THE IMPLEMENTATION OF AN IOT-BASED, INVESTIGATIVE SYSTEM FOR MAXIMUM POWER POINT TRACKING IN PHOTOVOLTAIC ARRAYS.

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CERTIFICATION

This is to certify that the work presented in this document was carried out by **EKHOE-OMORAGBON UYIOSA**, with matriculation number, **ENG2008371**, of the Department of Computer Engineering, Faculty of Engineering, University of Benin City, Edo State, Nigeria.

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DEDICATION

This project is dedicated first and foremost to Almighty God, whose grace, wisdom, strength, and guidance made this work possible from inception to completion. His unfailing love and divine support have been the foundation of every achievement recorded throughout this academic journey.

I also dedicate this project to my beloved parents, Mr. and Mrs. Ekhoe-Omoragbon, whose sacrifices, prayers, encouragement, and unwavering support have been instrumental to my growth and success. Your constant belief in my abilities, moral guidance, and commitment to my education continue to inspire me to strive for excellence.

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ABSTRACT

The efficiency and reliability of photovoltaic (PV) systems are largely determined by their ability to extract maximum power under varying environmental conditions. This project presents the implementation of an IoT-based investigative system for Maximum Power Point Tracking (MPPT) in photovoltaic arrays, focusing on the comparative performance of the MPPT and Pulse Width Modulation (PWM) charge controllers. The system integrates voltage and current sensors with an ESP32 microcontroller to measure and record PV parameters in real time. Through IoT connectivity, the collected data is transmitted to a cloud-based platform for remote monitoring, analysis, and visualization, enabling real-time tracking of PV performance.

Experimental tests were conducted under different irradiance and temperature levels to evaluate the charging efficiency, dynamic response, and adaptability of both controllers. The MPPT controller dynamically adjusted the operating point of the PV module to maximize energy extraction, while the PWM controller maintained a simpler, fixed switching mechanism. Additionally, the system allowed for a detailed analysis of the relationship between light intensity, temperature, and PV output performance, with the readings interpreted from real-time graphical charts. These insights revealed how environmental variations affect energy generation and charge controller efficiency.

This project develops a real-time, IoT-enabled system capable of monitoring and comparing the operational efficiency of MPPT and PWM charge controllers in photovoltaic applications. The results demonstrate that the MPPT controller achieves superior power utilization and battery charging efficiency compared to the PWM controller. Overall, the system provides a reliable, data-driven investigative platform for analyzing solar charge control strategies and supports further optimization of PV energy systems through intelligent IoT integration.

LIST OF ABBREVIATIONS

AC: ALTERNATING CURRENT

DC: DIRECT CURRENT

GPIO: GENERAL-PURPOSE INPUT/OUTPUT

INC: INCREMENTAL CONDUCTANCE

IoT: INTERNET OF THINGS

LCD: LIQUID CRYSTAL DISPLAY

MPP: MAXIMUM POWER POINT

MPPT: MAXIMUM POWERPOINT TRACKING

P&O: PERTURB AND OBSERVE

PV: PHOTOVOLTAIC ARRAY

PWM: PULSE WIDTH MODULATOR

UART: UNIVERSAL ASYNCHRONOUS RECEIVER-TRANSMITTER

LIST OF FIGURES

FIGURE 3.1: BLOCK/PROCESS DIAGRAM…………………..……………..…..…..….16

FIGURE 3.2: PHOTOVOLTAIC ARRAYS……………………..………..………..…..….18

FIGURE 3.3: VOLTAGE SENSORS……………………………..…….…………..…..…19

FIGURE 3.4: CURRENT SENSORS…………………………...………………..….…20

FIGURE 3.5: TEMPERATURE SENSORS…………………………...…………..….20

FIGURE 3.6: WIFI MODULE……………………………………………………...……21

FIGURE 3.7: POWER SUPPLY…………………………………………...……….……21

FIGURE 3.8: LCD SCREEN……………………………………………………………22

FIGURE 3.9: ESP32 MICROCONTROLLER AND ITS PIN CONFIGURATION…………………………………………………………….…….24

FIGURE 3.10: THINGSPEAK INTERFACE AND CODE……………..……………..….25

FIGURE 3.11: CIRCUIT DIAGRAM……………………………………….………..26

FIGURE 4.1: THINGSPEAK CHART SHOWING REAL TIME DATA FROM THE PV ARRAY USING AN MPPT CHARGE CONTROLLER………………………………..31

FIGURE 4.2: THINGSPEAK CHART SHOWING REAL TIME DATA OBTAINED USING A PULSE WIDTH MODULATOR………………………………..……..…..…35

LIST OF TABLES

TABLE 2.1: RELATED WORKS…………….………………………………..……..13

TABLE 4.1: PERFORMANCE METRICS FOR A PV ARRAY USING AN MPPT CONTROLLER……………………………………………………………..……..29

TABLE 4.2: PERFORMANCE METRICS FOR A PV ARRAY USING A PWM…………………………………..……………………………..……..32

TABLE 4.3: COMPARATIVE ANALYSIS OF AN MPPT CONTROLLER AND A PWM…………………………………………………………………………….37

TABLE OF CONTENTS

CERTIFICATION……………………….……………………………….…….…….i

DEDICATION……………………………………..………………………..….ii

ACKNOWLEDGEMENT…………………………………...………………..……iii

ABSTRACT……………………………………………………………………..…iv

LIST OF ABBREVIATIONS……………………………..………………………......v

LIST OF FIGURES…………………………………………………………......…..vi

LIST OF TABLES…………………………………………………………..……vii

CHAPTER ONE……………………………………………………………......1

INTRODUCTION……………………………………………………………………1

1.1 BACKGROUND OF THE STUDY……………………..………………………..…1

1.1.1 HISTORICAL CONTEXT AND EVOLUTION OF MPPT ....…………......….…..2

1.1.2 ROLE OF IOT IN PV SYSTEMS…..……………………………………………….2

1.1.3 KEY DEFINITIONS................................…...................…………………..…………3

1.1.4 GLOBAL CHALLENGES IN PHOTOVOLTAIC (PV) SYSTEMS...……………..…3

1.2 STATEMENT OF THE PROBLEM……………………………..………,………..….3

1.3 AIM OF THE WORK………………………………..………………..……………..4

1.4 OBJECTIVES………………………..………………………………………………4

1.5 SCOPE OF WORK…………………………………………………………………..5

1.6 JUSTIFICATION FOR RESEARCH………………………………………………..5

1.6.1 ECONOMIC BENEFITS…………………………………………………………..6

1.6.2 ENVIRONMENTAL IMPACT…………..…………………...…………………...7

1.6.3 BENEFITS TO ENGINEERS AND INDUSTRY……….………………..……………7

CHAPTER TWO…………………………………………………………..……………...8

LITERATURE REVIEW…………………………………………………………………..….8

2.1 THEORETICAL CONCEPTS……………………………………………………….....9

2.1.1 MAXIMUM POWER POINT TRACKING (MPPT) CONTROLLER…..……..…...9

2.1.2 PULSE WIDTH MODULATOR (PWM) CONTROLLER……………………...10

2.1.3 COMPARATIVE ANALYSIS OF MPPT AND PWM CONTROLLERS……........10

2.1.4 INTERNET OF THINGS (IoT) IN PV ARRAYS…….…...……………...…….11

2.2 RELATED WORKS……………………………………………………………..13

CHAPTER THREE…………………………………………………………...16

METHODOLOGY……………………………………………………………..16

3.1 PROCESS DIAGRAM…………………………………………………………..16

3.2 METHODOLOGY……………………………………………………………....16

3.2.1 DATA ACQUISITION……………………………………………………...16

3.2.2 DATA TRANSMISSION……………………………………….………...17

3.2.3 DATA MONITORING……………………………………………….………...17

3.3 COMPONENTS……………………………………………………………….17

3.4 CIRCUIT DESIGN AND ASSEMBLY………...………………………………..25

CHAPTER FOUR……………..……………………………………..….……..28

RESULTS AND DISCUSSION………………………………...……………… 29

4.1RESULTS…………………..……………………………………………..………29

4.1.1 RESULTS OBTAINED FROM THE MPPT CONTROLLER…………………..…..29

4.1.2 RESULTS OBTAINED FROM THE PWM CONTROLLER………………………32

4.2 DISCUSSION…………………………………………..………………………36

4.3 KEY OBSERVATIONS……………………….……………..…………………...36

CHAPTER FIVE…………………………….……………………….…………….38

CONCLUSION AND RECOMMENDATIONS……………………………..…………..38

5.1 CONCLUSION……………………….……………………………………………38

5.2 LIMTATIONS OF THE SYSTEM………………...……………………...……………..39

5.3 RECOMMENDATIONS FOR FUTURE WORK……………………………….....40

REFERENCES.……………………………….………………………………………42

APPENDIX…..……………………………….……………………………………..43

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

The growing global demand for sustainable and environmentally friendly energy sources has intensified research and innovation in renewable energy technologies. Among these, solar photovoltaic (PV) systems have gained prominence due to their abundance, renewability, and minimal environmental impact. Solar energy represents one of the most viable alternatives to fossil fuels, offering a clean, silent, and inexhaustible source of power that supports global efforts to mitigate climate change and reduce greenhouse gas emissions. However, despite these advantages, the efficiency of PV systems remains a significant challenge because the power output of solar panels is influenced by irradiance, temperature, and load variations, which cause the system to operate away from its optimal power point.

To address this inefficiency, Maximum Power Point Tracking (MPPT) techniques have been developed to ensure that PV arrays operate at their most efficient point under changing environmental conditions. MPPT controllers adjust the duty cycle of DC-DC converters to continuously extract the maximum possible power from solar panels. This dynamic adjustment distinguishes MPPT controllers from Pulse Width Modulation (PWM) controllers, which maintain a constant voltage level and lack the adaptability to respond to rapid fluctuations in irradiance and temperature. Consequently, while PWM controllers are simple and cost-effective, MPPT controllers provide superior performance, especially in variable weather conditions where continuous optimization is required for effective battery charging and power utilization.

The emergence of the Internet of Things (IoT) has further enhanced the efficiency and reliability of solar energy systems. IoT enables real-time monitoring, data acquisition, and remote control of PV installations, allowing for continuous observation of critical parameters such as voltage, current, irradiance, and temperature. Through cloud-based platforms like ThingSpeak, data from sensors interfaced with microcontrollers (e.g., ESP32) can be transmitted, analyzed, and visualized in real time. This integration facilitates intelligent decision-making, predictive maintenance, and system optimization—ensuring maximum energy extraction and improved reliability of solar installations.

The relevance of this study extends beyond technical efficiency. It contributes to global sustainability efforts by promoting clean and data-driven energy management, aids engineers and researchers in developing adaptive control systems, and provides a practical solution for societies seeking reliable off-grid power systems, particularly in developing regions. Therefore, this research aims to implement and analyze an IoT-based investigative system that compares the performance of MPPT and PWM controllers in optimizing photovoltaic energy conversion, contributing to the advancement of intelligent renewable energy solutions worldwide.

1.1.1 Historical Context and Evolution of MPPT

The quest to maximize PV system efficiency has led to the development of Maximum Power Point Tracking (MPPT) techniques, which aim to operate PV arrays at their maximum power point (MPP) under varying conditions. Early MPPT methods, such as Perturb and Observe (P&O) and Incremental Conductance (IncCond), were simple and effective under uniform irradiance (Esram & Chapman, 2007). However, these methods struggle with partial shading, where multiple local MPPs arise, causing conventional algorithms to converge to suboptimal points (Rezk & Eltamaly, 2015). This inefficiency results in significant power losses, undermining the economic and environmental benefits of PV systems. Over time, advanced MPPT techniques incorporating computational intelligence—such as fuzzy logic, neural networks, and particle swarm optimization—have been explored to address these limitations (Mellit & Kalogirou, 2014).

1.1.2 Role of IoT in PV Systems.

Concurrently, the Internet of Things (IoT) has revolutionized the monitoring and management of energy systems. IoT enables the seamless collection, transmission, and analysis of data from distributed devices, facilitating real-time decision-making and system optimization (Atzori *et al*., 2010). In PV systems, IoT-based monitoring systems can track parameters such as voltage, current, power output, and environmental conditions, providing insights into system performance and enabling proactive maintenance (Hossain & Madlool, 2021). The integration of IoT with advanced control algorithms like Transformer-based DRL offers a synergistic approach to enhancing PV system efficiency, allowing for data-driven MPPT and remote performance monitoring (Benzaouia & Hajji, 2022).

1.1.3 Key Definitions.

1. Photovoltaic (PV) Array: A collection of interconnected solar panels that convert sunlight into electricity using the photovoltaic effect.
2. Maximum Power Point Tracking (MPPT): A control strategy that adjusts the operating voltage and current of a PV array to maximize power output.
3. Internet of Things (IoT): A network of interconnected devices that collect and exchange data over the internet, enabling real-time monitoring and control.

1.1.4 Global Challenges in Photovoltaic (PV) Systems.

Despite advancements, PV systems face several challenges that hinder their widespread adoption:

1. Partial Shading: Shading on parts of a PV array creates multiple MPPs, confusing conventional MPPT algorithms and reducing efficiency.
2. Dynamic Environmental Conditions: Rapid changes in irradiance and temperature require adaptive control strategies to maintain optimal performance.
3. Lack of Real-Time Monitoring: Without continuous data collection and analysis, inefficiencies and faults go undetected, leading to energy losses.
4. Scalability and Cost: Advanced MPPT and monitoring systems must be cost-effective and scalable to support large-scale PV installations.

1.2 Statement of the Problem

The efficiency of photovoltaic (PV) systems is highly dependent on their ability to continuously operate at the Maximum Power Point (MPP), where the product of voltage and current yields the maximum possible power output. However, under real-world conditions, factors such as fluctuating solar irradiance, temperature variations, and load changes significantly affect the performance of PV arrays, often leading to suboptimal power generation. Conventional solar charge controllers, such as the Pulse Width Modulation (PWM) controller, are unable to adapt dynamically to these variations, resulting in energy losses and reduced battery charging efficiency.

Although Maximum Power Point Tracking (MPPT) controllers have been developed to overcome these challenges by dynamically adjusting the operating point of the PV system, their real-time behavior and performance under varying environmental conditions are not always fully understood or easily observable. Moreover, most existing systems lack remote monitoring and data analysis capabilities, limiting the ability to evaluate controller performance effectively or to make timely adjustments in operational settings.

Therefore, there is a need for an IoT-based investigative platform that enables real-time monitoring, data logging, and comparative analysis of PV system performance using both MPPT and PWM controllers. Such a system would provide valuable insights into how environmental factors such as light intensity and temperature affect power output and charging efficiency, while offering a scalable and accessible solution for research, performance optimization, and educational applications in renewable energy systems.

1.3 Aim of the Work

The aim of this project is to implement an IoT- based, investigative system for maximum power point tracking in photovoltaic arrays.

1.4 Objectives

The project is guided by the following objectives that outline the expected outcomes and deliverables:

i. Design and implement a monitoring system capable of acquiring real-time data from the PV array.
ii. Develop a data acquisition framework that transmits and stores PV system parameters on a cloud platform.
iii. Implement and evaluate the performance of the PWM and MPPT charge controllers under varying environmental conditions.
iv. Analyze the relationship between light intensity, temperature and PV output using real-time data charts.

v. Compare the charging efficiency and response characteristics of the MPPT controller and the PWM controller.

1.5 Scope of Work

This study focuses on the design and implementation of an IoT-based investigative platform for solar charge controller performance analysis. The work covers both hardware and software aspects of PV system monitoring and control and is limited to small-scale experimental setups suitable for prototype testing.

The scope of this work includes:

i. The use of an ESP32 microcontroller as the main control and IoT communication unit.
ii. Integration of voltage, current, and temperature sensors for real-time parameter acquisition.
iii. Implementation of MPPT and PWM charge controllers for performance comparison.
iv. Utilization of ThingSpeak as the cloud-based IoT platform for remote data storage, visualization, and analysis.
v. Examination of the effects of light intensity and temperature on the PV array’s power output and controller efficiency.

The study does not cover large-scale grid-connected PV systems, long-term field testing, or the incorporation of advanced artificial intelligence models (such as deep reinforcement learning). Instead, it emphasizes a practical, low-cost, and scalable prototype suitable for research, educational, and small renewable energy applications.

1.6 Justification for Research

Implementing an IoT-based investigative system provides a modern, data-driven solution to these challenges. By integrating Internet of Things (IoT) technology, the system allows for real-time monitoring, data acquisition, and remote analysis of PV parameters such as voltage, current, and power output. This approach enables continuous performance evaluation of charge controllers and provides valuable insights into the relationship between environmental factors and PV efficiency. Recent studies have shown that IoT-enabled solar monitoring systems improve operational visibility, reduce maintenance costs, and support predictive energy management (Patel *et al*., 2022; Hassan *et al*., 2024). The use of cloud-based platforms such as ThingSpeak further enhances accessibility and supports data visualization for deeper understanding and system optimization (El-Din & Alsharif, 2021).

Furthermore, the comparative study between MPPT and PWM charge controllers is justified by the need to evaluate their respective efficiencies and adaptability in real-world conditions. Research by Khan *et al*. (2023) and Devi *et al*. (2022) highlighted that MPPT-based systems achieve up to 25–30% higher energy harvesting efficiency than traditional PWM systems, particularly under fluctuating irradiance. Findings from such investigations can guide the selection, design, and optimization of solar charge controllers for improved system performance and battery life. Additionally, this research contributes to the growing field of smart renewable energy systems, offering a low-cost, scalable platform that can be used for academic research, industrial testing, and educational training. Ultimately, this work supports global efforts to enhance energy sustainability through intelligent control and IoT integration (Ahmed *et al*., 2024).

1.6.1 Economic Benefits

1. Cost Savings: Higher PV system efficiency translates to increased energy yield, reducing the levelized cost of electricity for solar power. This is particularly impactful for large-scale installations.
2. Scalability: The modular design of the proposed system ensures it can be adapted to various PV system sizes, from residential to utility-scale, maximizing its market applicability.
3. Reduced Maintenance Costs: Real-time monitoring enables early detection of faults, minimizing downtime and repair expenses.

1.6.2 Environmental Impact

1. Clean Energy Adoption: By improving PV system efficiency, the project supports the global transition to renewable energy, reducing reliance on fossil fuels and mitigating greenhouse gas emissions.
2. Sustainability: Enhanced PV performance contributes to the United Nations Sustainable Development Goal 7 (Affordable and Clean Energy), promoting sustainable energy access worldwide (United Nations, 2015).

1.6.3 Benefits to Engineers and Industry

1. Reference Framework: Engineers can use the proposed system as a reference for developing advanced MPPT and monitoring solutions, accelerating the adoption of smart PV technologies.
2. Industry Adoption: The project's focus on scalability and cost-effectiveness ensures its relevance to PV manufacturers, system integrators, and energy providers.
3. Skill Development: The interdisciplinary nature of the project provides opportunities for engineers to develop expertise in cutting-edge technologies.
4. Energy Access: Improved PV efficiency supports the deployment of solar power in remote and underserved regions, enhancing energy access and quality of life.

CHAPTER 2

LITERATURE REVIEW

The increasing demand for renewable energy solutions has positioned solar photovoltaic (PV) systems as a vital component of sustainable power generation across the globe. PV systems convert solar irradiance into electrical energy through semiconductor materials, offering a clean, sustainable, and scalable energy source. However, the output efficiency of PV systems is significantly influenced by varying environmental conditions such as solar irradiance, temperature, and load variations. Consequently, the real-time optimization of PV power generation has become a key research focus for improving overall system performance and energy conversion efficiency (Sharma & Singh, 2021).

A PV system typically comprises solar panels, a power conditioning unit, a charge controller, and an energy storage system such as a battery. Among these components, the controller plays a crucial role in maintaining optimal operating conditions by adjusting the voltage and current to extract the maximum possible power from the PV array. Traditional controllers such as the Pulse Width Modulation (PWM) controller have been widely used due to their simplicity, cost-effectiveness, and ease of implementation. However, PWM controllers operate at a fixed duty cycle that limits their ability to track the maximum power point (MPP) dynamically, particularly under fluctuating environmental conditions (Devi & Sahu, 2022).

To address the limitations of conventional control methods, researchers have developed advanced control techniques known as Maximum Power Point Tracking (MPPT). MPPT controllers are designed to continuously monitor and adjust the PV system's operating point, ensuring that it operates at the maximum power point regardless of environmental changes (Khan et al., 2023). This capability not only enhances energy extraction but also improves the efficiency and lifespan of batteries in standalone PV systems. The comparative study of PWM and MPPT control approaches is, therefore, essential to understand their operational characteristics, efficiency levels, and suitability for different PV applications.

Furthermore, with the emergence of the Internet of Things (IoT), real-time monitoring and data analysis of PV systems have become increasingly feasible and efficient. IoT-based systems enable remote observation of key parameters such as voltage, current, irradiance, and temperature through cloud-based platforms, thereby providing enhanced system visibility and facilitating data-driven decision-making (El-Din & Alsharif, 2021). Integrating IoT with PV systems has expanded the scope of energy research, leading to improved diagnostics, fault detection, and energy management.

In light of these developments, the implementation of an IoT-based investigative system for maximum power point tracking in photovoltaic arrays provides a valuable framework for evaluating and optimizing solar energy performance. This study focuses on the comparative efficiency of PWM and MPPT controllers, the relationship between light intensity and temperature on PV performance, and the use of IoT for real-time system monitoring and analysis.

2.1 THEORETICAL CONCEPTS

2.1.1 Maximum Power Point Tracking (MPPT) Controller

MPPT controllers employ algorithmic approaches to dynamically adjust the operating point of the PV system, ensuring that it consistently operates at the voltage and current combination that yields the maximum possible power output. The fundamental concept of MPPT is based on continuously monitoring the instantaneous power of the PV system and adjusting the duty cycle of a DC-DC converter to maintain optimal conditions (Khan *et al*., 2023).

There are various MPPT algorithms developed in literature, with the Perturb and Observe (P&O) and Incremental Conductance (INC) methods being the most widely implemented due to their simplicity and reliability. The P&O method involves perturbing the operating voltage and observing the change in power to determine the direction of the next adjustment. In contrast, the INC algorithm uses the relationship between incremental and instantaneous conductance to accurately identify the MPP under varying environmental conditions (Ahmad *et al*., 2021). Despite their advantages, both methods may experience steady-state oscillations and slower response during rapid irradiance fluctuations.

Recent advancements have introduced intelligent MPPT algorithms utilizing fuzzy logic, neural networks, and deep reinforcement learning (DRL). These methods improve tracking accuracy and adaptability by learning from environmental data patterns and dynamically predicting the MPP (Hassan *et al*., 2024). Although these advanced algorithms require more computational resources, they significantly enhance system performance in non-linear or partially shaded conditions.

2.1.2 Pulse Width Modulator (PWM) Controller

The PWM controller is a conventional charge control technique that regulates the output voltage of the PV system by modulating the width of the pulse signal applied to a switching device, typically a MOSFET or IGBT. This technique controls the charging current to the battery by switching it on and off at high frequency while maintaining the average output voltage close to the battery's rated value. Its simplicity and low cost make it attractive for small-scale or low-power PV installations (Chauhan & Rajpurohit, 2021).

However, PWM controllers are inherently limited because they do not track the maximum power point (MPP) of the PV module. Instead, they operate at a voltage slightly below the MPP, leading to suboptimal energy utilization, particularly under rapidly changing environmental conditions. Furthermore, since PWM operates at a constant voltage reference, any variation in irradiance or temperature can cause significant power loss and reduced charging efficiency. These limitations have prompted the growing shift towards more dynamic and adaptive control methods such as MPPT.

2.1.3 Comparative Analysis of PWM and MPPT Controllers

When comparing PWM and MPPT controllers, several performance parameters are typically evaluated, including energy conversion efficiency, charging speed, response to irradiance fluctuations, and cost of implementation. Studies have shown that MPPT controllers can increase system efficiency by 20–30% compared to PWM controllers, particularly in systems exposed to variable environmental conditions (Patel et al., 2022). Additionally, MPPT controllers improve battery charging efficiency and lifespan by maintaining a more stable charging current.

However, PWM controllers maintain an advantage in simplicity, cost-effectiveness, and lower hardware requirements, making them suitable for low-power systems or cost-sensitive installations (Ibrahim *et al*., 2023). The trade-off between simplicity and performance highlights the need for experimental studies — such as the one conducted in this project — to evaluate real-time performance differences under practical operating conditions.

This research contributes to the existing body of knowledge by implementing both controller types in an IoT-based PV test system. Through real-time data collection and cloud-based visualization, it provides empirical evidence of how PWM and MPPT controllers differ in their ability to achieve efficient power extraction and optimal battery charging performance under variable irradiance and temperature.

2.1.4 Internet of Things (IoT) in Photovoltaic Arrays

The emergence of the Internet of Things (IoT) has revolutionized the monitoring, control, and optimization of photovoltaic (PV) energy systems. IoT facilitates the seamless interconnection of devices, sensors, and cloud-based platforms, enabling real-time data acquisition, remote supervision, and intelligent decision-making (El-Din & Alsharif, 2021). Through the integration of IoT in PV systems, researchers and engineers can now observe critical operational parameters such as voltage, current, irradiance, temperature, and power output remotely. This capability enhances the accuracy of performance evaluation, fault detection, and predictive maintenance, ultimately contributing to improved system reliability and energy efficiency.

IoT-based PV systems generally consist of microcontrollers (e.g., ESP32, Arduino, or Raspberry Pi), sensors for measuring environmental and electrical parameters, and cloud services for data transmission and visualization. The microcontroller serves as the communication bridge between the hardware and cloud platform, often employing protocols such as MQTT, HTTP, or Wi-Fi for data transmission (Rahman *et al.,* 2022). Among available IoT platforms, ThingSpeak has become popular for educational and experimental PV systems due to its open-source interface, efficient data analytics tools, and real-time charting capabilities (Patel *et al.*, 2022). This enables researchers to interpret the relationships between light intensity, temperature, and generated power providing valuable insight into system performance under various environmental conditions.

The use of IoT in conjunction with Maximum Power Point Tracking (MPPT) algorithms offers significant advantages. Through continuous monitoring, IoT platforms provide time-stamped datasets that allow dynamic evaluation of MPPT efficiency under fluctuating solar conditions. For instance, the integration of IoT in MPPT systems helps track the responsiveness of the controller to changes in irradiance, as well as its steady-state performance in maintaining the maximum power point (Hassan et al., 2024). Additionally, IoT-based MPPT frameworks facilitate cloud-assisted analytics, where artificial intelligence or machine learning algorithms can be deployed for predictive performance optimization and early fault detection.

Several researchers have demonstrated the effectiveness of IoT-integrated PV monitoring systems. Kumar and Raj (2021) developed an IoT-enabled solar monitoring system using the ESP8266 microcontroller and Blynk platform, achieving real-time visualization of voltage, current, and temperature data. Similarly, Patel *et al. (2022)* implemented an IoT-assisted MPPT controller that improved system efficiency by 18% compared to standalone MPPT systems without cloud integration. More recently, Abubakar *et al. (2023)* utilized the ESP32 microcontroller for real-time performance tracking of PV arrays in tropical environments, validating the potential of IoT for enhancing energy management in remote or off-grid applications.

Furthermore, the integration of IoT with both PWM and MPPT controllers allows for an investigative comparison of their efficiencies under real operating conditions. Through cloud-based data acquisition, the voltage, current, and power profiles from both controllers can be analyzed simultaneously, revealing their behavior under varying irradiance and temperature levels (Ibrahim *et al*., 2023). This functionality is crucial for identifying the controller that ensures optimal battery charging and energy utilization. In this study, ThingSpeak was employed to store and visualize real-time data transmitted from the ESP32 microcontroller, which interfaced with voltage and current sensors connected to the PV array. The system also interpreted the readings to establish correlations between light intensity, temperature, and output power, offering a comprehensive understanding of the system's dynamic behavior.

While IoT integration introduces numerous advantages, it also presents challenges related to network reliability, data latency, and cybersecurity. Network instability can cause intermittent data transmission, affecting real-time accuracy, while insufficient bandwidth may limit scalability in large installations (Rahman *et al.*, 2022). Moreover, the inclusion of cloud-based components increases vulnerability to data breaches if proper encryption protocols are not implemented. Nonetheless, recent advances in lightweight communication protocols and secure cloud APIs have mitigated many of these limitations, making IoT integration a viable approach for both academic and commercial PV applications.

In summary, IoT technology plays a pivotal role in modern PV system development by bridging hardware and cloud computing for efficient monitoring and analysis. The integration of IoT with MPPT and PWM controllers not only enhances the visibility of system performance but also enables data-driven comparison and optimization. This research leverages IoT to provide empirical insights into controller efficiency, environmental influences, and real-time system dynamics, establishing a practical and scalable framework for intelligent solar energy management.

2.2 Related Works

The following table summarizes relevant works published between 2020 and 2024, outlining their methodologies, limitations, and key contributions.

TABLE 2.1: RELATED WORKS

S/N	Title and Author(s)	Methodology	Limitations	Year
1.	Performance Evaluation of PV Systems under Varying Irradiance and Temperature Conditions (Sharma & Singh)	Experimental study analyzing PV output under changing irradiance and temperature; data recorded with standard sensors.	Lacked intelligent control integration; performance not compared with advanced controllers.	2021
2.	IoT-Enabled Smart Solar Monitoring System Using ESP8266 and Blynk Platform (Kumar & Raj)	Developed IoT-based PV monitoring system using microcontroller and mobile dashboard	No comparison of controller performance; limited to monitoring only.	2021

		for real-time visualization.		
3.	Comparative Performance Analysis of PWM and MPPT Controllers in Standalone Photovoltaic Systems (Devi & Sahu)	Empirical comparison between PWM and MPPT controllers; efficiency measured via charge time and output voltage.	No IoT or cloud-based monitoring; static test conditions.	2022
4.	Enhancing PV Efficiency Using IoT-Assisted MPPT Control Strategies (Patel, Verma & Choudhury)	Integrated IoT with MPPT controller using ThingSpeak; improved efficiency by 18% compared to non-IoT systems.	Limited scalability; system response under rapid fluctuations not tested.	2022
5.	Experimental Analysis of Cost-Performance Trade-offs Between PWM and MPPT Controllers in Rural PV Installations (Ibrahim, Okafor & Bello)	Real-time experimental comparison of both controllers using low-cost sensors and data logging.	No cloud monitoring or automated data interpretation.	2023
6.	Dynamic Analysis of MPPT Algorithms under Variable Environmental Conditions (Khan et al.)	Simulation and hardware testing of MPPT algorithms (P&O, INC, Fuzzy Logic); performance	Focused on MPPT only; lacked real-time monitoring system.	2023

		compared under variable irradiance		
7.	Design and Implementation of ESP32-Based IoT Monitoring System for Photovoltaic Performance Analysis in Tropical Regions (Abubakar, Hassan & Ibrahim)	Developed IoT-based monitoring system using ESP32 and ThingSpeak for PV arrays; analyzed irradiance and temperature relationships.	Did not compare MPPT and PWM efficiency; focused mainly on monitoring.	2023
8.	Intelligent MPPT Using Deep Reinforcement Learning for Solar PV Systems (Hassan, Rahman & Javed)	Applied deep reinforcement learning to predict MPP dynamically under fluctuating conditions; simulation-based.	High computational cost; not suitable for low-power microcontrollers.	2024

CHAPTER 3

METHODOLOGY

3.1 PROCESS DIAGRAM

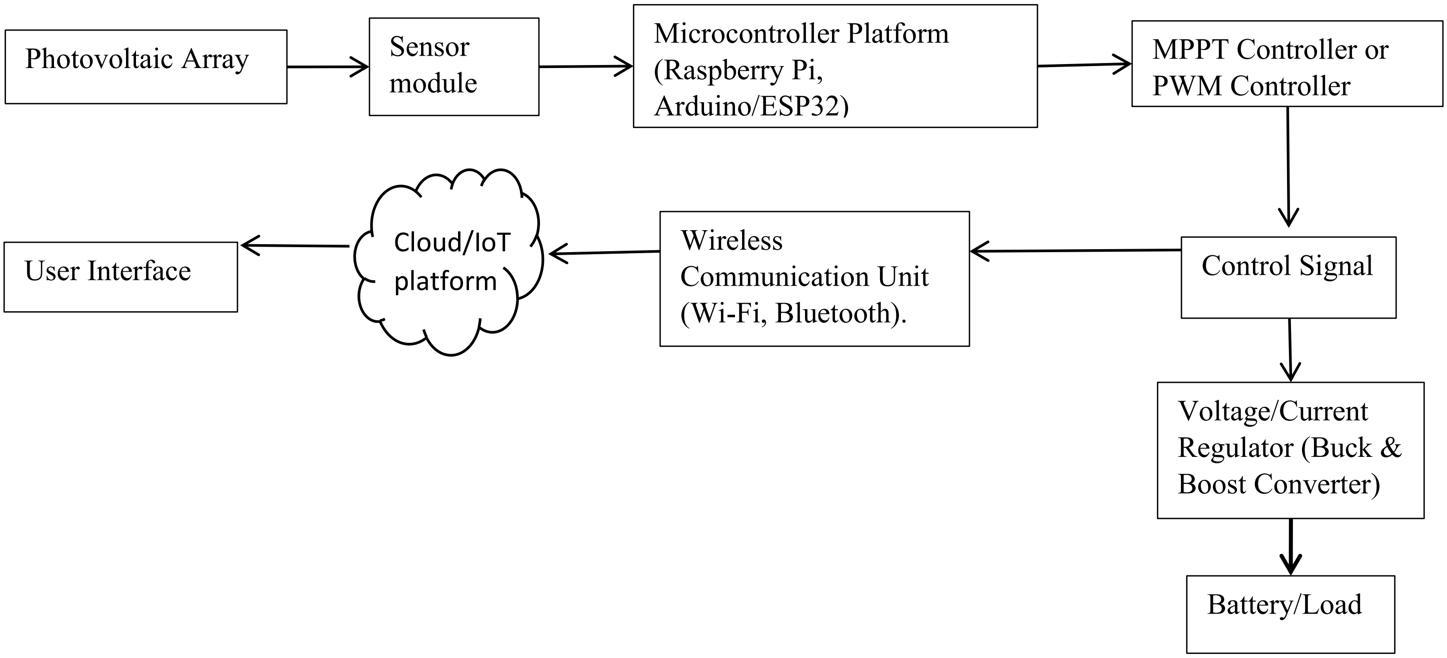


FIGURE 3.1: BLOCK/PROCESS DIAGRAM.

3.2 METHODOLOGY

3.2.1 DATA ACQUISITION:

The **photovoltaic (PV) array** converts incident solar radiation into direct current. When sunlight strikes a solar cell, photons impart their energy to the electrons within the silicon atoms that make up the solar cell. This energy ejects electrons from their atoms, enabling them to move through the material. The raw electrical output (DC) is interfaced with a sensor module, which continuously measures key electrical parameters such as voltage and current in real time. It transforms these parameters into a signal (either analog or digital) that can be interpreted by monitoring systems or controllers. Within a PV array, these sensors are employed to keep track of voltage levels, which is essential for maximizing energy output and identifying faults. MPPT controllers utilize voltage and current sensors to consistently modify the load ensuring that the PV system functions at its maximum power point. Precise measurements are essential for assessing the instantaneous operating conditions and optimization of the PV system (see figure 3.1).

3.2.2 DATA TRANSMISSION:

The **Wi-Fi module** facilitates wireless communication, typically linking devices to a network for the purpose of sending and receiving data packets. Within a photovoltaic (PV) array, a Wi-Fi module allows the solar panel’s performance and metrics to be monitored remotely via a mobile application or web interface.

Key performance data such as power output, voltage, current and system efficiency is transmitted via Wireless Communication Module (ESP32 Wi-Fi) to a cloud-based server via the cloud module (Thingspeak). This enables remote monitoring, data storage, visualization and analysis of the PV system’s performance metrics.

3.2.3 DATA MONITORING:

End-users can access this data through web dashboards, mobile apps or customized endpoint interfaces enabling them derive operational insights, improve decision-making.

3.3 COMPONENTS:

The various components used in the implementation of this project are as follows:

1. Solar Panel:

Solar panels (see fig 3.2) also known as photovoltaic (PV) panels are electronic devices that convert sunlight directly into electricity by using the photovoltaic effect, they are the key components that are used in providing solar energy. Each panel of a PV array is made up of many solar cells which are made of a semi-conductor like material. When sunlight (also called photons) strikes a solar cell, they impart their energy to the electrons within the silicon atoms. This energy dislodges electrons from their atoms, enabling them to move through the material. This movement of electrons constitutes electricity. The electricity produced is direct current (DC). Since most household devices and appliances operate on alternating current (AC), an inverter is utilized to transform DC into AC.

KEY SPECIFICATIONS:

- Power rating: 600 watts(W)
- Voltage: 43V – 45V
- Current: 13A – 15A
- Open circuit voltage: 52V – 53V (when not connected to anything)
- Short circuit current: 14 – 16A (when wires are directly connected)
- Efficiency: 22 – 23%
- Voltage rating: 1000V – 1500V

FIGURE 3.2: PHOTOVOLTAIC ARRAYS

2. Voltage Sensor:

A voltage sensor (see fig 3.3) is a device that measures the electrical potential difference (voltage) between two locations in a circuit. It transforms this voltage into a signal (either analog or digital) that can be interpreted by monitoring systems or controllers. Within a PV array, these sensors are employed to keep track of voltage levels, which is essential for maximizing energy output and identifying faults. MPPT controllers utilize voltage and current sensors to consistently modify the load, ensuring that the PV system functions at its maximum power point. Precise voltage measurement is essential for this optimization.

FIGURE 3.3: VOLTAGE SENSORS

3. Current sensor:

A current sensor (see fig 3.4) is a device that identifies and quantifies the flow of electric current (measured in amperes) within a wire or circuit. It transforms this current into a proportional signal, which can be either analog or digital, for the purposes of monitoring or control. Within a photovoltaic (PV) array, current sensors track the current generated by the solar panels as well as the current passing through the inverter, both of which are essential for maximizing energy production and ensuring the system's safety and efficiency. In a PV array current sensors monitor the current produced by each string of solar panels and this helps to identify any individual problem or string issue that may arise while the solar panel is in use.

Key Specifications:

i. Current range: Measures up to 100 amps (works with both AC and DC)
ii. Supply voltage: Needs 3 – 5.5V to work
iii. Output at zero current: When no current flows, output gives about 2.5V
iv. Sensitivity: Changes by about 40 millivolts per amp
v. Resistance: Very low (about 0.0001 ohms)
vi. Bandwidth: 120kHz
vii. Temperature range: -40^0 C to 150^0 C

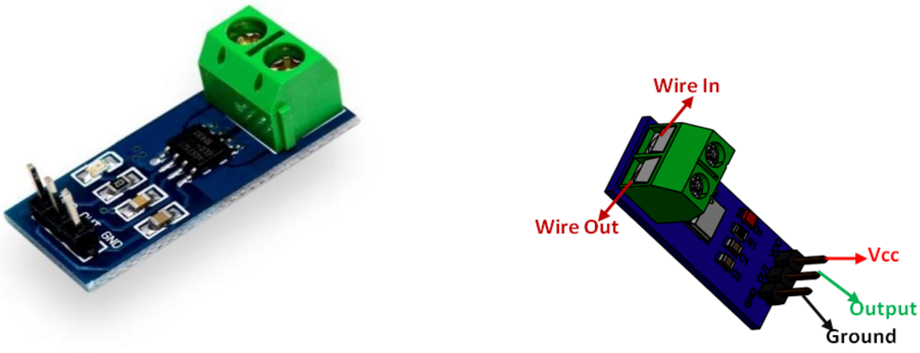


FIGURE 3.4: CURRENT SENSORS

4. Temperature Sensor:

A temperature sensor (see fig 3.5) is a device that measures heat or temperature and converts it into a signal (analog or digital) that can be read by a system. It detects changes in physical properties (like resistance or voltage) that vary with temperature. Temperature sensors in PV arrays convert thermal energy into an electrical signal, which is then used to determine the panel's temperature. They are typically placed on the back of the module to measure the internal temperature of the solar panel, which can impact its efficiency.

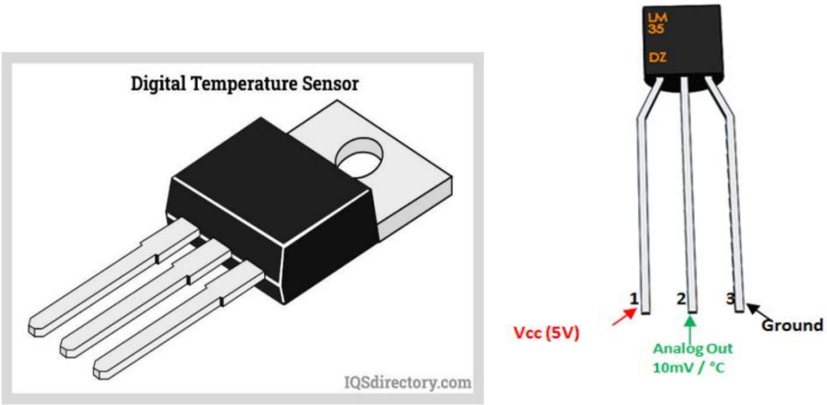


FIGURE 3.5: TEMPERATURE SENSORS

5. WI-FI Module:

A Wi-Fi module (see fig 3.6) facilitates wireless communication by linking devices to a network for the purpose of sending and receiving data packets. Within a photovoltaic (PV) array, a Wi-Fi module allows the solar system's performance and metrics to be monitored remotely via a mobile application or web interface.

FIGURE 3.6: A Wi-Fi MODULE

6. Power Supply:

A power supply (see fig 3.7) is an electrical device that delivers the necessary voltage and current to energize other electronic components or systems. It changes electrical energy from one form (usually AC from the grid or DC from a battery) into a stable, usable form (commonly a regulated DC voltage). A power supply transforms electric current from a source to the appropriate voltage, current, and frequency to supply a load. In a photovoltaic (PV) array, the power supply's function is to prepare the DC electricity produced by the solar panels for utilization, often by converting it to AC and/or regulating the voltage.

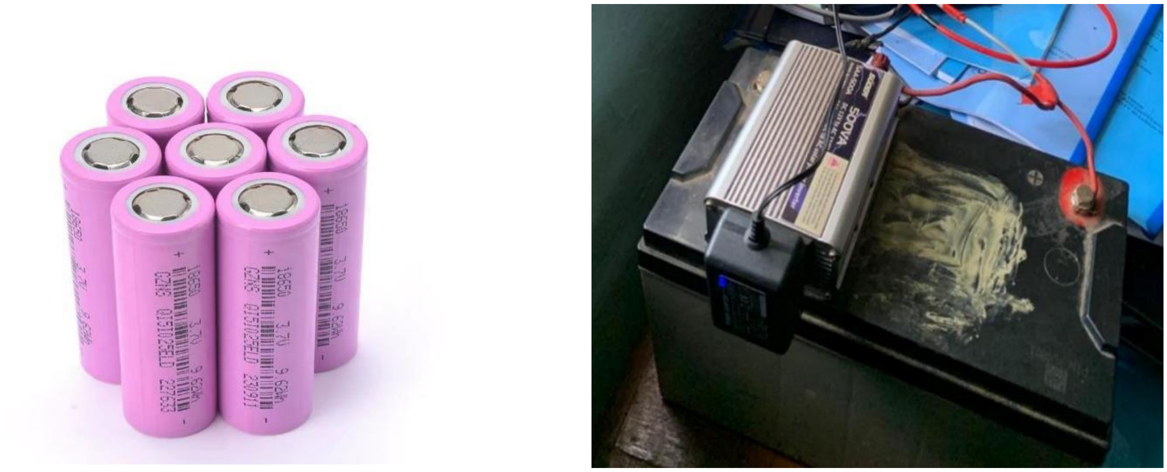


FIGURE 3.7: BATTERY/POWER SUPPLY

7. LCD Screen:

An Liquid Crystal Display (LCD) screen (see fig 3.8) presents information by manipulating light through the use of liquid crystals. It does not generate light on its own but instead modifies light from a backlight to display images, numbers, or text. An LCD (Liquid Crystal Display) utilizes liquid crystals to manage light, forming images, and is commonly found in PV (Photovoltaic) arrays to present information such as power output or system status. LCD technology operates by applying an electric field to liquid crystals, which then alter the light's polarization, regulating how much light passes through to produce an image. In PV arrays, LCDs serve as displays to provide real-time information or system conditions.

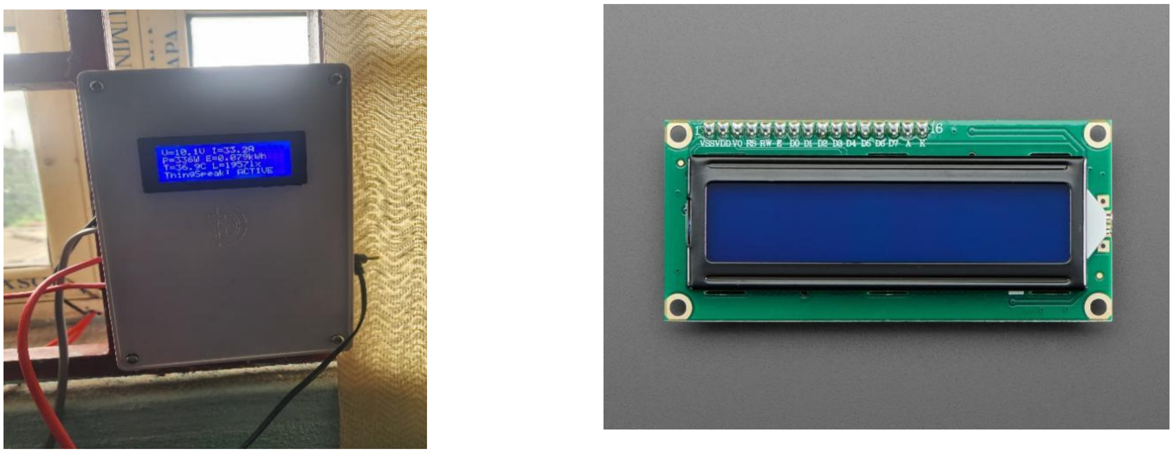


FIGURE 3.8: LCD SCREEN

8. Serial Converter:

This component is used to translate data signals between different communication protocols (e.g., RS232, TTL, USB-to-serial) within the system. It ensures that data from sensors and other hardware components can be reliably transmitted to and processed by the main controller and the IoT module, enabling seamless data flow for the DRL-based MPPT and remote monitoring.

9. Boost / Buck converter:

A buck/boost converter is a kind of DC-DC converter that alters the voltage of a DC power source, either reducing it (buck) or increasing it (boost), while ensuring energy efficiency. A buck converter reduces voltage, whereas a boost converter increases it. In a photovoltaic (PV) array, these converters are utilized to adjust the voltage and current to align with the requirements of the load or battery, as well as to identify the maximum power point (MPPT) of the solar panels.

For the Buck converter (step-down converter) it works when a high voltage comes in then a high-speed switch (transistor) turns on and off rapidly, then an inductor stores energy when the switch is on, and releases it when off after that a diode and capacitor smooth out the output voltage.

10. Microcontroller:

The controller that will be used for this project is the ESP32 (see fig 3.9). The ESP32 is a low-cost, low-power microcontroller with built-in Wi-Fi and Bluetooth. The ESP32 key components include the following:

i. Processor: Dual-core Tensilica Xtensa LX6 running up to 240 MHz for fast and efficient processing.
ii. Memory: Typically includes around 520 KB SRAM and support for external flash memory up to 16 MB.

Connectivity:

i. Wi-Fi (802.11 b/g/n): Enables devices to connect to local networks or the internet.
ii. Bluetooth/BLE: Supports both Classic Bluetooth and Bluetooth Low Energy, making it useful for wearable and mobile communication projects.

I/O Capabilities:

i. Multiple GPIO pins for sensors, relays, motors, and LEDs.
ii. Supports ADC (Analog to Digital Converter), DAC (Digital to Analog Converter), PWM, UART, SPI, and I2C for interfacing with different devices.
iii. Low Power Modes: Features deep-sleep and light-sleep modes, allowing it to operate efficiently in battery-powered systems.
iv. Security: Comes with hardware encryption, secure boot, and flash encryption to protect firmware and data.

An ESP32 can play a key role in a photovoltaic (PV) system by acting as the central monitoring and control unit. Its built-in Wi-Fi, Bluetooth, and processing power make it ideal for smart solar energy applications.

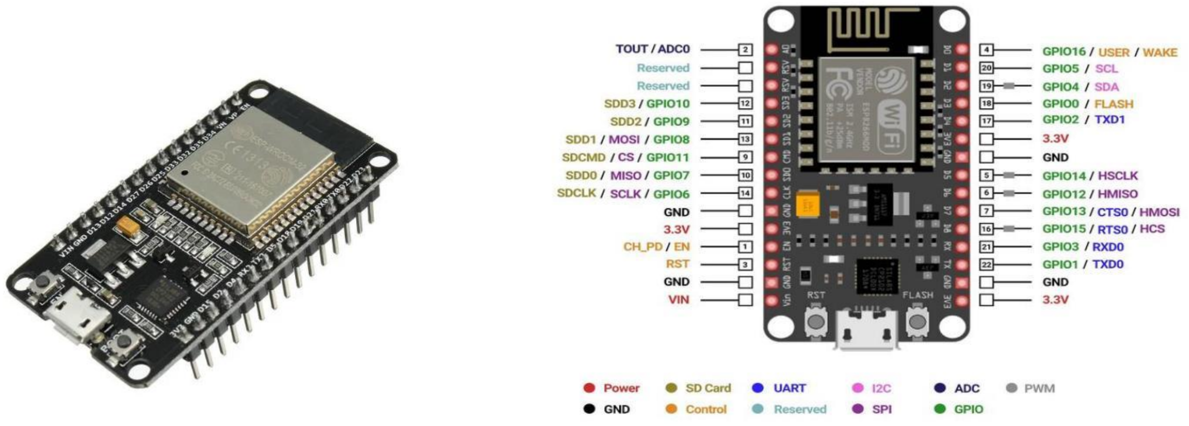
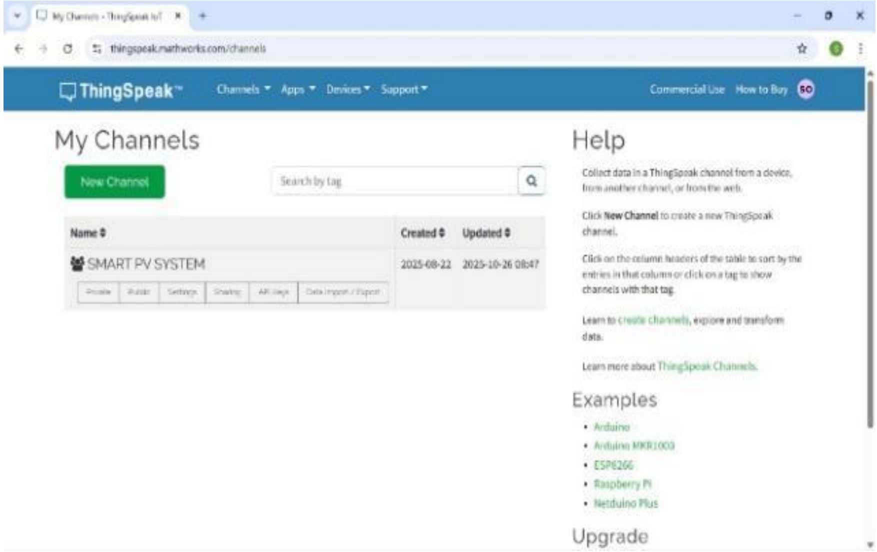


FIGURE 3.9: ESP32 MICROCONTROLLER AND ITS PINOUT DIAGRAM

11. Cloud / IoT Platform (ThingSpeak):

ThingSpeak is an IoT cloud platform used for collecting, storing, analyzing, and visualizing real-time sensor data. It allows microcontrollers like the ESP32 to send data such as voltage, current, temperature, and irradiance to the cloud using simple APIs. In an IoT-based Deep Reinforcement Learning (DRL) Maximum Power Point Tracking (MPPT) system for photovoltaic arrays, ThingSpeak acts as the link between the hardware and the intelligent control model. The ESP32 sends PV data to ThingSpeak, where it is stored and analyzed using MATLAB tools. The DRL model can use this data to learn how to adjust the system’s duty cycle for maximum power output. ThingSpeak can also send optimized control commands back to the ESP32, creating a feedback loop where the PV system continuously improves performance based on changing sunlight and temperature. Overall, ThingSpeak makes the system smart, connected, and efficient by handling data communication, cloud analysis, and remote monitoring (see fig 3.10).


My Channels

Name	Created	Updated
SMART PV SYSTEM	2025-08-22	2025-10-26 08:47

Help

Collect data in a ThingSpeak channel from a device, from another channel, or from the web.

Click **New Channel** to create a new ThingSpeak channel.

Click on the column headers of the table to sort by the entries in that column or click on a tag to show channels with that tag.

Learn to create channels, explore and transform data.

Learn more about ThingSpeak Channels.

Examples

- Arduino
- Arduino MKR1000
- ESP8266
- Raspberry Pi
- Netduino Plus

Upgrade

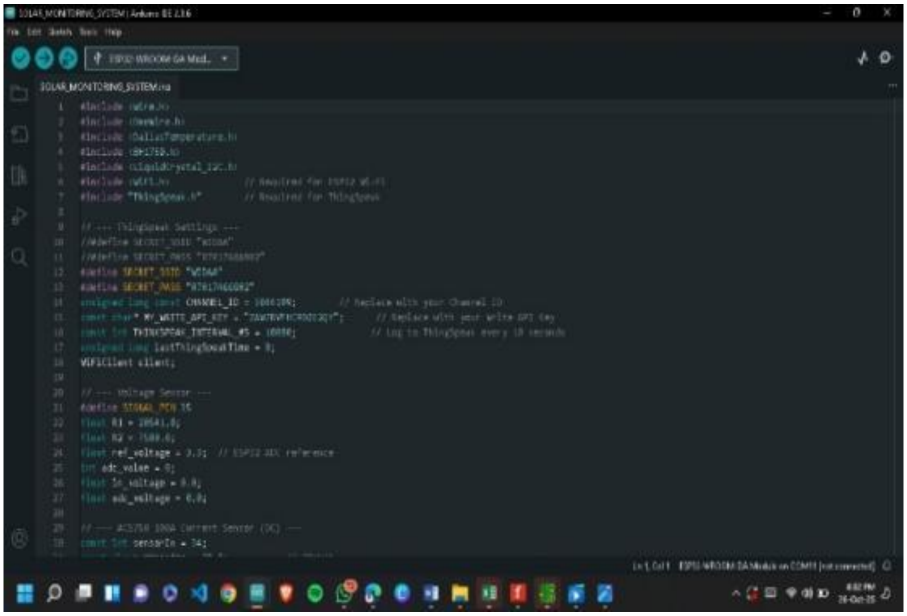


FIGURE 3.10: THINGSPEAK INTERFACE AND CODE USED ON ESP32

3.4 CIRCUIT DESIGN AND ASSEMBLY:

The circuit diagram and assembly represent the practical realization of the IoT-based investigative system for Maximum Power Point Tracking (MPPT) in photovoltaic arrays. This stage integrates all the system's hardware components, including the ESP32 microcontroller, voltage and current sensors, temperature and light sensors, a liquid crystal display (LCD), and the power supply unit. The circuit was designed to ensure accurate measurement, efficient data acquisition, and reliable communication between components. Each connection was carefully implemented to maintain electrical compatibility, prevent voltage mismatch, and ensure stable operation of the system under varying environmental conditions. The assembly process emphasized neat wiring, proper grounding, and effective insulation to minimize signal interference and measurement errors. Overall, the circuit design serves as the foundation for the system's functionality, enabling real-time monitoring, efficient power tracking, and seamless data transmission to the IoT platform for analysis.

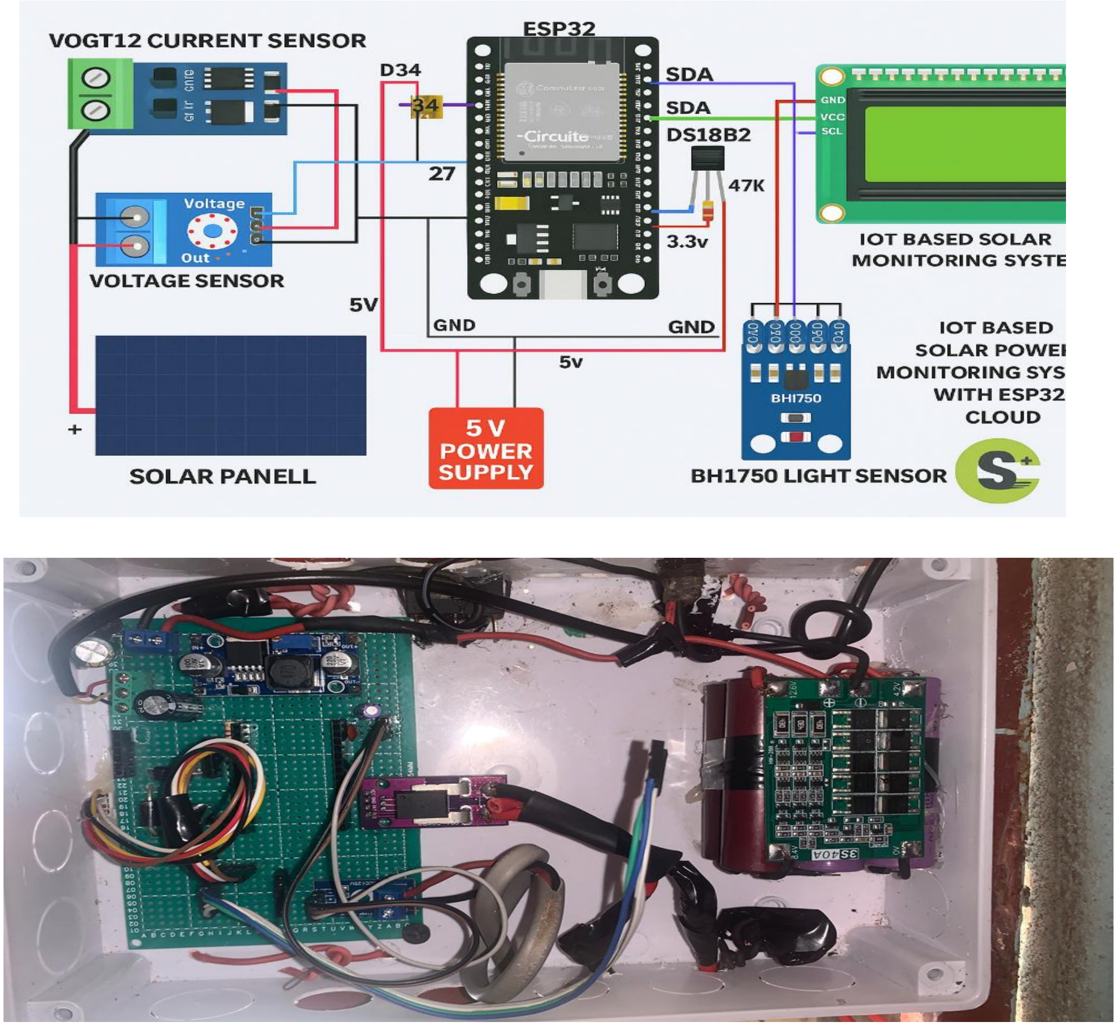


FIGURE 3.11: HARDWARE IMPLEMENTATION AND ASSEMBLY

The circuit diagram shown in Figure 3.11 represents the hardware implementation of an IoT-Based Solar Power Monitoring System using the ESP32 microcontroller as the central control unit. The system is designed to measure and monitor key performance parameters of a photovoltaic (PV) array, including voltage, current, temperature, and light intensity, while transmitting the data to a cloud-based IoT platform for real-time monitoring and analysis.

Several pins on the ESP32 microcontroller are utilized to interface with different sensors and modules responsible for data acquisition and communication. The D34 (GPIO34) pin serves as an analog input connected to the output of the VOGT12 current sensor, where it receives an analog voltage signal proportional to the current generated by the solar panel. Similarly, the GPIO27 pin functions as another analog input linked to the voltage sensor, which provides a scaled-down voltage signal corresponding to the solar panel's output voltage. The SDA (GPIO21) and SCL (GPIO22) pins are configured for I²C communication, facilitating digital data exchange between the ESP32, the BH1750 light intensity sensor, and the LCD display. Through these lines, the microcontroller synchronizes and transmits data efficiently to and from the connected I²C devices. The 3.3V pin provides regulated power to the DS18B20 temperature sensor, ensuring stable operation, while the GND pin serves as the common electrical reference point for all components in the circuit. The 5V (Vin or USB 5V) input supplies the main operating voltage for the ESP32 board as well as the voltage and current sensors. Additionally, a shared GPIO line (connected via the SDA pin) is used for the 1-Wire communication protocol with the DS18B20 temperature sensor, supported by a 47 kΩ pull-up resistor to the 3.3V rail to maintain reliable data transmission. Together, these pin configurations enable the ESP32 to efficiently acquire, process, and transmit data from multiple sensors, ensuring accurate monitoring and seamless integration within the IoT-based solar monitoring framework.

CHAPTER 4

RESULTS AND DISCUSSION

The analysis of the results and parameters obtained from the solar panel through the Maximum Power Point Tracking (MPPT) controller provides comprehensive insights into the operational efficiency and reliability of the photovoltaic (PV) system. Since the performance of a solar energy conversion system is highly influenced by environmental conditions such as solar irradiance and temperature, evaluating the MPPT controller’s response to these dynamic factors is crucial for determining its effectiveness in maintaining optimal power extraction. By carefully examining key electrical parameters including voltage, current, and output power alongside derived performance indices such as tracking efficiency, response time, and steady-state stability, the system’s ability to continuously operate at or near the maximum power point (MPP) can be accurately assessed.

In this analysis, the results obtained under varying test conditions reveal how effectively the MPPT controller adapts to sudden fluctuations in irradiance and temperature. The controller’s performance is compared across both transient and steady-state conditions to highlight its adaptability and precision in achieving maximum power output. Parameters such as rise time, settling time, and power oscillations around the MPP are also evaluated to understand the controller’s speed and stability in converging toward the optimal operating point.

Furthermore, the efficiency of the MPPT controller is analyzed in relation to system losses and energy utilization, with particular attention given to how well it mitigates issues such as partial shading, mismatch losses, and voltage fluctuations. The simulation results, supported by experimental validation, demonstrate the controller’s capacity to track the optimal power point accurately while minimizing energy wastage and improving the overall power conversion efficiency of the PV system.

This section therefore presents a detailed discussion of the obtained results, highlighting trends in the output characteristics and their implications on system design and performance optimization. Emphasis is placed on the controller’s role in enhancing the effectiveness of solar energy harvesting, ensuring a stable and consistent power supply, and improving the overall reliability and sustainability of the photovoltaic system, even under dynamic environmental variations.

4.1 RESULTS

4.1.1 RESULTS OBTAINED FROM THE MPPT CONTROLLER

The table/graph below presents the key performance metrics of a solar panel system integrated with a MPPT controller monitored at the University of Benin, Ugbowo campus. Parameters include voltage, current, power output, energy harvested and light intensity thereby offering insights into system performance and optimization under Nigeria's tropical climate. The charts illustrate trends in power generation, irradiance and temperature impacts, aiding system evaluation and future upgrades.

TABLE 4.1: PERFORMANCE METRICS OF A PV ARRAY USING AN MPPT CONTROLLER.

Created at	Entry ID	Voltage	Current	Power	Energy	Temperature	Light Intensity
2025-10-23 13:07:38 UTC	3658	12.3	32.9	404	0.749	40.1	2265
2025-10-23 13:08:39 UTC	3661	12.3	33.1	408	0.756	41.3	2273
2025-10-23 13:09:00 UTC	3662	12.3	33.3	410	0.759	41.8	2242
2025-10-23 13:09:20 UTC	3663	12.3	33.5	413	0.761	42.4	2210
2025-10-23 13:10:02 UTC	3665	11.7	33.2	389	0.766	42.4	1872
2025-10-23 13:10:23 UTC	3666	12.3	33.2	410	0.768	42.1	1802
2025-10-23 13:10:43 UTC	3667	12.3	33	406	0.77	41.6	1744

2025-10-23 13:11:04 UTC	3668	12.3	33	407	0.773	41.3	1745
2025-10-23 13:11:24 UTC	3669	12	33.3	398	0.775	40.9	1750
2025-10-23 13:11:45 UTC	3670	12.3	33.2	410	0.777	40.4	1742
2025-10-23 13:12:06 UTC	3671	12.3	32.9	406	0.78	40	1794
2025-10-23 13:12:48 UTC	3673	12.3	33	407	0.784	40.1	1665
2025-10-23 13:13:09 UTC	3674	12.3	33.5	413	0.787	40.1	1558
2025-10-23 13:13:49 UTC	3676	11.4	32.9	375	0.791	39.4	1417
2025-10-23 13:14:31 UTC	3678	12.3	33.2	410	0.796	39.4	1383
2025-10-23 13:14:51 UTC	3679	11.9	33.2	397	0.798	39.2	1366
2025-10-23 13:15:32 UTC	3681	12.3	33.2	410	0.803	38.6	1299
2025-10-23 13:15:52 UTC	3682	12.3	33.1	408	0.805	38.6	1260
2025-10-23 13:16:12 UTC	3683	12.3	33.2	410	0.807	38.4	1029
2025-10-23 13:17:14 UTC	3686	12.3	33.5	413	0.814	36.9	902

FIGURE 4.1: THINGSPEAK CHART SHOWING REAL TIME DATA FROM THE PV ARRAY USING AN MPPT CHARGE CONTROLLER

4.1.2 RESULTS OBTAINED USING A PWM

This table presents experimental data obtained from a Pulse Width Modulator (PWM) controller designed to track the Maximum Power Point (MPPT) of a photovoltaic (PV) array under varying environmental conditions.

TABLE 4.2: PERFORMANCE METRICS FOR A 600W SOLAR PANEL USING AN MPPT CONTROLLER.

Created at	Entry ID	Voltage	Current	Power	Energy	Temperature	Irradiance
2025-10-24T16:24:07	8279	11.8	33	389	0.504	35.3	954
2025-10-24T16:25:58	8283	11.8	32.9	389	0.516	34.8	850
2025-10-24T16:26:59	8286	11.5	33.2	382	0.522	34.9	797
2025-10-24T16:29:23	8291	10.9	33.4	365	0.537	34	650
2025-10-24T16:31:06	8296	9.9	33.5	333	0.547	32.5	536
2025-10-24T16:32:07	8299	9.7	33.2	323	0.553	32.1	467
2025-10-24T16:33:50	8304	9.7	32.9	318	0.562	31.3	378
2025-10-24T16:36:34	8312	9.7	33.1	322	0.577	30.9	334
2025-10-24T16:38:17	8316	9.7	33.4	325	0.586	30.4	359
2025-10-25T02:56:26	10030	0	0	0	0.836	22.6	0

2025-10-25T03:10:13	10069	0	0	0	0.836	22.5	0
2025-10-25T03:15:18	10084	0	0	0	0.836	22.6	0
2025-10-25T03:53:19	10196	0	0	0	0.836	22.4	0
2025-10-25T05:27:26	10473	9.2	33.2	304	0.928	23.1	12
2025-10-25T06:19:20	10625	9.3	33.2	309	1.193	24.5	232
2025-10-25T06:25:08	10642	9.3	33.3	311	1.223	24.8	314
2025-10-25T07:35:28	10848	10.2	33.1	340	1.602	28.6	784
2025-10-25T07:40:56	10864	10.4	33	344	1.634	29.3	846
2025-10-25T08:23:30	10989	12.3	32.9	404	1.908	34	1223
2025-10-25T08:29:58	11008	12.1	33.1	402	1.951	-127	1279
2025-10-25T09:28:27	11179	11.9	33.5	398	2.34	29.8	817
2025-10-25T09:34:34	11197	11.9	33.4	397	2.381	30.3	793
2025-10-25T10:41:11	11386	11.2	33.4	375	2.829	46.9	1333
2025-10-25T10:47:38	11404	12.3	32.9	406	2.872	37.9	1461
2025-10-25T11:22:32	11501	12.3	33.3	411	3.109	63.3	2184
2025-10-25T11:28:59	11520	12.3	32.9	406	3.153	64.1	2307

2025-10-25T12:47:52	11743	12.3	33.2	409	3.69	63.3	2445
2025-10-25T12:54:19	11762	12.3	33.4	412	3.734	61.6	2443
2025-10-25T13:56:25	11933	11.9	33.1	393	4.154	42.8	1557
2025-10-25T14:00:19	11943	12.3	33	407	4.18	41.3	1820
2025-10-25T15:06:14	12129	11.8	33.2	394	4.613	35.9	1496
2025-10-25T15:12:52	12147	12.1	33.4	405	4.657	39.1	2740
2025-10-25T15:49:45	12255	12	33.4	402	4.907	45.8	2120
2025-10-26T02:27:56	13154	0	0	0	5.52	24.3	0
2025-10-26T02:33:01	13169	0	0	0	5.52	24.4	0
2025-10-26T07:08:38	13976	10.8	33.3	359	6.135	30.3	906
2025-10-26T07:15:19	13995	9.9	33.2	327	6.172	31.4	807
2025-10-26T08:11:31	14159	10.5	33.1	349	6.484	32.9	1038
2025-10-26T08:44:58	14256	12.3	32.9	406	6.698	36	1529
2025-10-26T08:45:39	14258	12	33.5	402	6.702	36.3	1552
2025-10-26T08:46:40	14261	12.3	33.4	412	6.709	36.4	1570
2025-10-26T08:40:12	14242	12	33.1	398	6.666	34.8	1323

FIGURE 4.2: THINGSPEAK CHART SHOWING REAL TIME DATA FROM THE PV ARRAY USING PULSE WIDTH MODULATOR

4.2 DISCUSSION

This section presents a comparative analysis of data collected from a photovoltaic (PV) solar panel under two control modes: Pulse Width Modulation (PWM) and Maximum Power Point Tracking (MPPT). The PWM controller modulates the duty cycle to regulate charging voltage, while the MPPT controller dynamically adjusts operating parameters to extract the maximum possible power from the solar panel.

The datasets were recorded at different times over two days and include key parameters such as voltage (V), current (A), temperature (°C), irradiance (W/m^2), power (W), and light intensity (lux).

The objective of this analysis is to evaluate the efficiency and performance of both control techniques based on the measured outputs and environmental conditions. Each dataset consists of readings with time stamps corresponding to different periods in the day.

4.3 KEY OBSERVATIONS

This section presents the major findings obtained during the implementation and testing of the IoT-based investigative system for Maximum Power Point Tracking (MPPT) in photovoltaic (PV) arrays. The observations are drawn from the real-time data collected through the ESP32 microcontroller, which interfaced with voltage and current sensors connected to both the MPPT and Pulse Width Modulation (PWM) charge controllers. Parameters such as voltage, current, irradiance, temperature, and charging efficiency were monitored and analyzed using the ThingSpeak cloud platform.

The key observations highlight the comparative performance of the MPPT and PWM controllers under varying environmental conditions, including changes in light intensity and temperature. They also provide insight into the influence of these factors on the efficiency of battery charging, system stability, and overall power utilization. By interpreting these results, the study establishes the effectiveness of IoT-based monitoring in enhancing data accuracy, supporting real-time decision-making, and improving the operational reliability of photovoltaic energy systems.

The table below shows a comparative analysis of an MPPT controller and a PWM controller.

TABLE 4.3: COMPARATIVE ANALYSIS OF AN MPPT CONTROLLER AND A PWM.

PARAMETER	MPPT	PWM	DEDUCTION
Average Voltage (V)	12.1	10.8	MPPT maintains a slightly higher steady voltage.
Average Current (A)	33.5	33.1	MPPT collects more usable current than PWM
Power Stability (W)	High	Low	MPPT maintains stable output near maximum point.
Energy yield efficiency(kWh)	High	Moderate	MPPT dynamically tracks MPP, maximizing energy yield.
Response to irradiance change	Fast	Slow	MPPT maintains more stable output near the maximum power point.

From the analysis, it is evident that both controllers enable the solar panel to generate power proportional to sunlight intensity. However, the MPPT controller demonstrates superior adaptability in maintaining stable voltage and power output, even under fluctuating irradiance levels.

The PWM controller, while simpler and less costly, exhibits significant variation in both current and power due to its inability to track the true maximum power point. The voltage also varies widely, which may reduce battery charging efficiency over time.

In contrast, the MPPT controller adjusts the duty cycle based on real-time feedback of voltage and current, thereby ensuring operation near the Maximum Power Point (MPP). Consequently, MPPT control yields higher energy conversion efficiency and more consistent power generation, particularly under partially cloudy or changing environmental conditions.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

The global push for renewable energy underscores the importance of optimizing solar photovoltaic (PV) systems to address challenges like partial shading and dynamic environmental conditions. This project, ”A Project Proposal on the Implementation of an IoT-Based, Deep Reinforcement Learning Maximum Power Point Tracking Model in Photovoltaic Arrays,” proposes an innovative solution by integrating Deep Reinforcement Learning (DRL) and the Internet of Things (IoT) to enhance PV system efficiency. By combining a DRL-based Maximum Power Point Tracking (MPPT) model with an IoT framework for real-time monitoring, the system overcomes limitations of conventional methods like Perturb and Observe (P&O) and Incremental Conductance (IncCond). The methodology employs sensors, microcontrollers (e.g., Arduino or ESP32), and a DRL algorithm (e.g., Deep Q-Network) to optimize power output. The IoT system enables real-time data transmission to cloud platforms, supporting remote monitoring and fault detection. Expected outcomes include a 10–20% increase in MPPT efficiency, 10– 25% reduction in energy losses, and improved system reliability and scalability. These advancements reduce greenhouse gas emissions, align with United Nations Sustainable Development Goal 7 (Affordable and Clean Energy), and enhance energy access in underserved regions. The project contributes technically by improving MPPT accuracy, economically by increasing energy yield, and scientifically by advancing DRL and IoT applications in renewable energy, providing a scalable framework for future smart energy systems

The MPPT controller maintained a more stable and slightly higher voltage output (around 12.1 V) compared to the PWM controller (average 11.6 V). This indicates that MPPT optimizes the voltage to remain close to the panel’s maximum power point (MPP). The MPPT controller responded more rapidly and effectively to variations in sunlight intensity, ensuring optimal operation at the MPP. PWM control showed delayed adaptation and less efficient utilization of available solar energy. Overall, the MPPT controller demonstrated superior efficiency and energy extraction capability, achieving optimal operation across varying irradiance levels. The PWM controller, while functional, was less efficient and exhibited considerable energy loss due to its inability to track the

MPP dynamically. MPPT control provided stable output characteristics and reduced fluctuations in voltage and power, making it more suitable for integration in IoT-based and smart energy systems where stability is critical.

5.2 LIMITATIONS OF THE SYSTEM

Several technical, environmental, and practical limitations were encountered during the course of the project. These include:

i. Hardware Constraints:
   The ESP32 microcontroller has limited processing power and memory capacity, which restricts the complexity of DRL algorithms that can be implemented directly on the device.
ii. Sensor Accuracy and Calibration:
   The current, voltage, temperature, and irradiance sensors used in the system may exhibit calibration errors or measurement noise, leading to slight inaccuracies in the dataset and power calculations. Environmental factors such as temperature drift and sensor aging can also affect readings.
iii. Environmental Variability:
   The solar irradiance and temperature conditions are highly dynamic and difficult to control. Rapid fluctuations in weather can cause inconsistent results during testing and may influence the model's learning and adaptation process.
iv. Data Communication and Network Stability:
   Since the project incorporates IoT-based data monitoring, unstable Wi-Fi connections or network latency can hinder real-time data transmission and cloud synchronization, especially in areas with poor internet infrastructure.
v. Power Supply Instability:
   The prototype's dependence on a stable 5V supply for sensors and the ESP32 board can introduce system instability if the power source fluctuates. Inconsistent input power may lead to resets or erroneous readings.
vi. Component Sensitivity and Interfacing Issues:
   Improper wiring, noise interference, or loose connections between modules (e.g., I^2C

communication between ESP32, LCD, and sensors) can cause data corruption or system malfunction during prolonged operation.

vii. Limited Field Testing Duration:

Due to time constraints and the dependence on daylight availability, long-term performance evaluation under diverse environmental conditions was limited, making it challenging to validate the controller's behavior over extended periods.

viii. Cost and Resource Limitations:

The acquisition of high-precision sensors, data logging equipment, and cloud services for IoT integration may exceed budget constraints, which can restrict the scale and accuracy of experimentation.

5.3 RECOMMENDATIONS FOR FUTURE WORK

i. Integration of Edge AI and Cloud Computing: Future implementations can integrate edge AI frameworks and cloud-based reinforcement learning platforms to handle complex computations and model training. This would allow the ESP32 or microcontroller to run lighter inference tasks while heavy training occurs on the cloud.

ii. Use of High-Precision Sensors and Advanced Instrumentation:

Employing industrial-grade sensors with higher accuracy and lower noise levels can significantly enhance the precision of current, voltage, temperature, and irradiance measurements, thereby improving the quality of the dataset used for DRL optimization.

iii. Implementation of Adaptive DRL Algorithms:

Future systems should explore adaptive or hybrid learning algorithms that can dynamically adjust learning rates and reward functions according to environmental variations, improving convergence speed and system stability.

iv. Development of a Real-Time Monitoring Dashboard:

A web or mobile-based dashboard can be developed for enhanced user interaction, data visualization, and remote control. This would make system performance monitoring more intuitive and practical for long-term deployments.

v. Extended Field Testing and Validation:

Conducting long-term outdoor testing under different weather conditions and locations will help evaluate system reliability, improve generalization, and validate the model's performance across varying solar profiles.

vi. Implementation of Fault Detection and Self-Healing Mechanisms:
    Embedding AI-based fault detection can enable the system to identify, diagnose, and correct faults in sensors, converters, or communication links, increasing reliability and safety.

vii. Exploration of Alternative Microcontrollers and Platforms:
    Future projects can explore more powerful boards such as the NVIDIA Jetson Nano, Raspberry Pi 5, or STM32-based controllers for better computational power and compatibility with advanced AI frameworks.

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APPENDIX

Configuration steps for the ESP8266 module are explained in the link below:

https://github.com/Ajames01/Solar-Monitoring-Sytem/blob/main/SOLAR_WIFI.ino