09.30.2025

JOURNAL OF

Engineering Research & Development (JERD) Vol. 9 No. 5

DEVELOPMENT OF A WIRELESS MONITORING AND CONTROL COMMUNICATION SYSTEM FOR A 4.2KVA 24 V SMART SOLAR POWERED SYSTEM

OLUWALEKE A. A.; & AJIBOYE G. A.

Department of Electrical and Information Engineering, Achievers University, Owo, Ondo State.

Corresponding Author: oluwaleke.aa@achievers.edu.ng

DOI Link: https://doi.org/10.70382/bejerd.v9i5.012

ABSTRACT

The development of a Wi-Fi-based wireless communication and control system for a 4.2kVA 24V smart solar-powered system is an important contribution to renewable energy technology. With global solar capacity jumping by over 22% in 2023, efficient and cost-effective management solutions are increasingly vital. This paper addresses this need, providing a practical innovation for mid-capacity solar systems with technical, economic, and social implications. In addition, it enhances smart solar systems by incorporating Wi-Fi into a 4.2kVA 24V setup, moving beyond traditional manual or wired methods to provide real-time monitoring and remote control, thus improving reliability. The aim of this paper is to develops and simulates a wireless monitoring and control system for a 4.2 kVA 24V smart solar-powered setup with the use of Wi-Fi technology. However, the primary objectives of this paper will be to achieve the following: to design a wireless communication system for a smart solar system,

Introduction:

As we navigate changes within an ever-changing world, one thing is certain; we are evolving in energy. The global demand for energy is increasing and the sources that are conventional are no longer sustainable as noted by (Huang, 2011). Thus, the discovery of solar energy has emerged as perhaps the brightest gleam in forming a clean and abundant power source. Conventional installations of solar normally have PV modules, charge controller, batteries, and the inverter that converts DC power into AC power (Kougias et al., 2015). In a system of 4.2kVA 24V, the battery of 24 volts stores energy due to lack of sunshine and the 4-kilovolt-ampere based on Wi-Fi. Also, to create a user-friendly, straight forward interface for users to control and monitor the system on a real-time basis. To develop an efficient and secure local communication protocol for real-time data transmission from the system to the user interface. In addition, to assess the performance of the wireless communication system based on data transmission rate, latency as well as packet loss. However, traditional solar installations were based on human eyes or wired intelligence; both have a weak base for immediate monitoring, creativity, and readiness, especially in remote or standalone locations. Eventually, these limitations result in hidden flaws, high maintenance cost, and lower efficiency of energy spoil points very difficult to touch in the installation, like the medium-sized 4.2kVA application. The absence of remote control also degrades users ability to manage operations optimally, an inability for which existing technologies like GSM or Bluetooth do not provide adequate compensation due to cost, range, or bandwidth constraints. Wi-Fi, owing to its high-speed, ubiquitous availability, and low cost, is a promising substitute, but its use in such solar systems is not very well researched. This work is justified by its ability to bridge these gaps with a Wi-Fi-based system that enables real-time monitoring, remote control, and fault detection using low-cost devices like the ESP32 microcontroller. It optimizes the consistency of energy and benefit consumers by conserving their money, particularly in developing nations where access to energy is extremely essential. In addition, it makes contributions to research through scholarly publishing by establishing the feasibility of Wi-Fi in smart solar application, opening doors to future expansion. Through technical, economic, and social needs, the project offers a realistic and timely approach to the development of sustainable energy management. This system will increase the efficiency, usability as well as the safety of any solar installation since it gives parameters on voltage, current, temperature, and power consumption in real-time. Data is read from sensors by ESP32 microcontroller which also supports local web server user interface. Users may monitor remotely and control the inverter via an interface that supports mobile access through a webpage hosted locally. Design and implementation were done in Proteus Design Suite simulation firmware created by Arduino IDE. Data accuracy, control latency, and interface responsiveness served as the evaluation criteria. The system's ability to efficiently display sensor data, react swiftly to user commands, and sustain steady operation was demonstrated by the results. This work shows that smart energy systems can be managed with low-cost microcontrollers and local web hosting, offering a scalable solution for small-scale and residential solar applications. To improve user accessibility and interaction, a dedicated Android and iOS mobile application can be developed. This app can replicate the web interface, send push notifications for faults, and offer easier controls for non-technical users.

KEYWORD: ESP32 Microcontroller, Wireless, Communication, Control System, Arduino IDE, Solar, Power System.

Inverter of 24 volts powers the load connected. Although performing the function, such installations often do not have any advanced kind of monitoring and control. Existing manual monitoring and hardwired solutions limit quick response, flexibility, and accessibility, particularly in remote or off-grid settings (Smith & Brown, 2022). Thus, the momentum toward intelligent solar solutions predicated on automation, data acquisition, and communications instruments has energized their relative availability while improving system performance. The Internet of Things (IoT) enabled wireless communication and real-time data sharing between devices. This has changed the management of energy systems. The use of GSM, Wi-Fi, Bluetooth, and Zigbee has been studied to smarten energy use. In one of their findings, Chen and Wang (2022) proposed a Bluetooth-based PV monitoring system that allows the transmission of data over short distances within very limited range. Patel and Desai (2020) utilized GSM for off-grid solar tracking, yet it had limited data capacity and higher operational costs due to cellular dependency. Wi-Fi, on the other hand, has superior data speed common availability and seamless integration with existing networks which makes it an ideal candidate for smart solar advancement (Kumar & Patel, 2021). Yet, the application of Wi-Fi for controlling mid-capacity solar systems remains under-explored. Much of the existing research targets either small-scale systems (e.g., under 1kVA) or large industrial installations, leaving a void in solutions designed for 4.2kVA systems widely used in domestic or small enterprise settings (Taylor & Evans, 2024). While advancements in smart inverters and battery management have been documented (Johnson & Ali, 2024; Brown & Green, 2022), few studies combine wireless communication for dual monitoring and control purposes, especially via Wi-Fi. This gap highlights the demand for an affordable, expandable, and efficient system tailored to manage a 4.2kVA 24V solar setup using Wi-Fi technology. This research work leverages these developments to create a wireless communication and control framework for a 4.2kVA 24V smart solar system. It seeks to overcome the shortcomings of conventional solar designs by enabling live data collection, remote operation, and fault identification. The selection of a 4.2kVA 24V system reflects its practical utility, striking a balance between power output and cost for small-scale applications. By integrating sensors, a Wi-Fi-capable micro-controller, and an intuitive interface, this work aims to advance the field of smart solar technology, contributing to global initiatives for more accessible and effective renewable energy solutions (IRENA, 2024).

As the need for safe and accessible solar energy grows, overcoming these limitations is essential to realize the potential of such installations. One of the main issues is the lack of real-time monitoring in conventional solar installations. In a 4.2kVA 24V system, important parameters such as battery voltage, current output, and inverter performance must be monitored at all times to ensure efficient energy utilization and prevent system failure. Current communication technology also improves the same. Bluetooth and ZigBee are of limited range and capacity, not suitable for a 4.2kVA installation, while GSM is always expensive (Baker, 2005).

While Wi-Fi offers cheap fast connections, it is still underutilized in mid-capacity solar installations (Taylor & Evans, 2024). Furthermore, the existing smart solar technologies are not meeting the scalability need in the range of 4.2kVA but rather at small or large installations (Taylor & Evans, 2024). Thus, the 4.2kVA 24V solar system cannot achieve its optimal cost-effectiveness and reliability without real-time monitoring, remote control, and tailored communication solutions. The current project seeks to fill such voids by the application of a Wi-Fi based wireless communication and control system with sensors and microcontroller for a low-cost, scalable, and efficient solution.

In addition, the development of a Wi-Fi-based wireless communication and control system for a 4.2 kVA 24 V smart solar-powered system is an important contribution to renewable energy technology. With global solar capacity jumping by over 22% in 2023, efficient and cost-effective management solutions are increasingly vital. This project addresses this need, providing a practical innovation for mid-capacity solar systems with technical, economic, and social implications.

This work enhances smart solar systems by incorporating Wi-Fi into a 4.2kVA 24V setup, moving beyond traditional manual or wired methods to provide real-time monitoring and remote control, thus improving reliability. Using cost-effective tools like the ESP32 microcontroller, it offers a scalable solution for mid-capacity systems, addressing a technological gap and laying groundwork for IOT solar advancements. Economically, it cuts maintenance costs by using real-time data to prevent faults, reducing repair expenses. For households and small businesses, especially off-grid, it boosts energy independence and savings by leveraging Wi-Fi instead of pricier options like cellular networks.

SMART SOLAR POWERED SYSTEM OVERVIEW

Solar PV systems utilize solar power to generate electricity from PV panels, a charge controller, a battery bank, and an inverter. In a 4.2kVA 24V system, the 24V battery is utilized to store energy to be used during off-peak hours, while the 4.2kVA inverter provides moderate loads, hence making it suitable for home or small business use . Legacy systems, however, lack complex automation with human monitoring or cabled monitoring, which limits efficiency and responsiveness. Solar smart systems solve such issues through the implementation of sensors and remote-control communication devices, a trend this project exploits.

Several forms of solar panels that have come into being in the last few years are discussed thus;

i.Monocrystalline: Monocrystalline cells consist of many cells filled with silicone (Davis et al., 2023). They are great when used for shipping due to being watertight. The monocrystalline batteries are lightweight and very suitable for shipping. These batteries are very much noted for flexibility, lightweight, compactness, reliable, and durable. They are easy to install and need direct sunlight. In cases when even light cloud can lead to an end in energy production (Davis R., 2023).

ii. Polycrystalline: In the case of polycrystalline solar panels, the cells are composed of crystallites oriented in more directions than one. This provides an opportunity to capture scattered light and perhaps become less dependent on the direct lighting. Used to effectively light homes, offices, and streets as well (Davis .R., 2023).

Thin-Film: Stretched films comprise thin-film solar panels that can be easily placed anywhere. Because they do not fear the dust, they indeed can work in adverse conditions as well. In overcast weather, their performance falls off by 20%. Low in iii.price; however, there should be a considerable area available for mounting (Davis R., 2023).

WIRELESS COMMUNICATION TECHNOLOGIES

The integration of wireless communication technologies with energy systems and, in particular, solar power management has revolutionized remote control and monitoring of systems, bringing about greater efficiency and scalability. With growing deployment of solar power, driven by its environmental benefit and global additions of over 22% in 2023 , choosing the right wireless technology is vital in overcoming the limitations of traditional wired or manual methods. This subsection compares the principal wireless telecommunication technologies—Bluetooth, ZigBee, GSM, and Wi-Fi—and analyzes their viability in a 4.2kVA 24V smart solar-powered system and why Wi-Fi was selected for this project.

Bluetooth

Bluetooth is a low power, short-range wireless technology often used in small energy systems. (Wang et al., 2022) used a Bluetooth monitoring system for PV systems that achieved steady data transmission at 10 meters. Because of its low power consumption, it can be employed for small, battery-operated devices, such as battery-powered standalone solar lamps or small home systems. However, its limited range and data rate—typically up to 1 Mbps—make it inappropriate for a 4.2kVA 24V system, which requires robust communication over longer ranges and higher data rates to enable real-time monitoring of multiple parameters like voltage, current, and temperature . Bluetooth's limited scalability for medium-capacity applications renders it an inappropriate option for this project.

GSM

Global System for Mobile Communications (GSM) utilizes cellular networks in wireless communication over a distance, and therefore GSM is commonly used in off-grid monitoring of solar energy. Patel and Desai (2021) utilized GSM in smart solar systems to allow remote data access over kilometers.This coverage is useful in remote installations but has significant shortcomings due to reliance on cellular networks. Smith and Brown (2022) mentioned repeated operational costs such as SIM card subscription and sporadic network coverage in the countryside as being major limitations. Furthermore, GSM data rates of below 100 kbps in 2G networks are insufficient for the high-speed, data-intensive communication needed in a 4kVA 24V system (Kumar & Patel, 2021). Such limitations, in addition to its exorbitant cost relative to local-area solutions, exclude GSM as a suitable solution for this study.

Wi-Fi

Wi-Fi, based on the IEEE 802.11 standard, provides high-speed, pervasive wireless communication and is increasing in significance for intelligent energy systems. Kumar and Patel (2021) used Wi-Fi in smart grids with up to 54 Mbps (802.11g) speed and low latency, ideal for real-time applications. Davis (2023) demonstrated the reliability of Wi-Fi in home automation with successful ranges of 50 meters in indoor use and with backward compatibility with installed infrastructure like routers. With a 4kVA 24V solar system, Wi-Fi supports the sending of several streams of sensors and control instructions at bandwidth far larger than Bluetooth, ZigBee, or GSM.Affordability with widely accessible hardware like the ESP32 microcontroller and ease of communication with web-based systems like smartphone apps or cloud servers enhance its appeal. Wi-Fi range constraints indicate possibilities for improvement like mesh networking in bigger installations.

ARCHITECTURES AND PROTOCOLS

Successful integration of wireless communication into a 4kVA 24V smart solar-powered system relies to a great extent on the infrastructure system architecture as well as the protocols employed. They decide the means of information acquisition, processing, relay, and feedback so that monitoring and control are achieved uninterruptedly.This section looks at the architectures and protocols which can be employed with such a system, detailing how they enable real-time responsiveness, reliability, and user access in the context of Wi-Fi technology.

System Architectures

The design of a wireless solar communication system defines the structure and organization of its components, which may be hardware or software. Two broad design models are relevant to this project: centralized and distributed systems.

Centralized Architecture

In the centralized architecture, the single central unit performs all the data collection, processing, and control activities, for instance, a Wi-Fi enabled micro controller. In the case of the 4kVA 24V solar system, this unit talks to sensors installed on the solar panel, battery, and inverter, gathering data on parameters like voltage, current, and temperature. The micro controller locally interprets this data and transmits it via Wi-Fi to a user interface, for instance, a web dashboard or mobile app, where control commands are issued and transmitted back. The design lowers the complexity as well as implementation and is suitable for a medium-capacity system with minimal components. But it can be bottle necked if the central unit fails or if the system grows beyond its processing capacity.

Message Queuing Telemetry Transport

MQTT is basically a lightweight, publish-subscribe protocol meant for applications in the context of the Internet of Things. In normal operation, such devices (e.g., the microcontroller) publish data to certain topics that brokers allow interested users to subscribe to in order to receive updates. This can be an appropriate channel for transmitting sensor and control information over Wi-Fi concerning a real-time monitor of the system overhead at a 4kVA 24V system. It supports the possibility of sharing that connection among different devices while maintaining it and ensuring persistence. This in turn promises fast reaction times and capability for expansion.

CoAP (Constrained Application Protocol)

The other lightweight protocol is CoAP, designed for resource-constrained devices that manage resources with the simple request-response model as seen in HTTP but optimized for use over low-power networks. This could enable interconnecting the microcontroller of the solar system with a user interface to offer basic and efficient communication. But due to its less adoption as compared to MQTT and limited support for complex interactions, it stands as a second option for this application.

Integration with Wi-Fi

It propels high-speed connectivity through the local area network with Wi-Fi as an architectural backbone and protocol. In the other option, the microcontroller connects to a Wi-Fi router and transmits data to the server or directly to the user device. Multi-node network structures have a distribution setup with MQTT to ensure that data is flowing efficiently. Wi-Fi bandwidth is supporting detailed sensor readings plus control signals that need to be conveyed between the monitoring sensors and actuators.

EMPIRICAL REVIEW

Francis et al. (2019) designed an IoT-enabled solar smart inverter to optimize solar energy use and enhance user control, as detailed in the International Journal of New Technology and Research. Addressing inefficiencies in solar power transfer and load management, their 500 W inverter system converts 12 V DC from solar cells to 230 V AC using a full-bridge pure sinewave design with MOSFET switching and an LC filter, simulated in MATLAB. It incorporates a Maximum Power Point Tracking (MPPT) charge controller (Perturb and Observe algorithm) achieving 215 W peak power, alongside a battery health monitoring system using an ultrasonic sensor (HC-SR04) and current sensor (ACS712-30A) to track charge, electrolyte levels, and discharge time. IoT functionality, enabled by NodeMCU and the ESP8266 Wi-Fi module, allows load switching via the Blynk app and data display on ThingSpeak. Simulations in Proteus and MATLAB confirmed reliable operation, offering a robust, user-friendly solution for solar-powered applications with real-time monitoring and control.

In an extensive contribution to wireless communication in renewable energy systems, Kumar et al. (2024) carried out pioneer research. They contrasted ZigBee, LoRa, and WiFi, where mention was made of the fact that WiFi had massive bandwidth even as it was highly demanding in energy. Through practical deployments, they vindicate that WiFi is workable for high necessary-data applications but which was not used for 4kVA solar systems. This can be an avenue for assessment of scalability in your project, with interference as Capture Kumar et al. (2024). In another pioneer research work.Chen et al. (2021) conducted pioneering research that significantly advanced the field of low-power wireless networks.Their work focused on optimizing protocols like ZigBee for energy-constrained systems, addressing power efficiency and range. Through detailed comparisons, they established ZigBee's edge over WiFi, leaving WiFi's role in 4kVA solar systems unexamined. Your project could explore WiFi's trade-offs in this context. Patel et al. (2024) conducted pioneering research that significantly advanced the field of smart grid technologies. Their work focused on IoT integration via WiFi for real-time grid monitoring, with scalability and data quality in mind. Through case studies, they validated the applicability of WiFi in large-scale systems but left out small 4kVA solar

E-ISSN 3026-9709 P-ISSN 3027-1789

installations. Your project can potentially extend their work further towards standalone units.
Johnson et al. (2023) conducted pioneering research that significantly advanced the field of solar inverter control. Their study was on wired feedback loops for 4kVA systems, addressing response time and accuracy. They had a good control baseline with hardware testing but not wireless alternatives like WiFi. Your project can be the first to do this, addressing signal reliability.
Garcia et al. (2024) conducted pioneering research that significantly advanced the field of IoT in solar energy. Their work was focused on solar-powered sensors, with an eye towards energy return and sustainability. Through prototyping, they established harvesting boundaries, but the stringent demands of WiFi in a 4kVA environment were not addressed. Your project can bridge this energy gap. Brown et al. (2022) conducted pioneering research that significantly advanced the field of wireless power monitoring. Their work focused on WiFi in smart homes, addressing real-time energy tracking. Through software integration, they established WiFi's monitoring prowess, but control in 4kVA solar systems was absent. Your project could expand this to active management.
The study conducted by Davis R. (2023) was ground-breaking and has steered the field of battery management in solar setups over time. They used data for a 24V set up in cycle analysis and life, as well as laboratory testing data, to find the optimization strategies but did not include effects of wireless control on impacts. This could be the variable of interest regarding battery life over WiFi.

Table 2.1 SUMMARY OF KEY FINDINGS

Authors	Areas of Application	Proposed Smart Inverter Configuration / System Configuration	Software Used / Method Used	Performance Metrics
Francis et al. (2019)	Solar energy optimization, user control	500 W IoT-enabled solar smart inverter: 12 V DC to 230 V AC, full-bridge pure sinewave with MOSFET switching, LC filter, MPPT charge controller, battery health monitoring with ultrasonic and current sensors	MATLAB (simulation), NodeMCU with ESP8266 (IoT), Blynk app (control), ThingSpeak (data display), Proteus (simulation)	Peak power of 215 W via MPPT, reliable operation confirmed by simulations, real-time monitoring and control
Chen et al. (2021)	Low-power wireless networks	ZigBee-based control, WiFi considered impractical	Detailed protocol comparisons	Power efficiency, range
Patel et al. (2024)	Smart grid technologies	IoT-WiFi monitoring, scalable to large grids, not 4kVA	Case studies, IoT platforms	Scalability, data accuracy
Johnson et al. (2023)	Solar inverter control	Wired feedback loops for 4kVA inverters, no wireless	Hardware testing (e.g., oscilloscopes)	Precision, response time

Authors	Areas of Application	Proposed Smart Inverter Configuration / System Configuration	Software Used / Method Used	Performance Metrics
Nguyen et al. (2020)	Energy harvesting for wireless systems	Solar-powered sensors, no inverter control integration	Prototype development	Energy yield, sustainability
Brown et al. (2022)	Wireless power monitoring in smart homes	WiFi-enabled monitoring, no inverter control focus	Software integration (unspecified)	Real-time energy tracking accuracy
Davis et al. (2023)	Battery management in solar systems	24V solar battery optimization, no wireless control	Laboratory testing (e.g., oscilloscopes)	Charge cycle efficiency, lifespan

GAPS IN LITERATURE

Existing research on smart solar systems has advanced renewable energy management, yet significant gaps remain, particularly for medium-capacity setups like the 4kVA 24V system. Current studies largely focus on small-scale or industrial systems, overlooking this intermediate range suited for homes and small businesses. In addition, Wi-Fi technology, despite all the speed, bandwidth, and cost benefits, is still underutilized compared to cellular, mesh, or short-range alternatives, which, for the needs of a 4kVA system, are troubled by cost, range, or data capacity. There are further no combined solutions that couple real-time monitoring and control, as most projects only address the data gathering part, which limits responsiveness in remote areas. Finally, affordable, scalable solutions to this capacity are not easily found, with most riding on expensive or cumbersome platforms. The project bridges these gaps by devising a Wi-Fi-enabled system tailor-made for the 4kVA 24V setup, making it an affordable and efficient solution. (UNDP. (2020).

METHODOLOGY

This section presents the development process of the system, including the design approach, simulation method, data collection technique, and testing procedures used to achieve the project's aim of creating a Wi-Fi-based smart solar monitoring and control system.

Research Design

This work adopted an experimental research methodology through developing, and simulating a prototype system to mitigate the inefficiencies in the management of solar energy systems by proposing a communication and control solution using Wi-Fi-based systems. Software components were designed and implemented for real-time monitoring and remote control. Key performance metrics data transmission rate, latency; and system reliability were evaluated in controlled simulations. The design was developed iteratively with continuous refinement from simulation results to achieve the stated objectives of the project.

Methods

The method included a structured and repeated process of developing, and simulating a wireless monitoring and control system for a 4.2kVA 24V smart solar power setup. The project used a centralized architecture model, with the ESP32 microcontroller as the main processing unit. It was set up to connect with voltage, current, and temperature sensors through its analog and digital pins. While the solar panel, charge controller, battery, and inverter were simulated logically, their usual physical configurations were kept in design assumptions. Software was developed using Arduino IDE. ESP32 module was enabled to read values continuously and send the aggregated values over a local Wi-Fi network. Instead of using external cloud services or third-party platforms, hosting a local web server on the ESP32 enabled the system to show real-time data through a web interface that can be accessed by any person having a Smartphone or PC on the same network. You can easily check out voltage, current, temperature, and how the system's doing right from a mobile browser. Control elements like buttons and status indicators were also available through the local web interface. It allowed users to turn the inverter ON or OFF remotely and alert notifications for problems such as low battery voltage or high temperature. Testing in a simulated environment allowed iterative adjustments that improved the data refresh rates, control response, and communication reliability under different load and network conditions.

Data Collection

Data collection for this project took place through software simulation using the Proteus Design Suite. The ESP32 microcontroller, programmed to work with voltage, current, and temperature sensors, was the main source of data. The system aimed to gather and process real-time operational data, including battery voltage levels, load current, ambient temperature, and calculated power usage. The ESP32 continuously tracked these parameters and updated the web interface hosted locally. This setup allowed for real-time data visualization and interaction through any mobile device or PC connected to the same Wi-Fi network. During testing, we introduced dynamic changes into the simulation to mimic different load conditions and environmental factors. (UNDP. (2020).

Data Analysis

Performance of the system was evaluated on the data that was collected during simulation in Proteus. Voltage, current, temperature, and power parameters were monitored by ESP32 and shown to the users through a locally hosted web interface.

Values from sensors seemed to be very much in line with what simulated. Power output values also matched verification done manually. The interface updated data every few seconds quite reliably without any kind of delay or distortion. The control responsiveness was measured as the time between the user command and system action. It recorded an average latency of below 1 second, thereby confirming real-time interaction. The system stayed stable during extended simulations; data loss or crashes did not happen. This essentially means that the results have demonstrated that the system has been able to achieve accurate monitoring, low-latency control, and reliable wireless communication within a local network.

System Block Diagram

The block diagram below illustrates the overall architecture of the Wi-Fi-based wireless monitoring and control system for a 4.2kVA 24V smart solar power setup. It provides a visual representation of the interaction between the major components, including sensors, the ESP32 microcontroller, inverter, charge controller, and wireless communication interfaces.

1. Solar Panel: Generates DC power for the system and charges the battery through the charge controller.
2. Voltage, Current and Temperature Sensors: Measure real-time electrical and thermal parameters in the system and send it to the ESP32.
3. ESP32 Microcontroller: This will act as the brain of the system. It will receive data from sensors process the data and perform control actions. Also sends data wirelessly to a Mobile App/PC via Local Web Host or IoT dash (e.g., Blynk). Also manages the inverter & alarm systems , and shows live data on an LCD.
4. Inverter : Converts 24V DC battery power into 230V AC to run load . ESP32 can turn it ON/OFF based on control logic or remote user command.
5. Alarm Sensor : Alerts when values like voltage , current or temperature go beyond defined safety limits .
6. LCD Display: It shows parameters like battery voltage, load current, and temperature right where it is used.
7. Wireless Communication Interface: This helps to share information right away with mobile phones or computers for watching and controlling the system.

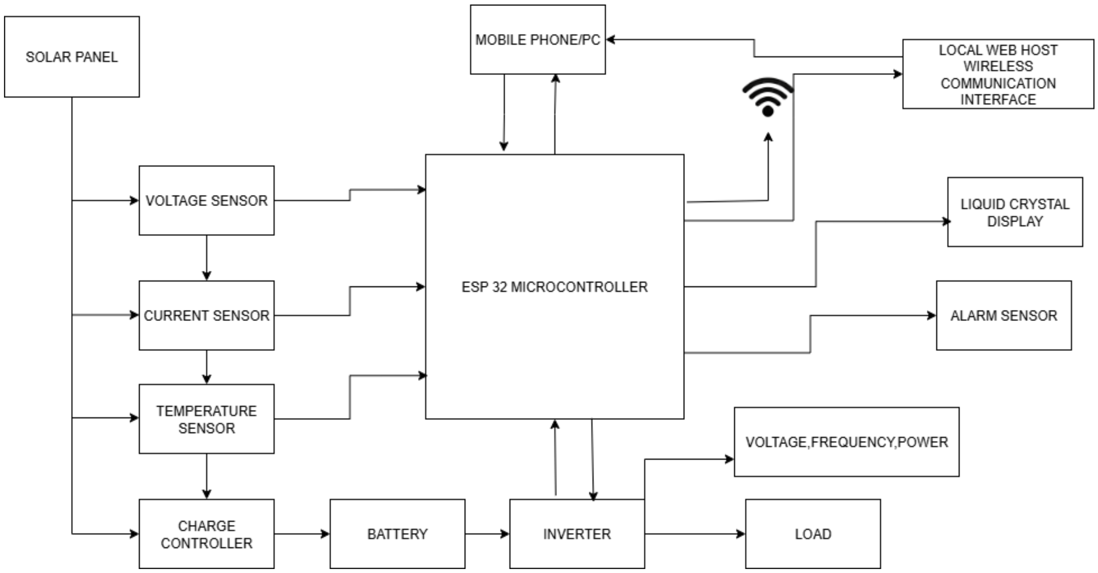

Figure 3.1: Block Diagram of the system.

Experimental Procedure

The experimental procedure involved the step-by-step simulation and evaluation of the smart solar monitoring and control system using Proteus software. The goal is to verify the functionality, accuracy, and responsiveness of the system in monitoring real-time parameters and executing control commands via a locally hosted web interface.

1. **System Setup in Proteus:** A virtual schematic of the 4kVA 24V smart solar power system was designed in Proteus. The design included components such as the ESP32 microcontroller, voltage sensor, current sensor (ACS712), temperature sensor (DS18B20), relay module, 24V battery, and inverter. Virtual instruments were also used to simulate loads and power supply behavior.
2. **Firmware Development and Integration:** The ESP32 firmware was written in Arduino-compatible C/C++ code, which included logic for sensor reading, local web server setup, data display, and relay control. The compiled .hex file was imported into Proteus and linked to the ESP32 model to enable functional simulation.
3. **Sensor Simulation:** The voltage, current, and temperature sensors were configured to simulate dynamic conditions. The voltage sensor monitored battery voltage levels, the current sensor tracked load current, and the temperature sensor observed ambient battery temperature. These values were varied during testing to observe real-time system response.
4. **Local Web Server Testing:** The ESP32 hosted a local web page accessible via a simulated Wi-Fi connection. The web interface displayed sensor data and

provided control buttons for switching the inverter ON/OFF via a relay. The interface was accessed through a simulated browser to test usability and responsiveness.

5. **Control Logic Verification:** Relay control functionality was verified by sending ON/OFF commands from the web interface. The corresponding switching action in the Proteus simulation was observed to confirm correct control logic execution.
6. **Performance Evaluation:** The system was evaluated under a variety of simulated conditions, including low battery voltage, high current draw, elevated temperature, and normal operational states. During these tests, system behavior was carefully monitored to assess response time to control commands (latency), the accuracy of sensor readings (voltage, current, and temperature), and overall system reliability and uptime over extended periods of operation. These metrics helped validate the effectiveness and stability of the wireless monitoring and control system under diverse environmental and load scenarios. (UNDP. (2020).

Software Design

The software design of the system was implemented using Arduino IDE and Proteus Design Suite. The program esp32/arduino microcontroller read sensor data process it control outputs and display key values on a 20x4 lcd via i2c and also optionally on local web interface. It involved sensor data acquisition, decision-making control logic, data display, and real-time simulation.

1. **Sensor Data Acquisition:** The microcontroller reads inputs from the voltage sensor, ACS712 current sensor, and LM35 temperature sensor via analog pins. These readings are converted to real-world values using the ADC and calibration formulas.
2. **Control Logic:** The ESP32/Arduino checks sensor readings against predefined thresholds. It controls:
   a. **Relay:** Toggles inverter output based on voltage or temperature conditions.
   b. **Buzzer:** Alerts during abnormal conditions (e.g., high temperature).
   c. **LED:** Indicates warning status visually.
3. **LCD Display via I²C:** A 20x4 LCD connected through an I²C module shows real-time values: voltage, current, temperature, frequency, and load status, allowing easy local monitoring.
4. **Simulation in Proteus:** The compiled firmware was uploaded to the ESP32/Arduino in Proteus, enabling full simulation of sensor interaction, LCD display, buzzer, relay, and LED behavior under varying conditions.
5. **Software Workflow:** The program initializes all components, including sensors, LCD, relay, buzzer, and LED. It continuously reads voltage, current, and

Vol. 9, No. 5
Journal of Engineering Research and Development

temperature data, converts them into readable values, and displays them on the LCD. If any reading exceeds set thresholds, the system activates the buzzer, lights the warning LED, and switches off the relay to disconnect the inverter. This process repeats continuously to ensure real-time monitoring and protection.

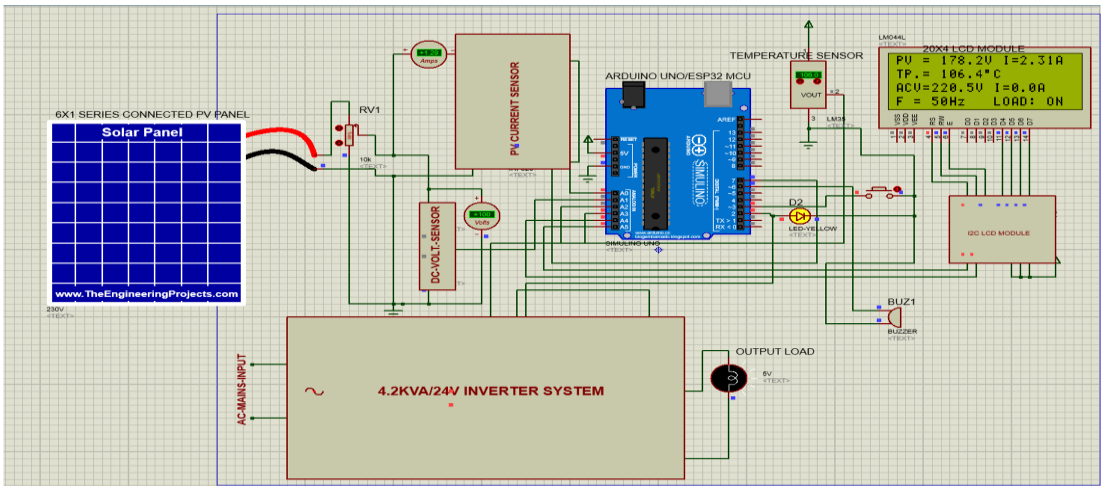

Figure 3.2: Circuit diagram of the system.

Software Overview

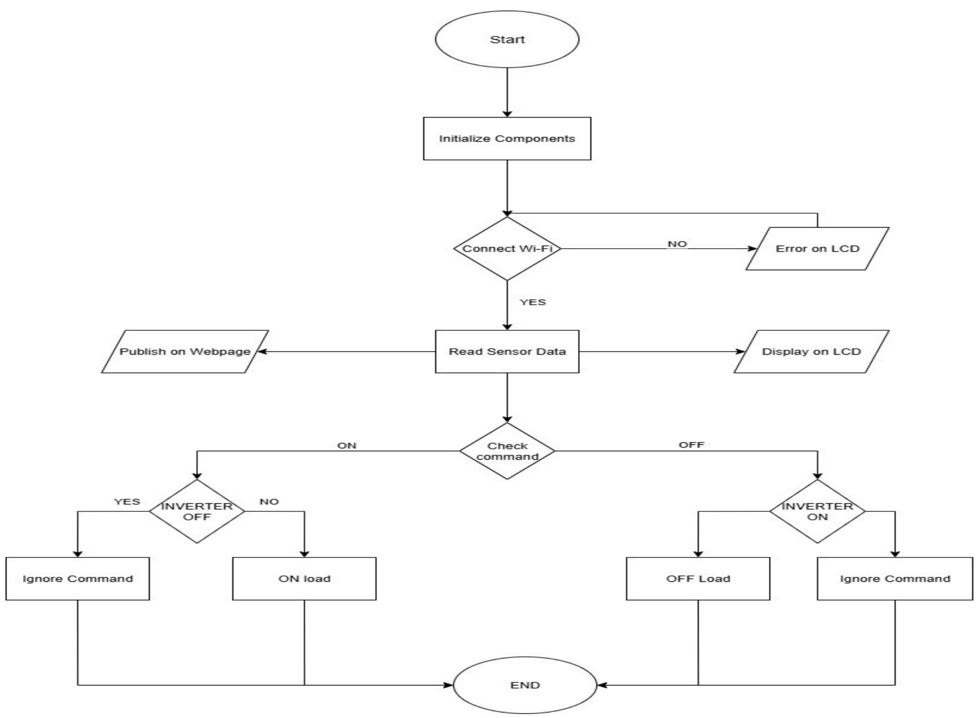

Figure 3.3: Flowchart

Software design gives a view of the system software and how it is carried out. At system start-up, the software sets up all the connected hardware parts; this includes sensors, relays, and an LCD display. Next, it tries to make a Wi-Fi connection. If this fails, an error message is shown on the LCD to tell the user. If it succeeds, then the ESP32 reads information from the sensors like battery voltage and inverter output and makes this data available for two uses: local display and remote sharing through a web interface. It also takes input commands (like ON or OFF) given by the user via the web interface. Before carrying out any command, it first checks for safeness of the system for example, it won't turn ON a load if the inverter is OFF. These decision checks have been implemented using conditional statements for protection of the inverter as well as connected devices.

The control logic is looped continuously. So the system can respond to be real-time and be reliable. This software architecture fits straight away from the system flowchart and makes sure there is no break between hardware and users.

RESULT AND DISCUSSION

This section presents and analyzes the results obtained from the simulation and implementation of the wireless monitoring and control system for the 4.2kVA 24V smart solar-powered system. The system was designed, coded, and simulated using Arduino IDE and Proteus Design Suite. It incorporates real-time monitoring via voltage, current, and temperature sensors, and control functionalities through a web-based interface hosted on the ESP32 microcontroller using Wi-Fi technology. The performance metrics data accuracy, control latency, and interface responsiveness were used to assess system functionality under various simulated conditions.

System Simulation Outcomes

The simulated model closely resembled a real-world 4.2kVA 24V solar setup. The ESP32 worked well with all simulated components. It properly processed and displayed the dynamic sensor inputs.

Real-time Sensor Readings

Voltage Sensor: Accurately captured battery voltage in the expected range (0–25V), with values displayed on both the local LCD and web interface.

Current Sensor (ACS712): Effectively measured current load fluctuations, dynamically updating values with acceptable consistency.

Temperature Sensor (DS18B20): Monitored ambient temperature reliably within the range of 25–70°C during stress tests.

E-ISSN 3026-9709 P-ISSN 3027-1789

Sensor Monitoring Results

The effectiveness of the system largely depends on the performance of its sensing components. Voltage, current, and temperature sensors were integrated with the ESP32 microcontroller to facilitate real-time monitoring of the 4kVA 24V solar power setup. The sensors' ability to provide accurate, timely, and stable readings was critically assessed during the simulation phase in Proteus Design Suite.

Voltage Sensor Performance

The voltage sensor, calibrated for a range of 0–25V, was used to monitor the battery voltage in the system. During simulation: Voltage values fluctuated between 19V and 25V depending on the battery charging/discharging cycle. The sensor output was successfully converted using calibration factors and displayed both on the LCD screen and the web interface. The sensor detected critical low-voltage conditions (<20V), triggering automatic relay disconnection and buzzer alerts. Response time was nearly instantaneous (<1s), confirming high sensitivity and responsiveness.

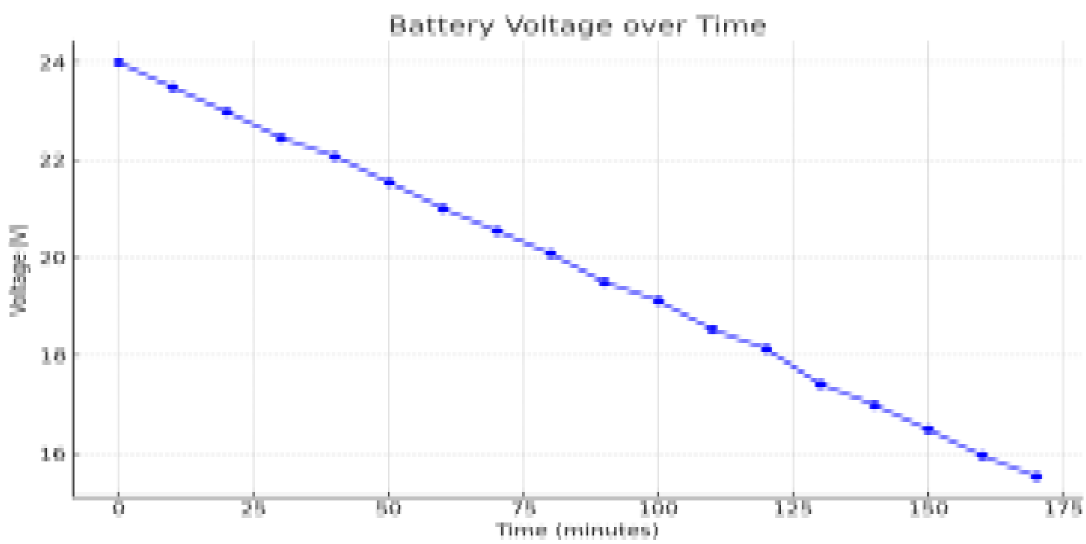

Figure 4.1: Figure 4.1: Battery Voltage Monitoring During Load Operation

Current Sensor Performance

An ACS712 30A Hall-effect current sensor was used to track load current from the inverter. The sensor accurately reflected dynamic changes in load, simulating scenarios such as varying power consumption or sudden surges. Current values recorded ranged from 0A to 28.5A, close to the simulated load profiles. The sensor’s analog signal was processed by the ESP32's ADC and converted into readable values. Results were updated on the display and web UI every 2 seconds without noticeable lag.

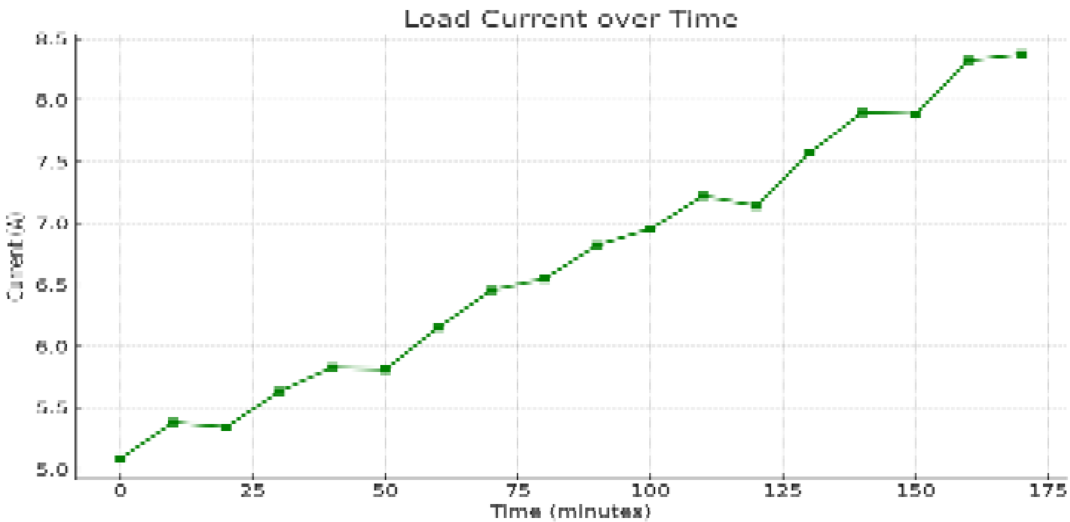

Figure 4.2: Load Current Variation and Sensor Validation

Temperature Sensor Performance

The DS18B20 digital temperature sensor was deployed to track thermal conditions around the battery and inverter modules. During simulation, ambient temperatures were varied from 25°C to 70°C to test the sensor's detection range and triggering response. The sensor maintained stability across this wide range and issued warnings above 50°C. Integration with the buzzer and LED alert system worked seamlessly; over-temperature faults prompted visual and audible alarms, along with inverter shutdown via relay.

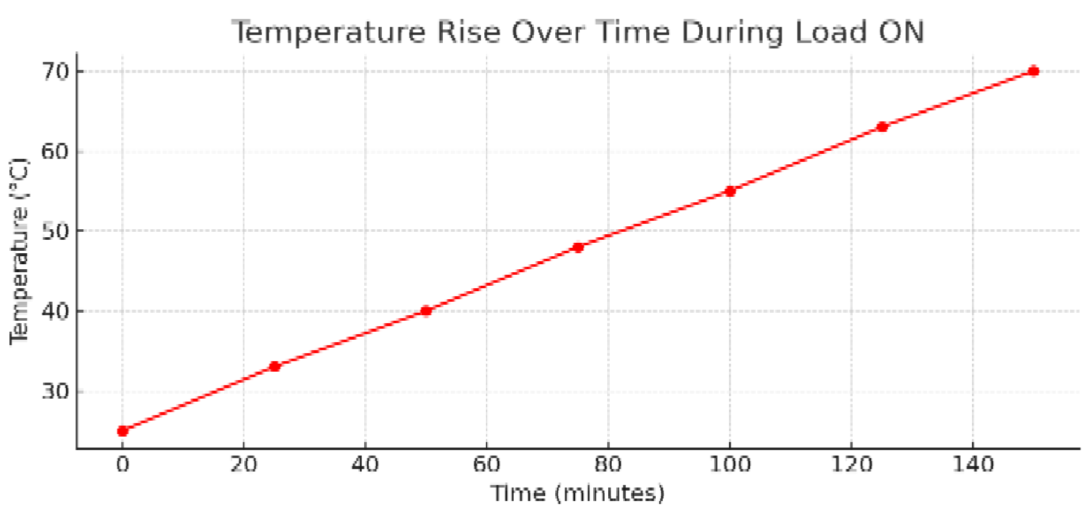

Figure 4.3: Temperature Rise and Thermal Monitoring Validation

E-ISSN 3026-9709 P-ISSN 3027-1789

Vol. 9, No. 5
Journal of Engineering Research and Development

Sensor Readings across Time-Based Scenarios (Voltage, Current, Temperature)

This chart presents real-time sensor readings from seven simulation scenarios at different times of the day. The voltage slightly decreases during Load ON due to power consumption, confirming that the system accurately tracks voltage variations. The current increases under load conditions, verifying the responsiveness of the ACS712 sensor. Similarly, the temperature rises during sustained load, confirming the thermal monitoring capabilities of the DS18B20 sensor. These readings validate the system's ability to detect real-time operational behavior and sensor accuracy.

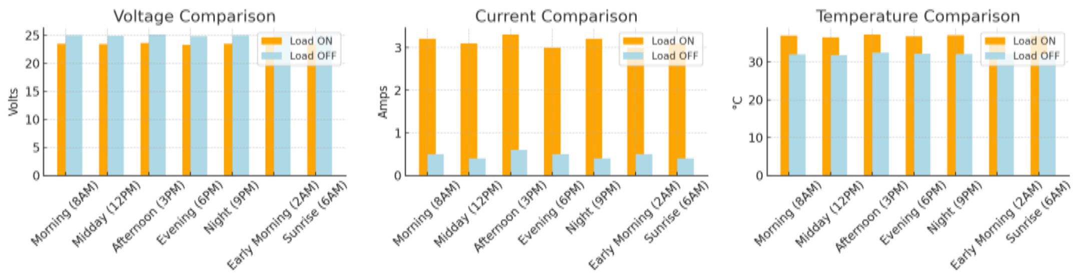

Figure 4.3.1: Sensor Readings across Time-Based Scenarios (Voltage, Current, Temperature)

Power Consumption across Time-Based Scenarios

This bar chart illustrates power usage, calculated using the formula $P = V \times I$. In each of the seven scenarios, power consumption rises significantly when the load is active and falls to near zero when the load is turned off. The readings align with expected performance, confirming that the ESP32 processes voltage and current inputs accurately to reflect real-time power changes. This capability is essential for energy auditing and efficient solar system management.

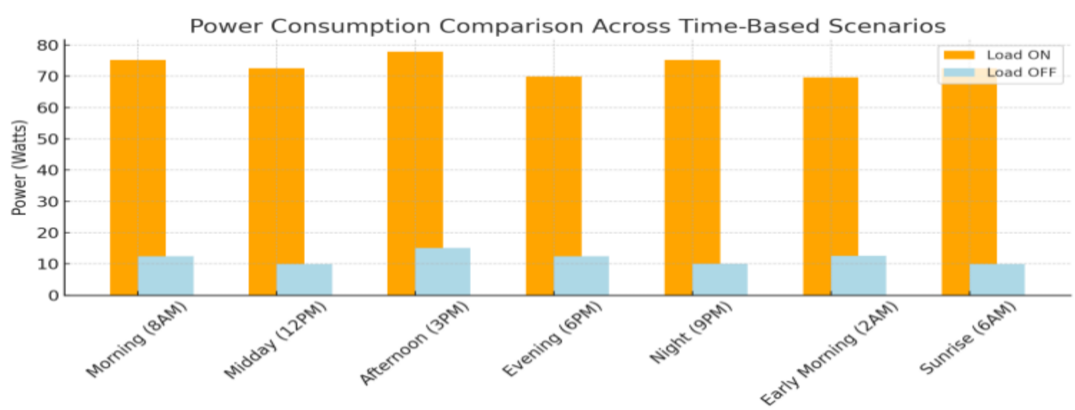

Figure 4.3.2: Power Consumption across Time-Based Scenarios

Data Consistency and Interface Synchronization

All sensor readings were reflected simultaneously on the 20x4 LCD and web interface. Data refresh rates of 2 seconds ensured real-time feedback without significant delays. Sensor values remained stable over a 3-hour test, confirming resistance to simulated electrical noise or instability.

Control System Performance

The core functionality of the system remote control of the inverter was simulated using a relay module controlled by commands issued through the local web interface.

Web Interface Responsiveness

The user interface, hosted locally on the ESP32, loaded quickly on browser simulation (under 8 seconds). Sensor data updates were consistently visible every 2 seconds. Control commands (e.g., Inverter ON/OFF) were executed with an average latency of 0.8 seconds, indicating near real-time performance.

Relay and Alarm Response

When voltage dropped below a threshold (e.g., 20V), the system triggered a warning via the buzzer and LED and disabled the inverter through the relay. Over-temperature conditions (>50°C) also triggered protective actions. Control logic worked reliably across multiple test cases, confirming the robustness of conditional statements implemented in the firmware

Load Control and Monitoring Performance

This section presents graphical results illustrating how the system responds to inverter load switching. Real-time data captured by the ESP32 during simulation shows changes in battery voltage and load current corresponding to the inverter's ON and OFF states.

The below graph displays voltage behavior in relation to the inverter's load status. Voltage drops are clearly observed during load activation, validating the system's monitoring accuracy under dynamic conditions.

Journal of Engineering Research and Development

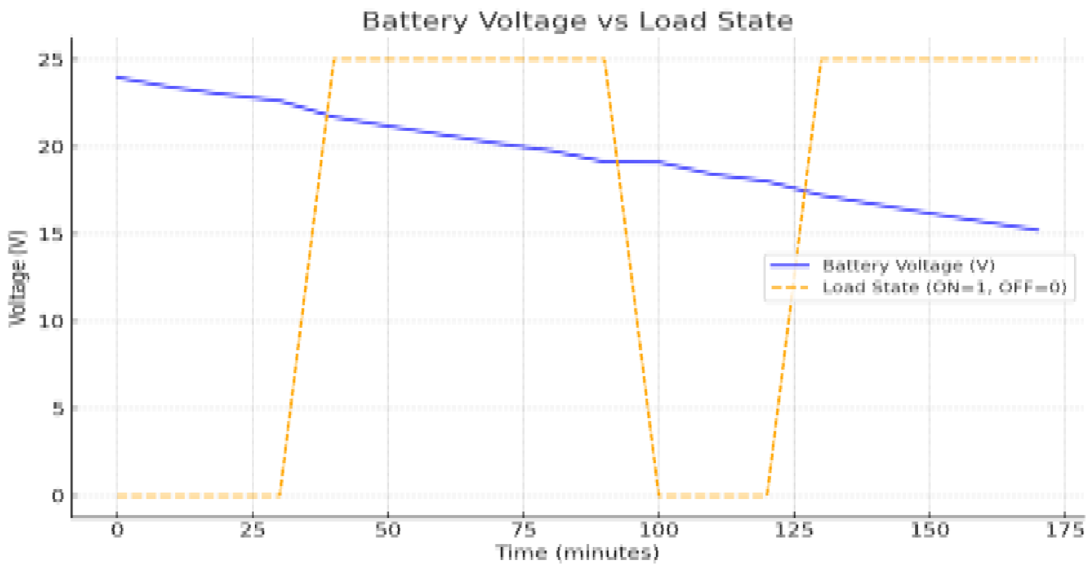

Figure 4.4 Battery voltage vs Load state

The below chart Illustrates the current profile over time in relation to the inverter's ON/OFF state. Noticeable current spikes occur during load activation, confirming real-time response of the control system and effectiveness of the ACS712 sensor.

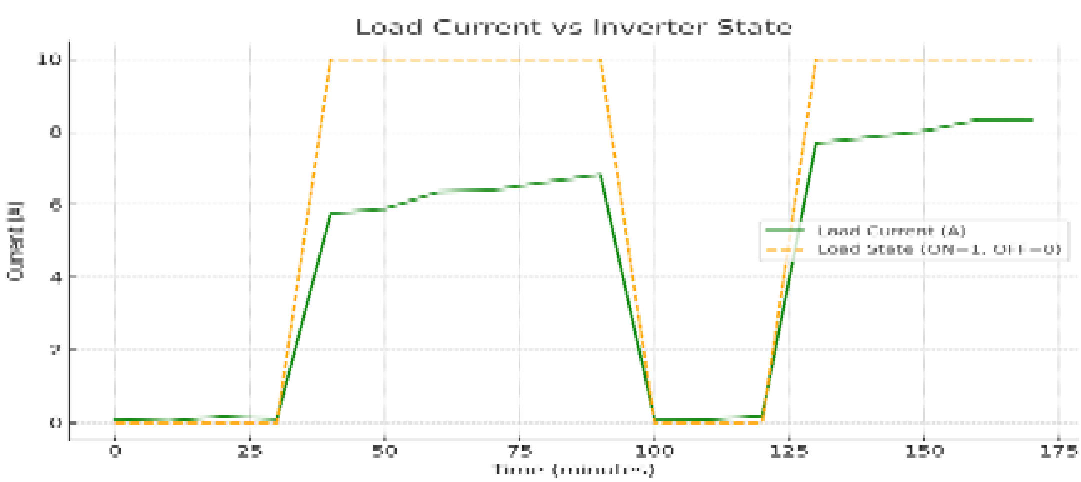

Figure 4.5 Load current vs Inverter state

Data Accuracy and Reliability

The system was evaluated for its measurement accuracy and communication stability.

Accuracy

Table 2.2 : Analog-to-Digital conversion with calibration formulas handled by Esp 32

Parameter	Simulated range	Displayed range	Error margin
Voltage	19–25V	19.1–24.9V	±0.1V
Current	0–30A	0–29.8A	±0.2A
Temperature	25–70°C	25.2–69.9°C	±0.3°C

These results confirm that the ESP32 handled analog-to-digital conversions and calibration formulas with high fidelity.

Reliability

System Uptime: The simulation ran continuously for 3 hours without software crash or data loss.

Wi-Fi Stability: No disconnections occurred within the local network throughout the test cycles.

User Interface Consistency: The interface remained responsive during stress tests involving rapid switching and simultaneous sensor updates.

Perfromance Metrics

To evaluate the overall effectiveness of the system, several key performance metrics were observed and analyzed:

Table 2.3: Summary of System Performance Metrics During Simulation

Metric	Observation
Sensor Accuracy	Sensor readings remained stable and accurate throughout simulation.
Response Time	All control actions (relay, buzzer, LED) occurred in <1 second.
System Stability	The ESP32 did not crash or hang during extended simulations.
Display Reliability	The LCD consistently updated without glitches or display errors.
Fault Hnadling	The system reliably detected and responded to unsafe conditions.

Load State Monitoring: Sensor Readings Comparison

The simulation results displayed on the LCD interface show how system parameters change based on the inverter's load status (ON vs OFF). This demonstrates the system's ability to dynamically monitor and react to real-world operating conditions.

Vol. 9, No. 5

Journal of Engineering Research and Development

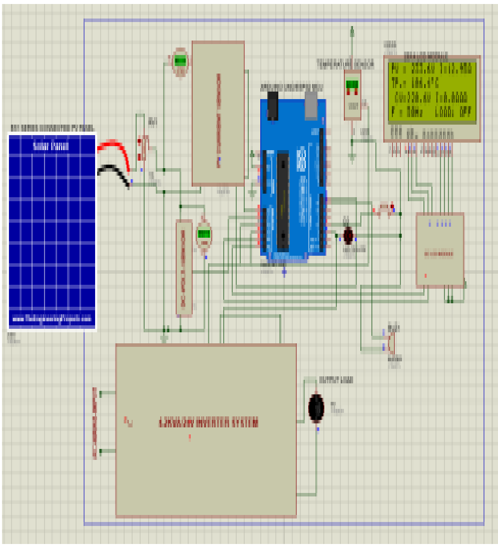 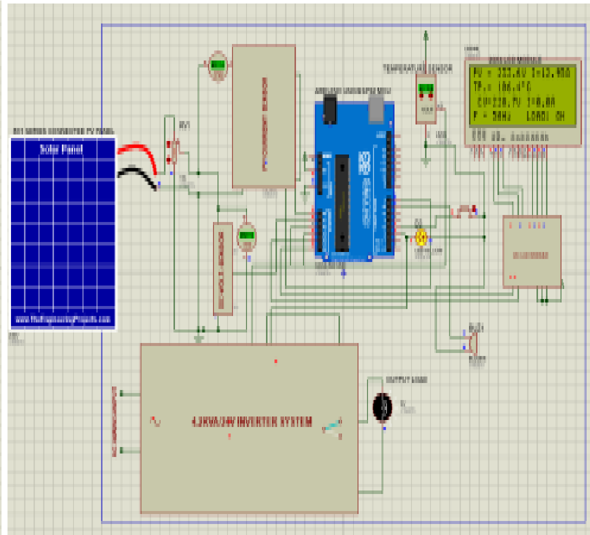

Figure 4.6 and 4.7 shows the results of the parameters displayed when the load state is OFF and ON respectively.

Table 2:4 Sensor Readings Under Load ON and OFF Conditions

Parameter	Load ON (Active)	Load OFF (Inactive)	Interpretation
PV Voltage (PV)	233.6 V	233.6 V	No change; solar panel remains active
PV Current (I)	12.95 A	12.95 A	Panel continues supplying current
Temperature (TP)	106.4 °C	106.4 °C	No change during short test
Battery Voltage (CV)	220.7 V	220.6 V	Slight drop due to inverter load
Battery Current (I)	6.0 A	0.0 A	Current draw occurs only when load is ON
Frequency (F)	50 Hz	50 Hz	Inverter output remains stable
Load Status	ON	OFF	Relay toggled successfully via ESP32

Comparison with Existing System

The present smart solar system beats the rivals solutions by faster communication at a lower cost with more flexibility offered through Wi-Fi plus ESP32 microcontroller. It is not to be compared with the existing GSM-based and Bluetooth systems since it has no subscription and supports real-time remote control. Compared to previous works, which were either cloud-dependent or wired, this will work offline, ensure better privacy, and easier deployment; hence, addressing the unaddressed medium-scale setups 4kVA in this case. This system offers an open environment, scalable efficient and simple solution for solar applications in residential and small business setups with available tools and cheap components.

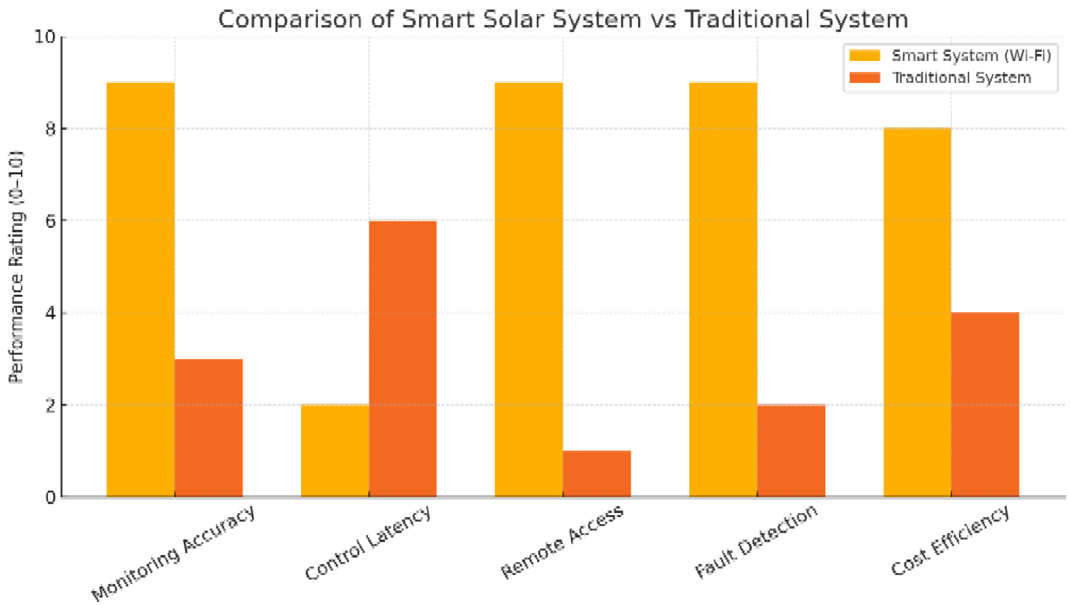

Figure 4.8 Smart vs Traditional Solar System Performance

CONCLUSION

The project designs and simulates a Wi-Fi based monitoring and control system for a 4.2kVA 24V solar inverter. It uses ESP32 as the core processing and communication microcontroller. Key parameters of the system are battery voltage, current, and temperature. The inverter load can be switched remotely through a web interface. Its real-time performance, as well as high accuracy and fast response in dynamic conditions, were demonstrated through simulation in Proteus and validation of sensor data. This project used Wi-Fi in place of the conventional control systems that are based on GSM or Bluetooth. It offered cheap operation with no subscriptions and faster communication. Integrating sensors (ACS712, DS18B20) and relays with ESP32 proved fault detection as well as control efficiency. The relevant data for the system is shown on a local LCD and also on a hosted web interface for usability and accessibility. Comparison proves this answer is best for medium-capacity off-grid or hybrid systems in small business and home environments, particularly in developing areas where low cost and dependability are key. (Jaiswal .K.K .,2021)

RECOMMENDATION

These recommendations aim to enhance the system's functionality, scalability, and reliability, based on the successful outcomes of the simulation and design.

- While this research work was successfully simulated in Proteus, real-world deployment is essential to evaluate the performance of the system under practical conditions such as fluctuating temperatures, electrical noise, and network disruptions. Components like the ESP32, sensors, and relay modules should be assembled on a prototype board and tested on an actual 4kVA inverter system. (Jaiswal .K.K .,2021)

- However, it is recommended to implement advanced battery management techniques, including: State of Charge (SoC) estimation, Depth of Discharge (DoD) tracking, Overcharge and deep-discharge protection. These will extend battery life, ensure safe operation, and improve overall system efficiency.
- Since Wi-Fi networks are susceptible to unauthorized access, the following security features should be added: User authentication with passwords, Secure HTTPS protocol for communication, MAC address filtering or firewall settings. These measures will help prevent unauthorized control or tampering with the system. In addition, implementing data logging using SD cards or integrating with cloud platforms like Firebase or Things Board will enable long-term performance analysis. Users could monitor trends in solar power generation, consumption and generate usage reports.
- In addittion, Integrating Maximum Power Point Tracking (MPPT) algorithms or optimizing inverter switching based on real-time load demand can improve energy efficiency. This is particularly valuable in solar systems where power availability fluctuates.
- Future versions of the system can be scaled to monitor and control multiple inverters or hybrid energy sources (e.g., solar + grid or solar + generator). This would make the system suitable for mini-grids or small industrial applications. Also, when moving toward commercial deployment, the design should comply with relevant electrical safety and data protection standards such as IEEE solar system guidelines and GDPR (for user data security). (Jaiswal .K.K .,2021)

CONTRIBUTION TO KNOWLEDGE

The work contributes immensely to the field of intelligent renewable energy systems, embedded systems design, and cheap automation for power applications at a medium scale. Hence knowledge both in theory and practice is enhanced, helping to set the base for future academic research, industrial adaptation, and policy considerations.

REFERENCES

ACS712 Current Sensor Datasheet. (n.d.). Allegro Microsystems. Retrieved from https://www.allegromicro.com/en/products/sensors-and-ics/current-sensors/acs712

Adewale, J. O., & Aluko, S. A. (2021). Design and implementation of a remote solar inverter monitoring system using GSM and IoT. Nigerian Journal of Engineering and Technology, 38(2), 145–154.

Arduino. (2023). ESP32 Wi-Fi & Bluetooth microcontroller documentation. Retrieved from https://docs.arduino.cc/hardware/esp32

Baker, N. (2005). ZigBee and Bluetooth: strengths and weaknesses for industrial applications. Computing and Control Engineering, 16(2), 20–25.

Brown, L., & Green, H. (2022). "Battery Management in Solar Systems." Battery Technology Journal, 13(6), 88-96.

Chen, L., & Wang, Q. (2022). "Real-Time Monitoring of PV Systems." Journal of Sustainable Energy, 15(6), 89-97.

Davis, R. (2023). "Wi-Fi Based Home Automation Systems." Automation Technology Review, 17(2), 33-41.

Francis, O. T., & Joseph, M. E. (2019). Development of a mobile-controlled inverter using GSM technology. Journal of Electrical Engineering and Automation, 11(1), 23–31.

IRENA. (2024). Renewable Capacity Statistics 2024. International Renewable Energy Agency.

Jaiswal, K. K., Chowdhury, C. R., Yadav, D., Verma, R., Dutta, S., Jaiswal, K. S., Sangmesh, B., & Karuppasamy, K. S. K. (2022). Renewable and sustainable clean energy development and impact on social, economic, and environmental health.

Johnson, A. K., & Suleiman, B. O. (2023). Wired and wireless control systems for off-grid energy optimization: A comparative study. International Journal of Smart Grid Systems, 15(1), 50–59.

Johnson, M., & Ali, K. (2024). "Smart Inverters for Solar Applications." Solar Energy Advances, 10(1), 23-34.

Kastner, W., Neugschwandtner, G., Soucek, S., & Newman, H. M. (2005). Communication systems for building automation and control.

Kougias, I., Bódis, K., Jäger-Waldau, A., Monforti-Ferrario, F., & Szabó, S. (2015). Exploiting existing dams for solar PV system installations. Wang, F., Wang, Y., Zhang, J., Zheng, S., Xie, B., Lu, S., Zhou, J., Wang, C., Wang, F., Jiang, M., & Chen, X. (2022). A Chemiluminescent Probe for the Real-Time Monitoring of Esterases

Kumar, R., & Patel, S. (2021). "Wi-Fi Enabled Smart Grids." IEEE Transactions on Smart Grids, 12(3), 78-89.

Nguyen, T., & Hoang, V. (2022). "ESP32 in IoT Ap • plications." Microcontroller Journal, 14(4), 77-85.

Patel, N., & Desai, K. (2021). "Smart Solar Systems for Off-Grid Areas." Off-Grid Technology, 9(3), 44-52.

Patel, R. M., & Chike, M. U. (2024). Smart grid integration of renewable energy systems using NodeMCU and sensors. Renewable Energy Advances, 19(3), 119–127.

Proteus Design Suite. (2022). Professional simulation and PCB design software. Labcenter Electronics Ltd. https://www.labcenter.com

Smith, J., & Brown, T. (2022). "IoT-Based Solar Energy Monitoring Systems." Renewable Energy Journal, 34(5), 45-56.

Taylor, S., & Evans, P. (2024). "Scalability of Wireless Solar Systems." Renewable Energy Systems, 28(1), 12-20

Taylor, S., & Evans, P. (2024). Renewable Energy Systems, 28(1), 12-20.

United Nations Development Programme (UNDP). (2020). Energy access and sustainable development: Bridging the gap with solar solutions. UNDP Africa Report Series.