures is a prerequisite for the use of sophisticated monitoring and control techniques and the associated ICT solutions. One of the most important characteristics of such an application is the complexity and the expense of installation of appropriate communication networks. Installing wired systems, like optical fiber in large areas (like hundreds of meters) or ethernet networks in small areas (like less than 100 meters) may come with associated costs, especially in older buildings or complex scenarios like a smart campus where buildings may be up to dozen or even hundreds of meters away from one another.

Because of this, the usage of wireless networks is becoming more widespread, especially when considering huge areas or hybrid contexts. Local Area Network (LAN) technologies, such as IEEE802.11 (WiFi), are typically utilized inside of buildings by utilizing infrastructures that have already been installed. However, using performing wireless technologies, like WiFi, has restrictions in coverage capacity in both outdoor and indoor settings (across separate buildings or between storeys of the same structure, for example). Finally, only a small percentage of the electrical network may be successfully used for Power Line Communication (PLC), which utilizes the existing electrical infrastructures within buildings. This limits the deployment of PLC to very basic user systems. Consider a Wide Area Network (WAN) strategy for dealing with more complicated systems, such campuses, where a mixed situation involving several buildings and exterior spaces is more realistic. Using minimal Power Wide Area Network (LPWAN) solutions in particular is becoming a practical choice because of its broad coverage, minimal complexity, and low power consumption. Because of its strong coverage capabilities (both in outdoor and hybrid situations), LoRaWAN technology might thus be a very attractive option. However, its most crucial aspects are its duty cycle constraint and very poor data throughput. Furthermore, the

integration of diverse IoT devices and protocols on a broad scale may be complicated by pertinent problems that arise from their adoption.

First, we will go through pertinent literature on hybrid energy systems, IoT applications in energy systems, and current smart monitoring methodologies in this study. The research gaps that our project seeks to fill will be easier to find thanks to this review. The approach used in developing and putting the smart monitoring network into place will then be presented. This covers the system design, hardware component selection and integration, software development, data gathering and processing methods, and software development.

1.2 BACKGROUND

Increasing energy consumption, environmental concerns, and the need for dependable and efficient power sources are just a few of the causes that are causing a substantial upheaval in the global energy landscape. Hybrid energy systems, which blend conventional and renewable energy sources, have emerged as a possible response to these issues. The development of Internet of Things (IoT) technology has created new possibilities for resolving these issues. IoT stands for the connectivity of objects, sensors, and actuators that can talk to each other and exchange data online. A smart monitoring network may be constructed to provide real-time monitoring, data gathering, analysis, and control of different system components by using IoT in hybrid energy systems.

The IoT-based smart monitoring network has a number of benefits. It enables operators to access and manage system parameters from a centralized place and enables remote monitoring and management of the hybrid energy system [13]. System performance, energy production, storage levels, and equipment condition may all be understood via real-time data gathering and analysis. Proactive decision-making, energy distribution optimization, and effective maintenance planning are all made possible by this information. Multiple renewable energy sources, including solar, wind, hydro, and biomass, are combined with traditional energy sources, such diesel generators or grid connection, in hybrid energy systems [14]. Through this integration, renewable energy may be used more effectively, system resilience can be increased, and power supply dependability can be increased. But managing and regulating the many hybrid energy system components is a significant challenge.

IoT integration offers smooth communication between the hybrid energy system and smart grids in addition to monitoring and control. Bidirectional energy flow, effective energy management, and the capacity to take part in demand response programs are all made possible by this integration. Hybrid energy systems may be very helpful in demand-side control, grid stability, and the integration of distributed energy resources by using IoT [15]. Additionally, IoT makes predictive maintenance easier by using cutting-edge analytics and machine learning algorithms to find possible system flaws or irregularities. Predictive maintenance decreases downtime, prevents equipment failures, and increases overall system dependability for hybrid energy systems.

Research and development are required in the field of smart monitoring networks given the advantages that IoT in hybrid energy systems offers. In this research, a smart monitoring network for a hybrid energy system utilizing IoT is proposed and shown, emphasizing the benefits, difficulties, and practical consequences of such a system. The objective of using IoT technology is to improve the functionality, effectiveness, and dependability of hybrid energy systems, helping to promote the intelligent and sustainable management of energy resources. Due to the many benefits that IoT integration provides, research and development in the area of smart monitoring networks for hybrid energy systems are essential. Several major difficulties may be addressed and energy management can be improved when IoT technology and hybrid energy systems are combined.

The achievement of optimum resource use is one of the main justifications for investing in research and development. IoT-enabled smart monitoring networks may be used to gather and analyze data in real-time on the several energy sources used by the hybrid system. Based on energy output and consumption trends, this enables operators to make well-informed choices about when to transition between renewable and conventional sources [16]. Energy waste may be reduced and overall system efficiency can be increased by maximizing the utilization of the resources that are already available. Adjustments may be performed in real-time to make sure that energy generation meets the needed load by continually monitoring energy supply and demand. A higher degree of system management and optimization results in greater system performance and better synchronization with energy needs.

The increased system efficiency that IoT integration delivers is another strong argument in favor of research and development. Operators may fine-tune the performance of the hybrid

energy system via IoT-enabled remote monitoring and control. An important benefit provided by IoT-enabled smart monitoring networks is predictive maintenance. Potential problems and malfunctions may be identified early on by constant monitoring of system components and the use of data analytics tools. Operators might find signs of equipment degradation or performance variations by looking for patterns and trends in the gathered data [17]. This enables preventative maintenance procedures to be carried out, decreasing downtime and raising the hybrid energy system's overall dependability.

The improved demand-side management, grid balancing, and efficient integration of distributed energy resources are all made possible by this two-way flow of information and energy. The entire energy system may function more effectively and promote the shift to a sustainable energy future by improving the interaction between the hybrid energy system and the smart grid. Additionally, investigation into the integration of hybrid energy systems with smart grids requires research and development initiatives. IoT technology makes it possible for the hybrid energy system and the larger grid infrastructure to communicate and work together seamlessly.

To summarize, in order to fully take advantage of the benefits that IoT integration has to offer, research and development in the area of smart monitoring networks for hybrid energy systems are crucial. Further research and development activities may greatly benefit critical areas including resource usage optimization, improved system efficiency, proactive maintenance, and integration with smart grids. We can realize the full potential of hybrid energy systems and open the door to a more sensible and sustainable management of energy resources by making progress in these areas.

1.3 PROBLEM STATEMENT

Problem Descriptions for an Internet of Things-Based smart and Intelligent System for Monitoring a Hybrid Energy System can be mentioned as:

- a. **Limited Real-Time Monitoring:** Traditional hybrid energy systems often lack effective real-time monitoring capabilities, making it difficult for operators to get precise and up-to-date data on energy production, consumption, and system performance. This results in inefficient energy use and prevents proactive decision-making.

- b. **Inefficient Energy Resource Allocation:** Without a sophisticated monitoring network, the hybrid energy system runs the danger of having inefficient Energy Resource Allocation. Operators may find it difficult to adequately balance the use of conventional and renewable energy sources, which may lead to energy waste or a dependency on fossil fuels during times of high demand. Also, in typical hybrid energy systems, the lack of predictive maintenance skills may result in unforeseen equipment breakdowns and downtime. The inability to predict and respond to future problems results in increased maintenance costs and decreased system dependability.
- c. **Challenges with Smart Grid Integration:** Without a strong smart monitoring network, integrating hybrid energy systems with smart grids may be difficult and complicated. The two systems' inability to communicate effectively may make it difficult to control demand effectively and restrict the system's capacity to take part in demand response initiatives. With concerns about data security and privacy have been raised by the introduction of IoT in the energy industry. Without a well-designed smart monitoring network, the exposure of critical infrastructure to cyber-attacks and illegal access might result from the vulnerability of data gathered from numerous sensors and devices.
- d. **Issues with scalability and flexibility** are important for the long-term viability of hybrid energy systems as they develop and grow. Lack of an IoT-based smart monitoring network may make it more difficult for the system to successfully integrate new technologies or additional energy sources. Traditional hybrid energy systems may not have full knowledge about load profiles, consumption trends, and energy generation projections. The system's capacity to engage in energy trading or market-based procedures and improve energy distribution may be hampered in the lack of these insights.
- e. **Remote Monitoring Difficulties** Without IoT-based smart monitoring networks, managing hybrid energy systems in off-grid or distant places might be difficult. Operators may struggle to get timely access to crucial data, which might result in system inefficiencies and higher operating costs. Conventional hybrid energy systems may rely on traditional decision-making processes without the power of real-time data analytics and machine learning, which restricts their capacity to effectively adapt to dynamic energy demand and fluctuating renewable energy sources.

- f. **Environmental and Regulatory Compliance:** The lack of a smart monitoring network may make it more challenging to comply with environmental and governmental regulations. It is difficult to show adherence to sustainability objectives and legal requirements without precise data on energy use and emissions. The efficiency, dependability, and sustainability of hybrid energy systems will be greatly improved by addressing these problem statements through the creation and application of a smart monitoring network using IoT technology, helping to create a more intelligent and resilient energy infrastructure.

1.4 OBJECTIVES OF THE STUDY

Using IoT to create a Smart Monitoring Network for a Hybrid Energy System can have the following objectives:

- a. Obtain an extensive understanding of the difficulties and constraints associated with controlling and monitoring hybrid energy systems using traditional techniques and examine the advantages and possibilities that IoT integration may provide for improving hybrid energy system monitoring and control.
- b. Review the efficiency and performance of the IoT-based smart monitoring network in terms of real-time monitoring, the distribution of energy resources, preventive maintenance, and smart grid integration.
- c. In order to allow real-time data collection, analysis, and control of different components within a hybrid energy system, it is necessary to design and install a smart monitoring network utilizing IoT technology and analyze the smart monitoring network's capacity to grow, adapt, and be strong enough to handle the addition of new energy sources and hybrid energy systems.
- d. Investigate the possibility of making data-driven decisions to optimize energy use, demand response, and involvement in energy trading or market-based procedures and address data security and privacy issues related to IoT integration in hybrid energy systems will help to secure sensitive data and important infrastructure.
- e. Examine the smart monitoring network's environmental and regulatory compliance components to make sure that sustainability objectives and legal requirements are met

to have suggestions for the adoption of IoT-based smart monitoring networks in hybrid energy systems.

- f. Encourage sustainable and intelligent energy management practices by contributing to the growth of knowledge and understanding in the areas of hybrid energy systems and IoT integration.

Through the accomplishment of these goals, the study intends to show the value and potential of IoT-based smart monitoring networks in improving the efficacy, dependability, and sustainability of hybrid energy systems.

1.5 SCOPE OF THE STUDY

The scope of this study includes the following:

- a. **Focus on Hybrid Energy Systems:** The research will pay particular attention to hybrid energy systems, which combine conventional energy sources (like diesel generators or grid connection) with renewable energy sources (like solar, wind, hydro, or biomass). The study will investigate how IoT technology might be added to these systems to improve monitoring and management.
- b. **IoT-Based Smart Monitoring Network:** The study's main focus will be on the creation and use of an IoT-based smart monitoring network. This network will make it possible to gather, analyze, and regulate data in real-time for different hybrid energy system components.
- c. The research will examine the real-time monitoring and control capabilities provided by the IoT-based smart monitoring network. In order to improve system performance, it will look at how operators may access and control system parameters, track energy production and consumption, and make data-driven choices.
- d. **Predictive Maintenance:** Using IoT data analytics and machine learning algorithms, the project will examine the possibility for predictive maintenance in hybrid energy systems. It will look at how proactive maintenance and early defect detection might be accomplished to increase system dependability.

- e. Integration with Smart Grids: The research will look at how hybrid energy systems are integrated with smart grids and what part the IoT-based smart monitoring network plays in enabling demand-side control, bidirectional energy flow, and efficient coordination with the grid infrastructure.
- f. Concerns about data security and privacy raised by the incorporation of IoT in hybrid energy systems will be addressed by the study. It will examine ways to safeguard sensitive data and key infrastructure.
- g. Implementation in Practice and Recommendations: The research will provide perceptions and suggestions for the deployment of IoT-based smart monitoring networks in hybrid energy systems. It will take into account elements like system flexibility, scalability, and adherence to environmental and regulatory standards.

It is important to highlight that the study's scope may not include every potential hybrid energy system or Internet of Things integration component. However, it will concentrate on the crucial components of intelligent monitoring and control utilizing IoT technology, hoping to provide insightful opinions and suggestions for the improvement of hybrid energy systems.

1.6 ORGANIZATION OF THE THESIS

The thesis is divided into six chapters: in chapter two, we present a review of the literature that was first presented by earlier studies; in chapter three, we provide the monitoring system's methodology as well as the key components utilized for simulation and real-time monitoring. Chapter Four now includes a simulation section that details the results and performance of using Matlab software. Chapter Five presents and discusses the experiments that we designed, simulated, and tested. We also explain our findings in this chapter. Chapter Six concludes with a demonstration and recommendations for future study.

2. LITERATURE REVIEW

There are a few technical issues that arise when integrating wind and solar power plants into existing power systems, with the primary concerns being stability, power quality, and dependability. Due mostly to unfavourable oscillations on the supply side that may impair the voltage control of transmission networks, the intermittent nature of such sources may raise grid stress. Diverse reactive power management solutions, such as active power curtailment, have also been put forward at a low- to medium-voltage level to aid in the integration of renewable energy sources. Short-term forecasting of PV output becomes a pertinent issue of interest as an additional way to ensure a balance between generation and demand, with lower capacity and operational reserve costs. In reality, the relevant literature has a number of techniques for estimating PV power over a short time horizon.

These techniques are dependent on the current weather and historical data on PV power generation. Therefore, updated weather and electric values would enable us to anticipate short-term PV power generation with greater accuracy. Real-time monitoring solutions may also provide pertinent, local, and correct information to guarantee grid control and dependability. According to Colak et al., present power systems need to be updated in terms of sensing, communication, measurement, and automation technologies to meet these objectives.

2.1 HYBRID ENERGY SYSTEM

Globally, there are about 770 million individuals without access to electricity. The demand for energy is predicted to rise by a third globally by 2035. Fossil fuels including coal, oil, and natural gas are now responsible for the majority of the world's energy consumption, which is on the rise. These fuels produce greenhouse gas emissions and global warming as side effects. According to the Statistical Review of World Energy by British Petroleum, fossil fuels accounted for 82% of primary energy usage in 2022. Following the pandemic, the share of coal and natural gas increased by 6% and 5.3%, respectively [18].

The subsequent list comprises significant findings and relevant research concerning hybrid energy systems:

In a study by Ali et al. (2020) [19], the authors proposed a modelling and optimization framework for hybrid energy systems in rural areas. The research emphasized the integration of renewable energy sources, energy storage, and smart grid technologies to achieve energy sustainability and cost-effectiveness. A compact hybrid renewable energy system (HRES) using wind and solar energy as its main energy sources is the subject of this research. An isolated island in South Korea with a daily mean load of 24,720 kWh and a peak load of 2291.54 kW served as the basis for the hybrid renewable energy system HRES model. The daily mean load and peak load for the island were 24,720 kWh and 2291.54 kW, respectively. To solve power surpluses and deficits, two energy storage systems (ESS) were simulated. Based on levelized cost of energy (LCOE) and net present cost, four alternative HRESs were assessed. Each component's economic effect is discussed, as well as the influence of sensitivity factors on choices.

Frimpong et al. (2023) [20] focused on the operation and control strategies of hybrid microgrids. The study emphasized the importance of intelligent control algorithms to manage the energy flow between different energy sources, storage systems, and loads in a hybrid energy system.

In order to balance each other out during power outages, different renewable energy sources must be combined. Determining an affordable and dependable mix of renewable energy is vital since renewable energy sources are not always accessible. SSP, an optimization technique inspired by nature, was utilized in the research to assess the viability, economics, and dependability of the energy mix. Hybrid renewable energy systems were assessed using past data from the National Renewable Energy Laboratory. For solar PV-wind-biomass, PV-biomass, PV-wind-biomass, and PV-wind-biomass-battery systems, SSP guaranteed optimum economic costs and met reliability limitations. This shows that SSP may provide the best outcomes and necessitates additional investigation into include it in the optimization strategy for hybrid solar PV-wind-biomass-battery systems.

Farghali et al. (2023) [21] investigated the economic and environmental benefits of hybrid energy systems in commercial buildings. The research demonstrated that integrating renewable energy sources, energy storage, and advanced control strategies can significantly reduce energy costs and carbon emissions.

While switching to electrical power from fossil fuels is sometimes seen as better for the environment, it also increases carbon dioxide emissions. By incorporating renewable energy into the power industry, employment can be created in 2030 and 4,188,000 jobs can be created by 2050. Systems using solar photovoltaic, battery storage, wind, hydropower, and biofuel may save expenses associated with producing water by 69% and have a 90% positive impact on the environment. The potential to reduce carbon emissions grows with the proportion of renewable energy sources. The most successful systems for combating climate change are photovoltaic, wind, and hydroelectric ones since they enhance electricity production by 2.11–5.46% and ensure share ratios of 3.74–71.61 percent. Hybrid energy systems are more dependable and better able to resist the effects of climate change on the electrical grid.

Ming et al. (2017) [22] proposed a multi-objective optimization model for the design and operation of hybrid renewable energy systems. The research considered factors such as system reliability, cost-effectiveness, and environmental impact to find the optimal configuration and operation strategy for a hybrid energy system.

The approaches for multi-objective optimum design of hybrid renewable energy systems (HRES) in grid-connected and isolated-island modes are presented in this work. The ideal design seeks to enhance dependability and renewable capability while reducing system costs and fuel emissions. This multi-objective issue is suggested to be solved using the localized penalty-based boundary intersection (LPBI) method of the multi-objective evolutionary algorithm based on decomposition (MOEA/D). The method performs better than rivals and generates HRES designs that are close to Pareto optimum. The decision-maker's preferred configuration may be determined by taking their preferences into account.

León Gómez, et al. 2023 [23] seek to conduct a review of the literature and statistical analysis using information culled from 38 papers that were published between 2018 and 2023. The main goal of this review was to compile a database of references that classifies the content of the articles into various categories, including system architecture, energy storage systems, auxiliary generation components used, and software, in addition to displaying the optimization algorithms and economic and reliability criteria. To offer an overview of the present state of simulation and optimization projects for hybrid renewable energy systems, 38 publications in total have been evaluated, compared, and categorized, emphasizing the

pertinent trends and findings in a clear and suitable manner. Additionally, a list of review papers covering the topics needed to comprehend HRESs has been supplied.

Abolfazl Ghaffari et al. (2019) [24] investigated the challenges and opportunities of integrating renewable energy sources into hybrid energy systems in developing countries. The study highlighted the need for policy support, technical expertise, and capacity building to promote sustainable and accessible energy solutions.

An effective and reliable optimization method for sizing hybrid power production systems that use renewable energy sources is presented in this research. The approach uses an adaptive awareness probability adjustment together with a modified version of the crow search algorithm (CSA). Under two constraints—loss of power supply probability (LPSP) and renewable energy portion (REP)—the sizing framework optimizes total net present cost (TNPC). The results of the simulations demonstrate that REP has a substantial influence on TNPC, and the ideal arrangement of PV, diesel generator, FC, electrolyzer, and hydrogen tank results in a dependable and affordable hybrid power production system. Compared to the original CSA, genetic algorithm, and particle swarm optimization, the suggested technique (CSA adaptive-AP) shows more promising outcomes.

Bishnoi D. et al. (2022) [25] focused on the optimization Optimized Designing for Hybrid Energy System with Onshore Oil and Gas Fields' Economical and Conservation Sustainability. The study emphasized the role of advanced planning and optimization techniques to design cost-effective and reliable energy systems for remote areas.

Due to pollution and unstable electrical infrastructure, gas flaring creates serious environmental and financial hazards. This study offers a framework for developing hybrid energy systems (HES), which produce electricity from locally accessible renewable energy sources and gas flare trash. Real-time simulations and optimization were performed using a cutting-edge dispatch technique. Based on economic and environmental considerations, the ideal configuration for the Lakwa and Geleky gas flaring sites in Assam, India, was examined and contrasted. In terms of net present cost, the suggested system beat the current power system by 35.52%. It also saved 850 tons of carbon dioxide emissions per year and generated 93.7% of its total energy from renewable sources. This method offers a potentially effective way to reduce pollution while producing power from flare gas waste.

These studies and literature review articles collectively contribute to the understanding of hybrid energy systems, their components, optimization techniques, control strategies, and the benefits they offer in terms of energy sustainability, cost-effectiveness, and environmental impact. They provide a solid foundation for further research on integrating IoT technology into hybrid energy systems to enhance monitoring, control, and overall system performance.

2.2 IOT ROLES IN SMART MONITORING

The IoT literature study is multidisciplinary, including topics like its technological foundation. IoT as it exists today would not have been possible without numerous technological advancements, starting with the hardware, which allowed for the construction of ever-smaller and smarter devices, and continuing with the communication technologies, which enable longer coverage distances and lower energy consumption, cloud computing, large-scale data storage, and the software sector. IoT is quite broad and has applications across several industries. IoT has begun to permeate daily life, from a key component of Industry 4.0 to the way we care for the elderly. It is quickly becoming a pervasive and omnipresent technology.

A connection between both individuals and objects at all times, at every place, with anybody or everything, and over any network and any service is known as the Internet of Things (IoT). Because of this, the Internet of Things (IoT) is a vast, dynamic global network architecture of objects that provide online services. One of the key Internet of Things (IoT) applications is the smart grid (SG). Data from transmission lines, distribution substations, and customers are gathered and analyzed by SG, a power grid-integrated data communications network. So, this paper presents the IoT implementation in SGs. Therefore, a brief overview of the significance of IoT deployment in SGs is provided initially. Then, three distinct degrees of creation, transmission, and dissemination of IoT applications are discussed. The generating level consists of IoT applications for thermal, solar, and wind power, among other renewable energy sources. Utilizing IoT at the transmission level may help control electrical system congestion while also assuring system security. At the distribution level, the effects of IoT are evaluated for distribution networks, smart cities, microgrids, and smart buildings.

The literature assessment on intelligent monitoring and control in energy systems based on the Internet of Things (IoT) produced the following pertinent works and important points:

Kothai Andal et al. (2022) [26] proposed a smart monitoring and control system for energy management in commercial buildings using IoT. The study highlighted the integration of various sensors, actuators, and IoT platforms to monitor and control energy consumption, optimize energy usage, and enhance building energy efficiency.

In hybrid renewable systems (HRS), which incorporate wind turbines, solar modules, the grid, and battery storage devices, energy management is essential for increasing power distribution efficiency. With the use of the Internet of Things (IoT), this effort intends to develop a real-time energy management system that can track the power produced and used by various Nano grids. Multi-function sensors wirelessly gather real-time data, which is then sent to cloud servers for processing. A micro grid consists of slave nodes (SN), where each SN's grid is made up of two or three renewable energy sources. Power was generated from wind and solar energy, and power transfer between slave nodes was controlled by an ARDUINO microprocessor. MATLAB software was used to build the algorithm structure, and simulated results and actual results agreed well.

Liang et al. (2021) [27] developed an IoT-based smart monitoring system for photovoltaic (PV) systems. The research focused on real-time monitoring of PV performance parameters, such as voltage, current, and irradiance, to ensure optimal energy generation and system health.

A web-based real-time monitoring system for electrical energy use in a home is what this project wants to create. The device makes use of a multi-junction solar cell, Fresnel lens, and spherical lens in a micro-CPV system. A relay and PZEM-004T current sensor are controlled by the sensor node's ESP8266 controller chipset. Using a PC, smartphone, and web server, the system continuously analyzes current and energy use. The system exhibits great accuracy for a 0.6% hit, highlighting its usefulness in settings such as smart homes.

Li et al. (2023) [28] explored the application of IoT in smart grid systems for monitoring and control. The research emphasized the use of IoT-enabled devices, data analytics, and intelligent control algorithms to manage energy distribution, demand response, and grid stability. Wind energy microgrids are increasingly popular as a clean, sustainable energy

substitute. However, effective control and management technology are crucial for their success. IoT-based technology promotes sustainability by reducing greenhouse gas emissions, reducing climate change effects, and optimizing resource utilization. IoT device data analysis helps identify maintenance requirements and optimize resource consumption, making wind energy microgrids more reliable and efficient. This technology supports the expansion of renewable energy sources and promotes sustainability.

Qays Mo et al. (2022) [29] explored the use of IoT in the monitoring and control of energy systems in industrial environments. The study focused on the integration of IoT devices, wireless communication, and cloud platforms to enable real-time monitoring, fault detection, and remote control of industrial energy systems.

Real-time information is necessary for managing assets due to the rising production of renewable energy, especially in distant places. There is presently no technology for cost-effectively monitoring the status of energy sources that are renewable in real time. In this study, a novel application for the SCADA system's monitoring of hybrid systems comprising solar, wind, and batteries that store energy is presented. Network administrators may remotely manage components thanks to the SCADA system, which monitors electrical conditions through the ThingSpeak website. For experimental study, the system has an interface with the software Matlab/Simulink and a hardware prototype. The suggested system is feasible, giving improvements over current methods in terms of dependability and cost-effectiveness, as shown by simulation and experimental findings.

Krishna Rao et al. 2024 [30] explain the sector of renewable energy is experiencing rapid growth with the increasing global focus on sustainable, environmentally friendly, and reliable resources. Climate change and the reduction in global energy consumption have been the two most important variables at present.

The implementation of PV forecasting played a critical role in optimizing the real-time control system's performance and mitigating any unintended consequences. Intelligent energy management systems for distributed energy resources, a forecasting model for solar irradiation, and thus photovoltaic energy production, have the potential to alleviate the effects of unpredictability on PV energy generation, enhance the reliability of the system, and augment the level of penetration of solar power generation. Internet of Things (IoT) and

intelligent sensor technologies are indispensable for tracking and regulating applications in a vast array of fields. Forecasting solar power generation was therefore crucial for the security and stability of microgrids and the strategic integration of solar photovoltaics. This paper investigates the application of IoT to a monitored solar photovoltaic system and demonstrates that the presented monitoring system represents a potentially viable alternative for intelligent remote and personally monitoring of a PV system.

Esmaili Shayan, 2024 [31] revealed an empirical investigation demonstrates the feasibility of a massing substantial data regarding microgrids operation through the implementation of a functional microgrids that combines a diverse range of household appliances with a hybrid wind-solar power source.

Metropolitan areas that are environmentally sustainable are distinguished by their capacity to efficiently generate and disseminate electricity while mitigating their ecological footprint. Smart residences are indispensable components of smart cities due to the fact that they increase urban efficiency and sustainability. One significant benefit of smart homes is their ability to reduce carbon emissions and energy consumption. This is achieved through the customization of energy consumption in residential appliances to meet the specific needs and preferences of individual consumers. Nevertheless, additional scholarly inquiry remains necessary to examine and enhance the operation of intelligent residential dwellings integrated into microgrids. In order to ensure effective management of microgrids, it is imperative to collect and analyze substantial volumes of electrical data pertaining to load energy consumption and power generation from microgrid sources. Non-Intrusive Load Monitoring (NILM) techniques for monitoring the electrical parameters of various loads in microgrids are investigated in this study. The study centers on the implementation of cost-effective smart metres that possess Internet of Things (IoT) functionalities.

Nawaf H. Al Hajri et al. 2024 [32] explained that, in the pursuit of sustainable energy solutions, there is a growing need for reliable and efficient power sources to support Internet of Things (IoT) applications. Designed for Internet of Things applications, their document describes a creative hybrid renewable energy system that integrates wind turbines, hydrogen fuel cells, and solar photovoltaic panels in a continuous fashion.

By leveraging machine learning algorithms, they suggested system not only guarantees continuous energy provision to IoT devices and consumers, but also optimizes energy generation in real-time, despite environmental fluctuations. This comprehensive strategy significantly reduces reliance on energy sources that are not renewable, thereby fostering an energy infrastructure that is both environmentally sustainable and resilient. By integrating hydrogen fuel cells into our system, we are able to effectively store surplus energy, guaranteeing a steady supply of power even in periods of reduced solar or wind outputs. Furthermore, through the synchronization of Internet of Things (IoT) equipment via an energy system, they acquired up-to-the-minute information regarding energy dynamics. This has enabled us to achieve unprecedented levels of efficiency and waste reduction. The system that has been demonstrated demonstrates how to achieve a sustainable future by utilizing machine learning techniques and the constantly expanding landscape of IoT applications to generate green energy in an efficient manner.

Ibrahim MM. 2024 [33] proved that the transition to renewable energy sources is crucial for preventing climate change. Hybrid energy systems, also known as hybrid power, are in their infancy but are expected to become more widely used and cost-effective.

This study compares and contrasts various theories and conventional approaches to controlling hybrid energy systems (HES) and energy consumption. The effectiveness of an EMS is determined by its control architecture and solution approach, with common topologies including hierarchical, decentralised, and centralised EMS. Supply side and demand side management are discussed later. Various hybridization cases of PV panels, wind turbines, battery storage, and diesel generators are designed, analyzed, and compared using Distributed System Management (DSM). DSM results show a 25% reduction in CO₂ emissions, 14.8% reduction in NPC emissions, 14% reduction in COE emissions, and an 8.5% increase in RF emissions. The technical and economic benefits of DSM are assessed using the DSM Quality Index and the DSM Appreciation Index.

These studies and literature review articles collectively contribute to the understanding of smart monitoring and control in energy systems based on IoT. They highlight the integration of IoT devices, data analytics, intelligent algorithms, and control strategies to enable real-time monitoring, optimization, and remote control of energy systems (figure 2.1). The findings provide valuable insights for the development and implementation of IoT-based

smart monitoring and control systems in various energy domains, ranging from commercial buildings and photovoltaic systems to smart grids and industrial environments.

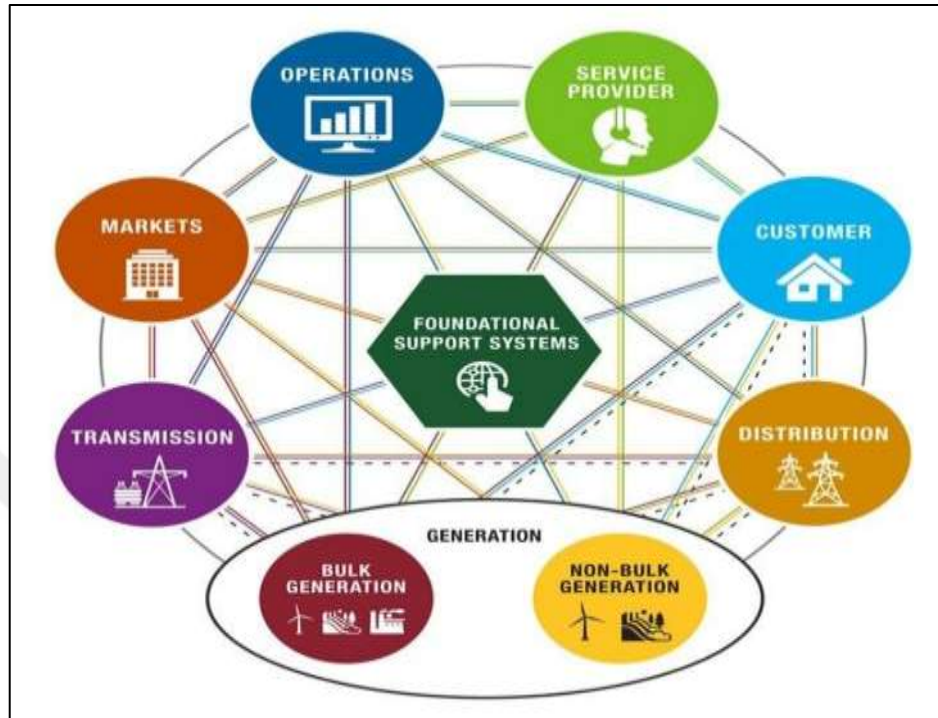


Figure 2.1: Smart Energy Systems Domain and Subsystems [17].

2.3 EXISTING SMART MONITORING TECHNIQUES

Hybrid energy systems, characterized by the integration of numerous conventional and renewable energy sources, have garnered considerable interest as environmentally friendly and sustainable alternatives to meet the escalating energy requirements. Over the past few years, the monitoring and administration of hybrid energy systems have been significantly transformed by the advent of Internet of Things (IoT) technologies, which enable the acquisition, analysis, and control of data in real time. This concise introduction presents a synopsis of current hardware intelligent monitoring methodologies employed in IoT-based hybrid energy systems.

Hydrogen, solar, wind, and solar energy are incorporated into hybrid energy systems alongside conventional fossil fuels in order to provide a continuous and dependable power supply. By capitalizing on the complementary characteristics of renewable and non-renewable resources, these systems optimize the processes of energy generation, storage, and distribution. Internet of Things (IoT) technologies comprise a network of interconnected

devices that are furnished with communication modules, sensors, and actuators. These components facilitate the exchange of data in a seamless manner and allow for remote monitoring. IoT enables the integration of various hardware components for real-time monitoring of energy production, consumption, and system performance within the context of hybrid energy systems.

P. Srivastava et al. 2018 [34] have concentrated on IoT-based hybrid energy system management. There are numerous energy combinations, and they are all interchangeable, including solar energy, wind energy, biofuels, fuel cells, and so forth. However, hybrid energy systems that are installed for commercial or residential use require regulation. IoT currently plays a significant function in system control. The primary criterion is the ability to seamlessly transition between the two energy sources, namely wind and solar, via a website utilizing an ESP8266 Wi-Fi module. The information is wirelessly transmitted via the website to the ESP8266 module, which regulates the energy sources. Using IoT, the transmitted data is remotely managed. This feature empowers users to exercise flexible control mechanisms remotely via a secure web connection on the internet. This system enables the user to manually and remotely manage energy sources via personal computer or smart phone. This system is extremely cost-effective, adaptable, and efficient.

Kothai Andal C. et al. 2022 [35] show how to maximize the efficacy of power distribution in a remote hybrid renewable system (HRS) that comprised of wind turbines, solar modules, a battery storage device, and the grid used as a fall back supply, energy management is crucial. As a result of their environmental consciousness, these systems are progressing on a global scale. Nonetheless, power flow management is critical in the hybridization of diverse sources.

In such study, an appropriate energy management system is developed and integrated through a suitable platform in order to provide real-time control of the hybrid energy system. The integration of energy management with the Internet of Things (IoT) offers significant benefits, such as the ability to monitor and process control data in real-time from devices. To facilitate the management of generated energy across multiple Nano-grids, this project is constructing an intelligent control system that utilizes the Internet of Things to monitor power consumption and generation remotely. A collection of multifunction sensors wirelessly detects real-time data, which is subsequently transmitted to multiple servers in the

cloud via the "Internet Connection" for format conversion. Microgrids consist of numerous slave nodes (SN). Each SN's personal grid is comprised of two to three distinct renewable energy sources that are connected to the master node of the central control unit. The prototype was powered by solar and wind energy, and power transmission between subordinate nodes was regulated and directed by an ARDUINO microcontroller to guarantee a successful outcome. MATLAB was utilized in the construction of the algorithm structure. The outcomes observed in practice closely mirrored those predicted by the simulation.

Usman Saleem M. et al. 2023 [36] proved that, to mitigate carbon emissions, the conventional grid is progressively incorporating renewable energy sources such as solar power. However, the predictive or real-time nature of energy management systems restricts the complete range of supply and demand responses. This limitation is surmounted through the integration of diverse concepts, including power system configurations and supply and demand side responses, into an integrated energy management system. This review examines the potential advantages of an energy management system that incorporates demand-side management, supply-side management, and solar power forecasting. Additionally, it suggests design factors that should be taken into account when developing models for solar energy forecasting. Ongoing research on the design and implementation of integrated energy management systems may be informed by the results.

Hambarde, S. M. et al. 2023 [37] enhanced the environmental impact of wireless networks through the provision of an antenna configuration that is operational on renewable energy sources, thereby introducing an innovative resolution to the aforementioned issue. The investigation of energy-efficient wireless network strategies is crucial in light of the escalating need for wireless communication as well as the growing concern for environmental sustainability. Through the integration of advanced antenna technology and sustainable energy collection methods, the proposed solution paves the way for the development of a wireless communication infrastructure that is both self-sufficient and environmentally conscious.

The feasibility of implementing a renewable-powered antenna design to improve the environmental impact of wireless networks is considerable. Through the utilization of renewable energy sources, this methodology not only mitigates the ecological repercussions of wireless communication but also fosters autonomy and robustness in the functioning of

the network. The results outlined in this article make a valuable contribution to the continuous endeavours to create energy-efficient solutions for the ever-changing wireless communication environment. Antenna systems powered by renewable energy sources integrated into wireless networks that conserve energy are a paradigm shift in the direction of environmentally friendly communication technologies. By integrating developments in energy harvesting, designing antenna, protocols of communication, along with network architecture, this endeavor aims to establish communication infrastructures that are both resilient and environmentally sustainable.

Chalal, L. et al. 2023 [38] explained that the convergence of climate change and the energy crisis is expediting the global implementation of renewable energy sources via incentive schemes. However, energy management systems and storage infrastructure are required for renewable energy sources owing to their discontinuous and unpredictable nature. Furthermore, the execution of software and hardware mechanisms for data acquisition and optimization is necessary due to their intricate nature. Although the technologies employed in these systems are in a constant state of development, their present level of maturation already enables the creation of novel methodologies and instruments for the functioning of renewable energy systems.

The utilization of technologies like (IoT) and Digital Twin (DT) in the context of standalone photovoltaic systems is the subject of this study. They present a framework that aims to enhance real-time energy management by leveraging the Digital Twin (DT) paradigm and Energetic Macroscopic Representation (EMR) formalism. The article provides a definition of the digital twin as a bidirectional data-communicating combination of the physical system and its digital model. Furthermore, MATLAB Simulink is utilized to integrate the digital replica and IoT devices into a unified software environment. In order to verify the functionality of the digital counterpart that was created for the purpose of demonstrating an autonomous photovoltaic system, empirical experiments are conducted.

Finally, it can be seen that a good distribution for the Research works by topics on IoT infrastructures for building energy systems as shown in figure 2.2.

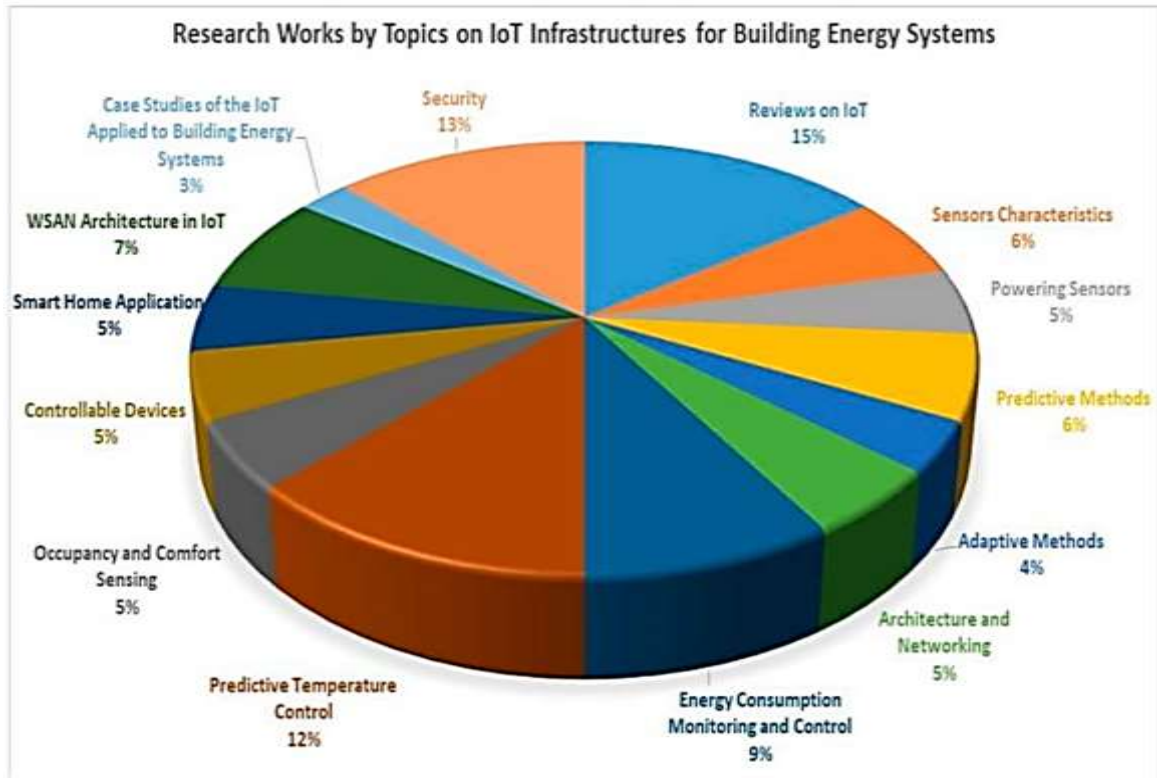


Figure 2.2: Investigations of IoT Infrastructures for Building Energy Systems Organized By Issues.

3. METHODOLOGY AND TECHNIQUES

3.1 INTRODUCTION

Hybrid energy systems emerge as a highly prospective strategy in the quest for sustainable energy solutions, as they amalgamate a diverse array of conventional and renewable energy sources. These systems provide efficiency, dependability, and resilience through the utilization of the complementary characteristics of various energy sources. In order to maintain hybrid energy systems at their peak efficiency and under effective management, however, robust monitoring and control mechanisms are required.

This introductory section presents a comprehensive outline of the requirements analysis procedure that is undertaken in order to develop a monitoring system that is specifically designed for hybrid energy systems. Through the systematic identification of stakeholder needs, establishment of key parameters, and definition of system objectives, requirements analysis establishes the foundation for the development of a monitoring system that effectively addresses the distinct challenges and objectives of hybrid energy applications.

The system design section for IoT-based real-time hybrid system performance monitoring focuses on architectural design and important considerations that must be made while establishing a monitoring system. This section objective is to give readers a comprehensive grasp of the design principles, requirements, and components involved in implementing IoT technology for PV and real-time PV system monitoring. By looking at the system design elements, this chapter establishes the foundation for building a dependable and efficient monitoring system that can capture, process, and present important performance data. The present section will provide further information on the design elements, techniques, and best practices that result in the effective implementation of real-time performance monitoring for PV systems using IoT technology.

3.2 DESIGN REQUIREMENTS

The involvement of participants is vital in influencing the specifications of the monitoring system. The stakeholders in this context comprise system operators, environmental agencies, regulatory entities, energy consumers, and maintenance personnel. The inclusion of stakeholders' viewpoints and requirements is guaranteed by their identification during the

requirements analysis phase. Participant input is gathered through seminars, surveys, and interviews in order to comprehend their needs, preferences, and priorities. By means of this procedure, collaboration and communication are enhanced, allowing interested parties to effectively articulate their anticipations regarding the monitoring system.

Conversely, it is critical to establish precise and succinct objectives in order to provide direction for the development and design of the monitoring system. The objectives of the system may encompass various aspects such as maximizing energy efficiency, assuring system reliability, minimizing outage, and optimizing energy production. A framework for prioritizing requirements and making design decisions is established by these objectives.

Additionally, key parameters denote the pivotal variables that require close observation in order to accomplish the objectives of the system. When considering hybrid energy systems, crucial factors to consider may consist of the following: energy storage levels (e.g., battery capacity, state of charge), grid interactions (e.g., electricity import/export), environmental conditions (e.g., temperature, humidity), and system performance metrics (e.g., efficiency, reliability).

The performance metrics are utilized to assess the monitoring system's efficacy and efficiency. Metrics such as accuracy, precision, response time, scalability, robustness, and cost-effectiveness are defined by these terms. By establishing performance metrics, the monitoring system can be guaranteed to operate with the desired degree of dependability and efficiency. Regulatory mandates and industry standards must be taken into account when establishing the monitoring system's requirements. Ensuring adherence to safety standards, certifications, and regulations guarantees that the monitoring system functions in accordance with pertinent legal and regulatory frameworks.

It is critical to document the requirements obtained from stakeholders in order to ensure transparency, traceability, and clarity. The objectives of the system, its most important parameters, performance metrics, regulatory mandates, environmental factors, and any other pertinent data are delineated in a requirements specification document. The purpose of this document is to provide guidance throughout the design, development, and implementation of the monitoring system.

The requirements analysis is a crucial step in the design process for a hybrid energy system monitoring system. Through the methodical identification of participant needs, the establishment of system objectives, and the determination of critical parameters, requirements analysis guarantees that the monitoring system adequately addresses the obstacles and aspirations associated with hybrid energy applications.

3.3 SYSTEM DESIGN

The implementation of numerous sensors and data recorders is required for the real-time performance monitoring of hybrid energy systems. Vital data, such as solar irradiance, temperature, voltage, current, and power parameters, are collected. By utilizing Internet of Things (IoT) technology, this monitoring system facilitates uninterrupted data acquisition, analysis, and communication, empowering operators to make well-informed decisions in order to maximize system performance.

Sensor selection, data logger integration, Internet of Things connectivity, data acquisition and transmission, real-time monitoring, data analysis, and visualization are all essential elements of the system design. By means of integrating these constituent elements, operators are granted prompt and practical insights into the hybrid energy system's performance, enabling them to undertake proactive measures for optimization and management.

In its entirety, the implementation of IoT technology in the system design for real-time performance monitoring of hybrid energy systems signifies a pivotal stride in the direction of attaining energy efficiency, dependability, and sustainability within contemporary energy infrastructure. Through the utilization of IoT technology, operators are able to efficiently oversee and control hybrid energy systems, thereby guaranteeing their sustained functionality and contribution towards environmental sustainability.

System Design can be analysed for Hybrid Energy System with IoT-Based Real-Time Performance Monitoring of:

a. **Sensor Selection:**

To ensure accurate and exhaustive data capture, the selection of sensors for monitoring parameters including solar irradiance, temperature, voltage, current, and power is crucial. The evaluation of the hybrid energy system's efficacy and efficiency is contingent upon these

parameters. To illustrate, solar irradiance sensors quantify the intensity of sunlight, whereas temperature sensors observe and record environmental conditions that have the potential to impact energy production and the functioning of equipment.

b. Data loggers:

Data recorders are indispensable for the real-time collection and storage of information from the sensors. Typically, these devices comprise memory storage, communication interfaces, microcontrollers, and other components that aid in the acquisition and transmission of data. Data recorders obtain measurements at consistent time intervals through sensor interfaces and retain them for subsequent analysis.

c. IoT Integration:

The incorporation of IoT technology facilitates the smooth exchange and transmission of information from the monitoring platforms that are centralized on the sensors. The implementation of IoT-enabled devices, including microcontrollers equipped with Wi-Fi or cellular connectivity, enables the hybrid energy system to be remotely monitored and controlled. This enables operators to optimize system performance by accessing real-time data from any location and making informed decisions.

d. Acquisition and Transmission of Data:

The hybrid energy system's sensors consistently determine the designated parameters, and the data recorders systematically amass this data at predetermined time intervals. Subsequently, the gathered information is conveyed to centralized monitoring platforms via cellular networks, Wi-Fi, or Bluetooth, among other wireless communication protocols. This process guarantees prompt retrieval of essential performance indicators and enables proactive administration of the hybrid energy system.

e. Real-Time Monitoring:

Real-time monitoring is a feature made possible by the Internet of Things (IoT), which grants operators immediate access to information regarding the efficacy of the hybrid energy system. Through the utilization of graphical interfaces or data dashboards on web-based platforms, operators are able to visually represent critical parameters in real-time, track patterns, and detect possible problems or irregularities that necessitate scrutiny. By adopting

a proactive monitoring approach, opportune interventions can be implemented to enhance the efficiency and dependability of the system.

f. Data Analysis and Visualization:

In order to process and interpret the gathered data, centralized monitoring platforms typically include data analysis and visualization tools. By employing algorithms and analytics methods, correlations, patterns, and trends in the data are identified, providing operators with actionable insights regarding the performance of the system. Graphs, charts, and alerts are examples of visualizations that offer intuitive depictions of data, thereby enhancing the ability to make well-informed decisions.

g. Flexibility and scalability:

The design of the hybrid energy system ought to possess scalability and adaptability in order to accommodate potential future expansions or modifications. Further sensors or data recorders may be readily incorporated into the pre-existing infrastructure, and it is imperative that the monitoring platform facilitates the smooth integration of novel devices or technologies. By doing so, the monitoring system maintains its flexibility in response to changing demands and advancements in technology.

As a brief outline, the system design pertaining to the utilization of IoT technology for the purpose of monitoring the real-time performance of a hybrid energy system comprises the following elements: appropriate sensor selection, data logger integration, IoT connectivity, data acquisition and transmission, real-time monitoring, data analysis, and visualization. Through the utilization of Internet of Things (IoT) technology, operators are able to acquire practical and implementable knowledge regarding the performance of hybrid energy systems, optimize energy efficiency, and guarantee dependable operation.

3.4 HARDWARE DESIGN REQUIREMENT

The setup and configuration of the hardware, the software, and the integration of IoT in the hybrid energy system are all covered in the implementation part. We will also go through the procedure for gathering data and analyzing it to get useful information for assessing system performance. The conclusions of our tests will be presented in the results and discussion section, which will also give a thorough analysis of the data gathered.

To assess the economic viability of the proposed smart monitoring network, we will also do a cost study. This research will evaluate the cost-effectiveness of new monitoring solutions to current monitoring solutions while taking into account equipment prices, installation costs, and maintenance costs.

Finally, we will summarize the main results, emphasize the research's contributions, talk about its limits, and provide some future areas for improvement and study in the area of smart monitoring for hybrid energy systems utilizing IoT. The information gleaned from this research will help hybrid energy systems run more effectively while also advancing the creation of IoT-based monitoring and control systems for other energy systems.

3.4.1 Design and Modeling of LoRa System

A limited amount of messages and minimal bandwidth are two characteristics of LoRa, a LoRaWAN physical layer technology that is freely licensed in ISM bands [24, 25]. It makes use of Chirp Spread Spectrum (CSS) modulation, which enables low power and long range [26]. Certain parameters, such the spreading factor (SF), coding rate (CR), and bandwidth (BW), can be altered in LoRa communication. The region in which the LoRa devices are deployed determines the values of each parameter. Bands of 868 MHz are used in Europe, 915 MHz in North America, and 433 MHz in Asia [25, 27]. However, the SF might range from 7 to 12. The signal-to-noise ratio (SNR), sensitivity, coverage range, symbol time (T_s) [28], and time on air (ToA), or packet transmission time, all increase with its value. Explicit and implicit packet formats are the two types of packet formats that LoRa modulation uses to transmit arbitrary frames. Preamble, header (optional), data payload (maximum 255 bytes), and optional payload CRC are the four main components of a packet structure [27, 29]. In Figure 3.3, the format is displayed.

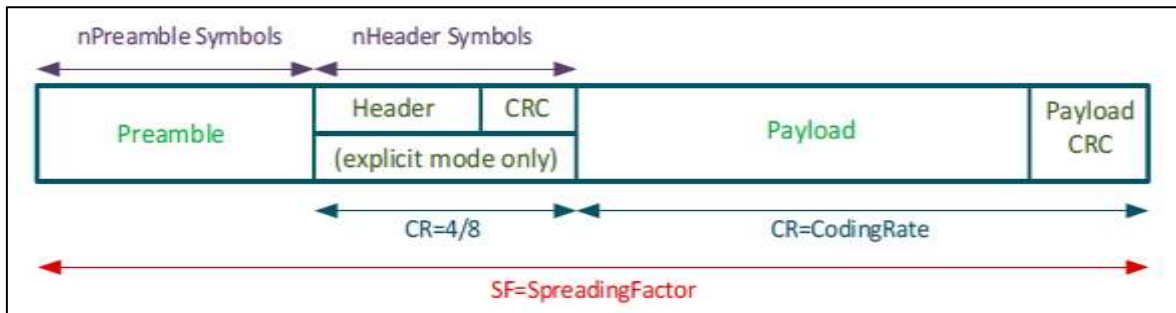


Figure 3.1: LoRa Package Format.

A 125 kHz, 250 kHz, or 500 kHz bandwidth is typically used by LoRa networks [30]. Higher transmission speeds are possible with additional bandwidth, but mistakes are more likely to occur [31]. The symbol time (T_s), bandwidth, and spreading factor (SF) are related in Equation (3.1).

$$T_s = \frac{2^{SF}}{BW} \quad (3.1)$$

This equation shows that when the spreading factor increases, the time of package transmission will eventually be multiplied and the span of the chirp frequency will be divided by two. Additionally, the bit rate doubles the transmission rate for any given spreading factor as it is proportionate to the bandwidth.

A forward error-correcting code is included with LoRa. With $n \in \{1, 2, 3, 4\}$, the code rate (CR) is calculated as $CR = 4/(4+n)$. Considering that the information is conveyed through symbols. Equation (2) defines the useful bit modulation rate R_b [32]:

$$R_b = SF \times \left(\frac{BW}{2^{SF}} \right) \times \left(\frac{4}{4+n} \right) \quad (3.2)$$

Equation (3.2) estimates the bit rate (R_b) in LoRa modulation.

To find out the time on air that LoRa packet can be transmitted [27], Equation (3.3) may be offered:

$$T_{oA} = \frac{2^{SF}}{BW} (NP + 4.25 + SW + \max(H, 0)) \quad (3.3)$$

$$H = \left\lceil \frac{8PL - 4SF + 28 + 16CRC - 20IH}{4(SF - 2DE)} \right\rceil (n + 4) \quad (3.4)$$

where n is the value of the parameter belonging to $CR = 4/(4 + n)$. NP is the Number of programmable symbols of the preamble. SW is the length of the sync word. PL is the number of PHY useful payload bytes. CRC is CRC presence (1 = yes; 0 = no). IH is the presence of the PHY header (1 = no; 0 = yes) and DE is the use of data rate optimization (1 = enabled; 0 = disabled).

The received signal strength indicator (RSSI) is an important measurement parameter that reflects the quality of LoRa links [28]. With the noise factor (NF) of the receiver and the transmitted power P_{TX} , it is possible to estimate the SNR of the measured RSSI values, according to [28,32]:

$$SNR = RSSI + 174 - 10(BW) - NF \quad (3.5)$$

where $NF = 6$ dB, which is the noise and RSSI is the receiver sensitivity -137 dBm [27],

$BW = 125$ Khz, $SF = 12$ and where $R_b = 293$ bps.

Within the domain of wireless communication and the Internet of Things (IoT), LoRa (Long Range) technology has surfaced as a potent remedy for facilitating low-power, long-range connectivity across a multitude of applications. The design and modelling of LoRa systems are of the utmost importance in minimizing power consumption while assuring dependable and efficient communication over long distances. This introduction highlights the significance of the design and modelling process for LoRa systems, which facilitates scalable and cost-effective Internet of Things deployments.

The implementation of LoRa technology has significantly transformed the wireless communication domain, presenting an appealing resolution for Internet of Things applications that necessitate extended battery life, low data rates, and long-range connectivity. LoRa is highly suitable for a wide range of applications, including but not limited to smart cities, industrial monitoring, environmental sensing, agriculture, and asset tracking, due to its distinctive modulation scheme and resilient error correction capabilities.

A comprehensive methodology is employed in the design and modelling of LoRa systems to systematically enhance a multitude of communication performance metrics—such as network scalability, coverage, data rate, latency, and power consumption. Through the utilization of various tools and techniques, including but not limited to frequency band selection, network topology design, link budget analysis, propagation modelling, and protocol optimization, LoRa systems can be customized by designers to align with the particular demands and limitations of their respective applications.

Critical factors to be taken into account during the design and modelling phase consist of the subsequent: choosing the most suitable frequency band, devising the network topology, optimizing antenna configurations, configuring LoRa parameters, executing power management strategies, and conducting simulation or field testing to validate system performance. In order to optimize the battery life of LoRa-enabled devices and ensure dependable and effective communication over extensive distances, it is imperative to adhere to the following procedures.

In addition to facilitating data exchange and seamless connectivity in IoT applications, the design and modelling of LoRa systems pave the way for cost-effective and scalable deployments. Organizations can construct resilient Internet of Things (IoT) solutions that encompass a diverse array of use cases, such as remote environmental monitoring and smart city infrastructure, while incurring minimal operational expenses and infrastructure prerequisites, by utilizing LoRa technology.

To summarize, the implementation of IoT relies heavily on the design and modelling of LoRa systems, which empowers businesses to utilize long-range, low-power connectivity for an extensive array of purposes. In an era of growing interconnectivity, stakeholders can harness the complete capabilities of LoRa technology and experience the advantages of connected IoT solutions by adhering to a methodical framework for design and optimization.

The LoRa system's design, which is being utilized to monitor Hybrid energy systems Performance in the institution region, is explained in this section. For the example study, a LoRa network may be implemented without the use of LoRaWAN; it requires low power monitoring because there isn't much of a network of nodes interacting through the gateway [39]. In addition, a LoRaWAN network's physical layer is represented by LoRa. The implemented system provides management, security, scalability, and affordability for the community's residents whose only source of revenue is agriculture inside the covered region.

Within this framework, the system will provide the foundation for the use of strategies like production forecasting, intelligent irrigation, and phytosanitary management, among others. Table 1 lists the essential components.

As depicted in figure 3.2, A LORA as a microprocessor can be connected in such system.

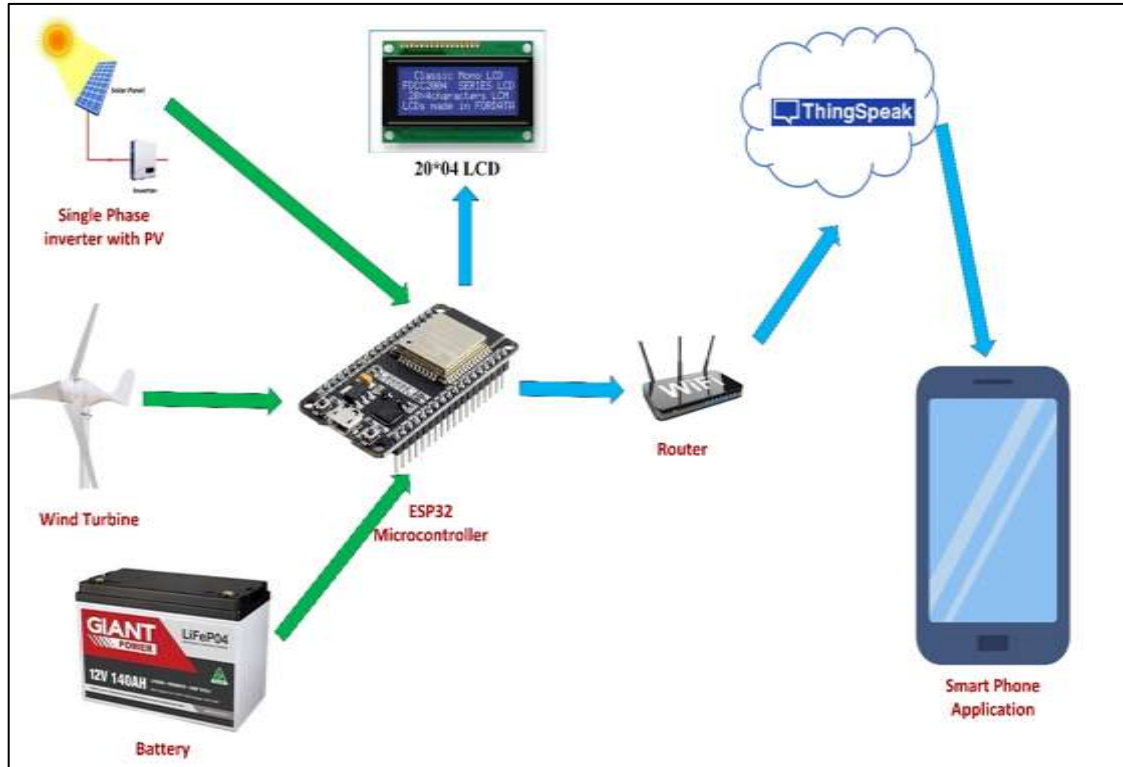


Figure 3.2: The Lora System's Design to Monitor Hybrid Energy Systems Performance.

Material selection is an essential phase in any engineering or development project, including the construction of an IoT-based smart monitoring network for a hybrid energy system. During this phase, researchers and engineers conduct a systematic survey of available hardware and software components to determine the most appropriate options for the project's specific needs.

This phase includes the evaluation and selection of the physical components that will comprise the IoT infrastructure. This consists of sensors for measuring solar irradiance, wind velocity, temperature, and other pertinent parameters. It also includes the selection of communication modules or devices, such as Wi-Fi, cellular, or LoRaWAN, that permit data transmission from sensors to a central control system or gateway. Additionally, hardware selection may involve choosing microcontrollers or processing units capable of managing data acquisition, storage, and real-time analytics. The selection procedure takes into account sensor precision, communication range, energy consumption, and overall dependability.

3.4.2 LoRa ESP32 as a Microcontroller

The ESP32 is a popular and versatile microcontroller and system-on-a-chip (SoC) that is widely used in various IoT (Internet of Things) and embedded systems applications. It is developed by Espressif Systems, a semiconductor company known for its contributions to the IoT and wireless communication technologies. A main key features and characteristics of the ESP32 is a dual-core Xtensa LX6 microprocessor, which allows for efficient multitasking and performance optimization. While for wireless connectivity it includes built-in Wi-Fi connectivity, making it suitable for IoT applications requiring wireless communication. The ESP32 supports both Classic Bluetooth and Bluetooth Low Energy (BLE), making it versatile for various Bluetooth-based applications such as Bluetooth Mesh networking that enabling the creation of large-scale IoT networks.

The ESP32 offers a significant number of GPIO pins for connecting sensors, displays, and other peripherals. These interfaces allow communication with a wide range of sensors and devices. It has ADC (Analog-to-Digital Converter) and DAC (Digital-to-Analog Converter) pins for analog signal processing. The ESP32 is designed for low power consumption, making it suitable for battery-powered or energy-efficient applications. While some ESP32 variants include integrated sensors like temperature and humidity sensors, which can simplify certain IoT applications.

It includes hardware-based security features, such as secure boot, Flash encryption, and cryptographic accelerators, to enhance device security. It is supported by the Arduino IDE, making it accessible to a broad community of developers and hobbyists. Due to its capabilities and versatility, the ESP32 is widely used in various IoT applications, including home automation, sensor networks, wearables, robotics, and industrial automation. Its combination of Wi-Fi, Bluetooth, and low power consumption makes it suitable for a wide range of wireless and connected devices. Developers appreciate its ease of use and the vast amount of documentation and community support available, making it a popular choice for IoT projects.

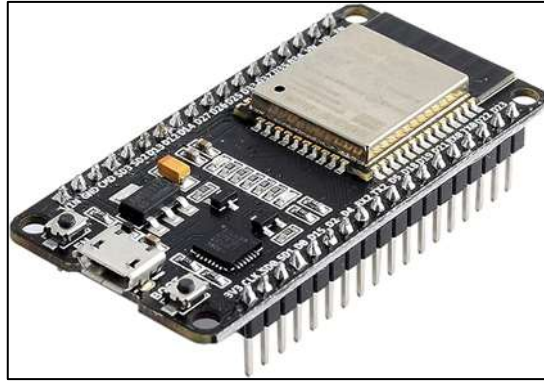


Figure 3.3: A Main Key Features and Characteristics of the ESP32.

Espressif Systems created the ESP32, a potent and adaptable microcontroller shown in Figure 3.3. Because of its many uses, cheap cost, and extensive feature set, the ESP32 is a popular choice for Internet of Things applications. a leading semiconductor company specializing in Internet of Things (IoT) solutions. It is a successor to the popular ESP8266 and has gained significant traction in the IoT and embedded systems community owing to its impressive set of features and capabilities. An overview of the ESP32 microcontroller is provided here [40]:

Dual-Core Device: The dual-core Tensilica Xtensa LX6 CPU that powers the ESP32 is one of its most notable characteristics. This makes parallel processing and multitasking possible, enabling the ESP32 to manage several tasks at once.

Wireless Connectivity: The ESP32 is suited for Internet of Things projects that need wireless connectivity since it has built-in Wi-Fi and Bluetooth capabilities. It is compatible with many Wi-Fi protocols, such as Bluetooth Low Energy (BLE) for low-power connection and 802.11 b/g/n.

Rich Peripheral Set: There are several peripheral interfaces available on the ESP32, such as SPI, I2C, UART, ADC, DAC, PWM, and more. The ESP32 can communicate with popular IoT devices such as displays, actuators, sensors, and other external hardware using these interfaces.

Low Power Consumption: The ESP32 is made to be energy-efficient even with its potent capabilities. It has features that assist lower power consumption and lengthen battery life in

battery-powered applications, including as numerous low-power modes, a power management unit (PMU), and dynamic voltage scaling (DVS).

Integrated Security mechanisms: The ESP32 has a number of built-in security mechanisms to guard against a variety of attacks. Security is a top concern for Internet of Things devices. These include of hardware-accelerated cryptographic algorithms, flash encryption, secure boot, and safe key and certificate storage.

Development Ecosystem: Espressif's ESP-IDF (IoT Development Framework), the Arduino IDE, and a number of third-party development platforms are just a few of the strong development ecosystems that support the ESP32. This facilitates developers' entry into the world of IoT programming and prototyping.

Affordability and Availability: The ESP32 is reasonably priced and easily accessible from a number of global providers. Due to its low cost, amateurs, professionals, and students can all afford it, which has led to its broad acceptance in the maker community and industry. Table 3.1 illustrate the primary characteristics of the microcontroller ESP32.

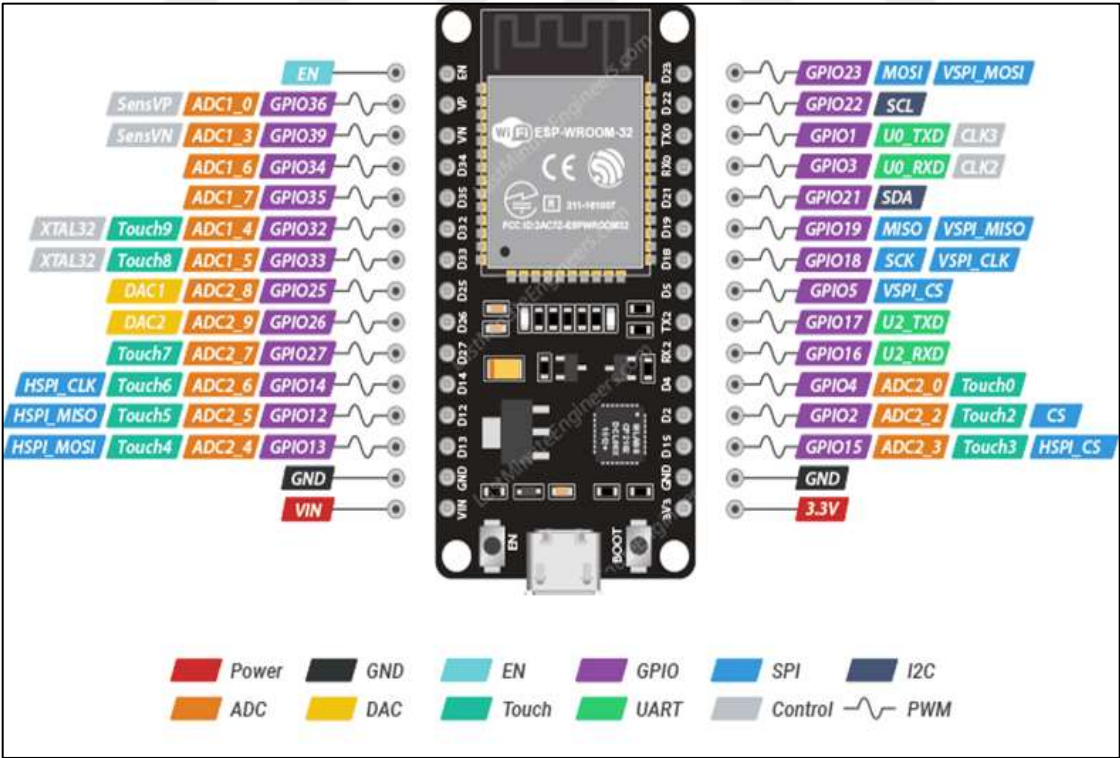


Figure 3.4: ESP32 Pinout Diagram [40].

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
Memory	Up to 520KB of SRAM
Wireless Connectivity	Wi-Fi 802.11 b/g/n and Bluetooth v4.2 / v5.0 BLE
Low-Power Modes	Supports various 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 (Pulse Width Modulation)	Enables 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

3.4.3 AC Voltage Sensor Turbine ZMPT101B

The ZMPT101B is an AC voltage sensor, an advanced electronic device developed for measuring the alternating current (AC) voltage in an electronic circuit. Typical applications for these sensors include industrial automation, power monitoring, and energy management systems. Consider the ZMPT101B AC voltage sensor and its common applications:

The ZMPT101B is a variety of AC voltage sensor designed for a particular AC voltage range. It is a useful sensor for applications involving low-to-medium voltage. Typically, it

generates a low-voltage AC output corresponding to the AC voltage it detects. The precise voltage output along with sensitivity can differ depending on the sensor's model and configuration. These sensors are small and comparatively simple to interface with microcontrollers, data acquisition systems, and other monitoring and control devices.

Common Applications:

- a. The ZMPT101B AC voltage sensor is primarily used to determine AC voltage levels in a circuit. It is commonly used to assess the voltage of an AC power supply in power monitoring systems.
- b. In power quality monitoring systems, AC voltage sensors are frequently used to evaluate the stability and quality of the electrical supply. Using these sensors, voltage variations such as sags, surges, and harmonics can be detected and analyzed.
- c. In an industrial context, these types of sensors are often utilized for tracking voltage across various loads or machines. Changes in levels of voltage may indicate variations in demand or prospective problems.

In energy management systems, these sensors measure and record AC voltage levels, enabling users to monitor usage of energy and optimize energy use. AC voltage sensors can also be incorporated into the protection systems of electrical installations, where they assist in detecting voltage anomalies and initiating protective measures.

The ZMPT101B and other AC voltage sensors include galvanic isolation and filtering to guarantee accurate and safe voltage measuring. Some models may include additional features such as adjustable sensitivity and voltage dividers to accommodate different voltage ranges. AC voltage sensors require regular calibration and maintenance to ensure their accuracy and dependability over time.

AC voltage sensors, such as the ZMPT101B, are indispensable components for determining and tracking AC voltage levels in a variety of applications, including power monitoring and industrial automation. By supplying precise voltage measurements and supporting real-time monitoring and control, they contribute to the safety and efficacy of electrical systems.

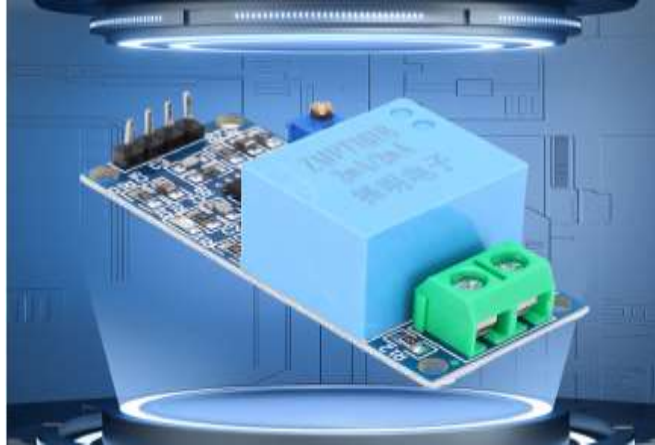


Figure 3.5: ZMPT101b AC Voltage Sensor Turbine.

3.4.4 The PZEM-004T Mustimeter Module AC

A module for monitoring electrical systems in AC systems, the PZEM-004T is made to measure a variety of characteristics. An outline of its attributes and capabilities is provided below:

a. **Measurement Parameters:** There are several electrical parameters that the PZEM-004T module can measure, such as:

- a. **Voltage (V):** Indicates the AC power supply's RMS voltage.
- b. **Current (A):** This indicator shows the circuit's RMS current.
- c. **Active Power (W):** Determines how much actual power the load uses.
- d. **Energy (Wh):** Calculates energy use by integrating power consumption over time.
- e. **Frequency (Hz):** Indicates the AC electrical signal's frequency.

Because of the non-invasive design of the module, electrical parameters may be measured without physically interrupting the circuit. Because of this, it is simple to install and operate, needing neither intricate wiring nor extensive electrical system adjustments.

b. **Communication Interface:** For data transfer to other devices, including microcontrollers or computers, the PZEM-004T module frequently has a communication interface. UART (serial), TTL, or RS485 are examples of common communication interfaces that allow for easy integration with a variety of monitoring and control systems. An embedded LCD

display is a feature of several PZEM-004T module variations, enabling users to examine measurements that occur instantly on the module. Usually, readings for voltage, current, power, energy, and frequency are displayed on the display.

c. Applications: The PZEM-004T module is useful in a number of situations where it's necessary to measure and monitor AC electrical properties. These consist of renewable energy installations, industrial control systems, smart home automation initiatives, and energy monitoring systems. The module's purpose is to deliver precise measurements within predetermined bounds. To guarantee measurement accuracy over time or in various operational environments, certain variations could provide calibration choices. It works with a broad variety of electrical systems and voltages; depending on the model, it can support AC voltages ranging from 80V to 260V and currents up to 100A.

With its non-intrusive design, integrated display, communication capabilities, and compatibility with various applications, the PZEM-004T Mustimeter Module AC is a popular option among engineers, professionals, and hobbyists alike. In general, it provides a practical and affordable solution for monitoring electrical parameters in AC systems.

Because of its precision and small size, the PZEM-004T in Figure 3.6 is well-suited for residential energy monitoring applications and is also noted for being easy to install. However, while working with electrical circuits, especially when handling high voltages and currents, it is imperative to follow safety protocols. All things considered, the PZEM-004T Mustimeter Module AC provides an affordable and useful way to keep an eye on and control electrical parameters, giving customers the ability to maximize power consumption and improve energy efficiency in their systems. Table 2 lists the primary attributes and features of the PZEM-004T micrometer module AC.



Figure 3.6: The PZEM-004T Mustimeter Module AC [41].

Table 3.2: The main properties of the PZEM-004T Mustimeter Module AC [41].

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
Compact Size	Compact and easy to install
Application	Ideal for energy monitoring, and industrial setups

3.4.5 Dc Voltage Sensor Battery

An energy source A DC voltage sensor is a tool or sensor that is used to gauge the voltage of a direct current (DC) source, like a battery, as seen in figure 3.7. For a multitude of applications, including renewable energy systems, electric cars, uninterruptible power supply (UPS), and other electronic devices, monitoring the state of charge (SoC) and voltage level of a battery is essential.

Measuring the battery's output voltage is the main job of the DC voltage sensor. The electrical potential or energy level of the battery is shown by this measurement. The voltage range in which DC voltage sensors are designed to function is specific. The kind and arrangement of a battery determines its voltage range. Batteries often operate in voltage ranges of 12V, 24V, 48V, and higher. Although the voltage measurement's precision is an important consideration, it is not the sole one. High-precision sensors are widely used in situations where accurate voltage monitoring is essential. DC voltage sensors typically produce an output signal that may be utilized for additional processing or observation. Typical output types are digital signals (UART, I2C) that can interact with microcontrollers or data acquisition systems, and analog voltage signals (0-5V, 0-10V).



Figure 3.7: DC Voltage Sensor for Batteries.

3.4.6 Breadboard Power Supply Module

For energizing breadboard circuits during experimentation and prototyping, the breadboard power supply module depicted in Figure 3.8 is a practical and indispensable electronic component. This module is specifically engineered to be affixed directly to the breadboard. It is capable of receiving an extensive variety of input power sources, generally ranging from 6V to 12V DC. Power can be supplied via a USB connector or barrel port connector. It provides a range of regulated output voltages, which are frequently selectable via a toggle or switch [42], including 3.3V and 5V.

Additionally, some modules may incorporate current-limiting functions to safeguard the circuit against excessive current. The power supply is easily controlled via an on/off switch, and status indicators (LEDs) display information such as whether the power is on or off. The module's diminutive dimensions guarantee its seamless integration onto the breadboard, preventing any hindrance to the circuit connections. Additionally, short-circuit protection may be integrated to safeguard against potential harm in the event of unintended short circuits.



Figure 3.8: BreadBoard Power Supply Module[42].

The Breadboard Power Supply Module eliminates the need for external voltage regulating and filtering capacitors for powering breadboard circuitry. Because of its intuitive design, it is a valuable tool for engineers, learners, and hobbyists engaged in rapid prototyping and electrical circuit investigations. Table 3.3 lists the essential attributes and functionalities of the breadboard power-supply module.

Table 3.3: The Main Properties of the Bread Board Power Supply Module [42].

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

3.4.7 Liquid Crystal Display (LCD)20*04

A 20x4 LCD is a common form of alphanumeric display found in a variety of electronic devices, such as microcontroller-based applications, digital instruments, and consumer electronics. The notation "20x4" refers to the dimensions and configuration of the display, indicating that each of its four lines can display 20 characters. The 20x4 LCD displays a total of 80 characters across four panels of 20 characters each. Each character position is capable of displaying alphabetic characters, symbols, and user-defined characters.

It typically supports a standard character set consisting of uppercase and lowercase letters, numerals, symbols, and special characters. Depending on the LCD controller used, the particular character set may vary. EL (Electroluminescent) or LED backlights are typically included on 20x4 LCDs. The illumination can be adjusted to enhance legibility in varying lighting conditions. The 20x4 LCD is typically commanded by an embedded controller processor based on the Hitachi HD44780 or a compatible controller. The controller manages the operation of the display, the generation of characters, and communication with the host device.

Typically, the 20x4 LCD interfaces with a microcontroller or other control circuitry via parallel communication. Common communication standards include parallel interfaces with 4-bit and 8-bit resolution. With the assistance of supplementary modules or controllers, certain models may offer serial communication options, such as I2C or SPI. The 20x4 LCD is an adaptable display that provides a sufficient quantity of space for displaying textual and numeric data in a variety of applications. Its simplicity and ease of integration make it a popular choice among both amateur and professional electronics enthusiasts.

It is possible for consumers to adjust the brightness of the display by adjusting the backlight on several modules. Since the LCD controller in the module is frequently HD44780-compatible, it may be combined with popular microcontrollers like Arduino with ease by utilizing freely available libraries and code examples. It works with a wide range of microcontroller platforms and voltages, often between 3.3V and 5V. Certain models incorporate a contrast adjustment potentiometer for fine-tuning readability.

Additionally, users have the option to define custom characters, which allows them to show own icons or symbols. The LCD 20x4 I2C module can be used for Internet of Things (IoT)

devices, temperature sensors, data loggers, and other applications that need for crisp visual output. Its ease of use, versatility, and interoperability have made it an indispensable component of embedded systems and Internet of Things applications, helping both novices and professionals with their electronic endeavors. Table 3.4 lists the primary attributes and features of the LCD 20x4 I2C module.

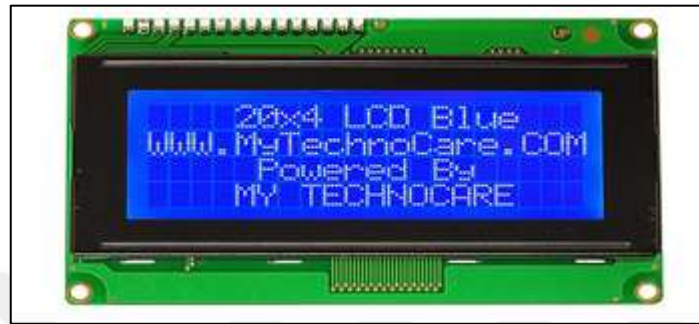


Figure 3.9: LCD 20*04 Module (Liquid Crystal Display) With I2C.

Table 3.4: The Main Properties of the LCD 20x4 I2C Module.

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

3.5 THINGSPEAK

Data from sensors or IoT devices may be collected, stored, processed, analyzed, displayed, and used to drive actions using an Internet of Things (IoT) platform called ThingSpeak. Remote device and system control and monitoring is a common usage for it. Developers may use ThingSpeak's API to programmatically transmit and receive data between their channels. It is widely used in applications such as industrial IoT, environmental monitoring, and home automation. ThingSpeak allows users to store data in channels, process data using MATLAB analytics, and analyze the collected data using user-made graphs and maps. Figure 3.7 shows the primary window of ThingSpeak [43].



Figure 3.10: The ThingSpeak Main Window.

One of ThingSpeak's primary features is its ability to collect and store data from Internet of Things devices in real-time. By setting up many channels, ThingSpeak enables users to manage and organize data streams from various sources. It is possible to offer a single channel with many fields that represent separate data points, giving customers the ability to specify and store various types of data.

3.6 MIT APP INVENTOR

With MIT App Inventor, non-programmers may design Android mobile applications with a drag-and-drop interface and customize the user interface and functionality. The tool is web-based. With MIT App Inventor, users may create a wide variety of apps, from simple games and utilities to more complex programs that interact with databases and web services. It is particularly popular in educational environments where computer science and the principles

of app development are taught to students of all ages. The platform enables quick concept testing and prototyping without the need for familiarity with traditional programming languages, encouraging experimentation and innovation. The main interface of MIT App Inventor is shown in Figure 3.10.

Using a drag-and-drop interface, App Inventor enables users to graphically create buttons, text boxes, sensors, and multimedia elements to create the functionality of mobile apps. The App Inventor provides an abstraction layer over traditional coding, which eliminates most of the challenge involved. This frees users from having to focus on the finer points of programming language, allowing them to focus on the logic and functionality of the app.

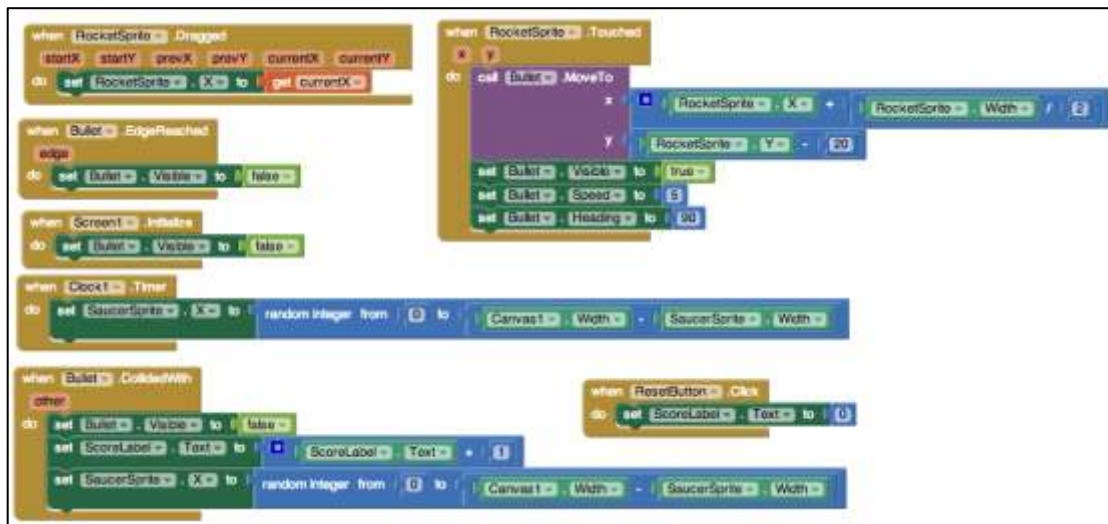


Figure 3.11: The Main Window of The Drag-And-Drop Interface For MIT.

All things considered, MIT App Inventor provides a ground-breaking platform that reduces the obstacles to entering the field of mobile app development, inspiring individuals of all ages and backgrounds to realize their app concepts and share them with the world.

- a. Can the volume of data and refresh time intervals needed for distributed energy resource monitoring and control on a smart campus be handled by LoRaWAN technology.
- b. How many devices can a single LoRaWAN gateway monitor and control?
- c. Is it possible to include the LoRaWAN infrastructure into an established monitoring and control architecture as a supplementary solution?

In order to respond to the first question, we looked through the scientific literature to find the control and monitoring designs that have been suggested for the administration of distributed energy resources in complex systems. In order to establish the refresh time intervals and the kind of messages that are sent between the various intelligent devices and the relevant supervisory entities, a generic architecture was therefore defined and utilized as reference architecture.

Second, a suitable structure for the data model was established to enable the calculation of the communication's payload. To the best of the authors' knowledge, no previous research has provided a comprehensive description of a smart campus use case or an associated data model; as such, this study's uniqueness includes this addition.

Finally, a suitable architecture built on LoRaWAN class A technology was put forth. Its viability was assessed by confirming that it could transmit the necessary quantity of data during the specified refresh intervals. The computation of the Time-on-Air duration of supervisory control messages and monitoring messages is how the evaluation is done.

4. HYBRID ENERGY SYSTEMS SIMULATION

4.1 OVERVIEW OF HYBRID ENERGY SYSTEMS

The creation of hybrid energy systems has drawn more attention in recent years as a viable way to fulfil rising energy demands while lowering dependency on conventional fossil fuels. In order to provide a more dependable and effective infrastructure for power generation, hybrid energy systems combine several renewable energy sources, including photovoltaic (PV) arrays, wind turbines, hydropower generators, and energy storage devices. Hybrid systems may overcome the erratic and unpredictable nature of individual renewable energy sources by integrating complementary energy sources, improving the stability and dependability of the system.

By combining various renewable energy sources and energy storage technologies, hybrid energy systems offer a cutting-edge solution to the problems associated with energy sustainability and stability. These systems maximize energy output, improve system dependability, and reduce environmental impacts by combining two or more renewable energy sources—such as solar, wind, hydro, or biomass—with conventional sources or energy storage systems.

Comparing hybrid energy systems to solo renewable energy systems reveals a number of benefits. Hybrid systems can reduce the erratic and unpredictable character of renewable energy production by taking use of the complementing qualities of several energy sources. Additionally, they can offer a more dependable and steady power source, particularly in isolated or off-grid areas with limited access to traditional grid infrastructure.

Hybrid energy systems may be customized to meet unique applications' and energy needs because to their flexibility. They may be made for a range of applications, from large-scale business or manufacturing systems to tiny domestic installations. Hybrid systems can also be set up to operate off-grid, on the grid, or in hybrid, providing flexibility in installation and interaction with pre-existing infrastructure.

4.1.1 Importance Integration of Renewable Energy

In order to solve critical global concerns like climate change, reliability of electricity, and environmental sustainability, it is imperative that renewable energy sources like solar and wind power be included into the energy mix. Renewable energy sources, as opposed to fossil fuels, provide a wealth of clean energy alternatives that can help lower emissions of greenhouse gases and lessen the negative consequences of climate change. Furthermore, by generating jobs and stimulating invention in renewable energy industry, the integration of renewable energy sources supports economic growth, energy independence, and supply diversification.

In order to move toward a sustainable and low-carbon energy future, the inclusion of renewable energy sources in the energy mix is becoming more and more crucial. Integration of renewable energy has numerous important advantages:

- a. **Environmental Sustainability:** By producing power with low greenhouse gas emissions, renewable energy sources like solar, wind, and hydro contribute to lessen air pollution and climate change.
- b. **Energy Security and Independence:** By reducing reliance on fossil fuels, diversifying the energy supply with renewable sources lowers geopolitical risks and improves energy security.
- c. **Economic possibilities:** The expansion of local communities' economies, the creation of jobs, and investment possibilities are all made possible by the renewable energy sector.
- d. **Resilience and dependability:** Because renewable energy sources are frequently dispersed and decentralized, they are less susceptible to centralized power generating and transmission infrastructure, which improves energy resilience and dependability.

4.1.2 Chapter Objectives

This chapter's main goal is to use MATLAB to simulate and research a hybrid energy system that combines wind turbine and photovoltaic (PV) technology. The particular goals consist of:

- a. Photovoltaic (PV) System Modeling: Create a mathematical model of a PV system to mimic how it would operate in different loads and environmental scenarios. Creating a mathematical representation of a wind turbine system allows you to simulate its power production at varying wind speeds and turbine features.
- b. Hybrid Energy System Architecture: Taking into account system design, control methods, and power management approaches, combine the PV with wind turbine systems form a hybrid energy configuration.
- c. Simulation Setup: Establish the settings and circumstances of the simulation, such as the system setups, environmental inputs, and performance measures.
- d. Simulation Results and Evaluation: Run simulations to gauge the hybrid energy system's performance, examine the PV along with wind turbine systems' output, and determine how the environment affects the system's operation.
- e. Optimization and Control methods: Investigate optimization techniques and control methods to enhance the hybrid energy system's dependability and efficiency while taking grid integration, energy storage, and power generation into account.

The main objectives of this study are to Examine how hybrid energy systems that combine wind turbine and photovoltaic (PV) technologies are designed and run, examine how well hybrid energy systems function and how reliable they are in varied loads and environmental scenarios. Compare the environmental advantages and economic feasibility of hybrid energy systems with those of conventional energy systems. Finally, use MATLAB to create simulation models and techniques for analysing and improving the performance of hybrid energy systems and offer analysis and suggestions for the development, use, and enhancement of hybrid energy systems in real-world settings.

By achieving these objectives, this study aims to contribute to the advancement of renewable energy technologies and support the transition towards a more sustainable and resilient energy infrastructure and to provide insights into the design, operation, and optimization of hybrid energy systems, contributing to the advancement of renewable energy technologies and the transition towards a sustainable energy future.

4.2 BACKGROUND

4.2.1 Overview of Photovoltaic (PV) Technology

The photovoltaic effect allows photovoltaic (PV) technology, an essential component of renewable energy systems, to directly convert sunlight into electricity. PV cells, often referred to as solar cells, are constructed from semiconductor materials that, when exposed to sunlight, produce electricity, such as silicon. Recent decades have witnessed tremendous breakthroughs in PV technology, improving its cost-effectiveness, durability, and efficiency. PV cells come in a variety of forms, including as monocrystalline, polycrystalline, and thin-film, each having unique benefits and drawbacks regarding cost, performance under various environmental circumstances, and efficiency.

A photovoltaic cell operates by causing photons from sunshine to dislodge electrons from semiconductor material, which results in the creation of an electric current. This electricity can be stored in batteries for later use or utilized directly to power electrical loads. PV systems offer clean, renewable energy for use in commercial, industrial, and residential settings. They can be set up for grid-connected or off-grid applications.

The following are some of the main features of PV technology:

- a. **Efficiency:** the proportion of sunlight that is converted to energy is known as PV cell efficiency. Higher efficiency levels brought about by advancements in cell design and manufacturing techniques allow PV systems to produce more power from a given area of solar panels.
- b. **Durability:** Photovoltaic cells are engineered to tolerate severe environmental factors, such as fluctuations in temperature, high humidity, and exposure to ultraviolet light. Long-term dependability and performance are ensured by strong construction and high-quality materials.
- c. **Scalability:** PV systems, ranging from tiny rooftop installations to massive utility-scale solar farms, may be adjusted up or down to satisfy certain energy requirements. PV technology may be used in a variety of installations and applications due to its scalability.
- d. **Environmental Benefits:** When compared to traditional fossil fuel-based energy generation, photovoltaic technology offers notable environmental benefits. Because

solar energy is environmentally friendly, renewable, and emits no greenhouse gases when in use, it helps to slow down global warming and lessen air pollution.

Numerous subjects are covered in the literature on PV technology, including as system integration, cell design, manufacturing procedures, performance modeling, and optimization strategies. In order to increase the efficiency, lower prices, boost dependability, and broaden the range of settings and applications for solar energy systems, researchers have looked at a variety of PV technology-related topics.

4.2.2 Hybridization of PV and Wind Systems

Combining solar and wind power production technologies within a single hybrid energy system is known as hybridization of photovoltaic (PV) with wind energy systems. This method enhances total system stability, energy production, and dependability by combining the advantageous qualities of wind and solar energy. When compared to one another, solar and wind energy sources have complementing generation patterns. Wind energy generation is more constant and can happen day or night, depending on the weather and geographic location. In contrast, solar energy output peaks during the day when sunlight is available. Through the integration of these two renewable energy sources into a hybrid system, the shortcomings of each source may be mitigated while the system can benefit from their combined strengths.

4.2.3 Advantages of Hybrid PV-Wind Systems

- a. **Higher Energy Yield:** By combining solar and wind energy, hybrid PV-wind systems can maximize energy output all day long and in a variety of weather situations. When compared to independent PV or wind systems, this results in a larger total energy yield.
- b. **Improved System dependability:** Hybrid systems have the capacity to improve system stability and dependability by diversifying their energy sources. The system may rely on the backup energy source to continue power generation during times of low sunshine or calm winds, lowering the possibility of energy shortages or blackouts.
- c. **Optimised Land Use:** When PV and wind technologies are integrated on one location, the available land or infrastructure may be used to its fullest potential, reducing both the land footprint and the infrastructure costs associated with separate installations.

- d. **Greater Grid Integration:** Power production from hybrid PV-wind systems may be engineered to be more consistent and reliable, which makes grid stability and integration easier. This is especially helpful in places where there is a significant use of renewable energy, since grid balancing becomes more crucial.
- e. **Synergistic Effects:** Power production variations can be smoothed and intermittency can be decreased in hybrid systems thanks to the synergistic effects of solar and wind energy. Increased system efficiency and performance may result from this.

4.2.4 Challenges and Considerations

Hybrid PV-wind systems provide benefits, but their design and execution for simulation must take into account a number of challenges and limitations:

- a. **System Integration:** To guarantee compatibility, optimum performance, and effective operation, PV and wind technologies must be integrated with care through system design and engineering.
- b. **Control and Management:** For equalizing power generation from various sources, maximize energy storage, and preserve system stability, hybrid systems need complex control and management techniques.
- c. **Resource evaluation:** Determining the viability and potential of hybrid PV-wind systems requires accurate resource evaluation. To optimum energy output, factors including sun irradiance, wind speed, and site parameters must be carefully considered.
- d. **Financial Concerns:** Although hybrid systems have the potential to provide more energy and be more reliable than standalone PV or wind systems, they may also come with greater initial costs.

When everything is considered, hybridizing wind and photovoltaic systems is a potential strategy for increasing the production of renewable energy and accelerating the shift to a sustainable energy future. To fully exploit the promise of hybrid systems in tackling energy concerns and reducing climate change, further research, development, and implementation are needed.

4.2.5 Previous Research on Simulated Hybrid Energy Systems

The design, operation, and optimize of integrating renewable energy systems have been greatly aided by earlier studies on hybrid energy system modelling. In order to simulate hybrid systems including photovoltaic (PV), wind, water, biomass, and energy storage technologies, these research have used a variety of modelling tools and approaches. Key conclusions and techniques from earlier research include the following:

- a. **System Modelling and Integration:** To include various renewable energy sources and energy storage technologies into hybrid topologies, researchers have created mathematical models and simulation frameworks. These models take into account variables including system components, grid integration needs, control methodologies, and resource availability.
- b. **Performance Evaluation:** The effectiveness of hybrid energy systems under various operating circumstances, such as changes in load demand, weather patterns, and energy storage capacity, has been assessed in earlier research. In order to evaluate the success of the system and pinpoint areas for modification, performance measures including energy output, system efficiency, dependability, and commercial viability have been examined.
- c. **Optimization Techniques:** To improve the performance of hybrid energy systems, optimization techniques such as genetic algorithms, particle swarm optimization, and mathematical optimization algorithms have been used. These methods seek to optimize system setup and control parameters, reduce operating costs, and increase energy output.
- d. **Environmental Impact Assessment:** Research has also looked at how hybrid energy systems affect the environment, taking into account things like carbon emissions, emissions of greenhouse gases, and the sustainability of the environment. The environmental advantages of integrating renewable energy have been quantified and compared to traditional energy generation using life cycle assessment (LCA) approaches.
- e. **Case Studies and Applications:** Practical knowledge about system design, functioning, and performance have been made possible by research on case studies in real-world utilization of hybrid energy systems. The viability and efficiency of hybrid systems in a

range of situations, including residential, commercial, industrial, and distant off-grid locations, have been proven by these studies.

- f. **Software Tools and Simulation Platforms:** MATLAB/Simulink, HOMER, RETScreen, and EnergyPlus are just a few of the software tools and platforms that have been utilized to model and simulate hybrid energy systems. These tools allow researchers to investigate various scenarios and design alternatives by providing abilities for modelling systems, optimization, and performance analysis.

All things considered, earlier research on the modelling of hybrid energy systems has advanced renewable energy technology and helped decision-makers in energy planning, policy creation, and project execution. The current work intends to advance our knowledge of hybrid energy systems and offer helpful insights for their construction, optimization, and implementation in practical applications by expanding on these discoveries and approaches.

4.2.6 Gaps and Limitations in Existing Research

Hybrid energy system simulation has provided valuable insights, but there are several gaps and limitations that need to be addressed. These include simplified modelling approaches, limited integration of multiple energy sources, static system analysis, limited consideration of uncertainty and variability, lack of standardized methodologies and metrics, limited real-world validation, and underrepresentation of socio-economic factors.

Simplistic models may not accurately capture the complexities of real-world hybrid energy systems, leading to inaccuracies in performance predictions and optimization outcomes. Additionally, some studies focus on hybrid systems that integrate only two renewable energy sources, neglecting potential synergies with hydro, biomass, or geothermal sources. Static system analysis techniques often do not account for dynamic interactions between system components, variations in weather conditions, or changes in energy demand over time. Dynamic simulation approaches are needed to provide more realistic performance assessments and optimization results. Probabilistic modelling techniques and uncertainty analysis methods are needed to assess and mitigate risks associated with resource variability.

Standardization efforts and consensus-building initiatives are needed to establish common frameworks and metrics for assessing hybrid system performance. Real-world validation

studies are essential to verify the accuracy and reliability of simulation models and ensure their applicability to practical applications.

Addressing these gaps requires multidisciplinary collaboration, advanced modelling techniques, robust validation methods, and a comprehensive understanding of the complex interactions between technological, environmental, economic, and social factors.

4.3 MODELLING OF PHOTOVOLTAIC (PV) SYSTEM

An essential component of modelling photovoltaic (PV) cells is simulating PV systems and comprehending how they behave under various operating scenarios. PV cell modelling is the process of creating mathematical models of the physical processes that take place in solar cells, such as current-voltage (I-V) characteristics, light absorption, and charge carrier production and recombination.

Understanding the functionality and efficiency of solar cells and PV modules is based on PV cell modelling. Researchers and engineers can forecast the electrical output of photovoltaic systems under a range of environmental variables, including temperature, shade, and intensity of sunshine, by precisely predicting the behaviour of photovoltaic cells. For system design, optimization, and performance analysis, this data is crucial.

4.3.1 PV Cell Modelling Components

Typically, PV cell modelling includes the following elements:

- a. Sun Spectrum and Light Absorption: Simulating how sunlight is absorbed by photovoltaic cells while accounting for the spectrum distribution of solar radiation and the optical characteristics of the cell components. This involves simulating the quantum efficiency and absorption coefficient of the cell.
- b. Charge Carrier Generation and Recombination: This involves simulating the formation and recombination of electron-hole pairs in the semiconductor material of the photovoltaic cell, which controls how well absorbed photons are converted into electrical current.

- c. **Current-Voltage (I-V) Characteristics:** This involves simulating how the PV cell's output voltage and current change with various operating circumstances. This covers modelling elements including the temperature dependency of cell performance, series and shunt resistances, and the diode ideality factor.
- d. **Temperature Dependence:** This involves modelling how PV cell properties, including fill factor, short-circuit current, and open-circuit voltage, change with temperature. The total effectiveness and performance of PV systems are significantly influenced by temperature impacts.

4.3.2 Modelling Approaches

The behaviour of PV cells is represented by a variety of modelling techniques, from straightforward empirical models to intricate physics-based models. Typical modelling techniques include the following:

- a. **Single-Diode Model:** This popular empirical model uses a single diode, a series resistance, and a shunt resistance to simulate the electrical behaviour of a photovoltaic cell. For system-level simulations, the single-diode model offers an accuracy and simplicity trade-off.
- b. **Two-Diode Model:** This model expands upon the single-diode model by including a second diode to account for more intricate phenomena including non-ideal performance and recombination losses. Although the two-diode approach can require more computing power, it delivers better accuracy.
- c. **Physics-Based Models:** Shockley-Queisser and detailed balance models, for example, are detailed models based on semiconductor physics principles and offer a more thorough understanding of PV cell operation. However, they necessitate in-depth knowledge of material properties and intricate numerical simulations.

PV cells Accurate modelling involves a number of tasks, such as:

- a. **Parameter Estimation:** Due to changes in cell production, material qualities, and ambient circumstances, determining precise values for parameters associated with the model,

which include the diode ideality factor, series resistance, as well as temperature coefficients, can be difficult.

- b. Non-Ideal phenomena: Device physics and experimental data must be carefully taken into account when modelling non-ideal phenomena such recombination losses, series and shunt resistance, and optical losses.
- c. Validation: To guarantee model correctness and dependability, PV cell models must be validated against experimental data from actual measurements.

4.3.3 Parameters Extraction and Characterization

Parameters extraction and characterization play a crucial role in accurately modelling photovoltaic (PV) cells and predicting their performance under different operating conditions. These parameters define the electrical behavior of the PV cell and are essential for developing mathematical models that represent the cell's current-voltage (I-V) characteristics. The process of parameter extraction involves determining the values of key parameters from experimental data or manufacturer specifications. Some of the important parameters for PV cell modelling include:

- a. Short-Circuit Current (I_{sc}): The short-circuit current represents the maximum current output of the PV cell when the voltage across the cell is zero. It is primarily determined by the intensity of sunlight and the efficiency of light absorption and charge carrier generation within the cell.
- b. Open-Circuit Voltage (V_{oc}): The open-circuit voltage is the maximum voltage across the PV cell when no current flows through it. It is primarily determined by the bandgap energy of the semiconductor material and the recombination rate of charge carriers within the cell.
- c. Maximum Power Point Voltage (V_{mpp}): The maximum power point voltage corresponds to the voltage at which the PV cell delivers maximum power output. It is typically lower than the open-circuit voltage and varies with temperature, sunlight intensity, and load conditions.
- d. Maximum Power Point Current (I_{mpp}): The maximum power point current corresponds to the current at which the PV cell delivers maximum power output. It is determined by

the balance between the internal series and shunt resistances of the cell and the external load connected to it.

- e. Fill Factor (FF): The fill factor represents the ratio of the maximum power output of the PV cell to the product of its open-circuit voltage and short-circuit current. It is a measure of the cell's ability to convert sunlight into electrical power and is influenced by factors such as series and shunt resistances, non-ideal diode behavior, and temperature effects.

4.3.4 Extraction Methods

Parameters extraction methods for PV cells typically involve experimental measurements and curve fitting techniques. Common methods include:

- a. Current-Voltage (I-V) Curve Measurement: Experimental measurements of the I-V characteristics of the PV cell under different operating conditions, such as varying sunlight intensity, temperature, and load resistance. These measurements are used to extract key parameters such as I_{sc} , V_{oc} , V_{mpp} , I_{mpp} , and FF.
- b. Single-Diode Model Fitting: Curve fitting techniques, such as the least squares method, are used to fit the experimental I-V data to the mathematical equations of the single-diode model. The fitted parameters include the diode ideality factor, series and shunt resistances, and temperature coefficients.
- c. Outdoor Testing: Field testing of PV modules under real-world conditions to validate the performance and reliability of the extracted parameters and the accuracy of the PV cell models.

The PV output voltage and the two parameters M_1 and M_2 determine the PV cell current I_1 . Following mathematical formulas are applied:

$$I_1 = I_{SC} \left[1 - K_1 \left(e^{(V_1 / (K_2 \cdot V_{OC}))} - 1 \right) \right] \quad (4.1)$$

$$M_1 = \left(1 - \frac{I_{MP}}{I_{SC}} \right) e^{(-\frac{V_{MP}}{(K_2 \cdot V_{OC})})} \quad (4.2)$$

$$M_2 = \frac{((V_{MP} / V_{OC}) - 1)}{\ln(1 - (I_{MP} / I_{SC}))} \quad (4.3)$$

Temperature and irradiance both affect the parameters M1 and M2. The temperature dependence formulae are provided by;

$$I_{SC}(G, T_c) = I_{SCS} \cdot \frac{G}{G_s} \cdot [1 + \alpha(T_c - T_s)] \quad V_{OC}(T_c) = V_{OCs} [1 + \beta(T_c - T_s)] \quad (4.4)$$

$$I_{MP}(G, T_c) = I_{MPS} \cdot \frac{G}{G_s} \cdot [1 + \alpha(T_c - T_s)] \quad V_{MP}(T_c) = V_{MPS} [1 + \beta(T_c - T_s)] \quad (4.5)$$

The datasheet of the PV modules that are being utilized specifies the parameters I_{SC} , I_{MP} , V_{OC} , and V_{MP} . These values are defined for standard test circumstances, which are $G_s = 1000 \text{ Wm}^2$ and $T_s = 298.15 \text{ K}$ [35]. The actual irradiance & cell temperature are represented by the values for G and T_c , and the data sheet also specifies the exact temperature coefficients for current and voltage, denoted by a and b .

The output current and voltage for the PV system that is being utilized in this study are determined by taking the current of Maximum Power Point (MPP) $I_{MP}(G, T_c)$ and the voltage at MPP $V_{MP}(T_c)$. In order to determine the parameters for an entire PV system rather than just a single PV module, the cell parameters block was changed. Consequently, the number of parallel strings increased the current, and the temperature-dependent voltage multiplied with the modules in series inside a single string.

Figure 4.1 depicts the solar photovoltaic system's electrical circuit. To create the whole solar photovoltaic array, the circuit is made up of solar modules. To obtain the appropriate voltage through the solar photovoltaic system, the solar panels are linked in series, or the modules have connections in parallel to obtain the necessary current. The intended power output via the solar PV system is used to determine the connection mode and quantity of solar modules [36].

The output current is computed as follows, taking into account the voltage and current characteristics seen in Figure 4.1:

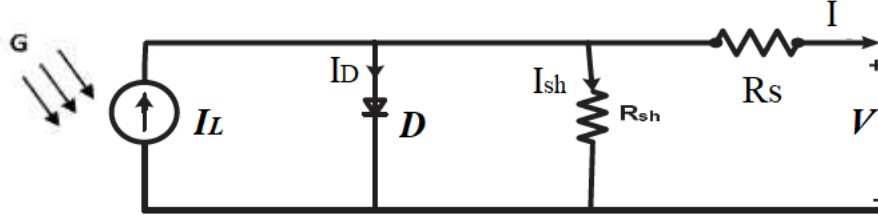


Figure 4.1: Diagram of Solar PV Module Electrical Circuit.

$$I_{out} = I_L - I_{sat} \left[e^{\left[\frac{Q(V + IR_s)}{nKT} \right]} - 1 \right] - \frac{V_t + IR_s}{R_{sh}} \quad (4.6)$$

where Q is the charge constant value, such as $1.6 \sim 10\pi 19C$, K has a value of $1:38 \sim 10\pi 23J$, T is the system's ambient temperature, R_{sh} and R_{ss} represent the shunt and series values of the resistances, respectively, and n is the ideal factor. Taking into account these solar cell parameters via Equation (4.6), the supplying power of the solar PV system can be determined from Equation (4.7).

$$P_{module} = \frac{V_{OC} - I_n(V_{OC} + 0.72)}{1 + V_{OC}} \left[1 - \frac{R_s}{V_{OC}/I_{sc}} \right] * \frac{V_{OC1}}{1 + \beta I_n G_o / G} * \left[\frac{T_o}{T_1} \right]^\gamma * I_{SCO} \left[\frac{G_1}{G_o} \right]^\alpha \quad (4.7)$$

where α denotes solar module technology, $\sim$ denotes nonlinear solar current characteristics, and γ denotes the impact of temperature on system voltage. The solar radiation in the case study region is represented by G_1 , the normal solar radiation is represented by G_0 , and the solar module system's beginning and final temperatures are represented by T_0 and T_1 . Equation (4.8) provides the electrical power supply provided by the solar PV array after accounting for various parameters [37].

$$P_{pv} = N_p * N_s * P_{module} * \eta_{overall} \quad (4.8)$$

In this context, $\eta_{overall}$ refers to the system's overall effectiveness which involves the maximum power point tracking MPPT losses caused by electrical factors and dust in the system. The numbers N_p and N_s stand for the number of solar modules arranged in series and parallel, respectively. P_{pv} stands for system-powered power supply.

4.4 WIND TURBINE MODELING

The wind speed needs to be sufficient for rotating the wind turbine to be able to produce the most electricity from it. The observation showed that the wind speed throughout the region was consistent between a range of (4–9) ms⁻¹. There is enough wind in the area to produce energy [38].

Numerous studies on wind turbines and wind generators have been published. Based on the characteristics of wind speed against wind turbine output power, a wind turbine model is presented for this study. The wind turbine's output power is determined by [39]:

$$P_m = C_p(\lambda, \beta) \frac{\rho A}{2} V_{wind}^3 \quad (4.9)$$

Here, P_m stands for the turbine's mechanical output power; C_p for its performance coefficient; λ for the rotor blade's tip speed ratio; ρ for air density; β for the blade pitch angle; A for the turbine's swept area; and V_{wind} for wind speed.

The model $C_p(\lambda, \beta)$ for performance coefficients utilized in this context and can be expressed as follows:

$$C_p(\lambda, \beta) = C_1 \left(\frac{C_2}{\lambda_1} - C_3 \beta - C_4 \right) e^{(-C_5/\lambda_1)} + C_6 \lambda \quad (4.10)$$

where the wind turbine rotor as well as blade design are determined by the constants C_1 through C_6 . One of the parameters in (4.11) is λ_i .

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (4.11)$$

Additionally, for normalized values of A and ρ , equality (4.9) could be simplified and normalized as in (4.12):

$$P_{m-pu} = K_p C_{p-pu} V_{wind-pu}^3 \quad (4.12)$$

where: P_{m-pu} = the power in per unit of nominal power for particular values of A and ρ , C_{p-pu} = the performance coefficient C_p , K_p = the power gain $V_{wind-pu}$ of the base wind speed.

4.5 COMPLETE HYBRID SYSTEM MODEL

Hybrid renewable energy systems are a viable way to satisfy the rising need for dependable and clean power generation in a time when sustainable energy solutions are crucial. The comprehensive hybrid system model that is being described here is an integrated method of utilizing the complimentary advantages of wind turbine and photovoltaic (PV) technologies, enhanced by energy storage and advanced control techniques. An overview of the hybrid system concept is given in this introduction, along with information on its goals, importance, and essential elements.

Hybrid energy systems have enormous promise for increasing energy independence, lowering carbon emissions, and strengthening energy resilience since they combine many renewable energy sources. Hybrid systems may reduce the erratic and unpredictable nature of individual renewable energy sources, such solar and wind power, by utilizing their natural advantages. This guarantees a more reliable and sustainable power source. The creation of all-encompassing hybrid energy solutions becomes essential to establishing a more sustainable and resilient energy future in light of changing energy landscapes and climatic issues.

Using MATLAB/Simulink software, the accessibility of renewable energy sources is determined from the local electrical energy demand data, taking into account the cost-effectiveness of the suitable grid-connected solar and wind hybrid system. Depending on the accessible nature of the energy sources in sufficient quantities, electricity can be produced at any moment from any combination of hybrid systems or from any one energy source in the hybrid energy generating system. Although none of the sources produces much energy, the suggested system in this study as shown in figure 4.2 is connected with an Electric Utility grid, allowing electricity to be supplied to loads. The voltage converters handle the hybrid renewable energy system's power source.

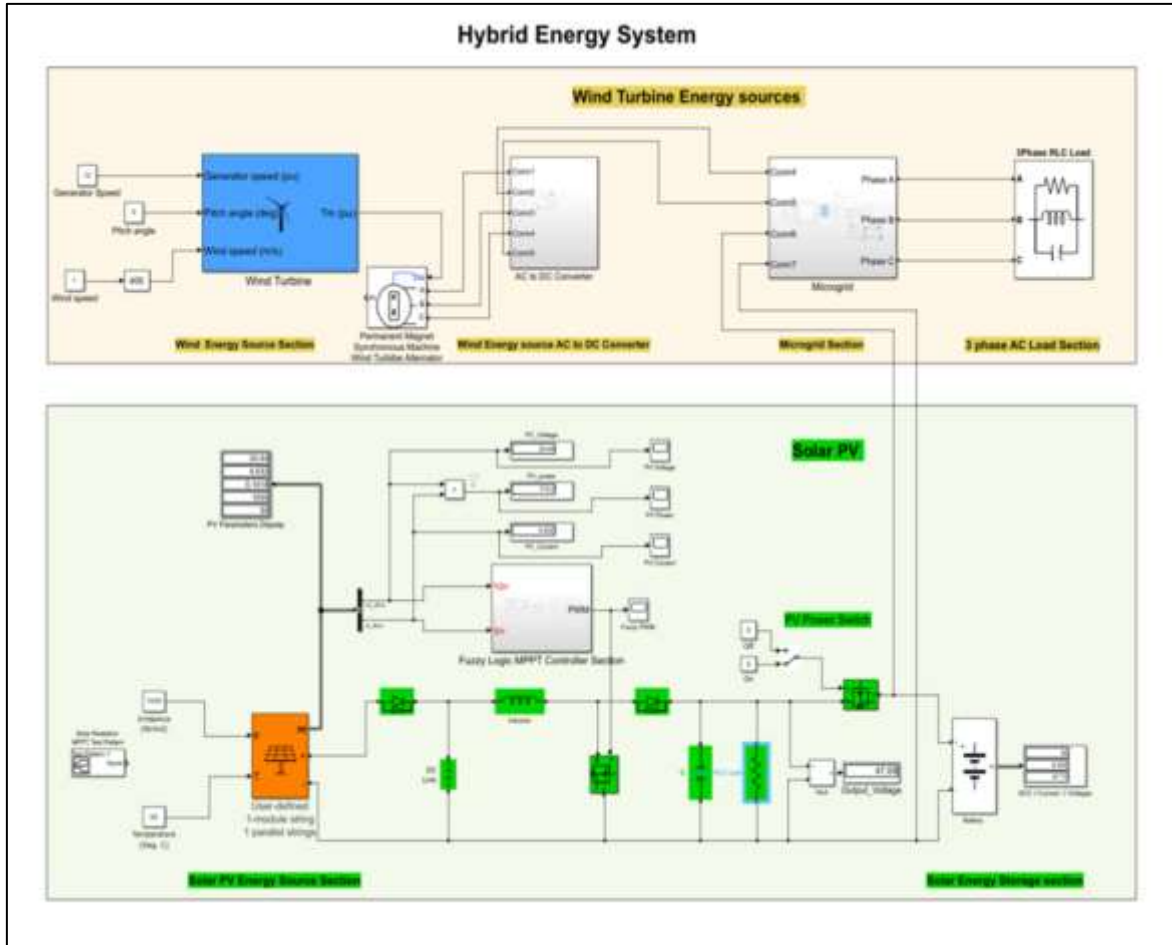


Figure 4.2: Complete Suggested Design of Hybrid System.

Simulating the performance and operation of an integrating PV-wind-battery combination under various load demands and climatic circumstances is the main goal of the entire hybrid system model. The approach specifically seeks to:

- Assess the viability and efficiency of combining wind and photovoltaic technologies in a hybrid energy framework.
- Make the best use of renewable energy sources to satisfy a target application's or system's fluctuating energy needs.
- Evaluate how energy storage contributes to increased energy autonomy, stability, and dependability of systems.
- Investigate cutting-edge control techniques to optimize energy efficiency and reduce operating expenses by coordinating the functioning of several energy sources and storage components.

- e. Offer information on the hybrid system's technical, financial, and environmental performance parameters to support well-informed system design and decision-making.

4.5.1 Key Components of the Hybrid System Model

Every component that makes up the entire hybrid system model is essential to the overall design and functionality of the system. These elements consist of:

- a. Photovoltaic (PV) Panels: Produce electricity from sunshine.
- b. Wind Turbine: Captures wind energy and transforms it into electrical power.
- c. Battery Storage of Energy System: Stores extra energy for use at a later time and acts as a backup power source when renewable resources are scarce.
- d. Power conditioning units, charge controllers, and inverters: Make sure that various system components are compatible and capable of converting electrical power effectively.
- e. Hybrid Controller: This device uses sophisticated control algorithms to coordinate the functioning of PV, wind, and battery systems in order to maximize energy output, storage, and use.
- f. Grid Interface: Enables bi-directional power flow and grid support functions by facilitating interface with the electrical grid.

The complete Hybrid system is divided in different sections. There is included Wind energy section, solar PV energy sections, converters, grid, Fuzzy MPPT Control and monitoring section etc. Subsystem blocks are essential for organizing and modularizing a Simulink model that represents a whole hybrid energy system. These subsystems enclose specific operations or components of the larger system, enabling the model a bit more organized, understandable, and easy to maintain. We'll look at two major subsystem blocks: The Grid and the MPPT FLC (Fuzzy Logic Control) block.

- a. The Grid Subsystem Block connects the hybrid energy system with the electrical grid. It encompasses all the elements and functionalities associated with grid interaction, including:

Grid link: This is the physical link that links the hybrid system with the electrical grid, which allows bidirectional power transfer.

Grid-Tie Inverter: that converts the DC power supplied via the hybrid system (derived both PV and wind sources) into synchronized AC electricity for the grid.

Grid Support Functions: Uses active power injection, reactive power control, along with frequency regulation to improve grid stability and reliability.

Islanding protective: Includes protective measures for detecting grid failures and ensuring safe separation from the grid to avoid islanding.

Grid Monitoring: Gathers information about grid parameters like voltage, frequency, etc. for control and monitoring purposes.

By incorporating these functionalities under a Grid subsystem block, the model created in Simulink becoming more modular and organized, making it easier to integrate, test, and analyze grid-related modules and functionalities.

b. MPPT FLC (Fuzzy Logic Control) Subsystem Block: This block implements the MPPT control algorithm using fuzzy logic control (FLC) approaches. It contains the MPPT algorithm and control logic for both solar and wind energy sources. The MPPT FLC subsystem block has the following key components and functionalities:

PV MPPT Control: Uses an MPPT algorithm designed specifically for PV panels to continuously monitor the maximum power point (MPP) under changing solar irradiation and temperature conditions.

Wind MPPT Control: Adapts the MPPT algorithm for wind turbines to maximize rotor speed and power output when wind speed changes.

Fuzzy Logic Controller: Uses fuzzy logic approaches to integrate human-like reasoning and language factors into the MPPT control algorithm, allowing adaptive and robust control in dynamic operating conditions.

In order to maximize MPPT performance, fuzzy logic control parameters, such as membership processes, rules, and inference processes, are defined and fine-tuned.

The Simulink model gets more modular and reusable by enclosing the MPPT FLC algorithm with a subsystem block. This makes it easier to integrate, test, and fine-tune the MPPT control algorithm inside the hybrid energy system model.

So that, in a Simulink model, subsystem blocks like the Grid and MPPT FLC blocks offer a structured and modular framework for arranging and executing particular capabilities of the entire hybrid energy system. The model's scalability, maintainability, and clarity are all improved by this modular approach, which eventually makes it easier to build, analyze, and optimize intricate hybrid energy systems.

4.5.2 Wind Energy Section

The Simulink model's Wind Energy section depicts the subsystem in charge of capturing wind energy and turning it into electrical power. Typical components included in this section include control systems, mechanical-to-electrical conversion processes, and wind turbine models. The wind turbine model shown in figure 4.3 captures the transformation of wind kinetic energy into mechanical power by simulating the actions of the turbine blades, rotor, and generator. The wind energy section maximizes energy capture under variable wind conditions by modifying the turbine's yaw angle, blade pitch, and rotational speed using appropriate control algorithms.

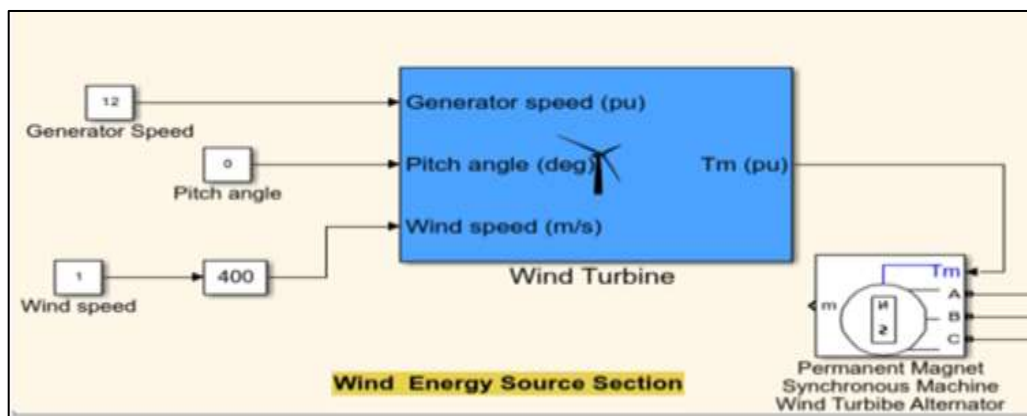


Figure 4.3: A Subsection of Wind Energy Source Section.

4.5.3 Wind Energy Source AC to DC Converter

Converting the alternating current (AC) output of the wind turbine generator through direct current (DC) power is the function of the Wind Energy Source AC to DC Converter

subsystem. Compatibility with other parts of the hybrid energy system, like batteries, inverters, and DC loads, depends on this conversion. To provide effective and reliable DC power conversion, the AC to DC converter subsystem shown in figure 4.4 usually consists of rectifiers, filters, and voltage regulators. This subsystem prepares the produced power for integration into the larger hybrid energy system by transforming wind energy output into DC form.

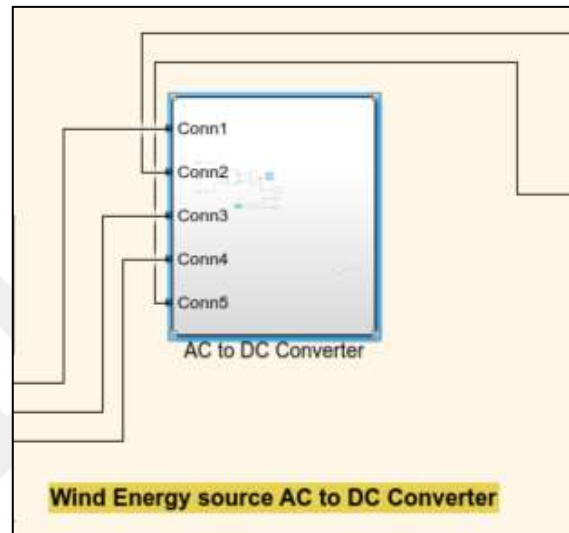


Figure 4.4: Wind Energy AC to DC Converter.

4.5.4 AC to Dc Converter Subsystem

Converting the alternating current (AC) output of the wind turbine generator through direct current (DC) power is the function of the Wind Energy Source AC to DC Converter subsystem shown in figure 4.5. Compatibility with other parts of the hybrid energy system, like batteries, inverters, and DC loads, depends on this conversion. To provide effective and reliable DC power conversion, the AC to DC converter subsystem usually consists of rectifiers, filters, and voltage regulators. This subsystem prepares the produced power for integration into the larger hybrid energy system by transforming wind energy output into DC form.

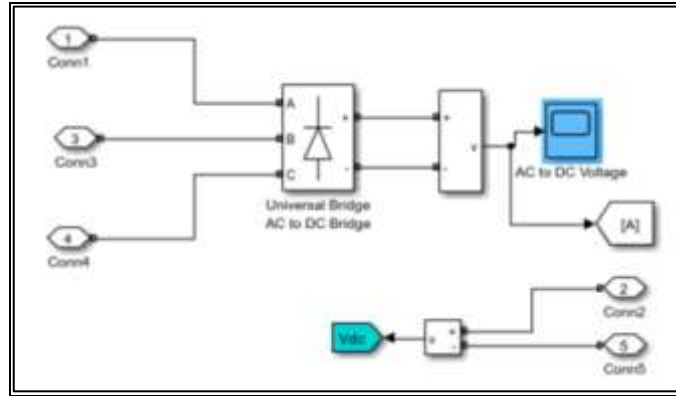


Figure 4.5: AC to DC converter Subsystem.

4.5.5 Microgrid Section

The subsystem in charge of overseeing the management and control of the microgrid inside the hybrid energy system is represented by the Microgrid part of the Simulink model as shown in figure 4.6. A microgrid is a small-scale energy system that may function both on its own and in tandem with the wider electrical grid. Typically, this area contains parts like control algorithms, power converters, and energy management systems. The microgrid section manages the generation, distribution, and storage of electricity inside the microgrid. It also optimizes energy flow, upholds system stability, and guarantees dependable performance in a range of operational environments.

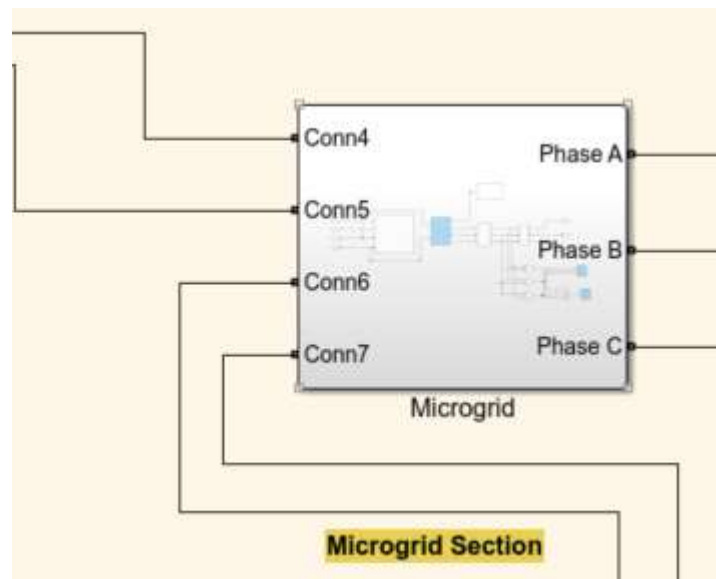


Figure 4.6: Microgrid Section.

4.5.6 Microgrid Subsystem Block

The Microgrid Subsystem Module includes the capabilities and components required to operate and control the microgrid inside a hybrid energy system. This modular block consists of controllers, inverter devices, energy storage systems, along with load management systems. The Microgrid Subsystem Module uses control techniques to regulate electricity flow, regulate both demand and supply, and ensure system stability inside the microgrid as shown in figure 4.7. By separating microgrid-related operations into subsystem blocks, the Simulink model appears more structured, scalable, as well as simpler to evaluate and improve. This modular approach makes it easier to integrate, test, and deploy microgrid control systems as part of a larger hybrid energy system.

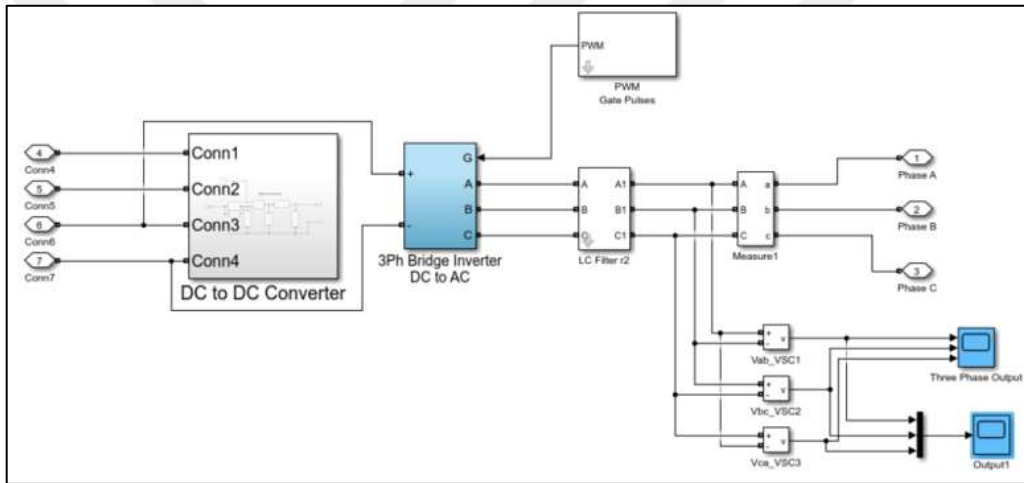


Figure 4.7: Microgrid Subsystem Block.

4.5.7 DC to DC Converters

DC to DC converters are crucial parts of hybrid energy systems because they change the voltage level of direct current (DC) electrical power. These converters are essential for controlling the energy flow between various system elements, including loads, energy storage devices, and renewable energy sources. DC to DC converters are frequently employed in systems to enhance energy conversion efficiency, match voltage levels, and control power flow shown in figure 4.8. To accomplish effective voltage conversion and regulation, they usually include control circuits and power semiconductor devices, including MOSFETs or IGBTs.

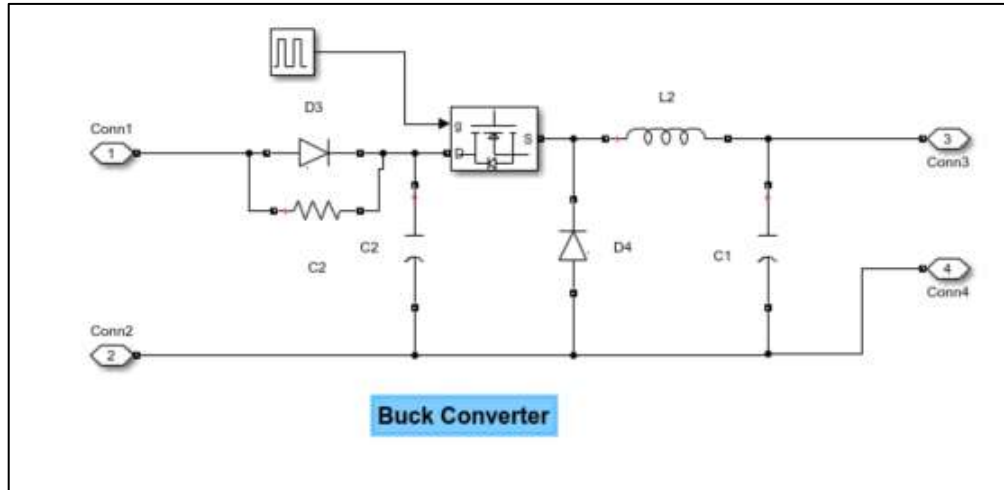


Figure 4.8: Microgrid Buck Converter.

4.5.8 Three Phase Inverter Subsection

Within the hybrid energy system, the Three-phase Inverter Subsection is a specialized component that is in charge of converting DC power into three-phase AC. In grid-connected systems and industrial settings, three-phase inverters shown in figure 4.9 are frequently utilized to synchronize with the electrical grid or provide power to three-phase loads. Power electronic switches, like IGBTs or MOSFETs, are commonly included in this area in addition to control algorithms that modulating the switching signals and adjust the inverter's output voltage and frequency. Three-phase inverters facilitate the integration of energy storage systems and renewable energy sources into AC-based electrical networks by converting DC electricity to AC.

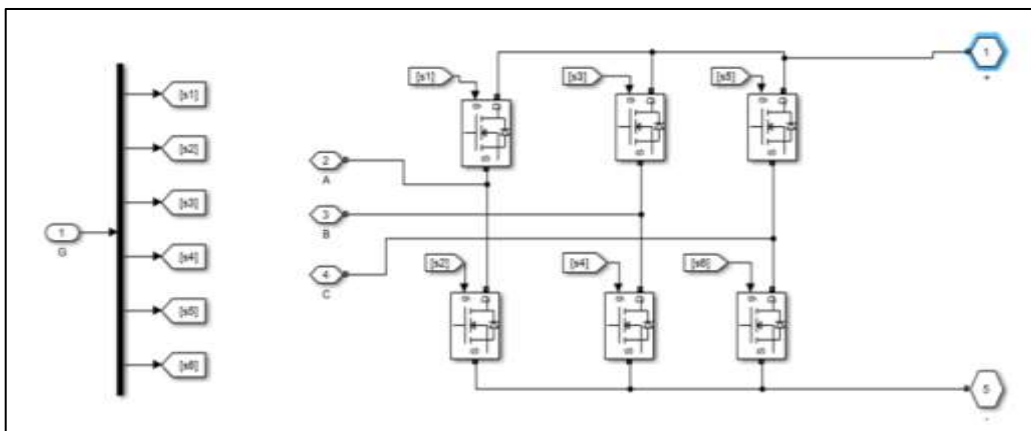


Figure 4.9: Inverter Subsystem.

4.6 FUZZY LOGIC BASED PV SOLAR ENERGY MANAGEMENT SYSTEM:

A control system that makes use of fuzzy logic concepts to maximize the performance of photovoltaic (PV) solar energy systems is known as a fuzzy logic-based PV solar energy management system. Fuzzy logic controllers are used by this management system to modify PV system operational parameters, including solar panel tilt angle, in order to optimize energy capture and efficiency under a variety of environmental circumstances. Fuzzy logic controllers provide adaptive and reliable management of PV systems in dynamic operating situations by imitating human thinking via the use of language variables and rules. PV solar energy management systems may increase energy output, boost system dependability, and lower operating costs by utilizing fuzzy logic-based control algorithms as shown in figure 4.10.

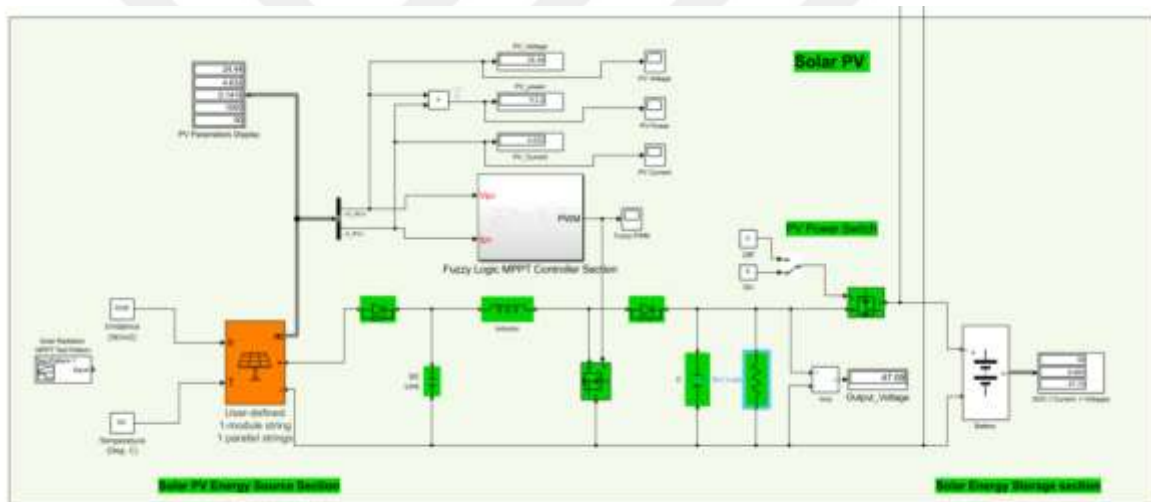


Figure 4.10: Solar PV Energy system.

4.6.1 Fuzzy Logic MPPT Controller

The hybrid energy system model's Fuzzy Logic MPPT Controller Section is a subsystem tasked with using fuzzy logic methods to Maximum Power Point Tracking (MPPT) control. In order to maximize power extraction from an accessible power source under a variety of operating situations, MPPT controllers as shown in figure 4.11 can optimize the functioning of renewable energy sources, like solar PV panels or wind turbines. Based on input variables including solar irradiance, temperature, and wind speed, fuzzy logic MPPT controllers adaptively modify the operational parameters of the renewable energy sources using fuzzy

inference systems. MPPT controllers can improve system performance and energy capture efficiency in dynamic operating conditions by utilizing fuzzy logic-based control techniques.

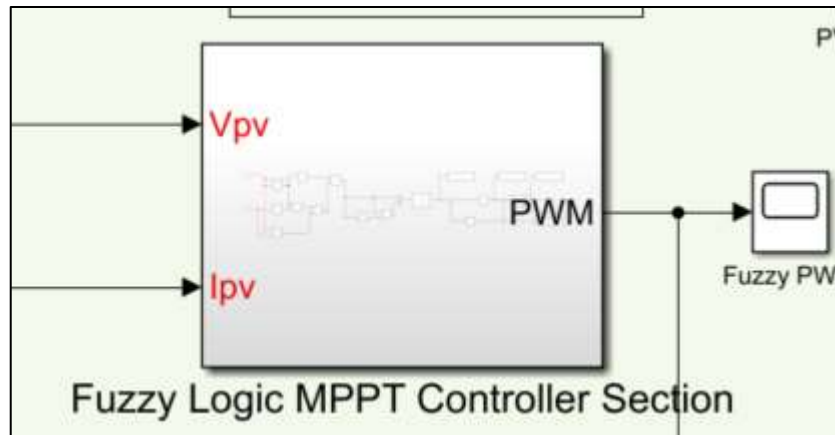


Figure 4.11: PV With Energy Storage System.

A sophisticated control mechanism used in renewable energy systems, especially solar (PV) systems and wind turbines, is the fuzzy logic maximum power point tracking (MPPT) controller. Its purpose is to maximize power output from the energy source under variable climatic circumstances.

The Fuzzy Logic MPPT Controller works on the basis of using fuzzy logic techniques to simulate human-like thinking and decision-making. Fuzzy logic controllers utilize linguistic variables, fuzzy sets, and heuristic rules to make choices in uncertain and dynamic contexts, in contrast to standard control approaches that depend on exact mathematical models.

The hybrid energy system model's fuzzy logic MPPT Controller Section is a crucial part that uses fuzzy logic approaches to achieve MPPT control, which is intended to maximize the performance of renewable energy sources like solar PV panels and wind turbines. Under order to simulate human-like thinking and decision-making, this part uses a Fuzzy Inference System (FIS). This allows for resilient and adaptive management of the renewable energy sources under a variety of environmental circumstances.

4.6.2 Components of the Controller

The fuzzy inference system, or FIS, is Linguistic variables, membership functions, fuzzy rules, and an inference engine comprise the controller's core, the FIS. Using fuzzy logic

principles, it converts input variables (such sun irradiance, temperature, and voltage) into output control actions (like duty cycle modifications).

Input variables: These are outside factors, such as sun irradiation, temperature, wind speed, and voltage, that affect the renewable energy source's power production.

Functions of Membership: Membership functions capture the link between input variables and language phrases (e.g., "low," "medium," "high") by defining the extent to which each input variable belongs to a fuzzy set.

Fuzzy Rules: Fuzzy rules associate sets of input variables with control actions that are output. These guidelines provide heuristic tactics or expert knowledge for maximizing the MPPT process in various operational scenarios.

Inference Engine: To produce output control actions, the inference engine analyzes the fuzzy rules and input data. It ascertains the proper modifications to the renewable energy source's operational characteristics in order to optimize power production.

4.6.3 Design of Fuzzy Logic Controller for MPPT

A Fuzzy Logic Toolbox in MATLAB is one of the tools used in the process of designing a fuzzy logic controller (FLC) for MPPT as shown in figure 4.12. This is a general overview of the design process:

The variables for input and output: Determine the input variables, including voltage, temperature, and sun irradiation as shown in figure 4.13. Determine the output variable (duty cycle for a DC-DC converter, for example), which denotes the control action to modify the renewable energy source's operational characteristics. The first input is voltage and second input is power.

Membership Function Definition: Select the proper membership functions for every variable in the input and output as shown in figure 4.14 as assign the membership function and define the range of input 1. Give definitions to the language phrases (such as "low," "medium," and "high") that correspond to each membership function. Also, Figure 4.15 illustrate the Power in membership function. While the Duty-cycle output membership function can be seen in figure 4.16.

Construction of Rule Bases: Make a rule base that connects different input variable combinations with control actions that are output. Define fuzzy rules using heuristic techniques or expert knowledge. Figure 4.17 clarify the Assign the rules.

Number of Rules

= Membership functions of first I/o

** Membership functions of second I/o*

*Number of Rules = 7 * 7 = 49*

Configuration of the Fuzzy Inference System (FIS): Utilize the Fuzzy Logic Toolbox to establish the framework of the FIS. Indicate rule linkages, membership functions, and input and output variables.

Rule Base Tuning: Adjust membership functions and fuzzy rules in accordance with system specifications and performance goals. Utilize experimental or simulation data to verify and modify the rule base when necessary.

Use defuzzification techniques like weighted average or centroid to get the crisp output value derived from fuzzy output membership functions.

Implementing a Controller: Integrate the FLC that has been built with other parts of the control system's structure, including feedback loops, actuators, and sensors. Also, Test the FLC in real-world tests or simulations to assess its performance and make any required design adjustments.

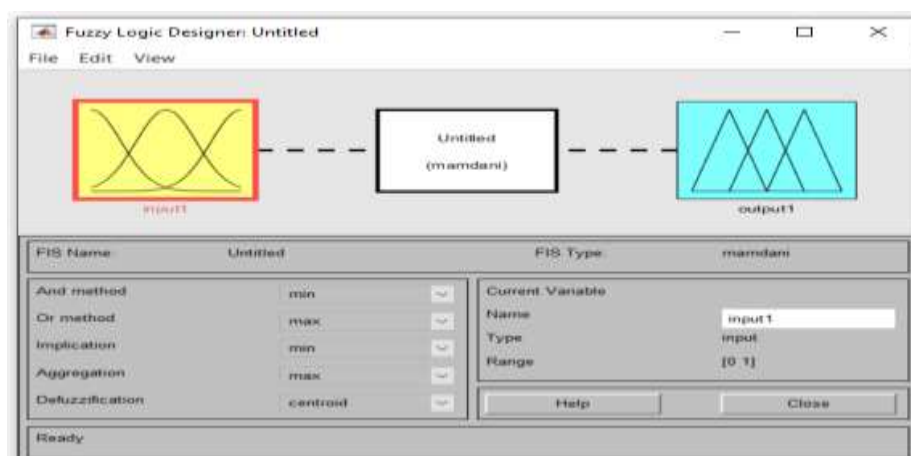


Figure 4.12: FLC Toolbox.

The input and output of FLC:

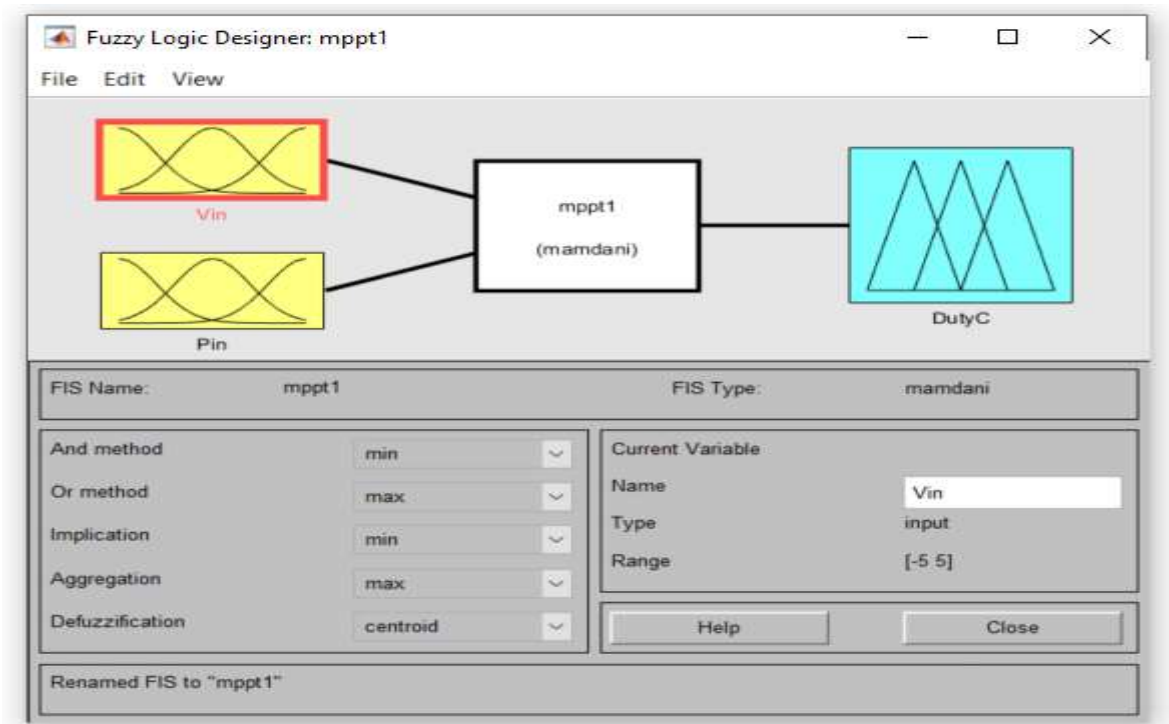


Figure 4.13: I/O of FLC.

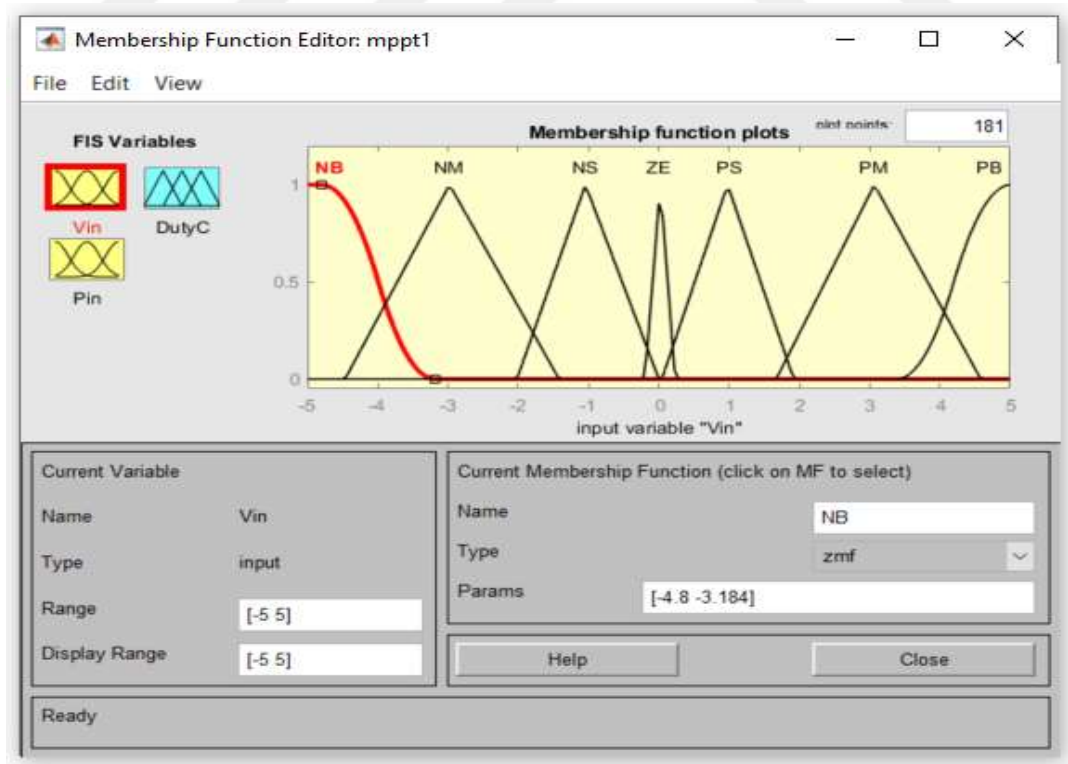


Figure 4.14: Vin Input Membership Function.

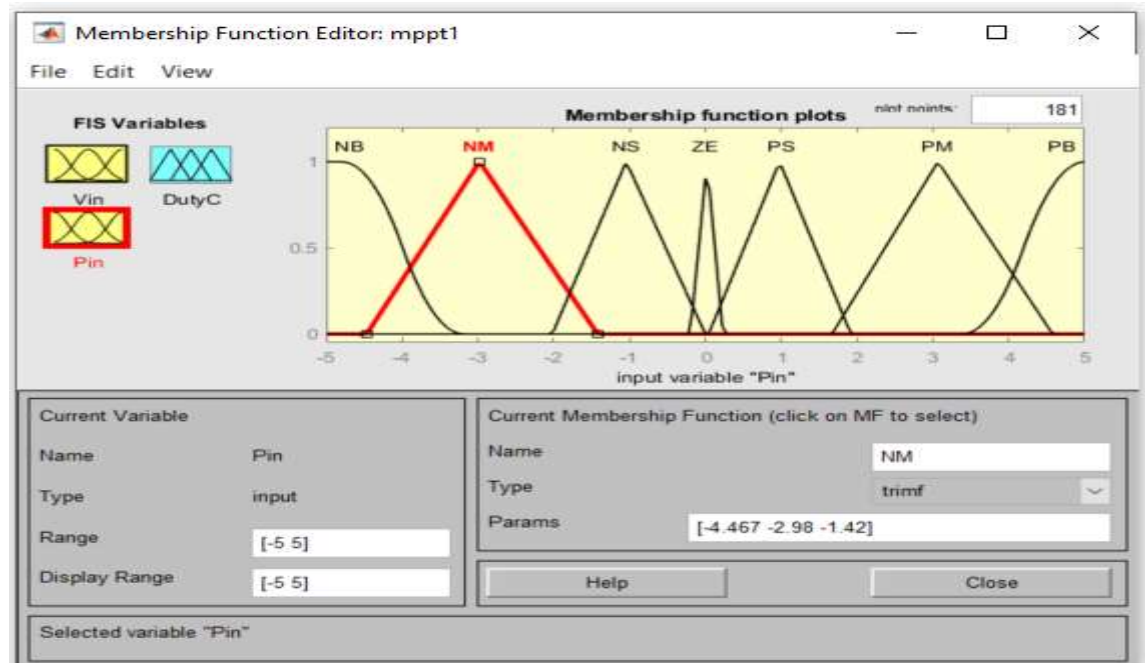


Figure 4.15: Power in Membership Function.

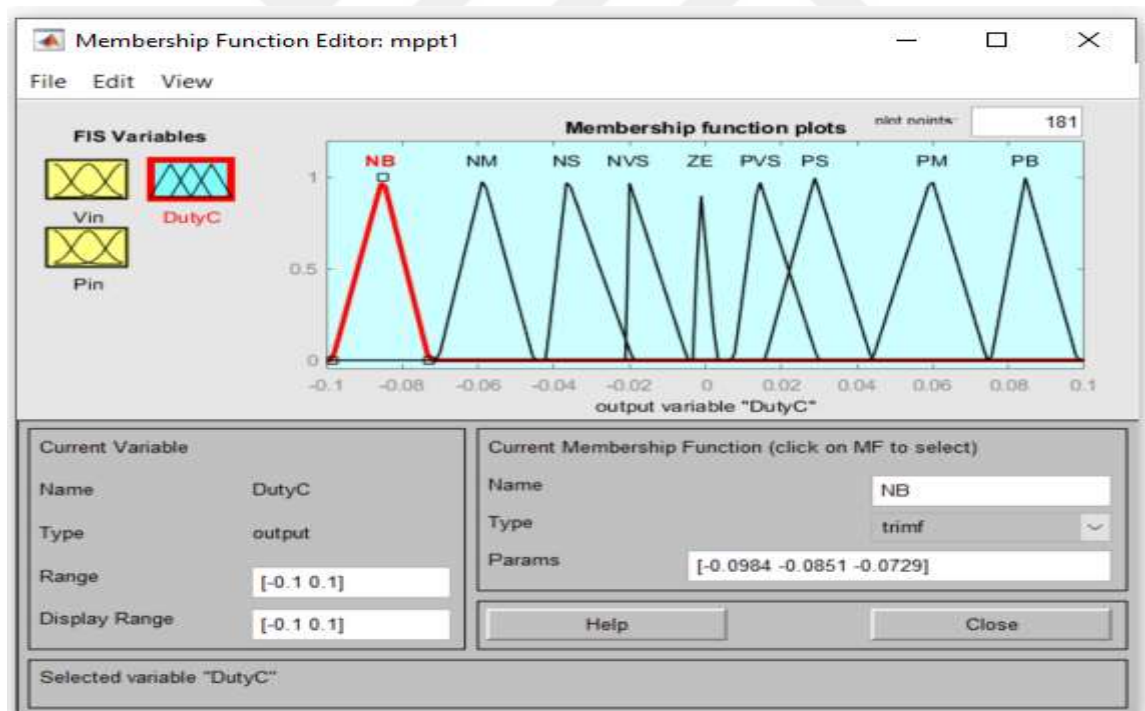


Figure 4.16: Output Membership Function.

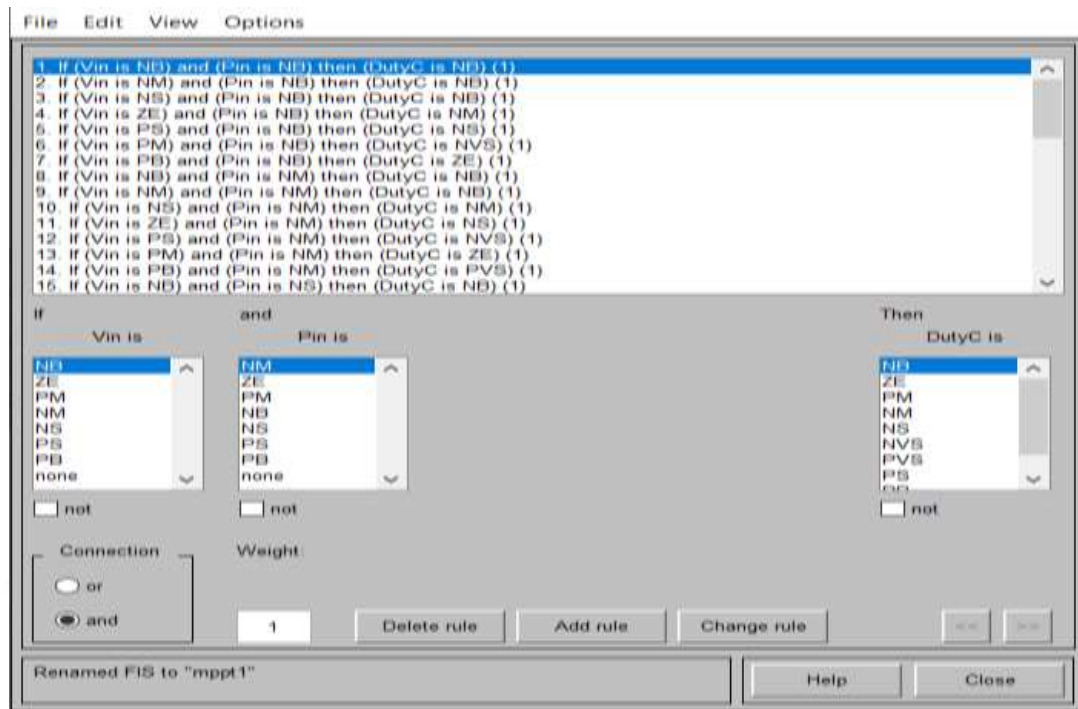


Figure 4.17: Assign the Rules.

4.6.4 Wind Turbine Characteristic

A wind turbine's characteristics define its behaviour in reaction to various operating settings and environmental circumstances. Understanding these features is essential to comprehending the effectiveness, dependability, and performance of wind turbines in producing electricity from wind energy. Table 4.1 show the characteristics of wind turbine power that used in simulation.

Table 4.1: Display Wind Turbine Power Characteristics.

parameters	values
Nominal mechanical output power (W)	2000
Base power of the generator (VA)	1500
Base wind speed (m/s)	9
Maximum power at base wind speed (pu)	0.73
Base rotational speed (pu of base generator)	1.2
Pitch angle beta to display wind-turbine (deg)	0

A wind turbine's power curve shown in figure 4.18 illustrates the connection between wind speed and electrical power production. Along with the cut-in and cut-out wind speeds—beyond which the turbine begins to generate electricity or ceases to do so—it usually displays the maximum power output at the turbine's rating wind speed. Comprehending the power curve facilitates evaluating a wind turbine's capacity to produce electricity in various wind scenarios.

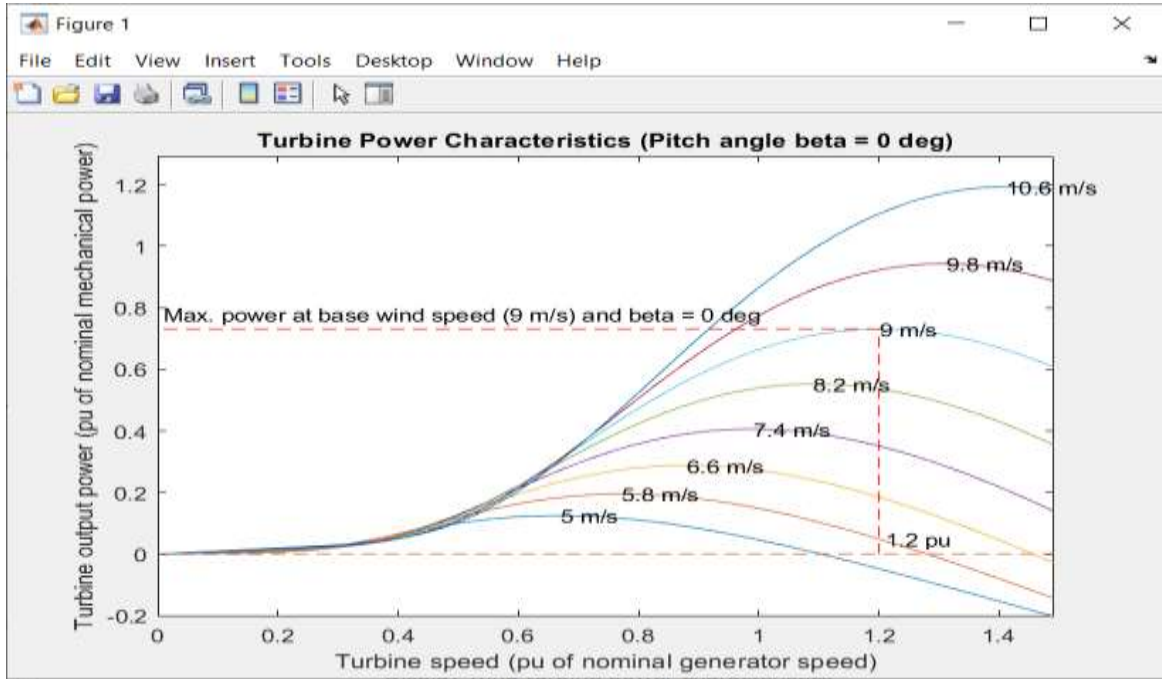


Figure 4.18: Wind Turbine Characteristic Curve.

4.6.5 Wind turbine Generator Parameters Configuration

Generator parameters are essential for the performance and efficiency of a wind turbine system. They describe the electrical characteristics of the generator and its interaction with the wind turbine rotor. Key parameters include rated power (P_r), rated voltage (V_r), rated current (I_r), efficiency (η), power factor (PF), synchronous speed (n_s), inertia constant (H), and rotor resistance (R_r). These parameters determine the turbine's capacity, power output, efficiency, stability, and reliability. The rated power determines the turbine's optimal performance point, while the rated voltage influences the design of the generator and its electrical components. The rated current determines the size and capacity of electrical conductors and protection devices. Proper selection and characterization of generator

parameters illustrated in table 4.2 are critical for ensuring the successful operation and performance of wind turbine systems in renewable energy applications.

Table 4.2: Generator Parameters.

Configuration	value
Stator phase resistance (ohm)	0.0485
Armature inductance (H)	0.000395
Flux linkage established by magnets(V.s)	0.1194
Inertia J(kg.m ²)	0.0027
Initial condition [ω_m (rad/s) θ_{em} (deg) i_a , i_b (A)]	[0, 0, 0, 0]

4.6.6 PV Array Model and Parameters

A photovoltaic (PV) array model is crucial for simulating the performance of solar panels in generating electricity from sunlight. It describes the electrical characteristics of the array and its interaction with environmental factors like solar irradiance and temperature. Key components include the number of modules, module parameters, fill factor, temperature coefficients, array configuration, angular and tilt angle, and environmental conditions. Analytical models use mathematical equations based on semiconductor device behavior, while empirical models use curve-fitting techniques based on experimental data. Simulation software like MATLAB/Simulink, PVSyst, and PVLib for Python provide software-based models for simulating PV array performance. An accurate PV array model with appropriate parameters is essential for predicting and optimizing the electrical output of solar panels in renewable energy systems. Some of these parameters used in the simulation are shown in table 4.3.

Table 4.3: PV Parameter Used in Simulation.

PV parameter	value
Maximum power (W)	129.94
Open cct voltage Voc (V)	36.3
Voltage at max power point Vmp (V)	29.2
Temp coeff. Of Voc (%/deg.C)	-0.36581
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)	0.045996

The National Renewable Energy Lab Database provides statistics on solar irradiation for T-cells at 50 °C. Radiation levels were observed to range from 4.5 to 5.8 kWh/m² daily. 5.23 kWh/m²/day is the average solar radiation value for the entire year. Maximum power may be generated with sufficient irradiance, with minimal values occurring from June to September. Table 4.4 displays solar irradiance data that was gathered from the meteorological agency for the research region, while Figures 4.19 and 4.20 gives the PV current and power behavior with changes in both temperature and radiation.

Table 4.4: Specified Parameters for PV Array at 1000 W/m² With 50 deg. C.

Parameter Model	value
Light –generated current IL (A)	4.832
Diode saturation current Io (A)	1.939×10^{-10}
Diode ideality factor	0.98499
Shunt resistance Rsh (ohm)	237.5583
Series resistance Rs (ohm)	0.59322

The PV array characteristic Plot is:

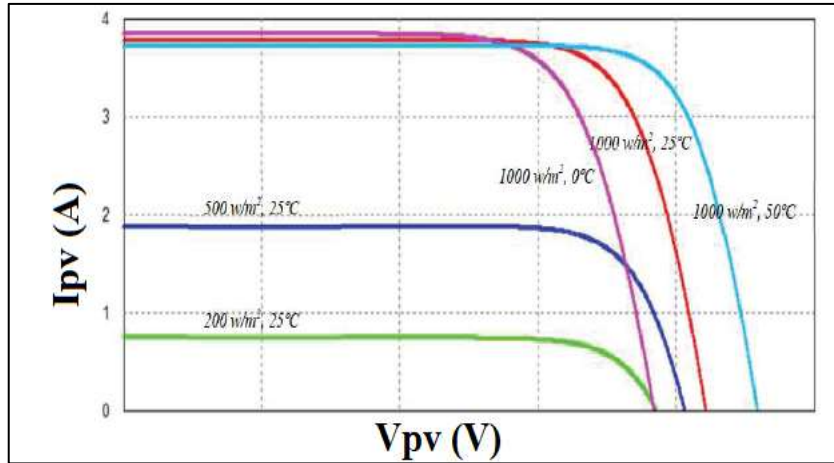


Figure 4.19: PV Current Behavior with Variation of Radiation Along with Temperature.

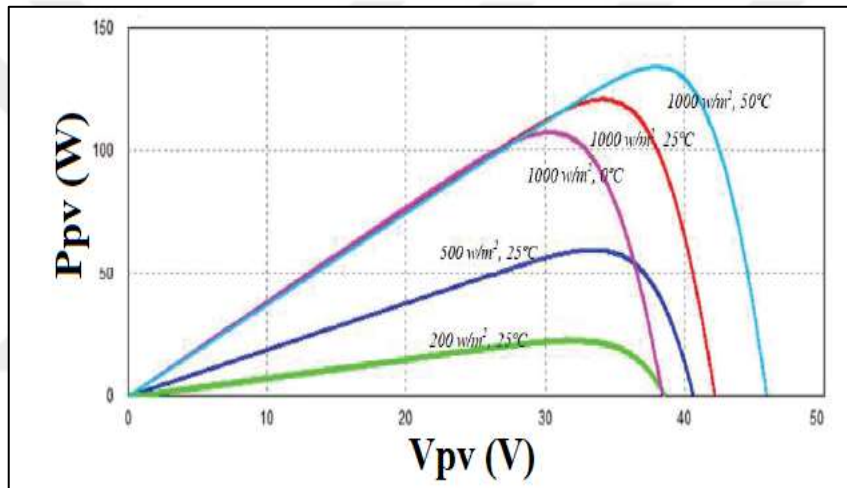


Figure 4.20: PV Power Behaviour with Variation Of Radiation Along With Temperature.

It is evident from figure 4.19 and figure 4.20 that the output of the sun's radiation strength controls the short circuit current of a solar module. On the other hand, open circuit voltage is influenced by temperature. A MPPT approach is used to get the necessary quantity of power based on variations in temperature and solar radiation.

4.7 SIMULATION OF THE MODEL

Based on the system's output, it can be shown that this model basically shown in figure 4.21 run for 1 seconds and observe the outputs and response of hybrid system:

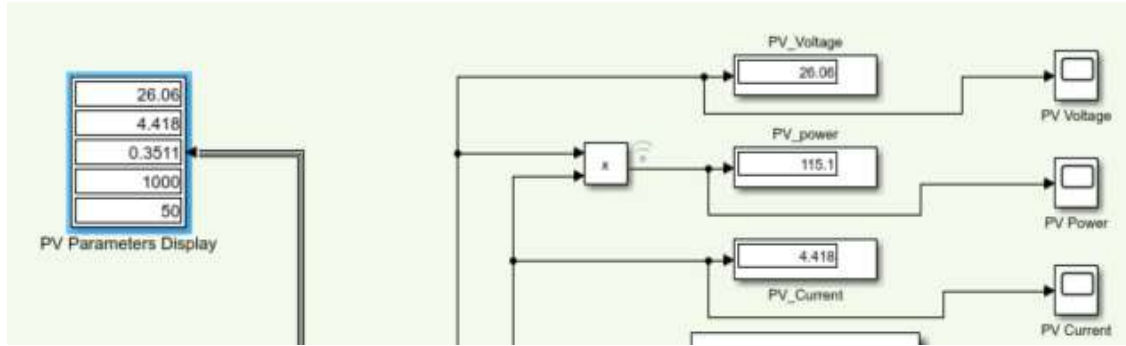


Figure 4.21: The Whole System Simulation.

The output results for specified parameters can be shown in table 4.5;

Table 4.5: Results for Our Monitoring Parameters.

parameters	value
V pv	26.06
I pv	4.419
I diode	0.3511
Irradiance (W/m2)	1000
Temp. (deg.C)	50

The maximum power output response with fuzzy MPPT control can be seen in figure 4.22. Typically, the y-axis shows the maximum power output of the PV array ($P_{\max}$) in watts, while the x-axis shows time connected to the PV system's operation. The plot can display simulated reactions from modeling and simulation, or it can display the actual observed $P_{\max}$ values over time. Fuzzy MPPT control may cause $P_{\max}$'s response to fluctuate dynamically as the control algorithm constantly modifies the PV array's operational voltage and current to keep it running at or close to the MPP. Variations in temperature, partial shading effects, solar irradiance changes, and system dynamics are some of the elements that affect this dynamic response.

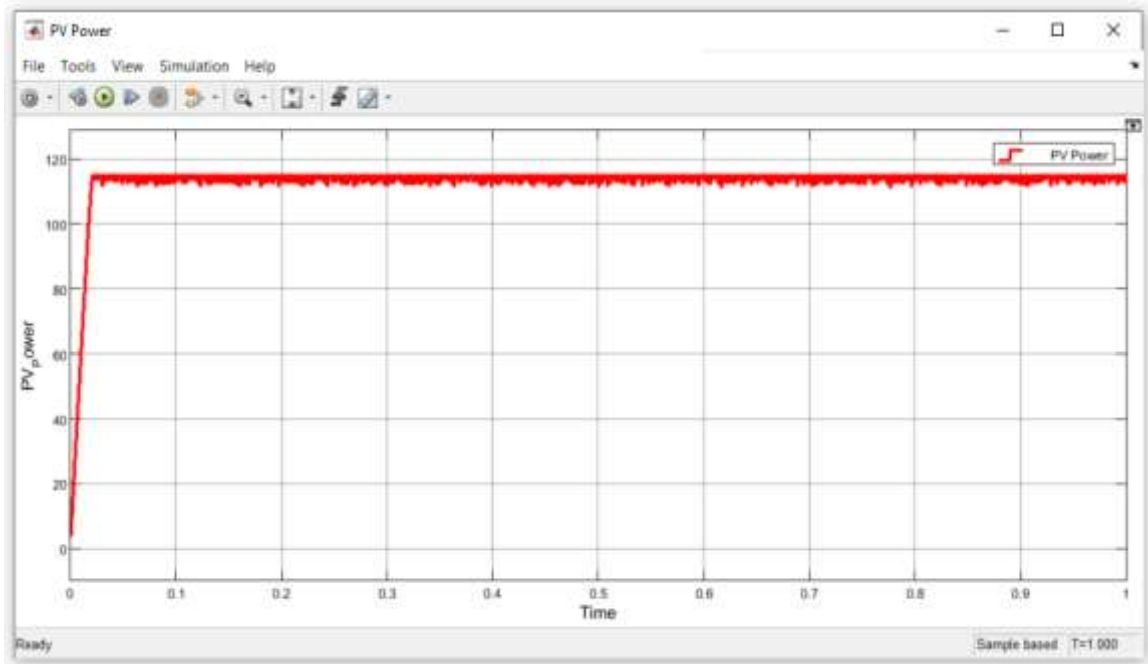


Figure 4.22: Maximum Power Output Response with Fuzzy MPPT Control.

4.7.1 PV Converters Voltage

The PV converters are crucial parts of solar energy systems because they transform the PV array's DC output voltage into a format that can be used directly or integrated into the grid. PV converter voltage needs are influenced by a number of variables, including as application requirements, grid connection standards, and system setup. Figure 4.23 shows the simulation PV converters that can be monitored.

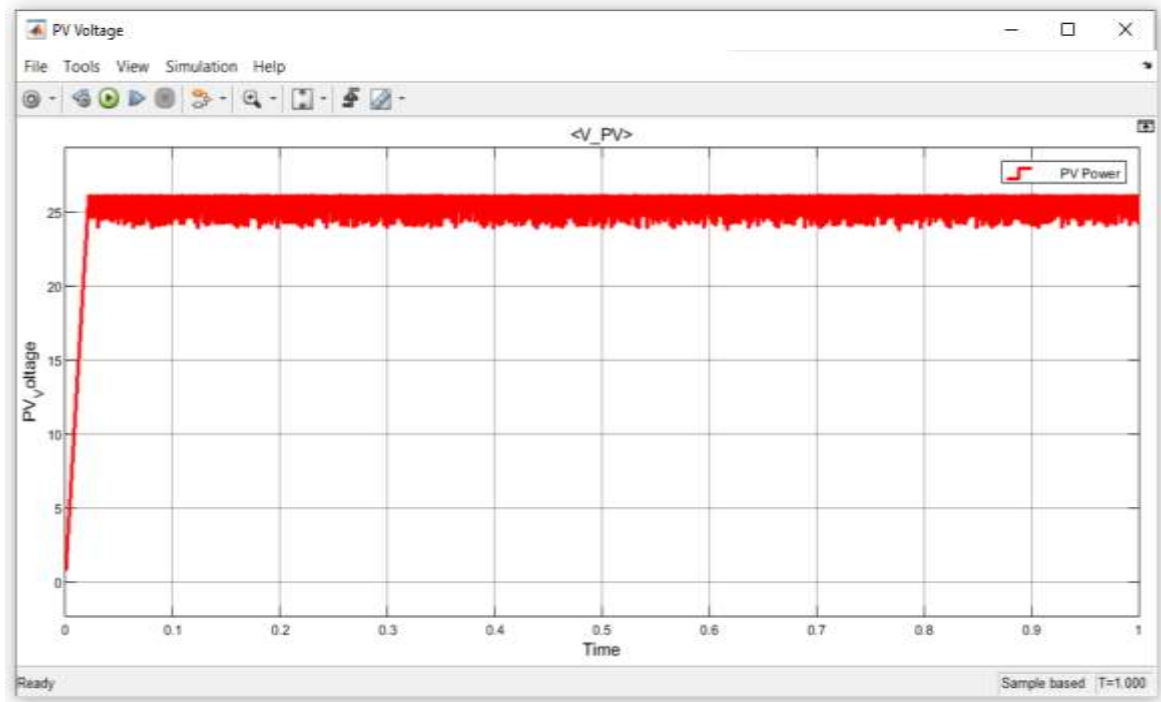


Figure 4.23: PV Converter Voltage.

4.7.2 PV converter PWM

In photovoltaic (PV) converters, pulse width modulation (PWM) is a widely used technique for controlling the PV system's output voltage or current. PWM control modifies a pulse train signal's duty cycle to provide the required output characteristics. Power semiconductor devices (like MOSFETs or IGBTs) are rapidly turned on and off at a high frequency using PWM control. The average voltage or current applied to the load is determined by dividing the duration of the device's on (the pulse width) by the overall switching period. PWM signal duty cycle may be changed to precisely regulate the output power by adjusting the effective voltage or current provided to the load. Figure 4.24 illustrate the PV converter PWM that allowing effective maximum power point tracking, current limiting, and accurate output voltage, current, and power control for system protection.

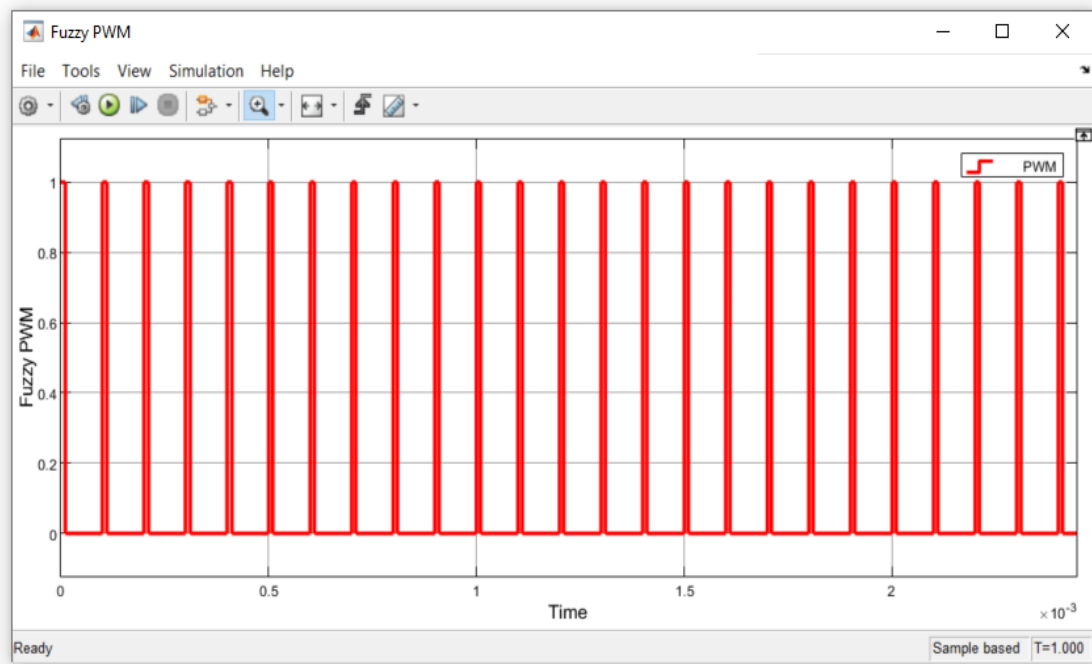


Figure 4.24: PV Converter PWM.

The voltages measured along the loads linked with every phase of the electrical system are referred to as the load voltages in three-phase systems. The arrangement of the electrical loads, the kind of load that is connected (resistive, inductive, or capacitive), and the properties of the power source all affect the load voltages. Figure 4.25 shows the actual values of output load voltages.

While the line-to-line voltage which can be considered as the voltage measured between any two phases (lines) of the three-phase system as shown in figure 4.26. In a balanced system, where all three phases have equal magnitudes and are 120 degrees apart in phase, the line-to-line voltage is $\sqrt{3}$ times the phase voltage (V_{ph}).

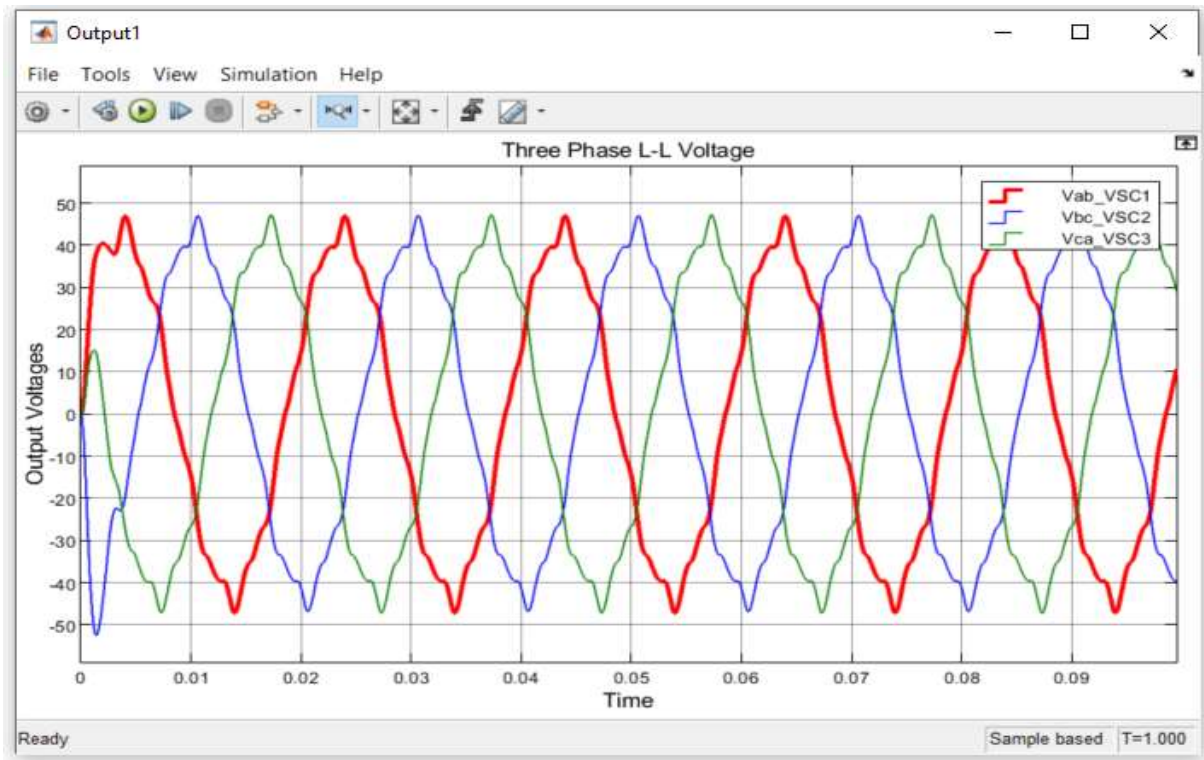


Figure 4.25: The Actual Values of Output Load Voltages.

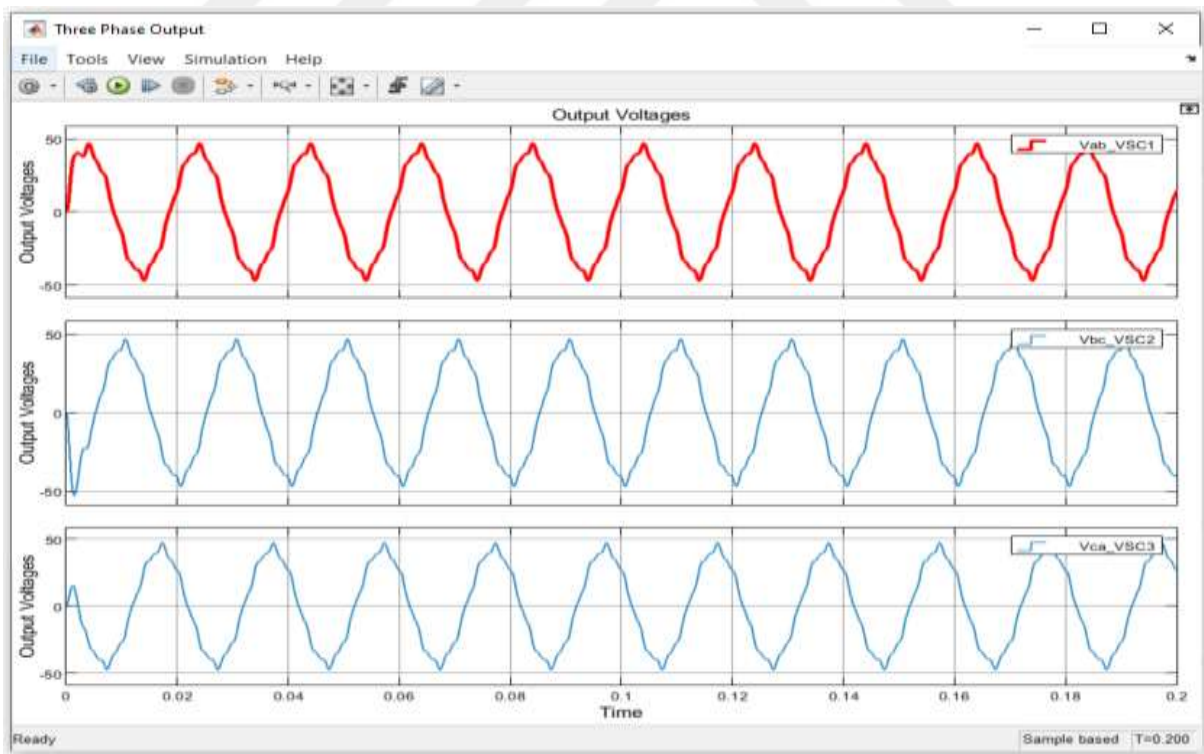


Figure 4.26: The Line-to-Line Voltage.

Taking into account variations in wind speed and solar radiation, Figure 4.27 shows how the hybrid renewable energy system's generated power varies during the course of a day. This image shows a graphical comparison between the system's total generated power and the load demand over the course of the day. Typically, time is represented on the x-axis of Figure 4.27 as a series of periods, such hours or minutes, that span the full day. The hybrid renewable energy system's power output is shown on the y-axis; this power is commonly expressed in megawatts (MW) or kilowatts (kW).

The produced power curve in Figure 4.27 illustrates how variations in solar radiation over time affect the combined output of the wind turbine and solar photovoltaic (PV) array.

This variance might be caused by a number of things, including the erratic nature of the wind, the weather, and variations in solar insolation throughout the day. The load demand curve, which is also shown in Figure 4.27, shows how much electricity the connected loads in the system used during that time. This curve represents the fluctuating energy use during the day, which can be impacted by the time of day, occupancy trends, and operational needs, among other things. A hybrid renewable energy system's ability to provide the associated loads with electricity may be evaluated by stakeholders by comparing the generated power curve with the load demand curve.

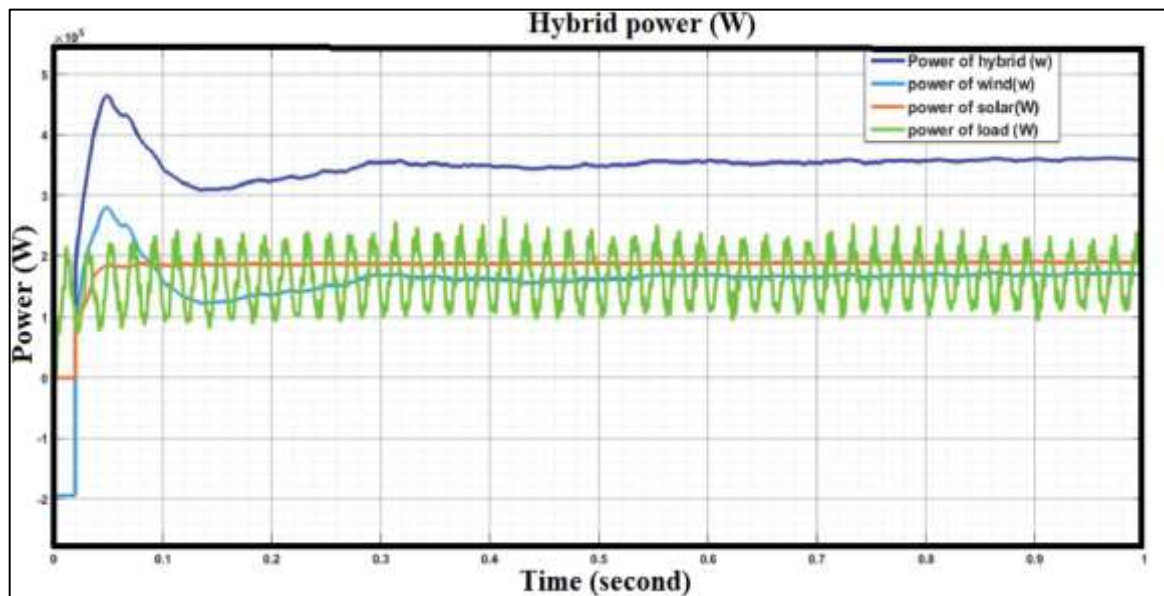


Figure 4.27: The Hybrid Renewable Energy System's Generated Power Varies.

4.8 SUMMARY

The modelling and simulation efforts carried out to examine the behavior and performance of the hybrid renewable energy system are fully summarized in the simulation chapter.

The simulation results show how the hybrid renewable energy system performs and behaves dynamically under a range of operational situations, such as variations in wind speed, load demand, and solar irradiation. A thorough scenario analysis is used to evaluate how well the system can use renewable energy sources and satisfy load needs.

Improvements in the hybrid renewable energy system's design, configuration, and control techniques can be made thanks to optimization studies. To optimize energy efficiency, dependability, and economic viability, the best system configurations and operational settings may be found by experimenting with various situations and factors.

To guarantee their correctness and dependability, the simulation models are checked and confirmed with experimental data, physical measurements, or published literature. The simulation findings closely reflect real-world data, as confirmed by the validation procedure, which boosts trust in the modeling methodology and analytical conclusions.

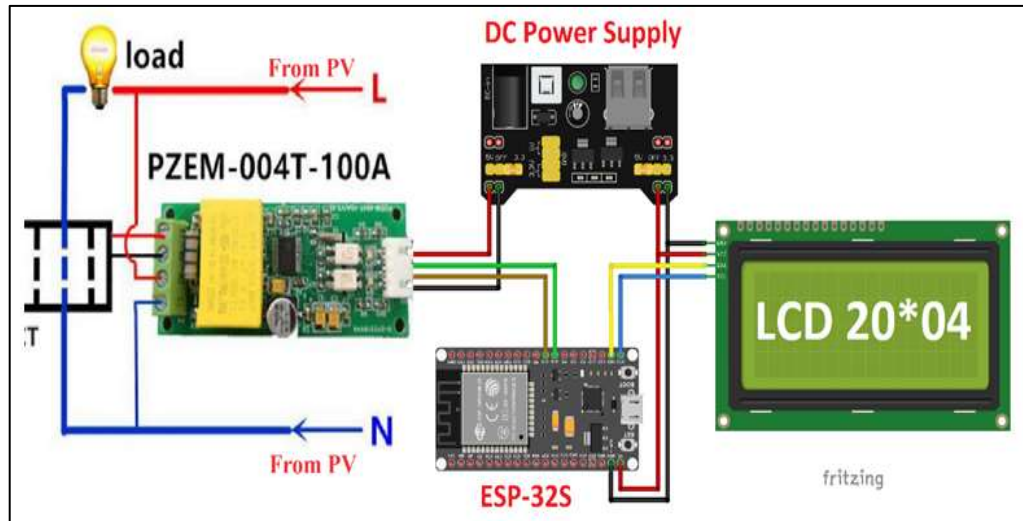
The simulation studies offer important insights into how the hybrid renewable energy system behaves, functions, and is optimized. Recommendations for improving overall system performance, choosing components, fine-tuning control algorithms, and system architecture are provided in light of the results.

5. RESULTS AND DISCUSSIONS

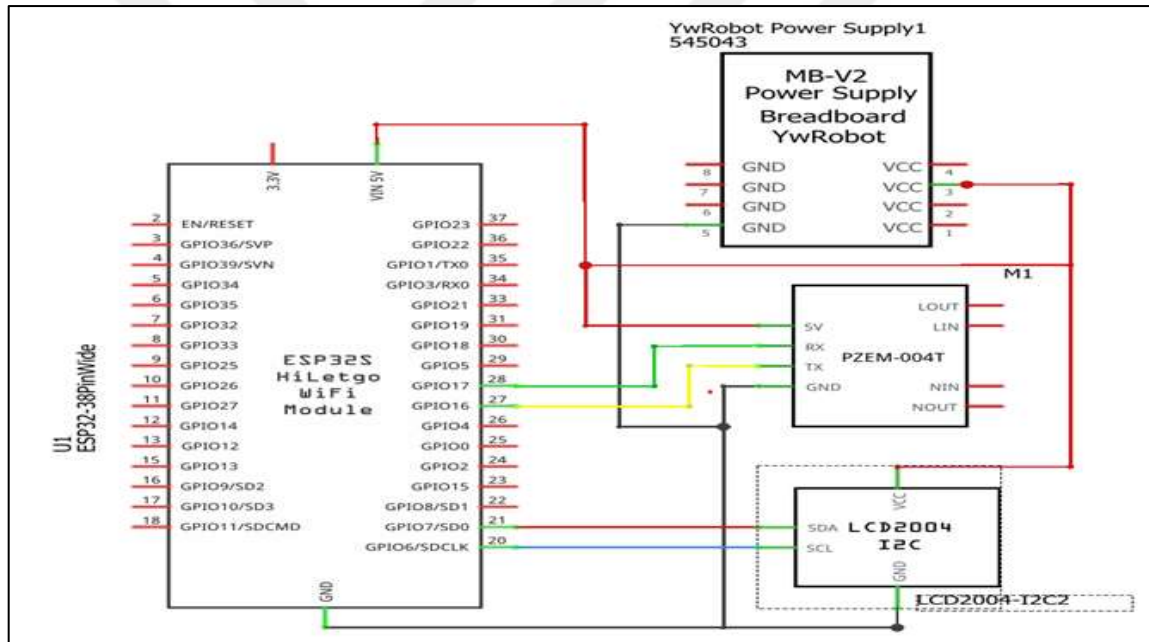
This section would normally provide comprehensive details on the setup of the hardware and software components used in the experiment, as well as the outcomes that were attained. Here are some things to expect from this section:

The hardware utilized in the experiment, including sensors, actuators, microcontrollers, communication modules (such as Bluetooth or Wi-Fi), and any other pertinent equipment, would be described. It would also describe the connections and arrangements that made up the hybrid energy system. This section contains details on the methods used to get data from the system's numerous sensors and components. This might include any preprocessing procedures done on the raw sensor data, as well as the sample rate and data gathering technique. An explanation of the protocol used for data transmission between the monitoring system and IoT devices. This might entail modified protocols made to meet the unique needs of the experiment, or it could utilize conventional protocols like MQTT and HTTP.

Using a free application called Fritzing, the system layout of the completed circuit is displayed in Figure 5.1 A&B. It can be used to develop, experiment with, and collaborate on other people's electrical concepts to produce a schematic and, a highly polished part that can be wired into wire diagrams. Making the own PCB design files is even better [27].



(a)



(b)

Figure 5.1: Complete System: (a) Block Diagram and (b) Schematic Diagram.

When building a smart monitoring network for a hybrid energy system utilizing the Internet of Things, various sensors may be used to monitor parameters including solar power generation, wind energy output, battery condition, and overall energy consumption. IoT devices collect this data and send it to a central server for analysis. These sensors are interfaced with by the ESP32 microprocessor, which gathers information on voltage, current, frequency, active power, and AC voltage. An LCD screen is used to show the data, providing

on-site monitoring and analysis capabilities in addition to acting as a user interface. The gathered data is transferred to the cloud for remote access and storage if Wi-Fi is accessible. In order to provide offsite data storage, centralized access, and data retrieval from any internet-connected location, the ESP32 sends the gathered data to a designated cloud server. This permits analysis and access to be consolidated.

Figure 5.2 shows the final, workable design of the monitoring circuit for the PV system's real-time performance. This circuit describes the components, setup, and procedure used in the testing to monitor the PV system's performance in real time.

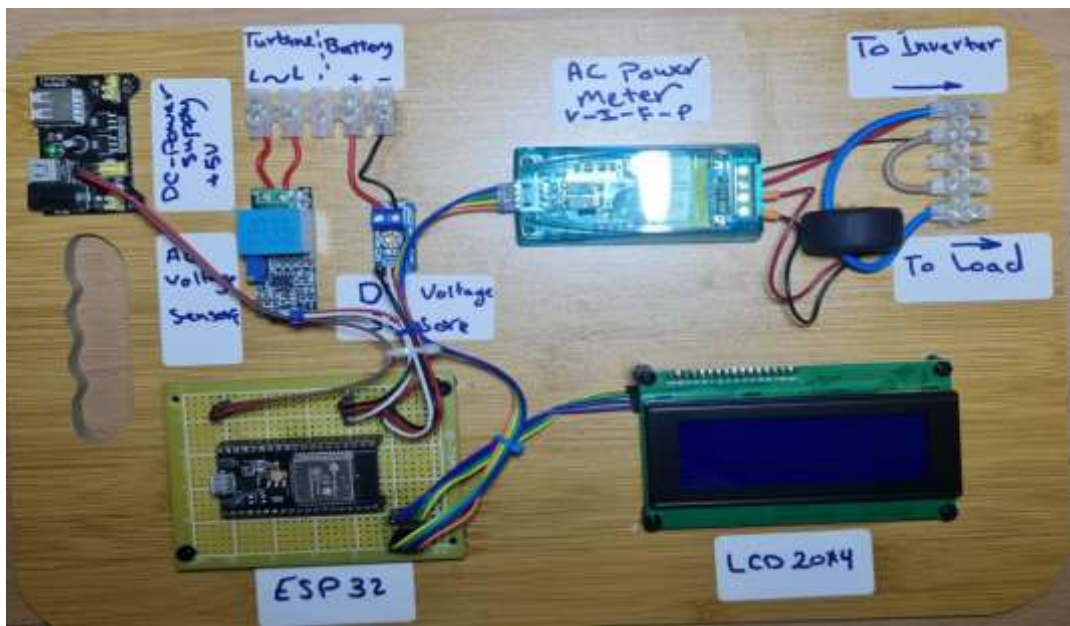
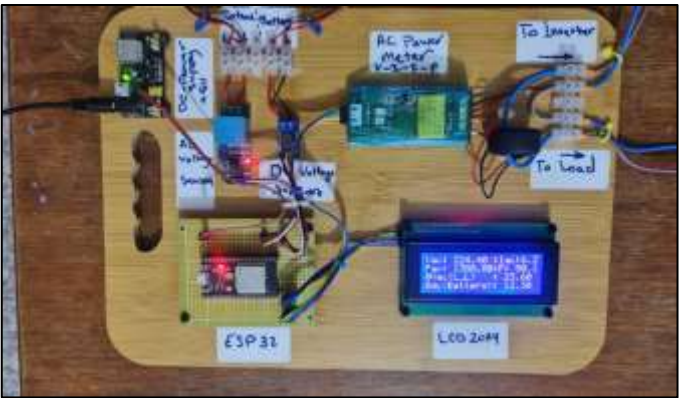


Figure 5.2: Hybrid Hardware Component System.

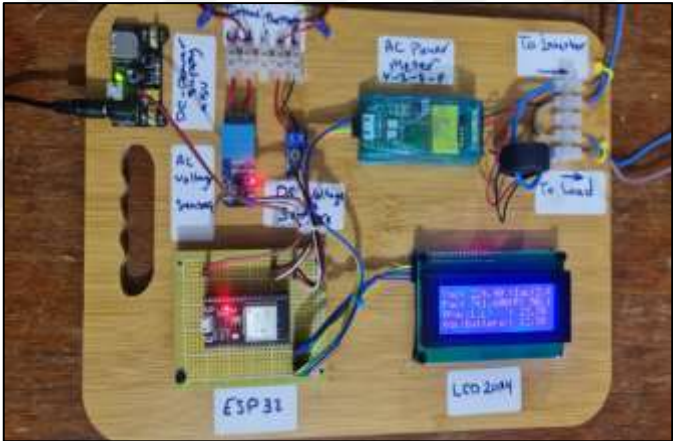
5.1 COMPREHENSIVE SYSTEM RESULTS

The hybrid energy system's monitoring system is fully depicted on the LCD in Figure 5.3A, B, and C, which displays real-time results of its operation in response to variations in load. The LCD's value representation provides a visual snapshot of many parameters, including power output, voltage, and current, and shows how the system reacts to varying loads. These statistics are essential for evaluating a system's effectiveness and stability across a variety of operational settings. The findings displayed on the LCD provide useful information for improving the PV systems under various load scenarios in addition to acting as a real-time monitoring tool for on-site evaluation. This visualization helps to ensure that the PV system

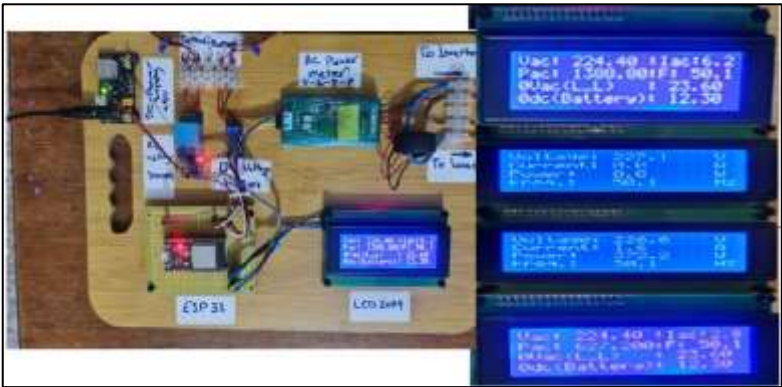
is resilient over a range of load profiles and helps to better understand how the monitoring system responds to variations in demand. It also helps to improve operational strategies.



(a)



(b)



(c)

Figure 5.3: A Real Time Results of Hybrid Energy Monitoring System.

5.2 THINGSPEAK CLOUD RESULTS

A comprehensive collection of results from the ThingSpeak cloud platform is displayed in Figure 5.4, which offers a complete view of how the monitoring system connected to the hybrid system operates in various load conditions. ThingSpeak displays critical properties like as voltage, current, and power output, among others, to allow for remote monitoring and access.

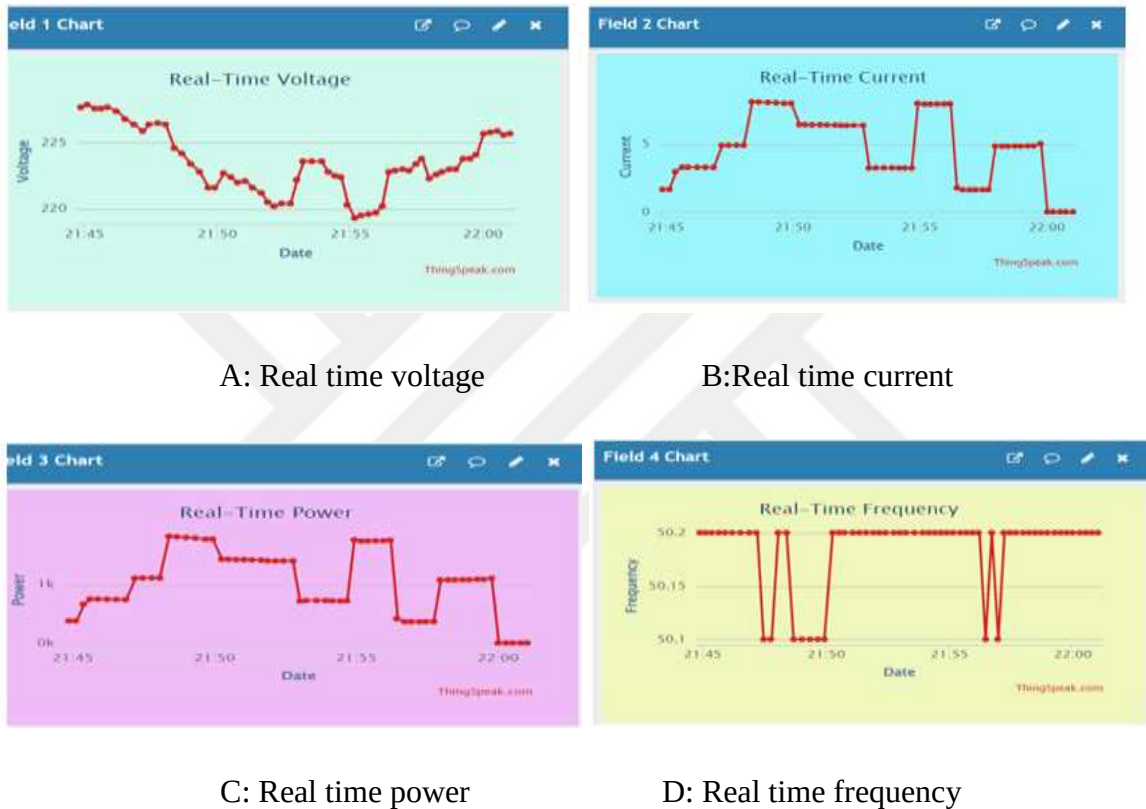


Figure 5.4: Final System Results on ThingSpeak Cloud.

The integration of cloud-based data visualization, enabled by platforms such as ThingSpeak, has noteworthy advantages for investigators, managers, and interested parties engaged in the observation of hybrid energy systems. Through the real-time presentation of data, participants are able to quickly evaluate how the hybrid energy system performs under various load conditions. Decisions and responses to anomalies or changes in the system may be made quickly because to the instant access to information.

ThingSpeak and other cloud-based monitoring systems are scalable, meaning they can manage massive amounts of data produced by the system. To further improve accessibility

and flexibility, stakeholders can use the monitoring system from any location with an internet connection. It offers features and tools for data analysis, visualization, and processing. This makes it easier to extract insightful information from the data, giving stakeholders a better understanding of trends, patterns, and performance indicators.

The hybrid energy system's long-term performance evaluation is made easier by the ThingSpeak cloud's capacity to retain data. Analyzing historical data may help plan and optimize future operations, spot possible deterioration or efficiency gains, and monitor system performance over time. Participants are better equipped to decide on system operation, maintenance, and optimization when they have access to real-time data on the ThingSpeak cloud. They can react quickly to events or changing circumstances, guaranteeing the hybrid energy system's dependability and best performance. Also, Participants have a better knowledge of how the hybrid energy system responds to different operating circumstances, load profiles, and environmental factors thanks to ongoing data monitoring and analysis on the ThingSpeak cloud. Improved optimization techniques and system management are made possible by this information.

Finally, the integration with ThingSpeak and the use of cloud-based data processing and presentation provide a strong foundation for the real-time analysis, monitoring, and optimization of hybrid energy systems. This improves system resilience, performance, and reliability and offers insightful information to stakeholders in system management and operation.

5.3 SMARTPHONE APPLICATION RESULTS

Nowadays, the application's home page has a number of key functions, including security, garden monitoring, sensors, smart homes, smart offices, and smart industries. If other features are required, they may be introduced in the same manner. There are supporting sub-functionalities for every feature. For instance, the Living Room, or Kitchen sub-functionalities are available inside the Smart Home. Virtual switches have been built by the system to control different appliances with varied characteristics. For instance, after selecting the Living Room option, customers will see options for switching lights, fans, table lamps, and air conditioning. A switch may be toggled from ON to OFF by touching it, and the ESP32 module at the sender end receives this ON/OFF signal over a Wi-Fi connection.

Such controlling signal is sent via the LoRa module to the ESP32 module at the receiving end in a matter of milliseconds. The receiver end's ESP32 module then sends this signal to the specific relay so that it may be used to turn on or off each individual appliance or gadget via a different I/O pin. Additionally, the system operated the window's open and close functions and the door's lock and unlock. In addition, a feature to turn on and off cameras was introduced for security. The system's Graphical User Interface (GUI) is displayed in Figure 5.5 along with the sub-functionalities for security and smart homes as well as the home page with options for smart home, security, garden monitoring, smart office, and smart industry.

The final product output is shown in Figure 13, which is a smartphone application created using MIT Inventor for real-time hybrid system performance monitoring under different loads. The application's spatially optimized UI intelligently adapts to changing load conditions, giving users an exciting and visually engaging experience.

The results shown on the smartphone app show how the parameters system responds to different loads, and MIT Inventor's spatial design ideas make it easier for the user to explore and understand the data in a natural manner. Spatial integration not only increases accessibility but also gives users an advanced means of comprehending the behavior of the system under different operating conditions. The application's spatial design can convert complicated performance data into a format that is both aesthetically pleasing and simple to understand with the aid of MIT Inventor. This enables remote monitoring of the PV single-phase system's performance in real time, enabling stakeholders to make well-informed decisions.



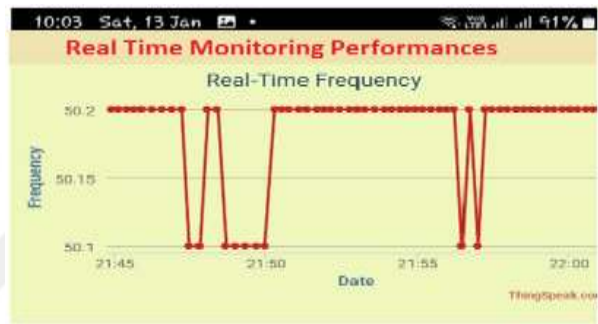
(A)



(B)



(C)



(D)

Figure 5.5: Smartphone Application Monitoring.

5.4 SUMMARY

The hybrid system monitoring results chapter provides a thorough analysis of the system's operation and its capacity to deliver up-to-date information on the hybrid energy system's performance. It starts with a thorough description of the whole system, including its organizational structure with a block diagram that clarifies how different components interact with one another. A schematic diagram also offers a concrete depiction of the actual configuration and interconnection of hardware components, such as sensors, controllers, and communication interfaces.

This chapter is primarily concerned with real-time monitoring results, including continuous data streams obtained from a variety of sensors. Vital indicators including solar irradiance, wind speed, PV array voltage and current, turbine RPM, battery voltage and state of charge, grid voltage and power production are all measured by these sensors. These data streams offer priceless insights into the operational dynamics, energy generation patterns, and usage trends of the system through painstaking visualization and analysis.

A thorough analysis of the hardware component system provides insight into the individual parts that make up the hybrid energy monitoring system. This includes a thorough explanation of the sensors, microcontrollers, data collecting devices, and communication modules that are all essential to the collection, processing, and transmission of data.

Additionally, the possibility of integrating the monitoring system with the cloud-based IoT platform ThingSpeak is investigated. This interface provides stakeholders with access to graphical representations, charts, and dashboards displaying critical performance data, as well as the dissemination and visualization of real-time system outcomes. This integration improves the insights from the monitoring system's usability and accessibility, which helps with system optimization and well-informed decision-making.

Another aspect of the chapter explores the creation and implementation of a smartphone application designed for remote hybrid energy system monitoring. With the help of this program, customers may even change system settings from their mobile devices, get notifications, and access real-time data. This adaptability highlights the dedication to accessibility and user-centric design, improving the system's usability and efficacy in practical applications.

To summarize, the results chapter offers a thorough examination of the capabilities of the hybrid energy monitoring system, giving stakeholders a plethora of up-to-date information and enabling them to make well-informed decisions about system management, optimization, and operation.

6. CONCLUSIONS AND SUGGESTED FUTURE WORKS

6.1 CONCLUSIONS

Through the deployment and evaluation of the smart monitoring network, it has been demonstrated that real-time monitoring significantly enhances the performance of hybrid renewable energy systems. The ability to gather and analyze data in real-time allows for more precise control and optimization of energy generation, storage, and utilization, resulting in improved system efficiency and reliability.

The implementation of IoT-based solutions for monitoring and control enables more efficient management of renewable energy resources. By dynamically adjusting operational parameters based on real-time data, such as solar irradiance levels, wind speeds, and battery state of charge, the system can maximize energy capture and utilization, minimizing wastage and improving overall system economics.

The smart monitoring network enhances the resilience of hybrid renewable energy systems by enabling proactive maintenance and fault detection. Real-time monitoring facilitates early detection of system anomalies or performance degradation, allowing for timely intervention and mitigation measures to prevent system downtime and ensure continuous operation.

The modular and scalable architecture of the smart monitoring network ensures adaptability to varying system configurations and scales. Whether deployed in small-scale residential installations or large-scale commercial or industrial setups, the monitoring network can accommodate diverse requirements and effectively manage the complexities of hybrid energy systems.

The findings of this research contribute to both academic knowledge and practical applications in the field of renewable energy integration. By demonstrating the feasibility and effectiveness of IoT-based monitoring solutions, this work provides valuable insights and guidelines for researchers, engineers, and policymakers seeking to deploy and optimize hybrid renewable energy systems.

While significant progress has been made in this research, there remain several avenues for further exploration and development. Future research efforts could focus on refining control

algorithms, integrating advanced forecasting techniques, enhancing cybersecurity measures, and conducting field trials to validate system performance in real-world scenarios.

In summary, the deployment and evaluation of the smart monitoring network for hybrid renewable energy systems have demonstrated its efficacy in improving system performance, resilience, and efficiency. By leveraging real-time data and IoT technologies, renewable energy systems can achieve higher levels of integration, reliability, and sustainability, paving the way for a cleaner and more resilient energy future.

In conclusion, this thesis has addressed the design, development, and implementation of a smart monitoring network for hybrid renewable energy systems using IoT technologies. Through comprehensive literature review, methodology development, simulation experiments, and practical implementation, several key findings and conclusions have been drawn:

- a. Importance of Real-Time Monitoring: The research has highlighted the significance of real-time monitoring in optimizing the performance, efficiency, and reliability of hybrid renewable energy systems. Real-time data acquisition enables informed decision-making and proactive management of energy generation, storage, and utilization.
- b. Advancements in IoT-Based Solutions: The design and implementation of the smart monitoring network have demonstrated the feasibility and effectiveness of IoT technologies in enabling remote monitoring and control of hybrid energy systems. IoT platforms provide scalable and reliable solutions for data acquisition, communication, and visualization.
- c. Optimization of Energy Management: Through simulation experiments and practical implementation, the research has shown the potential for optimizing energy management strategies in hybrid renewable energy systems. Smart monitoring enables dynamic adjustments to energy generation, storage, and consumption based on real-time data and system requirements.
- d. Enhanced System Performance: The deployment of the smart monitoring network has resulted in improved system performance, stability, and reliability. Remote monitoring and control capabilities enable proactive maintenance, fault detection, and troubleshooting, leading to enhanced system uptime and efficiency.

6.2 SUGGESTED FUTURE WORKS

Building upon the findings and conclusions of this research, several avenues for future exploration and development are suggested:

- a. **Advanced Control Strategies:** Investigate advanced control strategies, such as machine learning algorithms and predictive analytics, for optimizing energy management in hybrid renewable energy systems. Explore the potential of artificial intelligence techniques in enhancing system performance and efficiency.
- b. **Integration of Energy Storage:** Further explore the integration of energy storage systems, such as batteries and supercapacitors, into hybrid renewable energy systems. Investigate optimal sizing, placement, and control strategies for maximizing the benefits of energy storage in conjunction with renewable energy sources.
- c. **Cybersecurity and Data Privacy:** Address cybersecurity and data privacy concerns associated with IoT-based solutions for energy monitoring and control. Develop robust security protocols, encryption techniques, and access control mechanisms to safeguard sensitive data and ensure system integrity.
- d. **Field Testing and Validation:** Conduct extensive field testing and validation of the smart monitoring network in real-world hybrid renewable energy systems. Gather long-term performance data, user feedback, and operational insights to refine and improve the monitoring system.
- e. **Scalability and Interoperability:** Explore methods for enhancing the scalability and interoperability of the smart monitoring network to support larger and more complex hybrid energy systems. Investigate standardized communication protocols, modular hardware/software architectures, and interoperable IoT platforms.

By pursuing these suggested future works, researchers and practitioners can further advance the state-of-the-art in smart monitoring and control of hybrid renewable energy systems, ultimately contributing to the widespread adoption of sustainable energy technologies and the transition towards a more resilient and environmentally friendly energy future.

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