J. Inst. Eng. India Ser. B
https://doi.org/10.1007/s40031-024-01078-z

ORIGINAL CONTRIBUTION

Design and Construction of a Photovoltaic Monitoring System Based on Wireless Sensor Networks and Internet of Things Technology

Oluwaseyi A. Ilori[1] · Alexander A. Willoughby[1] · Oluropo F. Dairo[2] · Ayodele O. Soge[1]

Received: 4 January 2023 / Accepted: 11 May 2024

Abstract Poor monitoring of a photovoltaic (PV) system is responsible for undetected faults that reduce the energy produced by the system and in the long run, decrease its lifespan. However, this challenge can be overcome by live monitoring of the electrical and environmental parameters of the PV system. Several wireless real-time monitoring systems are available, but none have a backup storage device and can only monitor a few parameters at a relatively high cost. Besides, these systems cannot monitor the battery storage and the inverter output. In this paper, we report a robust monitoring system developed for both local and remote live monitoring of a PV system. The electrical and environmental parameters of the PV system were monitored and saved using wireless sensor networks and Internet of Things (IoT) technology. This was achieved using two Atmega 328P microcontrollers, which formed the data acquisition units, and an ESP32 microcontroller for the master terminal unit. The data acquisition unit consists of two nodes: the PV node, and the battery node. All data are received by the master terminal unit and sent to the ThingSpeak online server using the IoT capability of the ESP32 microcontroller. The developed system was installed in a 12 V, 200 W standalone PV system, and all desired parameters were successfully monitored, logged, and transmitted to the cloud in real-time for easy accessibility by the users via the internet.

✉ Ayodele O. Soge
sogea@run.edu.ng; ayosoge@gmail.com

[1] Department of Physical Sciences, Faculty of Natural Sciences, Redeemer's University, PMB 230, Ede, Osun State, Nigeria

[2] Department of Electrical and Electronic Engineering, Faculty of Engineering, Redeemer's University, PMB 230, Ede, Osun State, Nigeria

Keywords PV monitoring system · Wireless sensor network · Microcontroller · Internet of things · Data acquisition · Solar energy

Introduction

Solar energy is one of the most environmentally friendly kinds of energy which has received increased attention in recent years from individuals, organisations, and governments owing to an urgent need for carbon dioxide levels in the atmosphere—the major contributor to global warming [1]. The utilisation of fossil fuels to generate electric power is a major source of carbon dioxide. A better alternative is the use of photovoltaic cells, commonly known as solar photovoltaic modules for converting the sun's energy into electrical power. The worldwide use of solar panels as an alternate electricity generation source has increased rapidly, partly due to the fall in the price of setting up a photovoltaic system and strict government policies. Although solar panels provide clean and relatively cheap energy, their conversion efficiency is still low and lies between 15 and 20%. Solar panels are exposed to harsh weather conditions and can easily develop faults that affect their output power [2]. It is also easily affected by the level of radiation from the sun and other meteorological factors such as temperature, cloud cover, dust, solar hours, solar angle, wind speed, and relative humidity [3, 4]. Therefore, it is vital to track how much power is produced at any given time by real-time monitoring. In a PV installation, a photovoltaic monitoring system measures and analyses several parameters such as voltage, current, temperature, solar irradiation, etc. Using this information, the user can evaluate the PV system's performance and detect any fault or abnormality that may reduce the energy production levels [5].

Solar panels are commonly installed on rooftops, elevated platforms, and over large expanses of land. This setup can make monitoring difficult, resulting from complicated wiring procedures, which could lead to additional expenses. As a result of this, many PV systems are not adequately monitored. Poor monitoring has led to undetected faults in PV systems which cause a reduction in the energy produced by the system and in the long run damage or reduce the lifespan of the system. To overcome this challenge, wireless monitoring needs to be implemented to properly monitor the PV system.

The primary purpose of monitoring is for early and accurate fault detection. All operating parameters must be accurately measured and readily available to achieve this. The solar PV monitoring system design can be divided into three levels: data collection, data processing, data presentation, and storage. One major characteristic of a wireless monitoring system is that data transfer from the data acquisition stage to the data processing stage is wireless. A wireless sensor network (WSN) is a system consisting of radio frequency (RF) transceivers, sensors, microcontrollers, and power sources. WSNs play an essential role in several applications, such as disaster management, environmental monitoring [6], agricultural monitoring [7], industrial monitoring [8], home automation [9], structural health monitoring [10], and medical applications.

Several wireless monitoring systems with different architectures have been proposed and designed to achieve cheap and efficient monitoring of a PV installation [11]. A typical example was illustrated by Suryono and Khuriati [12], using a microcontroller as the remote terminal unit (RTU) based system to measure solar radiation, PV voltage, and current. Data was transferred over an Ethernet card using the TCP/IP protocol, and radio was used to relay this data to a master terminal unit (MTU). For cheap and efficient monitoring, Su et al. [13] implemented a two-level WSN for live monitoring of a PV system with the aid of an nRF24L01 transceiver and CC2530-based ZigBee network. The system comprises sensing nodes and routing nodes mounted on PV modules and combiner boxes of PV sub-arrays respectively for accurate data collection. Finally, on a host computer, there is a sink node and a data management center. A low-cost Internet of Things (IoT) device data acquisition system for a photovoltaic system was designed by Gupta et al. [14]. The proposed system is primarily made up of four NODEMCU boards, a pyranometer PYRA300, temperature and humidity sensor DHT22, INA219 sensor, LM35 temperature sensor, anemometer, and dust sensor. All the sensors are connected to the four NODEMCU ESP8266 microcontrollers to measure their corresponding meteorological variables. Asnil et al. [15] designed a wireless monitoring system using an Atmega328 microcontroller interfaced with voltage, current, and temperature sensors. The voltage, current, and temperature of the photovoltaic cell are measured and the data is wirelessly sent to a personal computer with the aid of an nRF24L01 transceiver serving as a wireless communication link. A real-time and cost-effective Internet of Things data monitoring device is presented by Batikan [16]. The device consists of an ESP8266 microcontroller interfaced with a weather shield for the acquisition of meteorological parameters and other sensors. Parameters measured include the PV voltage, current and temperature, battery voltage, current, and temperature. Others include humidity, ambient temperature, and irradiance values. The system is also interfaced with a Global Positioning System (GP-735 GPS) which provides the location of the installed system. The acquired data is transmitted to an online server which enables real-time visualization. In addition, the data are employed for PV power estimation using machine learning techniques [17]. In the event of a fault within the photovoltaic system, users are alerted through a mobile application.

The authors in [18, 19] designed and implemented an IoT monitoring system that made use of Arduino and a Raspberry Pi. The Arduino is used for collecting electrical parameters which include voltage and current. Moreover, the atmospheric humidity and temperature of the PV module are also measured. The Raspberry pi is interfaced with the Arduino and serves as a web server that can be accessed by the user through the Internet with the aid of a web browser. In [19] the data is sent to EmonCMS web server to improve security. Paredes-Parra et al. [20] also presented a similar system. In this design, the Arduino Uno board was used to measure the electrical (voltage and current) and meteorological (temperature, humidity, solar irradiance, and wind speed) parameters. In this case, the solar irradiance was measured with the aid of a 5 Wp short circuit encapsulated polycrystalline silicon module [21] and was calibrated using a CMP21 ISO pyranometer. The monitored data are transmitted wirelessly to the Raspberry Pi which acts as the server and is transmitted to the Web.

Uzari et al. [22] implemented a low-cost system that combines the Arduino Uno board, and ESP8266 NodeMCU controller for effective monitoring. In this design, the Arduino is used in measuring parameters such as the PV voltage, current, and temperature. The dust intensity and relative humidity are also measured. All data acquired is transmitted to the ESP8266 controller the serial communication and finally using the Wi-Fi capabilities of the ESP8266 [23] the data is sent to a cloud server which can be easily accessed by the user.

An IoT supervisory and diagnosis system was designed by [24]. The proposed system monitors the daily usage of a solar farm through the aid of the Arduino nano and SIM800l. The PV electrical parameters are measured, and the level of solar irradiance is measured using a light-dependent resistor [25]. The recovered data is transmitted over the internet through the SIM800l module and finally, the data are viewed using an Android mobile application. Using the proposed system, the user has access to real-time data and can monitor the system for abnormalities. Several low-cost wireless data acquisition systems exist for PV monitoring but with limited capabilities. Some limitations are related to the number of parameters being monitored, the absence of multiple storage devices, the cost of using an internet server, and the high cost of hardware.

In this paper, we propose a robust PV monitoring device to measure electrical parameters such as the PV voltage, short circuit current, PV temperature, battery voltage, charging current, inverter output, and battery temperature. Additionally, environmental parameters comprising solar irradiance, atmospheric temperature, and relative humidity are also measured in real time. The measured data are transmitted wirelessly to a monitoring console, where the data are displayed on a liquid crystal display, logged locally on a storage device, and transmitted to an online server via the Internet.

Contributions of the Research

The major peculiarity of the proposed system is its capability for both local and remote monitoring of the electrical and environmental parameters of a PV system in real-time. This was achieved by introducing a handheld monitoring console to display all monitored parameters on an LCD. The monitored parameters are also stored on a memory card for easy accessibility using a handheld monitoring device apart from the personal computer. Besides, data loss is prevented due to the device's multiple storage capabilities serving as alternatives if one storage method fails.

The system also monitors the battery storage and the inverter output, enabling the user to have adequate knowledge of how the PV installation is operating.

The PV node is powered directly by the solar cell to conserve energy. This ensures that it is only powered when the solar cell is active and eliminates the requirement for an external power supply.

Furthermore, the proposed PV monitoring device is a low-cost device with ease of fabrication and can measure eleven parameters.

Material and Methods

System Design

The proposed system design is divided into two wireless sensor nodes or data acquisition units and a master terminal unit that displays, stores, and transmits the received data to the cloud. The first wireless node measures the solar panel's electrical and environmental parameters while the second measures the battery voltage, charging current, battery temperature, and inverter output. The proposed system's overall architecture is described in Fig. 1.

Remote Terminal Units (RTU)

RTUs are stand-alone data acquisition and control units that are used to convert electronic signals received from field instrumentation into the communication protocol for transmitting data over a network [26]. The RTUs are also responsible for collecting the required data and transmitting it to the MTU for further processing. Considering the number of parameters to be monitored, two data acquisition units were employed: the photovoltaic module node and the battery node.

Photovoltaic Module Node (PMN)

The PV module node is situated close to the solar panel. It consists of an Atmega 328P microcontroller interfaced with a wide variety of sensors and devices: NRF24L01 wireless transceiver, temperature, and humidity sensor (SHT20), temperature sensor (DS18B20), current sensor (ACS758LCB-100B), voltage sensor, a pyranometer, and an anemometer. With the aid of the listed sensors, the microcontroller is programmed to measure the corresponding physical parameters which are transmitted wirelessly to the MTU.

Design of the Photovoltaic Module Node

(a) Power Supply

For proper operation, the supply voltage of the PMN ranges between 12 and 30 V, this is due to the wide range of sensors used and their power consumption. The power supply unit consists of an LM7805 regulator, which supplies 5 V to the microcontroller, current, temperature, and humidity sensor. The LM317 voltage regulator supplies 3.3 V to the NRF24L01 module, while the pyranometer and anemometer can be powered directly from the input supply.

(b) Voltage and Current Sensor

The PV voltage (21 V) is measured using a voltage divider network that steps down the voltage to a value not exceeding 5 V which is the maximum input voltage of the microcontroller. Two precision resistors (22 kΩ and 4.7 kΩ) were connected in series to achieve this, i.e. $[4.7\ \text{k}\Omega/(22\ \text{k}\Omega+4.7\ \text{k}\Omega)]*21\ \text{k}\Omega=3.69$ V. With the aid of the analogue to digital converter on pin 26 of the microcontroller and Eq. (1), a program was written to calculate the actual voltage of the PV module.

For the PV current, a Hall Effect sensor, ACS758LCB-100B, an analogue bidirectional current sensor, is connected

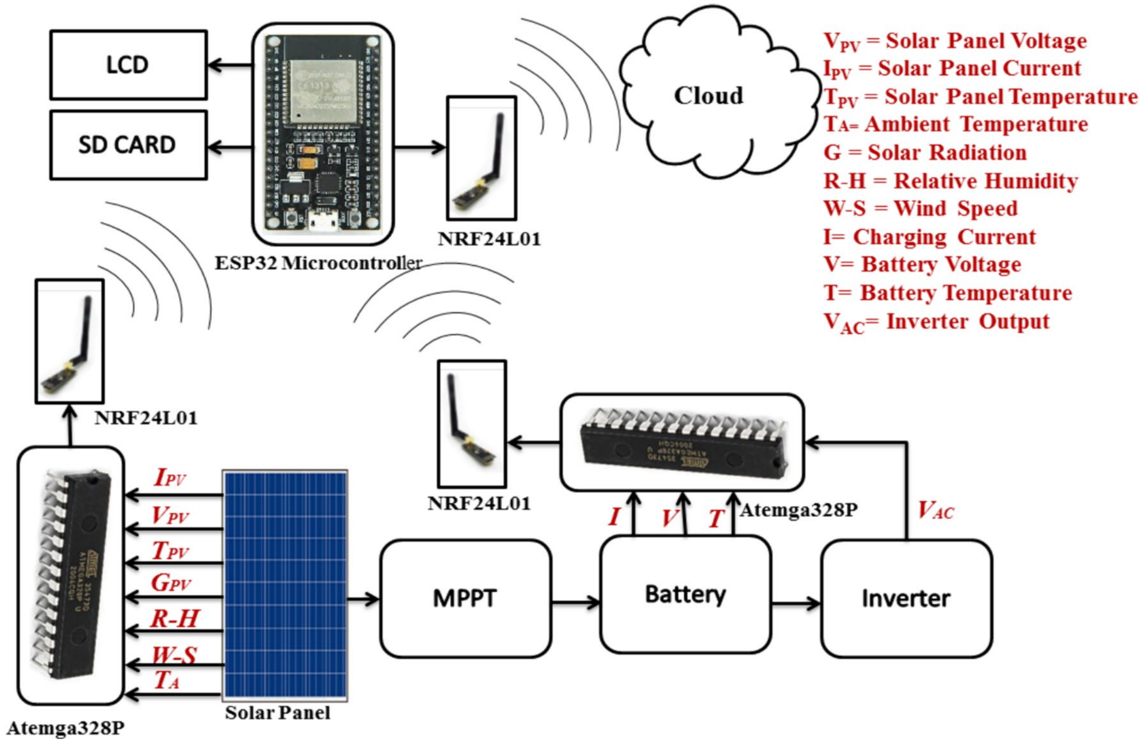


Fig. 1 Architecture of the proposed monitoring system

in series to the output of the PV module. The sensor's output is connected to analogue pin A0 of the microcontroller. Using Eq. (2), the actual current generated by the solar panel is measured.

$$V_{PV} = \frac{22k + 4.7K}{4.7K} \times \frac{5}{1023} \times V_{ADC} = 0.027738530 \times V_{ADC} \tag{1}$$

$$I_{PV} = \frac{\left(\left(\frac{5}{1023} \times V_{ADC}\right) - (0.5 * VCC)\right) + 0.007}{0.02} \tag{2}$$

where V_{PV} = PV Voltage, I_{PV} = PV current, V_{ADC} = analogue to digital equivalent, VCC = supply voltage (5 V), 0.5 = quiescent output voltage, 1023 = maximum analogue to digital equivalent of the 10 bits ADC converter, 0.007 and 0.002 = calibration constants.

(c) SHT20 Temperature and Humidity Sensor

The SHT20 digital sensor is used for the acquisition of the ambient temperature and relative humidity around the photovoltaic installation. This is a high-precision sensor with low power consumption and high response speed. It can measure temperature from − 40 to + 125 °C and relative humidity of 0–100%. The communication protocol is based on I2C. This sensor is enclosed in a waterproof casing to prevent exposure to moisture.

(d) DS18B20 Temperature Sensor

This sensor measures the solar module's back plate's temperature. The DS18B20 sensor is a digital sensor having an output resolution that ranges between 9 and 12 bits. For proper operation, an input power supply of 3–5 V is required, and it can measure temperature within the range of − 55 to + 125 °C.

(e) Anemometer and Pyranometer

These sensors measure the level of solar radiation incident on the PV module and the wind speed, respectively. They are analogue sensors with an output ranging from 0 to 5 V; therefore, they can be connected directly to the microcontroller. Pin 24 (A1) and 25 (A2) of the microcontroller were used for the anemometer and pyranometer, respectively. The pyranometer has a measuring range of 0-1800W/m^2 while the anemometer ranges between 0 and30 m/s. Using Eqs. 3 and 4, the solar radiation and wind speed are calculated using the microcontroller analogue–digital converter (ADC).

$$G = V_{GADC} \times \frac{1800}{5} \times \frac{5}{1023} = V_{ADC} \times 1.75 \tag{3}$$

$$W = V_{WADC} \times \frac{30}{5} \times \frac{5}{1023} = V_{ADC} \times 0.0293 \quad (4)$$

where G = Solar radiation, W = Wind Speed, V_{GADC} = output voltage from pyranometer, and V_{WADC} = output voltage from anemometer.

(f) NRF24L01 Wireless Transceiver

Several wireless communication modules are available for communication between sensor nodes. Some other common examples that have been used in literature include; low-power long-range (LoRa) transceiver [27], BLE (HM10BLE) transceiver [28], HopeRF RFM69CW module [29], CC2420 transceiver [30], and Huawei E3372 Megafon dongle [31]. Among the vast number of transceivers available the nRF24L01 module was chosen because of its low cost, low power consumption, and reliability with very low data loss [32, 33]. Besides, it makes the system to be easily scalable since each device has 6 channels with the ability to communicate with 6 similar devices. The device operates within the industrial scientific and medical (ISM) frequency band which lies between 2.400 and 2.4835 GHz and has a recommended operating range of 10–100 m. Although the device can communicate at higher ranges, this may lead to the loss of packets as the range increases [33]. Hence, the implemented system cannot be used in very large systems. The NRF24L01 module is set up and controlled using a serial peripheral interface (SPI) and has an air data rate of up to 2 Mbps. With the aid of this transceiver, all data collected by the sensors are transmitted to the MTU.

(g) Atmega 328P Microcontroller

All other components in the PV node are interfaced with the microcontroller unit. The AT328P is an 8-bit AVR microcontroller integrated with a 10-bit resolution ADC converter for data acquisition from the different sensors. The microcontroller has embedded software, and the software design flow chart is described in Fig. 2a, while Fig. 2b shows the complete circuit schematic. The program was developed using the Arduino Integrated Development Environment (IDE) and uploaded on the microcontroller using the Arduino Uno board.

Battery Node

The second wireless node is located in the PV system's battery compartment. The system is like that of the solar panel node. The primary function of the battery node is to continually measure the required parameters and transmit the data to the MTU for processing. Its main components are the Atmega 328P microcontroller interfaced with an NRF24L01 wireless transceiver, a voltage divider to measure the battery voltage, an AC voltage sensor, a current sensor (ACS-758LCB-100B), and a temperature sensor (DS18B20).

Design of Battery Node

The battery node has two input terminals (positive and negative) connected to the charge controller's output which is used in charging the battery. This node is powered directly from the battery, whose output lies within the range of 12–14 V. As displayed in Fig. 3b, the power supply consists of an LM7805 regulator that supplies 5 V to the microcontroller, temperature sensor, current, and AC voltage sensor. Additionally, an LM317 variable voltage regulator is configured to supply 3.3 V to the NRF24L01 wireless transceiver.

With the aid of a voltage divider network (R2 and R3) whose output is connected to analogue pin A0 as shown in Fig. 3. The battery voltage is measured by the microcontroller using Eq. (1). With the aid of a Hall Effect current sensor (ACS758LCB-100B) with output connected analogue pin 1 the current is measured.

Furthermore, the battery temperature is measured using a temperature sensor (DS18B20) connected to pin 14 of the microcontroller. The AC output of the inverter is also measured using the ZMPT101B module, consisting of a micro precision voltage transformer with a measuring range of 0–1000 V. Like the PV node, this node also includes a wireless transceiver for communication with the MTU. Lastly, all devices are interfaced with an AT328P microcontroller, which was programmed using the Arduino IDE and the Arduino Uno board. The flowchart of the uploaded program is illustrated in Fig. 3.

Master Terminal Unit (MTU)

All data acquired from the remote terminal units are transmitted to the MTU. This unit acts as the master console and it consists of a 38-pin ESP32 microcontroller interfaced with an NRF24L01 wireless transceiver, storage memory card, real-time clock, and an LCD to display received data. The system is IoT-enabled, which allows the data to be sent to the cloud and monitored from any location via an internet connection. The ThingSpeak IoT platform was used for this work because it is free and data stored can be retained for up to a year. The complete block diagram of the MTU is shown in Fig. 4.

Design Master Terminal Unit (MTU)

(a) Power Supply

The MTU has an input supply between 12 and 15 V. It comprises an LM7805 linear regulator and an LM317 variable voltage regulator. A 5 V voltage is supplied to the

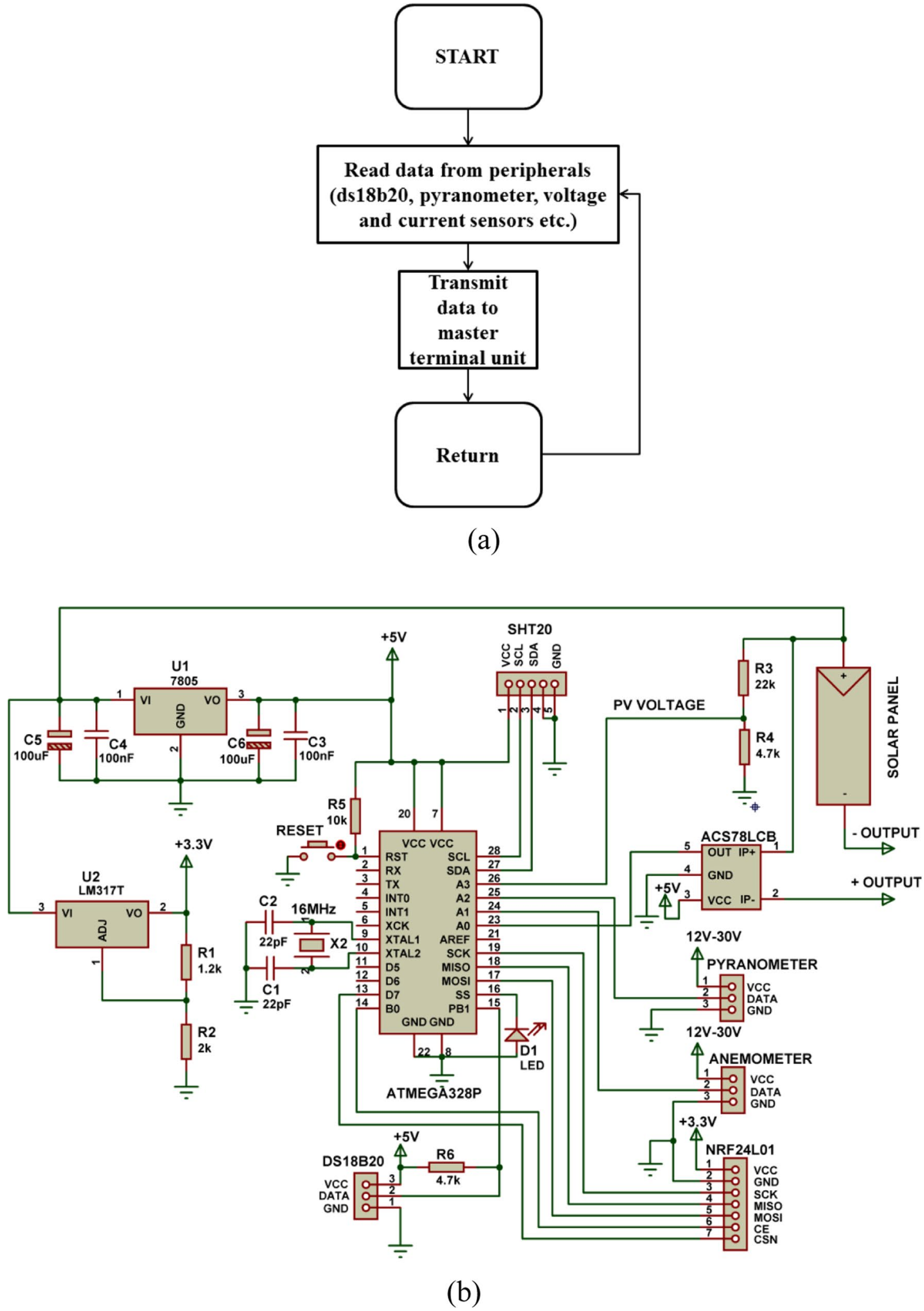


Fig. 2 **a** Flowchart of the software in the photovoltaic node, and **b** the complete circuit diagram of the PV node

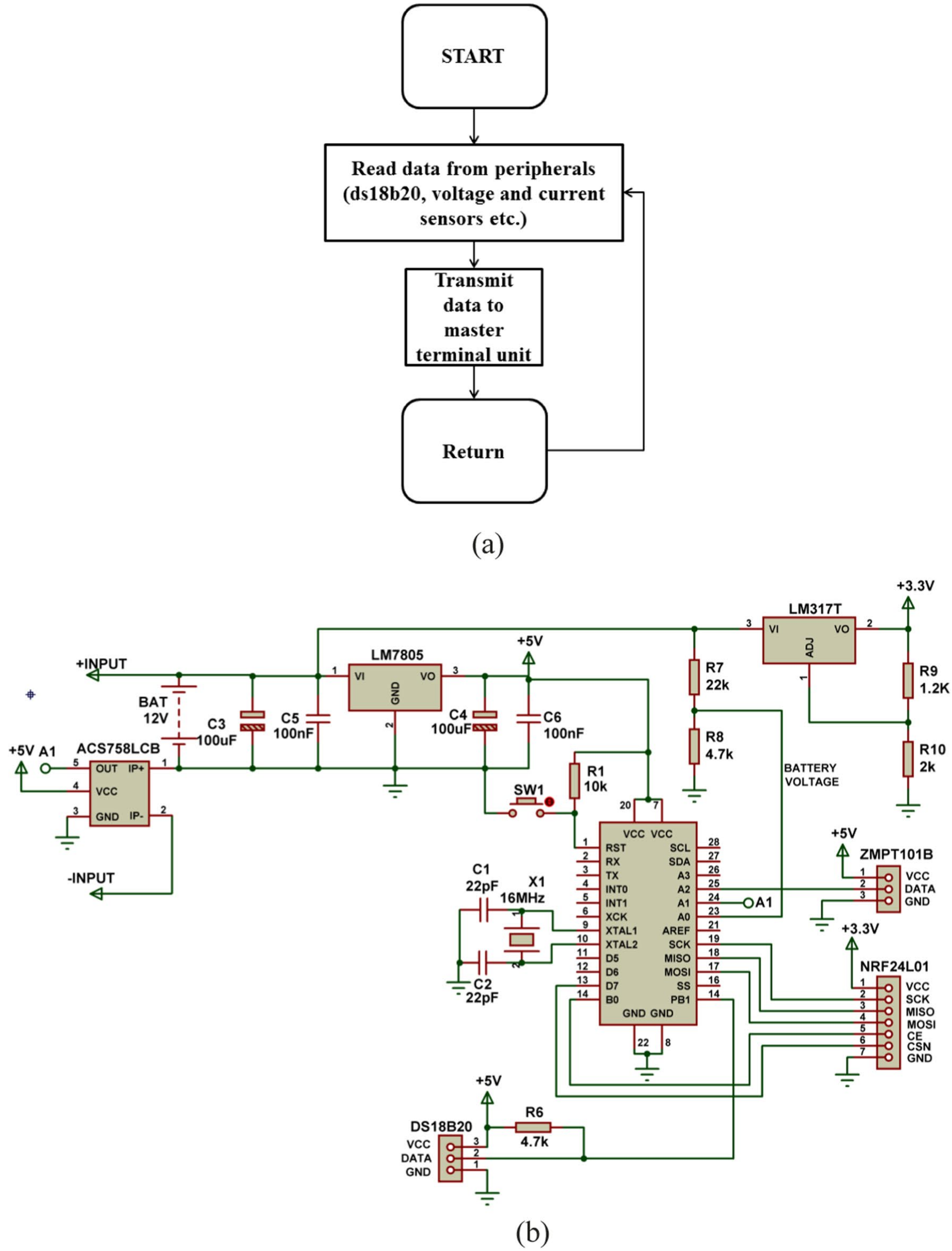


Fig. 3 **a** Flowchart of the software in the battery node, and **b** the circuit schematic of the battery node

ESP32 board, real-time clock (RTC), liquid crystal display (LCD), and SD card module through the LM7805 regulator. The NRF24L01 is powered by 3.3 V, which the variable voltage regulator supplies. Besides, the MTU has a 12-V battery which acts as a backup power supply to ensure that the device remains active if the main source of power fails.

(b) Real-Time Clock

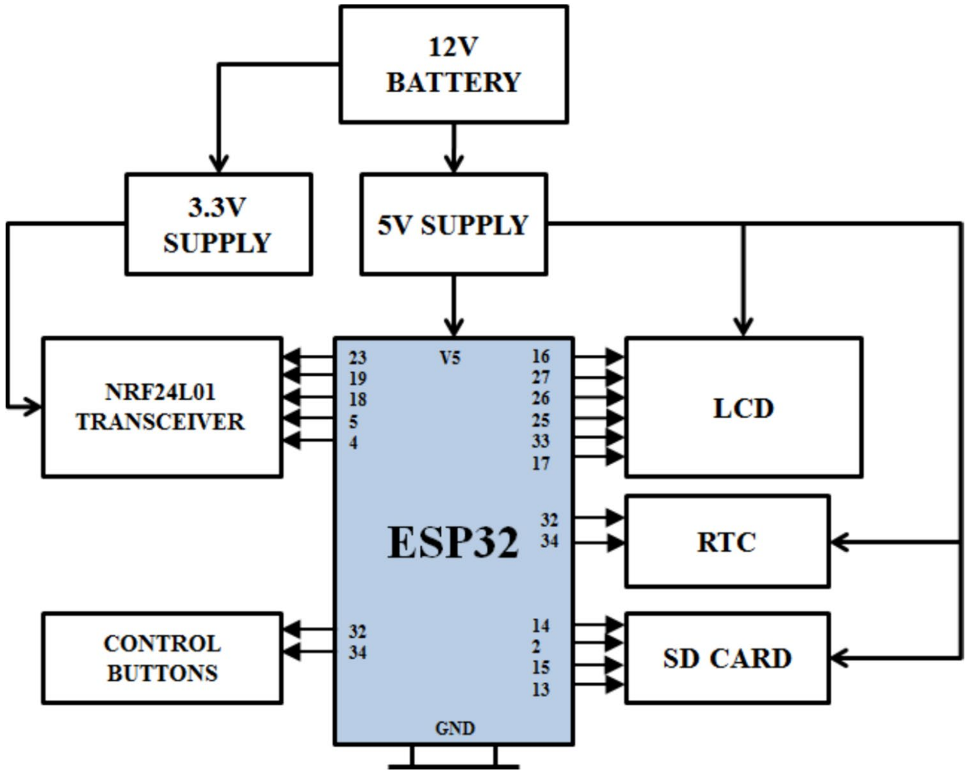


Fig. 4 Complete block diagram of the master terminal unit

The major function of the MTU is to record the date and time alongside other electrical and meteorological parameters. An RTC was interfaced with the microcontroller using the I2C protocol to maintain an accurate time and date. The major components of the RTC are a DS3231 integrated circuit and a battery to keep it powered always.

(c) SD Card

All data received from the RTU (photovoltaic and battery nodes) is logged on an SD card. This serves as a backup in the absence of an internet connection. The SD card is interfaced with the ESP32 microcontroller using a serial peripheral interface.

(d) Liquid Crystal Display (LCD)

A 16×4 LCD was interfaced with the MTU. This enables the user to view all received parameters in real time. Some parameters that are displayed are the level of solar radiation, PV voltage, current, atmospheric temperature, and relative humidity. Due to the limitation in the size of the LCD, using control buttons, the user can scroll up and down to view other data received from the RTU.

(e) ESP32 development board

This is a major part of the MTU which is responsible for receiving, storing, and uploading to the webserver all the data sent from the PV and battery nodes. The ESP32 microcontroller was chosen for this work because of its numerous digital pins, ability to communicate with multiple SPI devices (e.g., nRF24L01), and IoT capabilities. Serial communication can be used to link it to a computer and in addition, it is compatible with the Arduino IDE. The embedded software was written using the Arduino language and the flowchart is illustrated in Fig. 5a while Fig. 5b shows the complete schematic of the Master Terminal Unit.

Hardware Implementation and Results

A 200-W stand-alone system was set up as illustrated in Fig. 6a, consisting of four 50-W solar panels connected in parallel with the electrical specifications given in Table 1. The three devices shown in Fig. 6 were installed and used to monitor the PV system parameters (meteorological and electrical) for about one month in real-time through the ThingSpeak IoT platform. The data was also logged on a memory card which served as a backup.

Results and Discussion

Figure 7a shows a plot of the photovoltaic and battery currents with the level of solar radiation. using the data collected by the monitoring device. From the plot, it can be observed that both PV and battery current are rising in tandem as the level of solar radiation increases. The current stabilises at midday and gradually declines as sunset towards

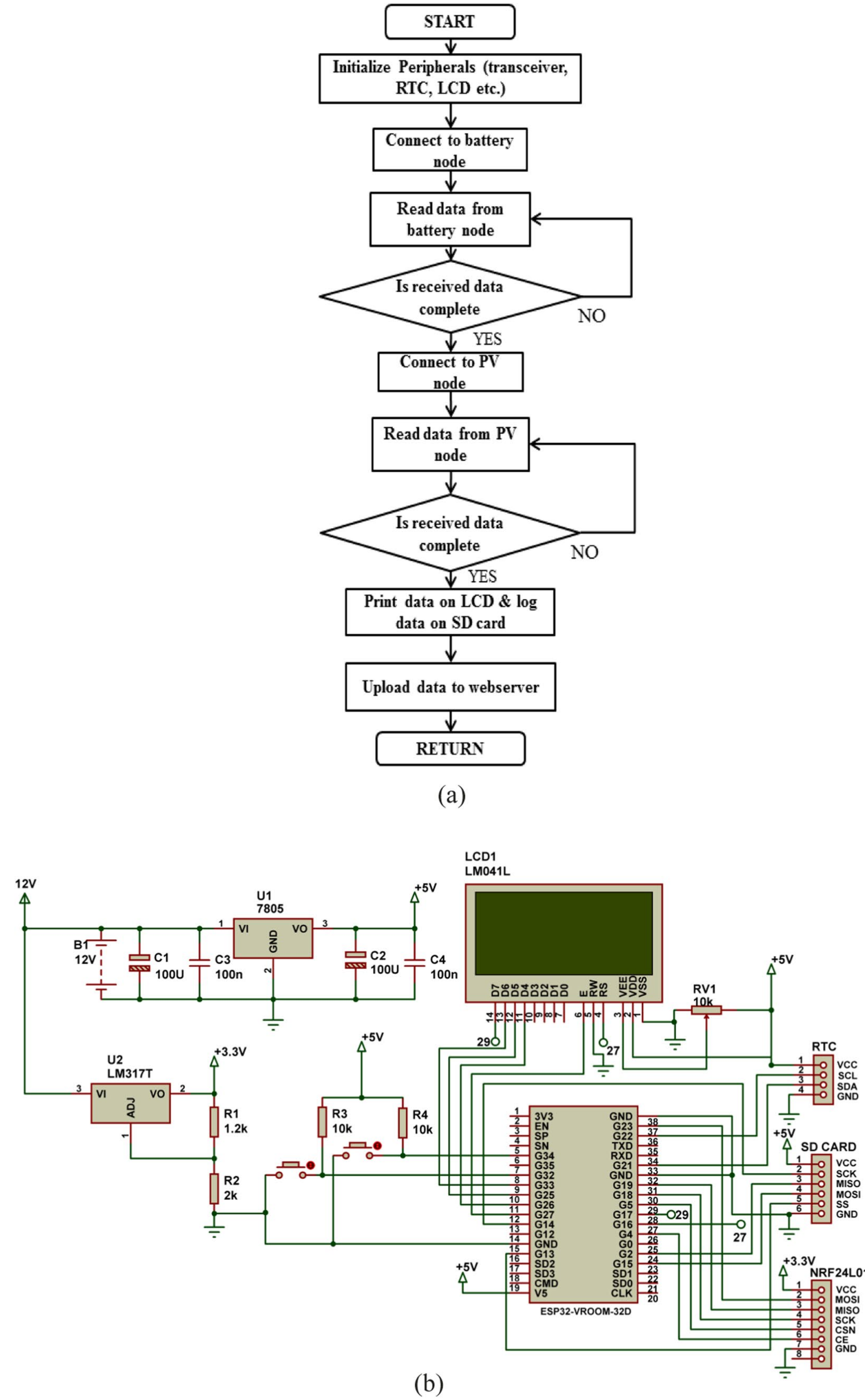


Fig. 5 **a** Flowchart of software in the MTU and **b** the circuit schematic of the master terminal unit

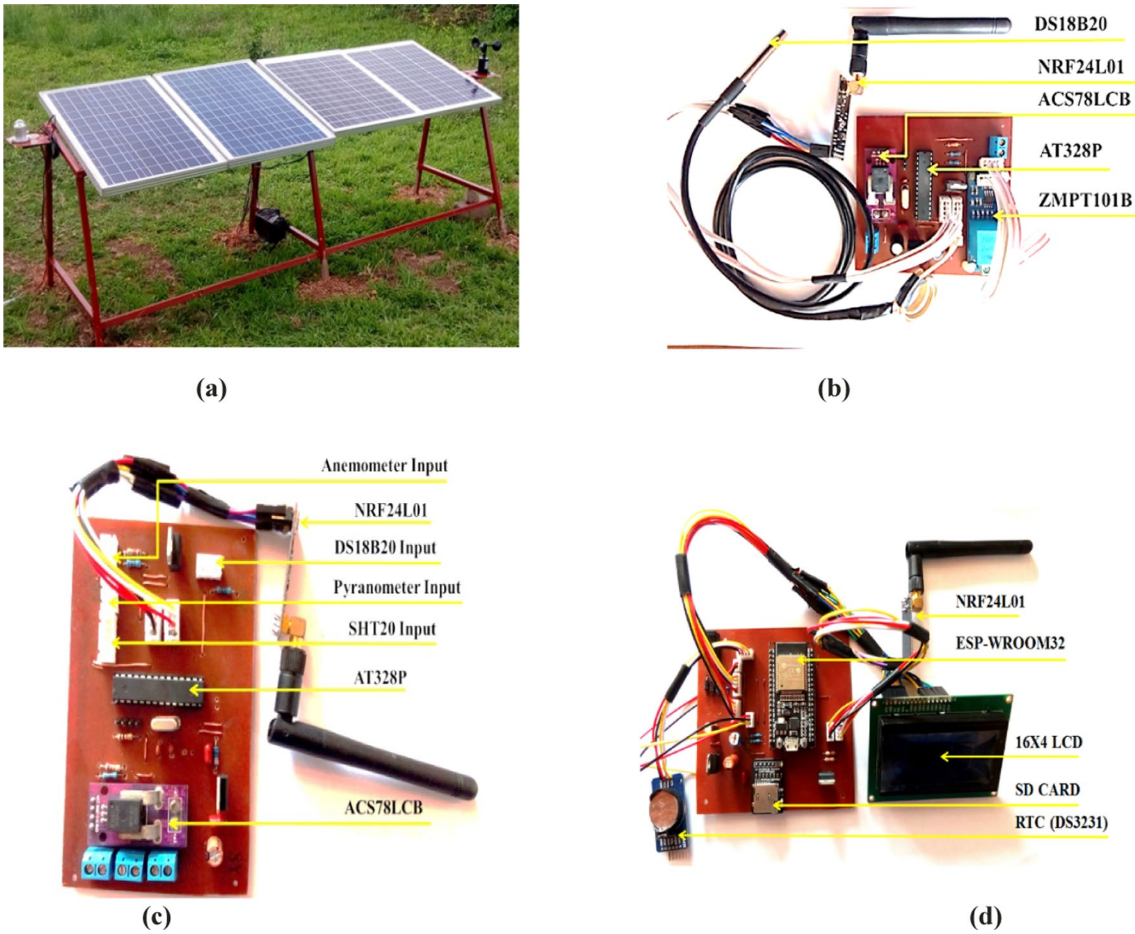


Fig. 6 **a** the 200-W solar installation, **b** the battery node, **c** the photovoltaic node, and **d** the master terminal unit

the end of the day. The plot in Fig. 7b compares the battery and PV voltages with the level of solar radiation. The PV voltage increases steadily as the solar radiation increases and peaks at about 20 V when the solar radiation is above 250 W/m^2. The battery voltage is stable with few fluctuations due to changes in solar radiation. Figure 7c shows the plot of the solar panel, ambient, and battery temperatures compared with the level of solar radiation The temperature of the back plate of the solar panel increases steadily as the sun rises. The temperature peaks typically above 40 °C towards mid-day and oscillates between 40 and 50 °C due to fluctuations in the level of solar radiation. The ambient temperature on average lies between 35 and 40 °C but can rise above 40 °C on a very hot day. As for the battery temperature, it lies around 25 °C at the beginning of the day and peaks at about 30 °C until sunset.

Table 1 Electrical characteristics of the photovoltaic module

Open circuit voltage (V_{OC})	21.8 V
Voltage at maximum point (V_{MP})	17.6 V
Short circuit current (ISC)	3.14 A
Current at maximum point (I_{MP})	2.58 A
Maximum power	50.16 W

Figure 8a describes a composite plot of the PV voltage, current, temperature, solar radiation, relative humidity, AC voltage, battery voltage, and wind speed of the experimental data generated on 17 May 2022. From the plot, as the level of solar radiation increases or decreases there is a corresponding increase or decrease in the PV and battery voltage, panel and ambient temperature, and the battery temperature. In Fig. 8b, the experimental data generated by the solar panel and the level of solar radiation on 28 May 2022, a sunny day, is compared to that of a cloudy day that occurred on 6 May 2022. It can be concluded that more power was provided to the system on a sunny day than on a cloudy day, irrespective of the frequent fluctuations of the incident solar radiation.

Figure 9 displays the experimental data that was uploaded to the ThingSpeak IoT platform and with this interface, the user can monitor the system performance

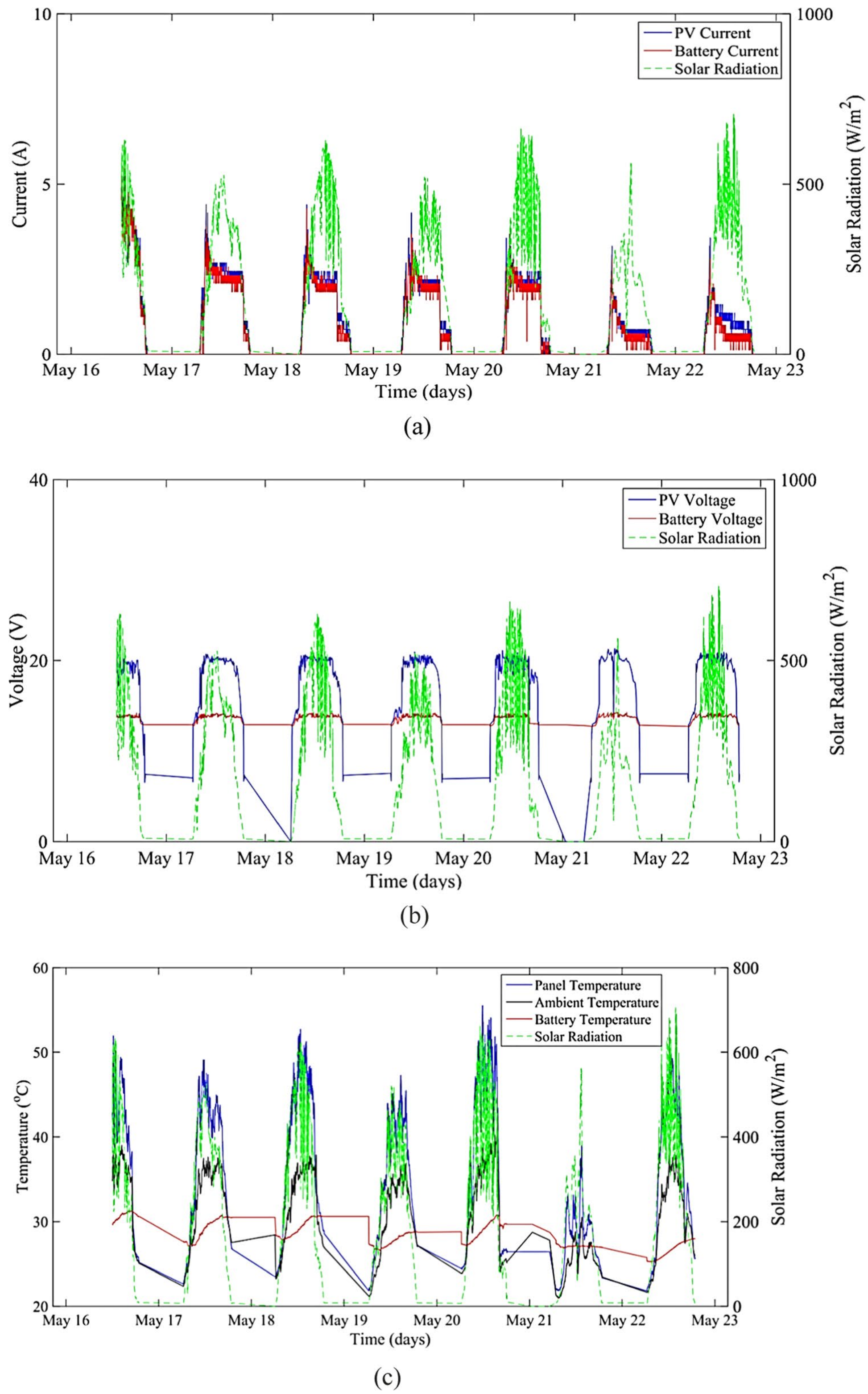


Fig. 7 **a** PV and battery currents compared with the solar radiation, **b** PV and battery voltages contrasted to the level of solar radiation, and **c** solar panel, ambient, and battery temperatures compared with the level of solar radiation

in real-time via the internet. Some of the information captured from ThingSpeak includes solar radiation, solar panel temperature, PV current, PV voltage, and battery voltage as illustrated in Fig. 9.

Detecting Partial Shading Fault with Device

A typical application of PV monitoring is the early detection of faults—among the most prevalent faults in a PV

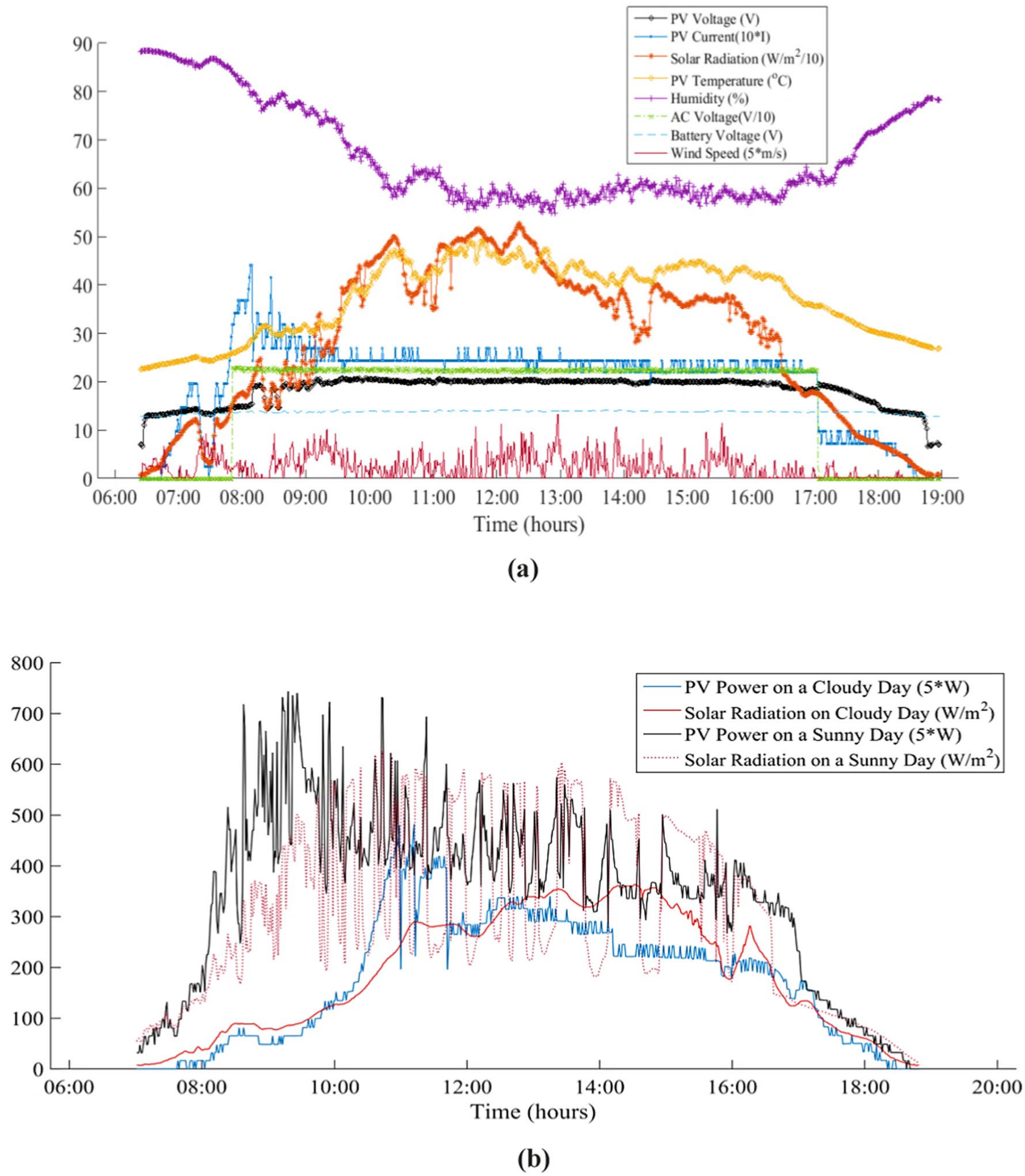
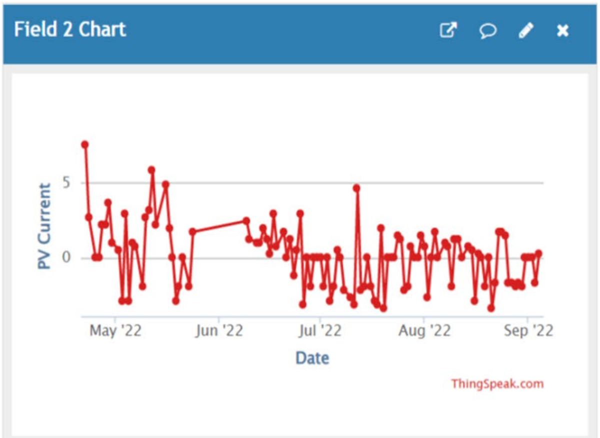
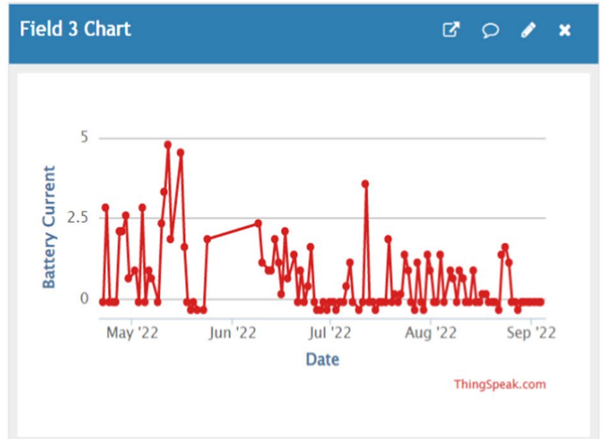


Fig. 8 Composite plots of experimental data generated on **a** 17 May 2022, and **b** a cloudy (6 May 2022) and sunny day (28 May 2022)

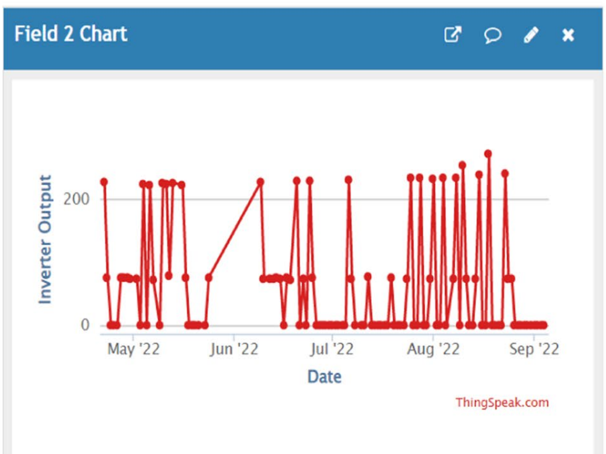
installation is partial shading [34]. The device's capabilities for detecting partial shading faults were tested by collecting data under normal operating conditions and when the PV cells were shaded. Data was collected for one week under each condition and a scatter plot of the PV current against the solar radiation was carried out as shown in Fig. 10. From the plot, it can be deduced that as the number of partially shaded PV cells increases, the PV system requires a higher level of solar radiation for the same amount of current. For instance, when no PV cell was shaded at solar radiation of 100 W/m^2, the system generated approximately 1-A current (Fig. 10). Conversely, when three panels were shaded, about 0.2-A current was produced (Fig. 10). There was a drop in the PV current which in turn caused a reduction in the amount of energy produced.



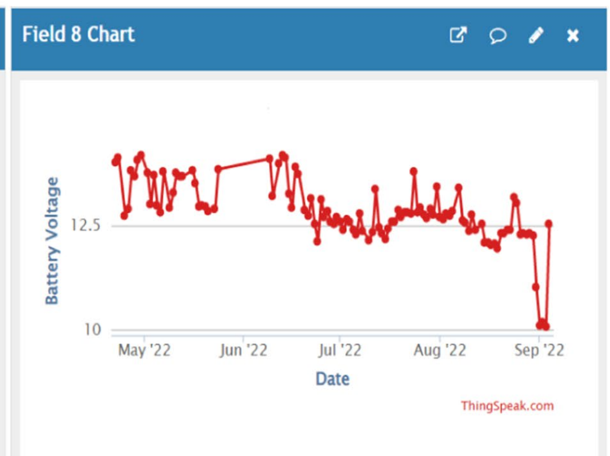
(a) PV current



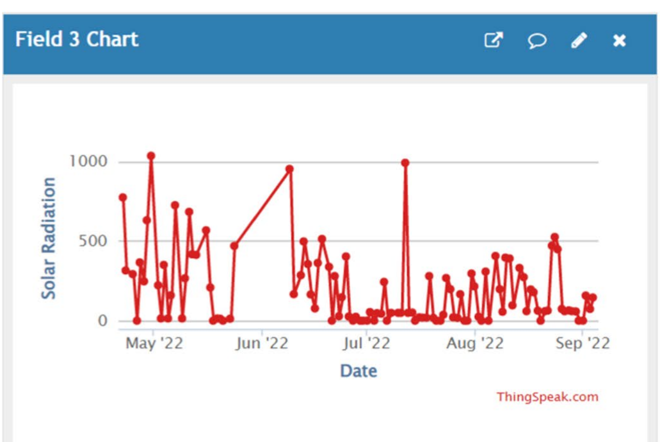
(b) Battery current



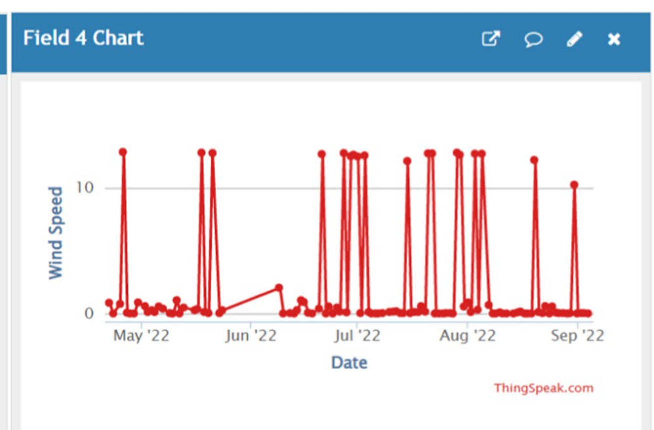
(c) Inverter output



(d) Battery voltage

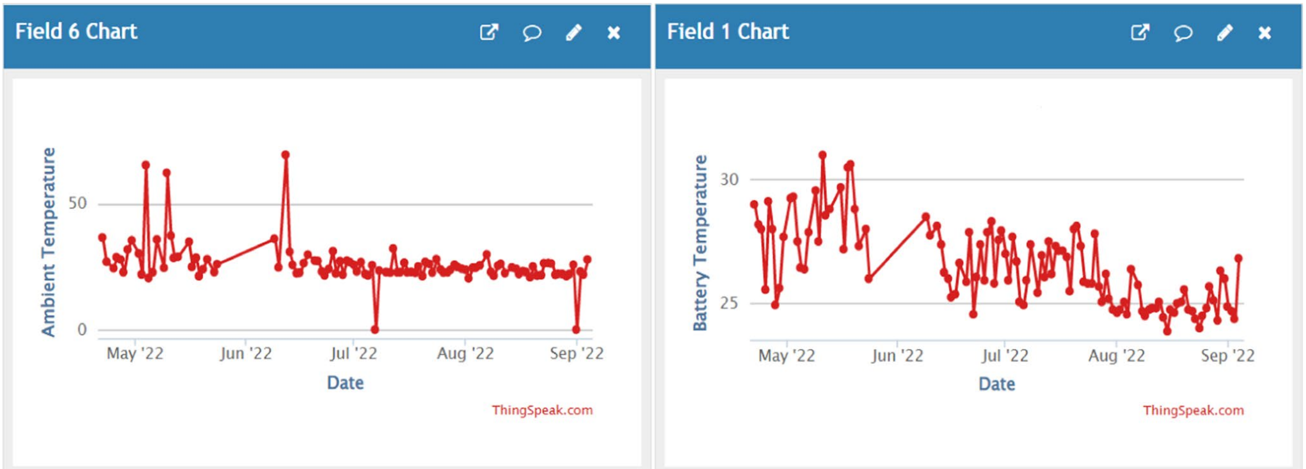


(e) Solar radiation



(f) Wind speed

Fig. 9 Snapshot of plots retrieved from the ThingSpeak IoT platform



(g) Solar radiation **(h)** Battery temperature

Fig. 9 (continued)

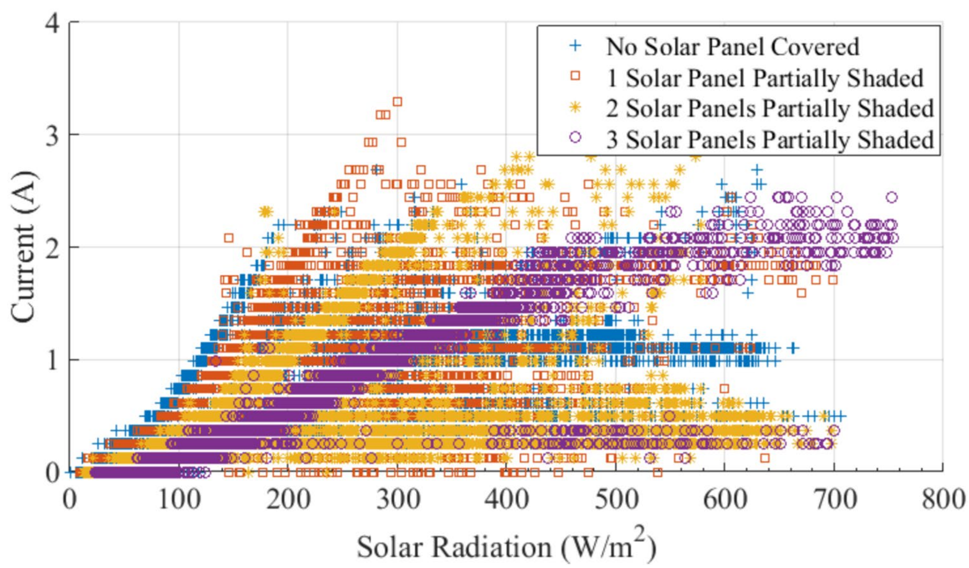


Fig. 10 Scatter plots of PV current against the solar radiation

Conclusion

As more PV systems are installed daily, real-time monitoring has become essential to ensure optimum PV system performance due to the harsh operating environment. In this paper, a robust and cost-effective PV monitoring system that employed wireless sensor networks and IoT technology was developed and deployed to monitor a mini stand-alone system. This methodology was chosen because it reduces the manual monitoring process and gives the user the ability to remotely monitor the PV installation via the Internet. The system comprises two wireless sensor nodes and one master terminal unit capable of remotely measuring 11 parameters, including PV voltage and current, panel temperature, ambient temperature, solar radiation, AC voltage, and lots more. Although the device was deployed in a 200-W system, it has the capability of being used in larger PV systems because the current sensor used has a maximum rating of about 100 A. Experimental results revealed that the device could continuously monitor all parameters effectively and log the acquired data on a memory card. The operational data is used to evaluate the performance of the PV system in real-time and detect when any fault occurs.

Author Contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Oluwaseyi Ilori, Alexander Willoughby and Oluropo Dairo. The first draft of the manuscript was written by Oluwaseyi Ilori, Alexander Willoughby and Ayodele Soge, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding No funding is associated with this work.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

References

1. A. González, R. Aquino, W. Mata, A. Ochoa, P. Saldaña, A. Edwards, Open-wise: a solar powered wireless sensor network platform. Sensor **12**(6), 8204–8217 (2012)
2. Z. Chen, L. Wu, S. Cheng, P. Lin, Y. Wu, W. Lin, Intelligent fault diagnosis of photovoltaic arrays based on optimized kernel extreme learning machine and I-V characteristics. Appl. Energy **204**, 912–931 (2017)
3. S.R. Pendern, S. Mikkil, Modeling, simulation and performance analysis of solar PV array configurations (Series, Series-Parallel and Honey-Comb) to extract maximum power under Partial Shading Conditions. Energy Rep. **4**, 274–287 (2018)
4. G. Boubakr, F. Gu, L. Farhan, A. Ball, Enhancing virtual real-time monitoring of photovoltaic power systems based on the internet of things. Electronics **11**(15), 2469 (2022)
5. Syafaruddin and Zinger D, Review on methods of fault diagnosis in photovoltaic system applications. J. Eng. Sci. Technol. **12**(5), 53–66 (2019)
6. K.S. Adu-Manu, A. Katsriku, J.D. Abdulai, F. Engmann, Smart river monitoring using wireless sensor networks. Wirel. Commun. Mobile Comput. **2020**, 1–19 (2020)
7. T. Cao-hoang, C.N. Duy, Environment monitoring system for agricultural application based on wireless sensor network, in *Seventh International Conference on Information Science and Technology (ICIST)* (2017)
8. S. Metia, H.A.D. Nguyen, Q.P. Ha, IoT-enabled wireless sensor networks for air pollution monitoring with extended fractional-order Kalman filtering. Sensors **21**(16), 5313 (2021)
9. A.A. Willoughby, A.O. Soge, M.A. Adeleke, O.A. Ilori, An IoT-based home automation and weather monitoring system. Int. J. Res. Innov. Appl. Sci. (IJRIAS) **7**(3), 26–29 (2022)
10. G. Loubet, A. Takacs, D. Dragomirescu, Implementation of a wireless sensor network designed to be embedded in reinforced concrete, in *IECON 2020 The 46th Annual Conference of the IEEE Industrial Electronics Society* (2020)
11. A. Parikh, F. Pathan, B. Rathod, S. Shah, Solar panel condition monitoring system based on wireless sensor network. Int. J. Sci. Eng. Technol. Res. **4**(12), 4320 (2015)
12. S. Suryono, A. Khuriati, Wireless sensor system for photovoltaic panel efficiency monitoring using Wi-Fi network, in *Second International Conference on Informatics and Computing (ICIC)* (2017)
13. F.P. Su, Z.C. Chen, H.F. Zhou, L.J. Wu, P.J. Lin, S.Y. Cheng, Y.F. Li, A distributed monitoring system for photovoltaic arrays based on a two-level wireless aensor network, in *IOP Conference Series: Earth and Environmental Science*, vol. 93 (2017)
14. V. Gupta, M. Sharma, R.K. Pachauri, K.D. Babu, A low-cost real-time IOT enabled data acquisition system for monitoring of PV system. Energy Sour Part A Recov. Util. Environ. Effects **43**(20), 2529–2543 (2020)
15. A. Asnil, K. Krismadinata, I. Husnaini, F. Gunawan, Wireless monitoring system for photovoltaic generation with graphical user interface. Int. J. Sci. Technol. Res. **9**(8), 528–533 (2020)
16. B.E. Demir, A new low-cost internet of things-based monitoring system design for stand-alone solar photovoltaic plant and power estimation. Appl. Sci. **13**(24), 13072 (2023)
17. Y. Ledmaoui, A.E. Fahli, A. Chehri, A. Elmaghraoui, M.E. Aroussi, R. Saadane, Monitoring solar energy production based on internet of things with artificial neural networks forecasting. Procedia Comput. Sci. **225**, 88–97 (2023)
18. K.K. Srinivasan, Vimaladevi, S. Chakravarthi, Solar energy monitoring system by IOT. Int. J. Adv. Netw. Appl. Special issue, 46–51 (2019)
19. L.O. Aghenta, M.T. Iqbal, Development of an IoT based open source SCADA system for PV system monitoring, in *IEEE Canadian Conference of Electrical and Computer Engineering (CCECE)* (2019)
20. J.M. Paredes-Parra, M.A. Antonio, S.N. Guillermo, C.B. María, M.G. Ángel, PV module monitoring system based on low-cost solutions: wireless raspberry application and assessment. Energies **11**(11), 3051 (2018)
21. N. Rouibah, L. Barazane, M. Benghanem, A. Mellit, IoT-based low-cost prototype for online monitoring of maximum output power of domestic photovoltaic systems. ETRI J. **43**(3), 459–470 (2021)
22. M. Uzair, S. Al-Kafrawi, K. Al-Janadi. I. Al-Bulushi, A low-cost, real-time rooftop IoT-based photovoltaic (PV) system for energy management and home automation. Energy Eng. **119**(1), 83–101 (2022)
23. Y. Cheddadi, H. Cheddadi, F. Cheddadi, F. Errahimi, N. Es-sbai, Design and implementation of an intelligent low-cost IoT solution for energy monitoring of photovoltaic stations. SN Appl. Sci. **2**(7), 1–11 (2020)
24. P. Santhosh, M. Deepanraj, G. Kathiravan, M. Jayaram, L.A. Kumar, IoT based supervisory and diagnosis system for solar farm, in *9th International Conference on Advanced Computing and Communication Systems (ICACCS)* (2023)
25. M. Khan, J. Iqbal, M. Ali, A. Muhmmad, A. Zahir, N. Ali, Designing and implementation of energy-efficient wireless photovoltaic monitoring system. Trans. Emerg. Telecommun. Technol. **33**(2), e3685 (2019)
26. P. Zhang, *Advanced Industrial Control Technology* (Elsevier, Amsterdam, 2010)
27. M. Mabon, M. Gautier, B. Vrigneau, M.L. Gentil, O. Berder, The smaller the better: designing solar energy harvesting sensor nodes for long-range monitoring. Energy Conserv. Harvest. Wirel. Sens. Netw. **2019**, 1–11 (2019)
28. P.N. Borza, M. Machedon-Pisu, F. Hamza-Lup, Design of wireless sensors for IoT with energy storage and communication channel heterogeneity. Sensors **19**(15), 3364 (2019)
29. I. Zaman, M. Gellhaar, J. Dede, H. Koehler, Demo: design and evaluation of MoleNet for wireless underground sensor networks, in *2016 IEEE 41st Conference on Local Computer Networks Workshops (LCN Workshops). Dubai, United Arab Emirates* (2016)
30. X. Xiong, M. Zhang, B. Gao, Z. Wang Z, Study of the communication module of wireless sensor networks node platform, in *2011 IEEE International Conference on Cyber Technology in Automation, Control, and Intelligent Systems. Kunming, China* (2011)

31. M. Baire, A. Melis, M.B. Lodi, C. Dachena, A. Fanti, A. Farris, T. Pisanu, G. Mazzarella, WSN hardware for automotive applications: preliminary results for the case of public transportation. Electronics **8**, 1483 (2019)
32. R. Murtiningrum, B. Purwantana, F.S. Muzdrikah, M.S. Nuha, M. Rivai, Design of wireless sensor network (WSN) with RFModule for smart irrigation system in large cultivated area, in *2018 International Conference on Computer Engineering, Network and Intelligent Multimedia (CENIM), Surabaya, Indonesia* (2018)
33. S.O.O. Abdelrahim, M.Z.M. Hassan, A.M.S. Salih, A.A.M. Abdo-Alrahiem, M.A. Mohamed, Rf performance evaluation of The Nrf24L01+ based wireless water quality monitoring sensor node: Khartoum City propagation scenario. J. Electr. Syst. Inf. Technol. **9**(1), 13 (2022). https://doi.org/10.1186/s43067-022-00052-3
34. R.K. Pachauri, O.P. Mahela, B. Khan, A. Kumar, S. Agarwal, H.H. Alhelou, J. Bai, Development of arduino assisted data acquisition system for solar photovoltaic array characterization under partial shading conditions. Comput. Electr. Eng. **92**, 107175 (2021)