


Development of a smart cloud-based monitoring system for solar photovoltaic energy generation

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ABSTRACT

The main controllers overseeing both solar panels and loads have all panels connected with sensors. The radiation striking the solar cell determines the power produced and real-time monitoring is crucial to evaluating the performance of a solar photovoltaic system. The emerging Internet of Things provides an opportunity to significantly enhance the monitoring of solar energy output and plant operations. To achieve this, a remote monitoring system is necessary, utilizing the Internet of Things to gather and transmit data. This study aims to utilize the Internet of the Things to monitor solar photovoltaic systems and assess their effectiveness. The monitoring system includes components such as a data gateway, data collection, and presentation for a cloud application. The collected data were stored in the cloud, enabling a visual representation of the sensed parameters. The system achieved a better accuracy rate, with an average transmission time of 53.01 s. The results indicate that the recommended monitoring system allowed users to observe current, voltage, and daylight, which could serve as a viable substitute for smart monitoring of solar energy output and plant operations.

1. Introduction

Access to energy is a fundamental need in the modern world, supporting various aspects of daily life such as home appliances, public transit, lighting, heating, and refrigeration. The demand for energy is increasing rapidly, but conventional sources are depleting simultaneously. Power generation involves both renewable and non-renewable sources such as coal and natural gas with renewables including solar and wind power [1]. Solar energy, often considered an inexhaustible power source, has gained significance globally. Developed countries, in particular, have witnessed substantial growth in their solar energy sectors, surpassing their targets and aiming for further expansion. As of 2024, global solar energy utilization continues to grow rapidly. China leads with an installed solar capacity exceeding 509 GW, maintaining its position as the global leader in solar power. The United States follows in second place with over 149 GW of installed capacity. Germany ranks third with approximately 91 GW, while Japan is fourth with 84 GW. India is in fifth place with a capacity of over 77 GW, reflecting substantial growth in recent years [2].

Solar energy is primarily harnessed through photovoltaic (PV) systems using solar panels to convert sunlight into electricity. However, the unpredictability of solar energy production due to factors like sunlight intensity, angle, temperature, weather, and dust poses challenges [3]. To ensure the reliability of electricity transmission, routine monitoring is essential. Conventional monitoring techniques, such as manual remote wired monitoring and inquiry, have drawbacks like being time-consuming and challenging. To address issues of inadequate power and ensure efficient monitoring, the IoT has been employed to create a solar power monitoring system. The IoT, a network of physical items with sensors, electronics, and network connectivity, offers an innovative solution to conventional monitoring techniques. It enhances efficiency, accuracy, and economic benefits by enabling remote sensing and control, overcoming challenges associated with manual monitoring. The IoT, with its ability to connect and control devices remotely, provides a more effective solution. It enables quick with easy interaction with PV systems in remote areas, assuming the limitations of human inspection [4].

Solar energy has gained widespread popularity due to advancements

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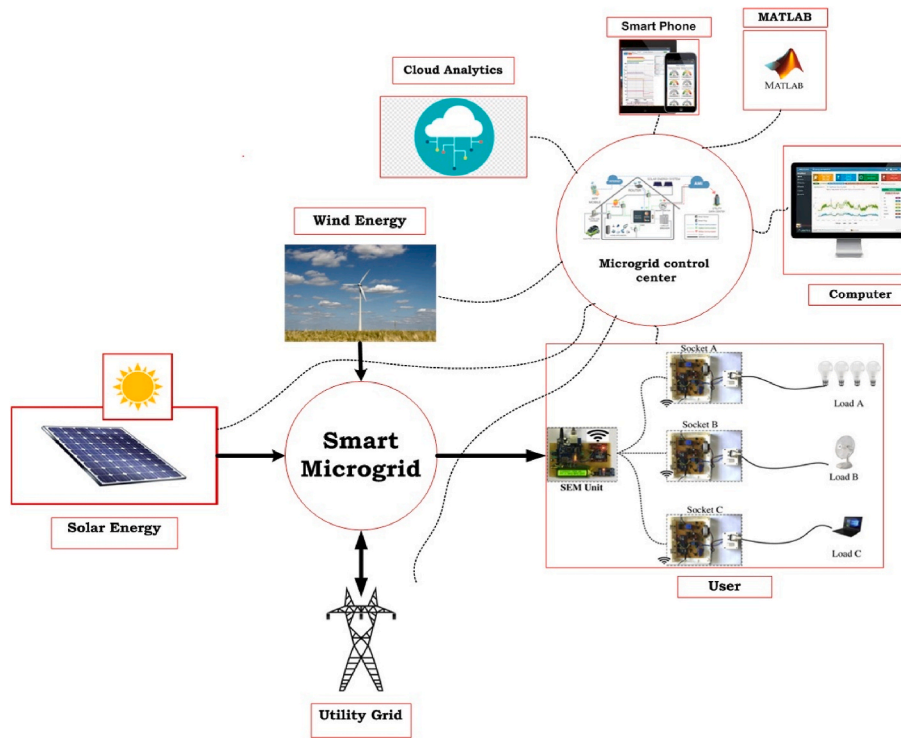


Fig. 1. Intelligent smart energy management system.

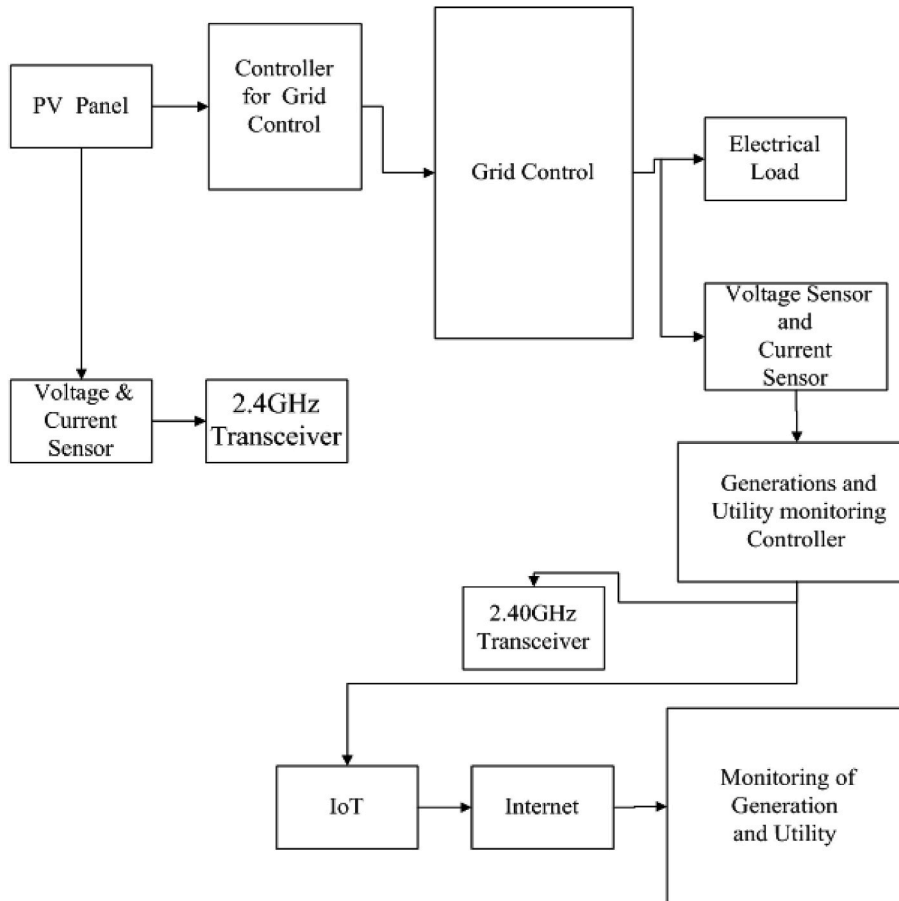


Fig. 2. Block diagram of solar PV power monitoring System with IoT [2].

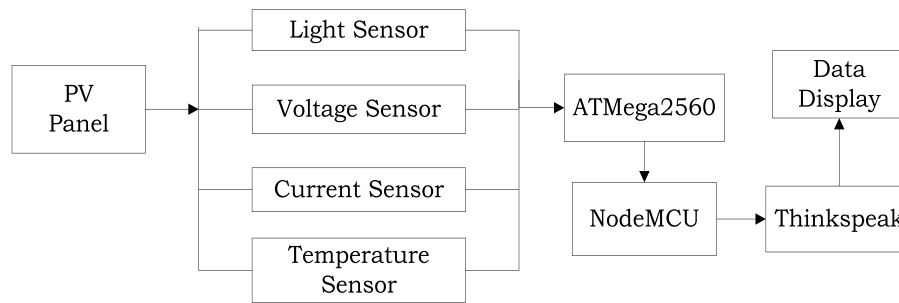


Fig. 3. IoT-connected PV monitoring system.

in photovoltaic and thermal technologies, further enhanced by the integration of IoT solutions. PV systems, utilizing the photovoltaic effect, directly convert sunlight into electricity, while IoT-enabled solar systems employ sensors and connected devices to monitor and optimize performance in real time. These systems track parameters such as voltage, current, temperature, irradiance, and panel alignment, enabling predictive maintenance and efficient energy management [5]. Incorporating the IoT into solar systems provides significant cost advantages. Real-time monitoring reduces maintenance expenses by detecting faults early and minimizing downtime. IoT platforms also enable detailed energy usage and production analysis, helping optimize energy consumption and storage. Over time, these efficiencies lower operational costs and improve the return on investment (ROI) for solar installations. Additionally, IoT analytics can assess cost-performance ratios, considering factors like solar panel efficiency, installation costs, and energy savings, ensuring that solar energy systems remain cost-effective and sustainable. By adapting to geographic and environmental conditions, IoT-based solutions further enhance energy generation, making solar power an economically viable choice for households, businesses, and communities as in Fig. 1.

This study discusses the growing need for energy, the significance of solar power, India's progress in the solar energy sector, challenges in photovoltaic systems, and the application of the Internet of Things to enhance solar power monitoring. Fig. 2 illustrates a block schematic of the proposed IoT-based monitoring system [6]. The IoT represents a transformative technological paradigm, significantly enhancing the quality of life through intelligent connectivity. By leveraging IoT, machines can seamlessly connect to the cloud, enabling efficient data exchange among devices across the globe.

This network of web-enabled gadgets facilitates communication without human intervention; making it a crucial technology for solar power monitoring systems [7]. This requires a robust system for data processing, which is where the IoT comes into play. The IoT facilitates remote, real-time monitoring of solar panels, enabling efficient data collection and analysis [8]. The proposed approach leverages sensors to track various performance indicators, providing valuable insights into the operational status of solar panels for improved management and energy optimization. LCDs display information about current voltage, temperature, and power. The sensors are connected to an IoT device, establishing a functional remote network monitoring system [9].

The paper is structured into five main sections. Sections I and II provide an overview of the field, while Section III summarizes the existing literature. Section IV describes the suggested work, and Sections V and VI discuss the findings and conclusions.

The main objective of this article is to increase the efficiency of solar panel electricity generation by utilizing sensors within the IoT framework. These sensors monitor and display crucial properties such as voltage and current, providing notifications in case of any performance issues with the solar panels [10]. The system described in this work not only measures the solar radiation received by the solar PV panel but also monitors other factors, including voltage, current, and temperature [11]. To gather this data, an Arduino microcontroller was employed,

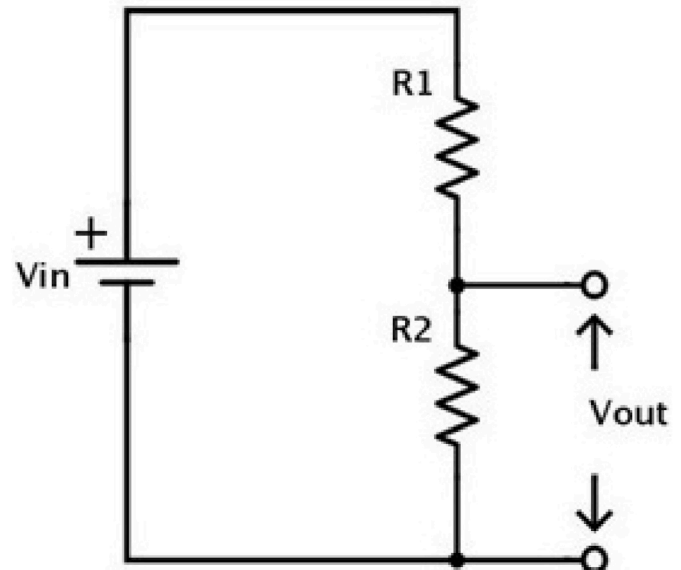


Fig. 4. Potential divider.

and a NodeMCU ESP8266 wireless transmitter was used to upload data to the internet. The open-source IoT cloud platform, Thinkspeak, was chosen to create and build the IoT system for monitoring solar power installations, allowing remote access via an internet connection [12].

For data acquisition, a PV system comprising a solar charge controller and a monocrystalline solar photovoltaic panel was used. The panel had a maximum output voltage, current, and power of 18.0 V, 5.560 A, and 100 W, respectively. To sense the solar PV voltage, a voltage divider circuit with specific parameters was implemented, resulting in a calculated sensor output voltage [13]. The wireless transceiver employed in this system was an ESP8266, while the microcontroller used was an Arduino ATmega2560. Thinkspeak served as the selected IoT platform, facilitating the creation of a comprehensive system for monitoring solar power installations and enabling remote access and display of the collected data as in Fig. 3. Fig. 4 illustrates the voltage divider circuit utilized in the solar PV voltage sensing process [14].

$$V_{out} = V_{in} \times \frac{R_2}{R_1 + R_2}$$

In the monitoring system, a Hall effect-based current sensor of type ACS712 is employed to measure the current flowing through the circuit. The ACS712 operates in a magnetic field perpendicular to the conductor carrying the current, causing the Hall Effect. The Hall Effect sensors detect magnetic fields by measuring the voltage generated when a magnetic field interacts with a current-carrying conductor. This voltage, called the Hall voltage, is proportional to the magnetic field strength. These sensors are widely used in position sensing, current measurement, speed detection, and proximity sensing applications [15]. It has a total

output error of 1.5 percent and a maximum accuracy range of 30 A. To gauge the panel temperature, an LM35 temperature sensor is utilized, which operates at a low current of approximately 60 A and provides precise readings across the temperature range of 0–100 °C. Additionally, a light intensity sensor measures the amount of sunlight striking the panel. Calibration of all sensors with appropriate standards was initially conducted to ensure accurate data gathering [16].

The performance of the PV system is measured over three days, each lasting 10 h (from 7:00 to 19:00). The PV system is installed on top of a building, receiving direct sunlight with minimal interference from surrounding shadows. The system is permanently oriented towards the northern sun at a 300-degree angle, without the use of a solar movement tracker. The microcontroller responsible for collecting and processing sensor data is an Arduino built ATmega2560. The Arduino uses a serial communication protocol to transmit the data to the NodeMCU Wi-Fi module [17].

1.1. Arduino Uno

One of the key components in the monitoring system is the Arduino Uno, featuring ATmega328P microcontroller chipboard with a USB connection. The additional characteristics of the Arduino Uno, including a power connector, reset button, and a crystal oscillator running at 16.0 MHz the Arduino IDE controls the 14 digital input and output pins and 6 analog input and output pins, requiring 5 V to function. The microcontroller encompasses all the necessary features for efficient operation [18].

1.2. PV panels

Photovoltaic panels, commonly known as solar panels consist of multiple individual solar cells, typically composed of materials such as silicon, phosphorous, and boron. The integration of these components allows solar panels to harness energy from the sun by capturing local electrons and photons [19]. The generated power can be utilized for various applications and purposes.

1.3. Regulated power supply

The rectifier integrated circuit plays a crucial role in converting an alternating current source into direct current. This process ensures a stable voltage for devices that rely on a constant power source [20]. Although the output of the regulated power source can be either unidirectional or alternating, it typically remains within the range of DC. Often referred to as a linear power supply, this type of DC power source is commonly utilized in various applications.

1.4. ESP8266 module

The arrangement incorporates the ESP8266 module which serves to connect the microcontroller a Wi-Fi network through a microprocessor TCP/IP protocol stack. Equipped with sufficient onboard computing power and storage, the ESP8266 can effectively communicate with various sensors and devices. However, it is important to note that an external logic level converter is required, as the module cannot shift from 5V to 3V [21]. This external converter ensures seamless compatibility in voltage levels within the system.

1.5. Voltage sensor

The system integrates a voltage sensor designed to capture and monitor electrical signals at various levels. This sensor is pivotal in detecting and measuring both AC and DC voltage magnitudes within the system. In addition to voltage detection, it offers versatile output options, including switches, analog voltage signals, and current signals, making it a multifunctional component for system operations [22].

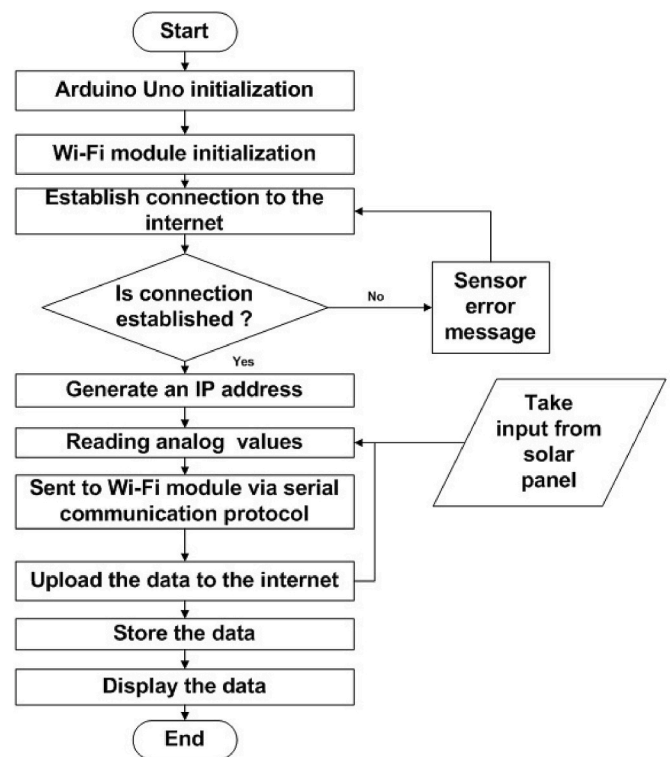


Fig. 5. PV monitoring system procedure using IoT.

1.6. Current sensor

This tool serves as a detector for electrical current flow within materials, presenting in analog or digital form. An ammeter is employed to measure the current using these signals, allowing for an accurate assessment of the current flowing through the system or material under consideration [23].

1.7. NodeMCU

To execute IoT operations, a microcontroller is essential, and it works in conjunction with the Wi-Fi module. The microcontroller transmits data to a predetermined network server using a dedicated Wi-Fi connection. NodeMCU is a development board that integrates various I/O ports, functioning as a microcontroller connection board. It relies on the Wi-Fi module and has been programmed using the Arduino Uno environment [24]. While the microcontroller is capable of performing various calculations, it specifically handles communication tasks related to Wi-Fi.

1.8. LCD

For presenting data across various devices and circuits, a liquid crystal display (LCD) is a commonly used technology. Typically, LCDs operate based on light. The specific display used in this system is a 16x2 type, indicating that it can show 16 characters across 2 lines [25]. LCDs consist of both liquid and solid components. Visual images on the screen are created using liquid crystals in order to provide a clear and legible display [26].

2. Hardware implementation of system

In this study, the open-source IoT cloud platform application Thingspeak is utilized. This program employs the HTTP protocol to collect and store sensor data online. The Arduino board connected to the Wi-Fi module uploads the sensor data to the cloud. Users can access a

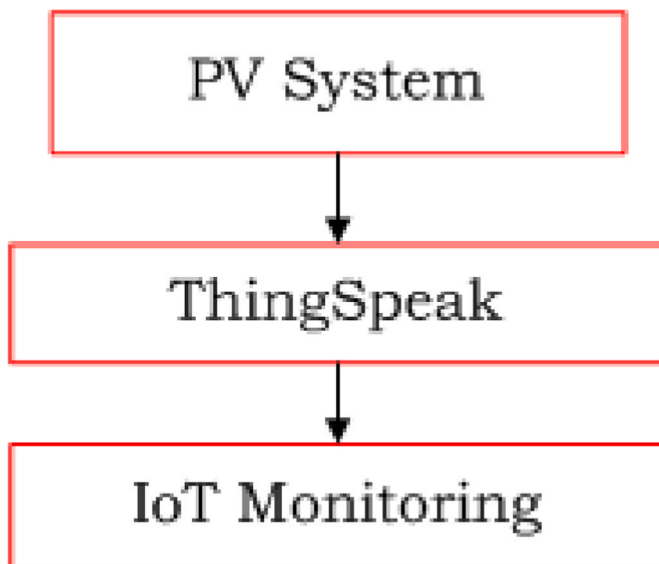


Fig. 6. IoT with ThingSpeak.

status application where all the data gathered from the sensors are continually updated. To utilize these functions, users are required to create an account with a unique IP address, providing access to multiple channels for tracking various characteristics of the system. Fig. 5 presents the data gateway system flowchart diagram, illustrating the flow of information within the system.

With internet-based monitoring, the user of the platform might display the data graphically and it would be simple to access via an online interface. This technology's key advantage is that it makes it simple to check output values from solar PV panels from any where with an internet connection.

3. Photo Voltaic power monitoring system

Users can access data instantly from PCs, cell phones, and other devices through the Thingspeak IoT platform, utilizing the data generated by the platform via the Thingspeak website (<https://thingspeak.com>). To enhance convenience and ease of access to the data, a smart-phone application model has been developed. This application allows users to view data from up to four sensors simultaneously, providing a more visually appealing representation of the information.

3.1. IoT architecture using ThingSpeak cloud service

The Internet of Things (IoT) architecture provides a framework for connecting various devices and sensors to collect, analyze, and exchange data. In the context of a Photovoltaic system, IoT can optimize the monitoring and management of solar energy production as in Fig. 6. ThingSpeak, an open-source IoT platform, is widely used to support such systems by enabling real-time data collection, storage, and analysis. In an IoT-based PV system, sensors installed on solar panels or other components gather crucial data such as energy production, temperature, voltage, and efficiency. This data is sent to the ThingSpeak cloud platform, where it is stored and analyzed. ThingSpeak offers powerful visualization tools, allowing users to monitor energy output and performance metrics in real-time. Additionally, machine learning models can be applied to predict maintenance needs, optimize energy consumption, and improve overall system performance. Using ThingSpeak in a PV system helps ensure reliable monitoring, efficient energy management, and proactive maintenance, making it an ideal cloud service for enhancing the performance of solar energy systems.

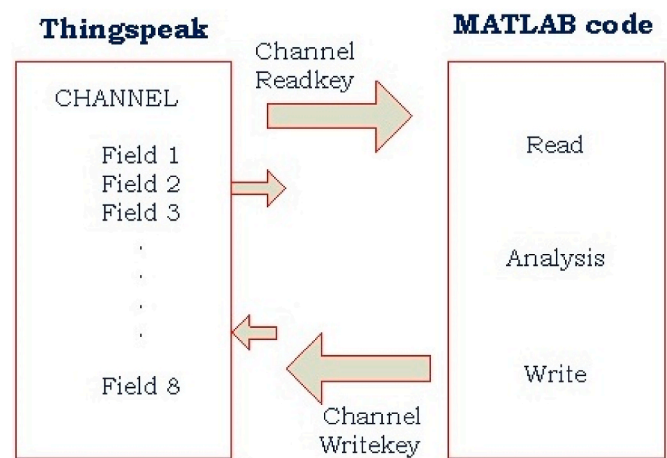


Fig. 7. ThingSpeak and MATLAB configuration diagram.

3.2. ThingSpeak integrates with MATLAB

The architecture of an IoT-based solar power monitoring system using the ThingSpeak cloud service is designed to efficiently collect, process, and analyze data from solar panels and associated equipment. In this system, IoT devices such as solar irradiance sensors, temperature sensors, voltage sensors, and current sensors are deployed to monitor various parameters of the solar power generation process. These sensors gather data from the environment, such as the amount of sunlight, the temperature of the panels, and the electrical output. The collected data is then periodically sent to the ThingSpeak platform over the internet using communication protocols like HTTP, MQTT, or RESTful APIs.

A gateway or the IoT devices themselves transmit the sensor data to ThingSpeak using internet connections like Wi-Fi, Ethernet, or cellular networks, ensuring seamless and reliable data transfer to the cloud as in Fig. 7. ThingSpeak serves as the central platform that receives, stores, and organizes this incoming data in a time-series database. It provides a REST API for communication between the devices and the cloud, enabling real-time monitoring of solar power system performance. ThingSpeak also offers visualization tools, such as live graphs and customizable dashboards, allowing users to view and analyze real-time data from the solar panels and equipment, including energy production, efficiency, and system health.

ThingSpeak integrates with MATLAB to provide advanced data processing and analytics. MATLAB can retrieve the stored data from ThingSpeak via its API and perform detailed analysis, such as calculating power generation efficiency, detecting anomalies, or predicting future performance based on historical data. MATLAB scripts can be triggered by specific conditions, such as a sudden drop in power output, to run predictive models or perform fault detection in the solar power system. Additionally, ThingSpeak supports setting up alerts and automation based on predefined conditions, such as triggering an alert if the solar power output falls below a certain threshold or if the temperature of the panels exceeds safe operating limits. MATLAB can further enhance these alerts by creating advanced logic for taking corrective actions, such as sending notifications to the user or activating actuators to optimize system performance. ThingSpeak also allows integration with external applications, APIs, or services to extend the system's capabilities, such as integrating with smart home systems or energy management platforms. This architecture ensures that solar power systems are efficiently monitored and managed in real-time, providing users with valuable insights into their energy generation and consumption, while also enabling proactive maintenance and optimization.

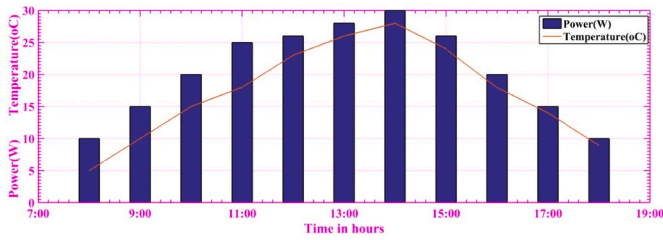


Fig. 8. PV performance of PV power versus temperature.

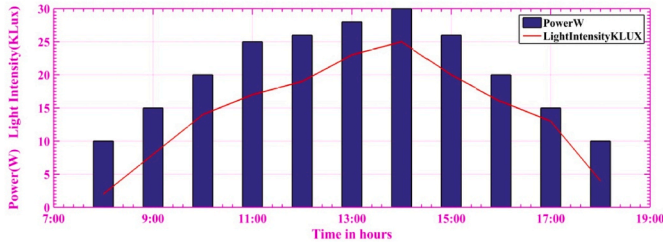


Fig. 9. PV output against light output.

4. Results and discussion

The findings of this study are categorized into two sections: PV system performance and monitoring performance. In this model, sensors measure current and voltage readings as solar panels convert light energy to electricity. The received voltage and current information are displayed on the LCDs using the IoT. To enable wireless access to this information, the sensors are connected to a Wi-Fi module, allowing users to confirm the data on their mobile devices through a Wi-Fi network. This real-time updating feature ensures that any change in the measured data is promptly reflected on the user’s mobile device. The integration of IoT technology enables the monitoring of solar panel performance, providing a mechanism to identify and troubleshoot issues if they arise.

4.1. PV system performance

The performance of the PV model was evaluated during a period spanning from 7:00. to 19:00. over three days, totaling 30 h. During this time, readings were taken for current, voltage, temperature, and light intensity sensors. The Watt unit, employed in equation $P = V \times I$ is used to calculate power based on voltage and current values, which played a central role in the assessment. Additionally, measurements of the panel temperature and light intensity were taken to compute the

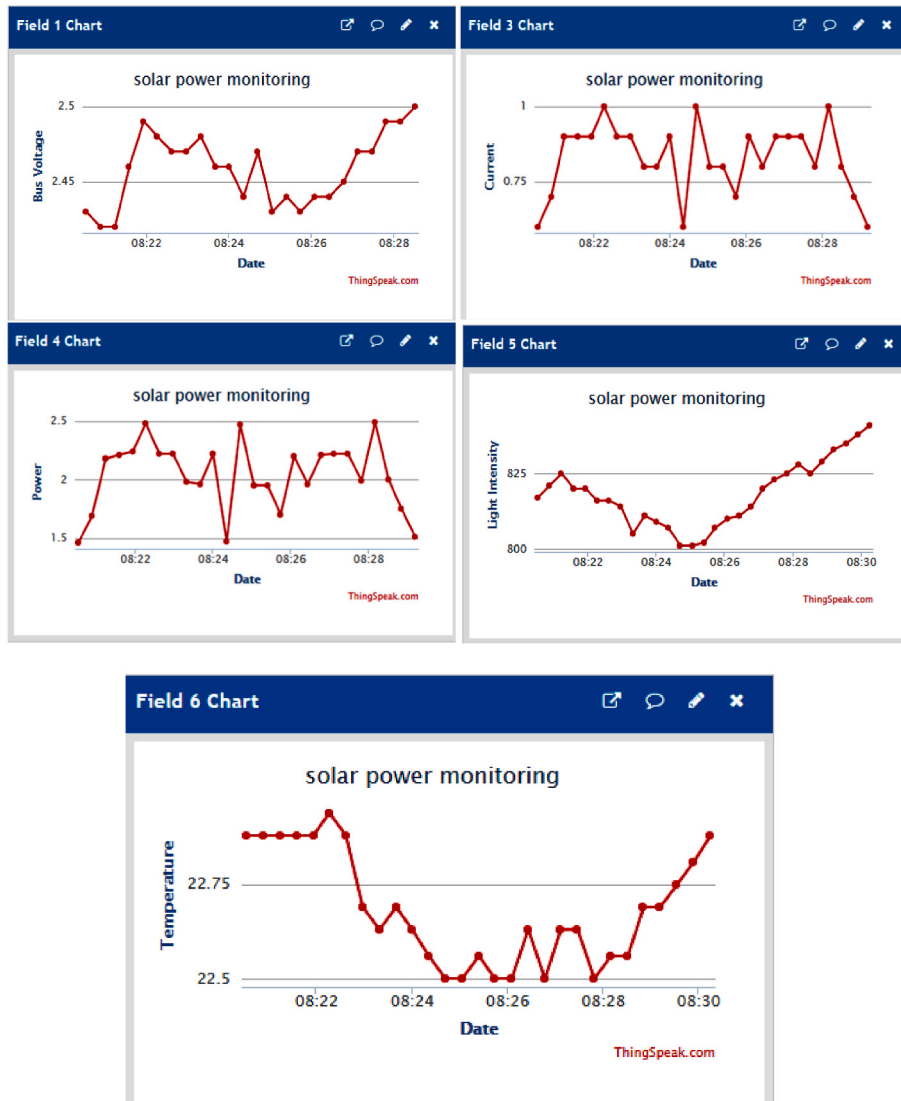


Fig. 10. PV monitoring system parameters in Thinkspeak.

environmental contribution to overall power production. Fig. 8 provides a comparison of the impacts of both power and Temperature, offering insights into the relationship between these variables in the PV system's performance.

Over a three-day period, the power output reached its peak at 14:00, registering a value of 29.85 W. Simultaneously, the peak temperature recorded at that time was 28.19 °C. The graphical representation indicates a discernible correlation between the power output and the panel temperature. It is noteworthy that the amount of sunlight received in a specific area, or the increase in solar irradiation, may influence the temperature. However, changes in solar flux have minimal impact on the output voltage and current of a solar panel because of its relationship with solar irradiation. This characteristic could potentially enhance the output power of the photovoltaic system.

4.2. PV monitoring system performance

The PV panel monitoring model is facilitated through both the PV monitor application and the Thinkspeak website, as recommended in this work. It is demonstrated that the data presented is consistent across both approaches. Fig. 9 illustrates a comparative analysis of the effects of both irradiance (light intensity) and power output, offering a detailed understanding of the relationship between these parameters in the photovoltaic (PV) system's performance.

The graph quantitatively represents how variations in solar irradiance directly impact the electrical power generation, thereby highlighting the system's responsiveness to changes in environmental conditions. This visual correlation provides insights into the system's efficiency and its ability to optimize power conversion under varying light intensity levels, enabling more accurate performance modeling and prediction of energy output. Numerical values are simultaneously displayed online, as illustrated in Fig. 10. The PV Monitor program offers users the flexibility to choose which data should be visible while concealing the rest.

The efficiency of the PV monitoring method was assessed by examining the time it took for the data to traverse various stages, including data collection, the data gateway, the program for presentation, and ultimately reaching the data destination. The average transmission duration was determined to be 53.02 s, with the shortest and longest transmission times recorded at 29 and 100 s, respectively. This evaluation provides insights into the speed and effectiveness of the data transmission process within the monitoring system.

5. Conclusion

The proposed approach involves regular adjustments to the voltage and current settings while continuously storing the latest data. This method facilitates convenient and straightforward daily or monthly monitoring of the solar photovoltaic system. By consistently observing the solar panels, operating at their optimal efficiency, it becomes possible to promptly identify any system defects. An Internet of Things implementation designed for monitoring solar PV plants comprises three main components: data collection, a data gateway, and a display integrated into a smartphone app. The accuracy of the data collection achieved was impressive, with an average data transmission time of 53.02 s to the smartphone application in graphical form. These results strongly suggest the effectiveness of the proposed monitoring approach, supporting both local and remote monitoring of a solar PV system.

CRediT authorship contribution statement

Challa Krishna Rao: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sarat Kumar Sahoo:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation.

Franco Fernando Yanine: Writing – review & editing, Writing – original draft, Supervision, Resources, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Harnessing solar energy efficiently requires continuous monitoring and analysis of critical parameters such as solar irradiance, panel temperature, voltage, and current. This guide provides a step-by-step process to set up a solar monitoring system using ThingSpeak, an IoT analytics platform, along with hardware like Arduino or Raspberry Pi. By integrating sensors, ThingSpeak, and MATLAB, you can collect, visualize, and analyze real-time data to optimize your solar power system. From configuring ThingSpeak channels to creating alerts and automating actions, this setup ensures efficient performance and ease of maintenance.

Step 1. Set up ThingSpeak account and channel

Create a ThingSpeak account: Go to ThingSpeak and create an account or log in if you already have one.

Create a New Channel: After logging in, click on "Channels" and then "New Channel."

Add fields for each parameter you want to monitor:

Field 1: Solar irradiance.

Field 2: Panel temperature.

Field 3: Voltage.

Field 4: Current.

Enable the "Public" or "Private" setting depending on preference.

Save the channel, and a Channel ID and write API key be sent.

Configure the ThingSpeak API: 7J8W7O53KPCJZVIZ.

Note down the write API key provided for your channel. This will be needed to send data to ThingSpeak.

Step 2. Set up the hardware

Connect the sensors:

Use sensors like a solar irradiance sensor (BH1750), temperature sensor (eDHT22), voltage sensor, and current sensor.

Connect these sensors to an Arduino or raspberry Pi and wire them correctly for reading data.

Set up the gateway:

Use a Wi-Fi module like ESP8266 or ESP32 with the Arduino or raspberry pi to send data over the internet.

Install required libraries:

For arduino, install the following libraries through the Arduino IDE: WiFi.h for Wi-Fi connection (for ESP8266/ESP32)

ThingSpeak.h for communication with the ThingSpeak platform.

Step 3. Upload the Arduino code

Write and upload the code:

Open the Arduino IDE and write the provided Arduino code. The code collects data from the sensors and sends it to ThingSpeak.

Modify the code to use your Wi-Fi credentials, ThingSpeak Channel ID, and write API key.

Upload the code to Arduino:

Upload the code to your Arduino or ESP32/ESP8266 board.

Open the serial monitor to check if data is being sent successfully to ThingSpeak.

Step 4. Monitor data on ThingSpeak

Check data on ThingSpeak:

After uploading and running the code, go to your ThingSpeak channel.

The data is seen coming in real-time, with graphs displaying values for solar irradiance, panel temperature, voltage, and current.

Visualize the data:

Use Thingspeak's built-in charting and graphing tools to visualize the real-time data from the sensors. The dashboards can be established and create multiple widgets for easy monitoring.

Step 5. Set up MATLAB for data analysis

Access ThingSpeak MATLAB analysis:

In the ThingSpeak interface, go to the "Apps" section and select MATLAB Analysis.

Write MATLAB code for data analysis:

Use the MATLAB code provided to perform advanced analytics on the incoming data. This could include calculations for power output, detecting anomalies, and sending alerts.

Modify the MATLAB script, if needed, such as by adjusting thresholds for alerting or refining the analysis.

Run MATLAB script:

Run the MATLAB script to analyze the solar power data stored in your ThingSpeak channel.

This will perform calculations such as power output (voltage * current), check if values fall below thresholds, and send alerts.

Step 6. Set up alerts and automation

Create alerts in ThingSpeak:

ThingSpeak allows email or SMS alerts to be setup when certain conditions are met (when power output falls below a threshold).

Go to the Alert section in ThingSpeak to configure these notifications.

Set up automation in MATLAB:

We can use MATLAB to automate actions like triggering emails, activating actuators, or sending alerts based on the analysis.

Use send mail or integrate with other services to notify users or take corrective actions if certain conditions are met.

Step 7. Integrate with external systems

External integration:

If additional features are needed (integrating with smart home systems or other APIs), ThingSpeak allows you to connect external applications or services via REST APIs or web hooks.

MATLAB can be used to interface with external systems as well, such as controlling devices or fetching additional data.

Step 8. Monitor and maintain the system

Regular monitoring:

Continuously monitor the system through Thingspeak's dashboards and MATLAB analytics to ensure the solar power system is performing optimally.

Maintenance:

Periodically check the sensor connections and ensure the gateway is functioning correctly to maintain consistent data flow.

Refine MATLAB scripts as necessary to improve analytics or automate more actions.

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