IoT-Enabled Smart Solar Energy Management System for Enhancing Smart Grid Power Quality and Reliability

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ORIGINAL RESEARCH

IoT-Enabled Smart Solar Energy Management System for Enhancing Smart Grid Power Quality and Reliability

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Abstract
Voltage fluctuations and power grid instability are caused by the growing use of distributed renewable energy sources (RESs) like solar energy. The efficient monitoring and management of solar energy produced by solar panels can improve the quality and reliability of grid power for the smart grid (SG) environment. Additionally, we build solar power plants in remote locations that people cannot regularly access, so this method will enable them to virtually control their systems from those locations. In this regard, this paper suggests an Internet of things (IoT)-based smart solar energy management system (SEMS) to enable users to remotely monitor solar or PV (photovoltaic) panel systems via their smartphones from any location in the world. In this system, data collected from the panels is transmitted via the Internet to the Android apps for later use. The user can obtain data on the solar panel's temperature as well as the current and previous average values for parameters such as ampere, voltage, power, and energy. Remote users can also manage the solar panel's loads. Operators of on-grid and off-grid solar systems can enhance the quality and reliability of their power by using these data. This system can function as a smart meter (SM) in a smart grid environment. Future smart grids with significant solar energy penetration may find this system to be effective. A hardware prototype has been developed to validate the system's operation.

Keywords IoT · PV · Solar power · Smart meter (SM) · Smart grid (SG)

Introduction

The Internet of things (IoT), which enables the connecting of most physical items over the Internet to exchange data for remote monitoring and management of the devices, where the devices become intelligent, is playing a significant and vital part in people's everyday lives. Without requiring human interaction, machine-to-machine (M2M) or device-to-device (D2D) communication can be made possible through the Internet of things. With the help of this technology, a wide range and variety of things can be connected, including animals, people, smart grids, virtual power grids, smart cities, vehicles, heart monitoring systems, environmental sensing, shopping systems, automated homes, energy management, assistance for the disabled and elderly, cochlear implants, tracking of things, equipment manufacturing, supply chain management, warehouse management, agriculture, emergency monitoring systems, and electric utilities as shown in Fig. 1. IoT is expanding quickly since there are so many potential applications. According to a poll conducted by [1], from 2019 to 2022, there would be a growth of 52.27%. By 2022, 13.4 billion devices will be linked to the Internet. According to Fig. 2, the number of linked devices might reach 30.5 billion by 2030. This shows that the Internet of things is spreading quickly over the world and is anticipated to achieve a worldwide IoT industry of $1 trillion in 2030 [1].

IoT has the potential to be the next big thing in modern life by simplifying our lives with more advanced wireless technology, such as generation 6 (6G) technology [2–6], more powerful and effective sensors, and cutting-edge computing techniques. IoT has already been used in numerous, extensive applications such as smart grids [7], smart cities [8, 9], connected automobiles [10, 11], wearables [12, 13], smart retail [14], smart health [12, 13, 15, 16], smart farming [17, 18], smart supply chain [19], industrial Internet [20], smart home system [21–23], digital water management

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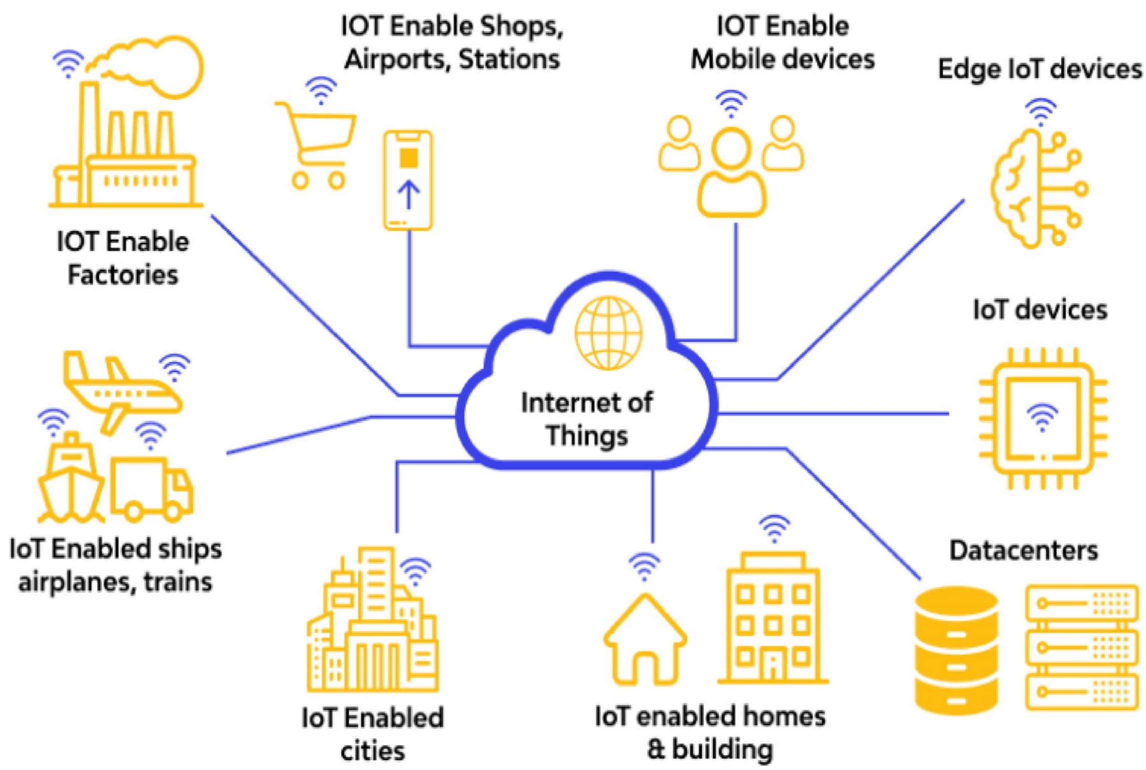

Fig. 1 IoT with connected things [27]

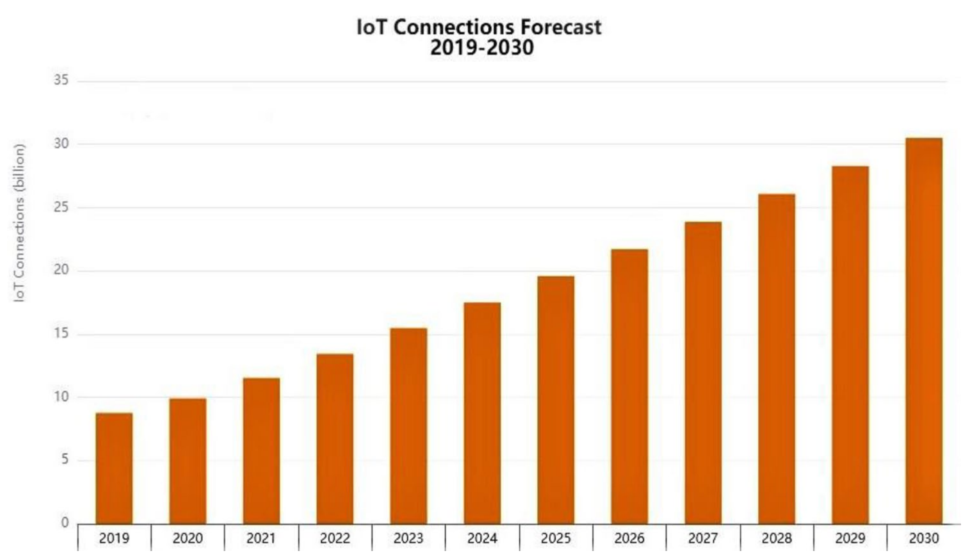

Fig. 2 IoT connections forecast [1]

[24], smart agriculture [25], and smart environment monitoring [26].

Due to recent environmental concerns regarding the use of fossil fuels in the production of electricity and their limited availability, the power sector is switching to clean renewable energy sources such as solar and wind power. The conventional power grid is being put under additional strain because of solar energy's irregular availability. Also, it causes voltage imbalances, grid instability, etc. In this regard, IoT-enabled smart grids can be an efficient solution for enhancing power quality, stability, and reliability using smart meters (SM). As a result, IoT technology has been used in this work to monitor and regulate solar energy in a smart grid environment. A typical solar module is made up of 6×10 photovoltaic solar cells that can produce electricity for residential applications. Additional panels must be installed if more power is needed. The panel generates DC output power in the 100–365 Watt range. The acronyms and abbreviations used throughout this article are listed in Table 1.

The remaining portion of the paper is structured as follows:

"Introduction" discusses the motivation and necessity for conducting this research. "Related Works" discusses related works of this research and their limitations. "Proposed System Methodology" delves into the proposed system methodology in depth. "Results and Discussion" contains the findings of this research as well as relevant discussions. "Conclusions" concludes the article with closing remarks and the scope of possible future works.

Related Works

Several research studies have been conducted to incorporate renewable energy sources. A new energy management strategy for PV-based electric vehicles has been proposed in [28] for SG ancillary services. This study, however, does not cover remote monitoring and control of solar energy. Wei et al. [29] proposed a new reinforcement learning technique for energy management that takes advantage of wind and electric vehicle penetration. However, no hardware implementation of the system was presented. Furthermore, wind power-controlled load control and monitoring are not covered. In [30], a novel control strategy is proposed to improve the stability of PV centralized SGs. Remote control and monitoring of PV power plants have not been discussed in this paper either. Hussain et al. proposed an IEC (International Electrotechnical Commission) 61,850-based communication model for solar home systems (SHSs) [31]. They did not, however, demonstrate remote control and monitoring of loads using the communication model. It also lacks the hardware prototype for the SHSs. A smart home management strategy has been proposed in [32] for smart grid applications to reduce electricity consumption costs and system uncertainties. However, it only presents a simulation study with no practical implementation. The authors of [33] proposed an IoT solution for real-time monitoring of solar home systems based on an Arduino microcontroller along with 3G technology. However, the proposed system based on 3G technology is quite costly due to the use of a modem, router, and SIM card. In [34], a low-cost IoT-based monitoring system for tracking the maximum power point of a PV system is proposed. The proposed system, however, lacks any feature for alert notifications for any abnormal system conditions.

In this context, this work focuses on designing and developing a hardware prototype of an IoT-based smart solar energy management system to improve the smart grid's power quality and reliability. Power system operators can monitor and control solar power plants from anywhere in the world using this system. This system allows real-time remote control and monitoring of the system's connected AC loads. The voltage, current, and consumed power of the AC load, as well as the temperature of the PV panel, can all be monitored in real-time with this system. As a result, power system administrators can perform real-time data processing, analysis, and visualization of the solar power plant's performance parameters. Future smart grids that heavily rely on solar energy will require this kind of smart system. By charging the battery modules, this system can also be used to build energy storage systems (ESSs). During a power outage, these ESSs can provide power to the grid. Additionally, these ESSs can power electric vehicles (EVs). Additionally, the proposed IoT-based SEMS can be implemented at a low cost, which can be very helpful for developing nations where people in rural off-grid areas can take advantage of this opportunity with an affordable IoT system.

Table 1 List of acronyms and abbreviations used throughout this article

Abbreviation	Definition	Abbreviation	Definition
SG	Smart grid	6G	Six generation
RES	Renewable energy sources	PV	Photovoltaics
IoT	Internet of things	IEC	International Electrotechnical Commission
SEMS	Solar energy management system	SHS	Solar home system
SM	Smart meter	DC	Direct current
M2M	Machine to machine	AC	Alternating current
D2D	Device to device	ESS	Energy storage systems
EV	Electric vehicle	MCU	Microcontroller unit
RTOS	Real-time operating system	STC	standard test conditions
NTC	Negative temperature coefficient	DSO	Distribution system operators
BESS	Battery energy storage systems	PF	Power factor

Proposed System Methodology

This chapter describes the system's necessary instrument, the proposed system's operating principle, and the final prototype view.

Required Instruments

A brief overview of the system's instruments is given in the following:

ESP8266 Microcontroller Unit (MCU)

A low-cost fully integrated Wi-Fi MCU for Internet of things applications is the ESP8266 Node MCU. This device was selected for this work as a result. The Tensilica 32-bit RISC processor used in the ESP8266 microcontroller uses very little power and operates at the highest clock speed of 160 MHz [35]. The real-time operating system (RTOS) and Wi-Fi stack enable user application programming and development to access about 80% of the processing power. A 3.3 V operational voltage power source is capable of powering the ESP8266 Node MCU [35]. This device is compact due to the inclusion of a 32-bit Tensilica CPU, common digital peripheral interfaces, an RF balun, antenna switches, low noise receive amplifier, power amplifier, filters, and power management modules. They are all contained in a single, compact package. It has a wide operating temperature range and can function dependably in industrial settings. Due to its low external discrete component count and fully integrated on-chip functionality, the chip offers dependability, compactness, and resilience. With the aid of several patented technologies, the ESP8266 Node MCU, created for mobile devices, wearable electronics, and Internet of things applications, achieves low power consumption. Active mode, sleep mode, and deep sleep mode are the three stages of operation for the power-saving architecture. This enables battery-powered systems to function continuously [35]. It serves as the system's primary controller, making it an essential component of the suggested system. The prototype Node MCU ESP8266 microcontroller is shown in Fig. 3.

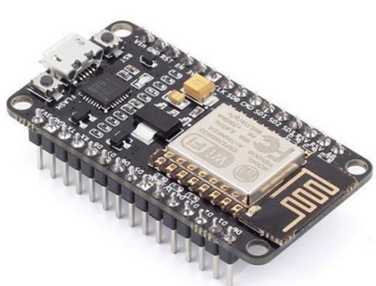

Fig. 3 Node MCU

Solar Panel

A solar panel is a collection of electrically connected solar photovoltaic modules that are mounted on a base. A packaged, attached assembly of solar cells is known as a photovoltaic module. The solar panel can produce and supply electricity for use in residential and commercial applications as part of a larger photovoltaic system. Each module's rating, which typically ranges from 100 to 320 watts, is based on its DC output power under standard test conditions (STC). The area of a module for a given rated output depends on the module's efficiency. There are limits to how much electricity one solar module can provide, thus most setups use many modules. A panel or array of solar modules, an inverter, and occasionally a battery, solar tracker, and interconnecting cables make up a photovoltaic system. Solar cell modules can only generate power, while the sun is out. Since they cannot store energy, it is required to store part of the energy generated to maintain the flow of power when the sun is not shining. The most straightforward answer is to employ batteries, which chemically preserve electric energy. Rechargeable batteries are referred to as secondary or accumulator batteries. Electric energy is converted to chemical energy and stored in the battery's cells during charging. A solar panel is depicted in Fig. 4

Solar Charge Controller Circuit

A charge controller circuit regulates how quickly electric current is supplied to or removed from electric batteries to prevent overcharging, overheating, and electrical overload. A solar charge controller circuit for utilizing solar energy to charge a battery is shown in Fig. 5. Voltage and current regulation, as well as excessive voltage cutoff capabilities, are features of the charge controller. A solar panel and the

Fig. 4 A solar panel

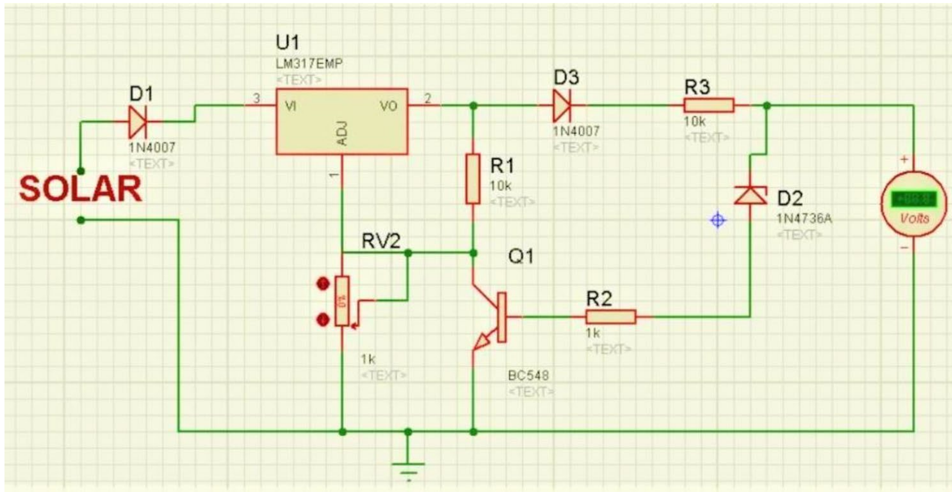

Fig. 5 Solar charge controller circuit diagram

IC LM317 [36] variable voltage regulator are used in the circuit. Each solar cell of the solar panel has a 1.2-V rating. The battery may be charged using the panel's 12-V DC supply. Through diode D1, the charging current is sent to the voltage regulator IC LM317. Both the output voltage and current can be controlled using the adjustable pin. R3 resistor limits the charging current, while Zener diode D2 stops the battery current from being discharged. When the battery is full, BJT Q1 and Zener diode D2 function as a cutoff switch. Q1 is typically off, and the battery receives a charging current. When the battery's terminal voltage exceeds 6.8 V, the Zener conducts and supplies base current to Q1 at that point. After that, it activates grounding the LM317's output to cease charging.

Current Sensor Module

The ACS712 current sensor module can detect current flows of up to 20 A. The supply voltage range for this device is 4.5–5.5 V. Numerous applications, such as battery chargers, switching mode power supplies, over-current safety circuits, digital watt meters, and programmable current sources require the ability to sense and regulate the flow of current. This has been employed in this study to gauge the solar panel's current flow. A microcontroller's analog *I*/*O* port can be used to monitor the current signal. The image of the current sensor module is shown in Fig. 6a.

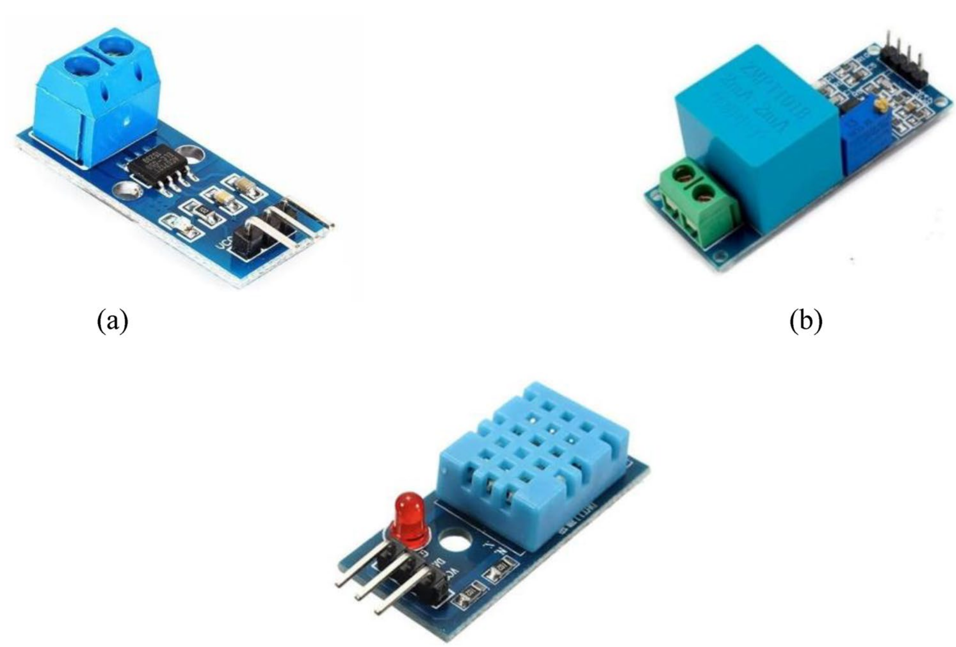

Fig. 6 A snapshot of **a** the current sensor module, **b** voltage sensor module, **c** temperature sensor module

Voltage Sensor Module

A high-accuracy voltage transformer serves as the foundation for the ZMPT101B AC Single-Phase voltage sensor module. The finest AC voltage sensor for detecting precise AC voltage with a voltage transformer is the ZMPT101B. This is the perfect option for measuring the AC voltage with microcontrollers. As a result, this sensor was chosen to accurately measure the AC voltage of this SEMS system, which also aids in calculating the consumed AC power of the loads. The supply voltage range for this device is 5–30 V. Figure 6b shows the image of the sensor.

Temperature Sensor

In this work, the temperature of the solar panel is measured using a low-cost DHT11 digital temperature and humidity sensor. The DHT11 uses a 3–5.5 V DC power supply. To achieve high reliability, precision, and great long-term stability, this sensor makes use of temperature and humidity sensor technology and offers 16-bit resolution for the temperature and humidity data. A high-performance 8-bit microcontroller is coupled to the resistive element and NTC temperature measuring devices that are part of the sensor.

The power generated by the PV panel is proportional to the temperature. The generated power will increase as the temperature rises. Due to this, this sensor has been used in this work to measure the module's temperature and track how the power changes as the temperature changes. The temperature sensor used is depicted in Fig. 6c.

Inverter Circuit Board

To operate AC loads, this work uses an inverter circuit board to convert DC voltage to AC voltage. It accepts a 12 V DC input and outputs a 110–220 V single-phase AC with a 100W output load. A photograph of the actual inverter circuit board is shown in Fig. 7a.

Relay Module

The AC load of the system is controlled by a 5 V single-channel relay module in this work. It has a status LED (RED) to indicate the relay's status and a power LED to show whether the power source is connected to the module. The maximum contact voltage for this 5 V relay module ranges from 250 V AC to 30 V DC, and the maximum output current is 10 A. Figure 7b shows the relay module of the proposed system.

Buck Converter Module

This work employs a DC–DC buck converter module LM2596 to generate the required supply voltage for the proposed system's MCU. It has a supply voltage range of 4–35 V and can output any variable voltage between 1.23 and 30 V. The LM2596 module runs at a 150 kHz switching

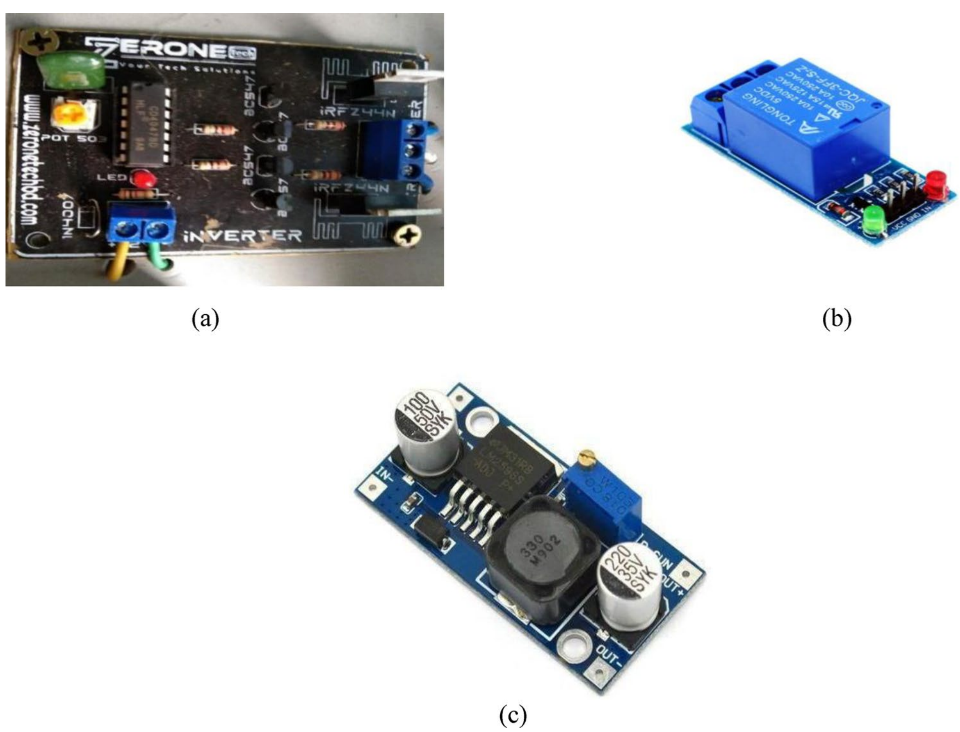

Fig. 7 A snapshot of the **a** inverter circuit board, **b** relay module, **c** buck converter module

frequency. It is a non-isolated, non-synchronous rectification buck converter. Figure 7c illustrates the LM2596 buck converter module.

Working Principle of the Proposed System

The proposed system's block diagram is depicted in Fig. 8. The system is controlled by a Node MCU ESP 8266. Power supplied by the solar panel serves as the system's primary power source. When the sun's energy is absorbed by the solar panel and continues to charge the battery until it is fully charged. DC voltage is converted to AC voltage by the inverter. The DC voltage required by the MCU is produced by the Buck module. The data sensed by the voltage, current, and temperature sensors are transmitted to the microcontroller unit for processing. The MCU unit analyses the data and regulates the system's AC load. The MCU transmits data to the Blynk Android app via the Internet so that a remote user can view and manage the solar system's generated power, output current, and output voltage. During a power outage, the battery can also be used as an energy storage system (ESS) to supply power to the grid. Electric vehicles (EVs) can be powered by this ESS as well. The Proteus circuit simulation software simulates and validates the entire system. The proposed system's flowchart is shown in Fig. 9.

Results and Discussion

Figure 10 depicts the interface of the Android app that monitors real-time data from the IoT-enabled solar system. Through a Wi-Fi connection, a user can access real-time data on the temperature, current, voltage signal, and energy generated by the solar system from anywhere in the world. Users can use the proposed system to monitor changes in current, voltage, and energy data over time, as shown in Figs. 11, 12, 13. As shown in Fig. 14, the app is also capable of notifying the user when the battery charging voltage falls below a certain threshold. Only one AC load was connected in this work. However, the system can accommodate any number of loads in accordance with user demand. The system's AC loads can also be managed by the user. When they are not using the load, they can turn it off remotely using the Android app by establishing a Wi-Fi connection. The proposed system's Android app controls an AC load, as shown by the system prototype in Figs. 15 and 16. Distribution system operators (DSOs), who manage distribution systems, can benefit from this. They can use battery energy storage systems (BESS) to store the excess solar power during the day's off-peak hours because there is a low demand for electricity during this time. Then, during the day's peak period, they can supply this power to the grid to meet the additional power demand from their users. So, at a time when energy prices are high, they can balance out the decline in solar power. They can also keep their power level constant all day long. Control strategies on BESS will make use of the battery to reduce discrepancies between the scheduled and actual solar power generation throughout the day. Therefore, the next generation smart grid with a high penetration of solar power plants has great potential for this solar system integrated with BESSs to improve the power quality. The proposed BESS integrated solar system can also increase the stability and reliability of the power system. When there is an imbalance between the generation and the load because of a load or unit trip, frequency deviation occurs in the power grid. The proposed BESS integrated solar system can rapidly

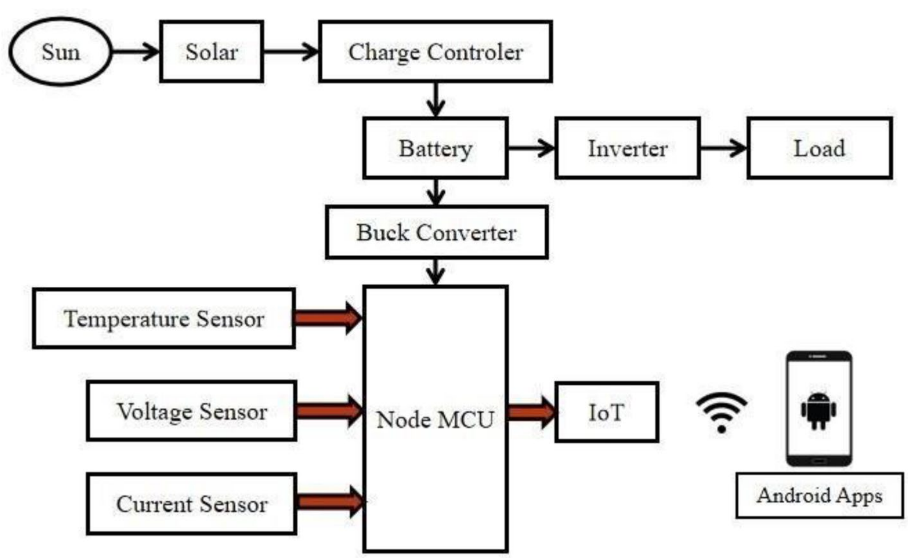

Fig. 8 A block diagram of the proposed system

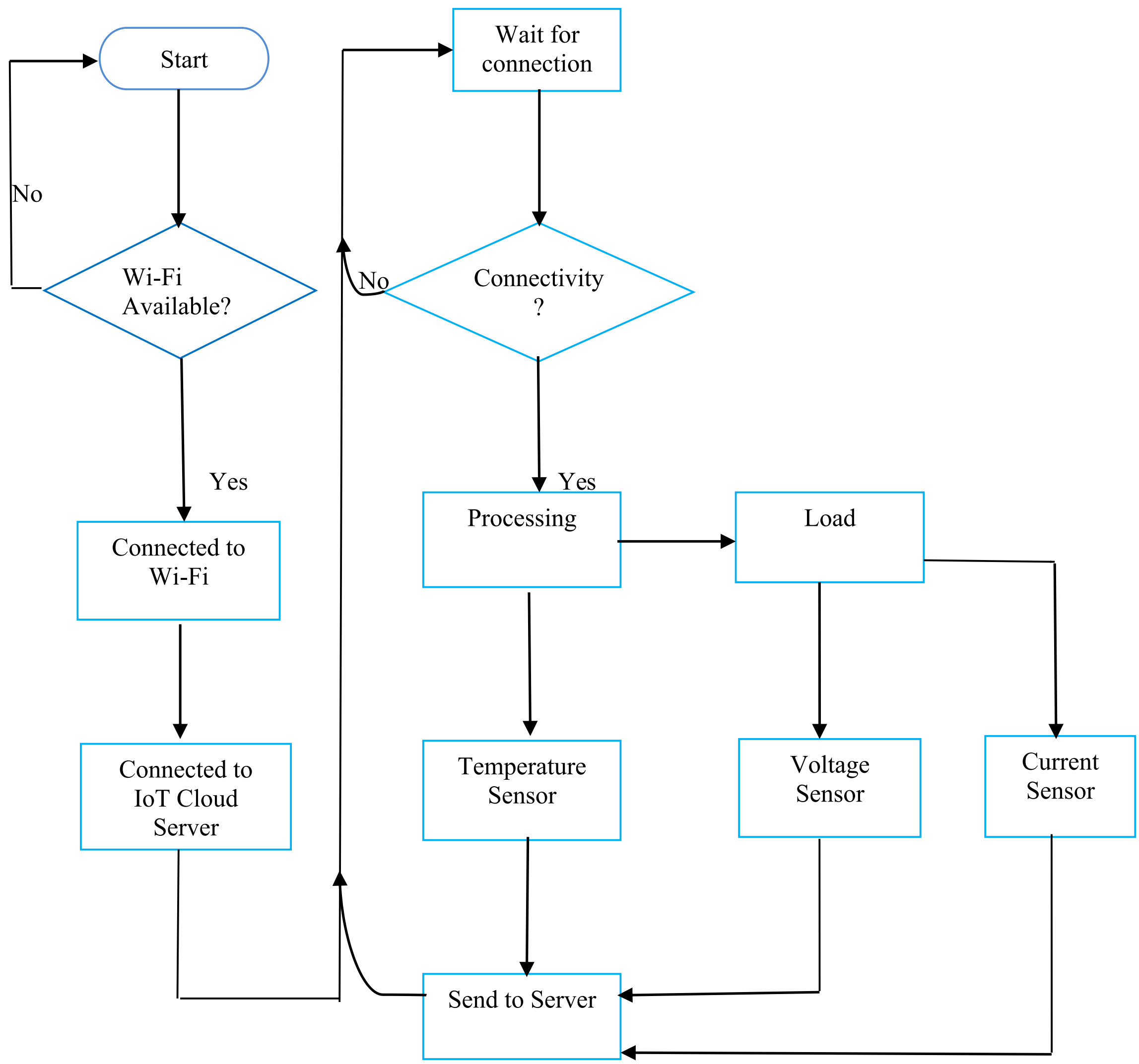

Fig. 9 Flowchart diagram of the system

provide the real power needed to restore the system to its nominal frequency range if the generator unit trips. Another challenge in today's smart grid is maintaining the required voltage level and power factor (pf) at the distribution end. To maintain the system voltage level and pf, distribution feeders typically use shunt capacitor banks to deliver reactive power. However, when the capacitors are switched, these shunt capacitor banks produce substantial switching transients. In this situation, the proposed BESS integrated solar system can provide the system with the necessary reactive power without causing switching transients to maintain system voltage level and pf. Consequently, the integrated solar system of this BESS can increase the reliability and stability of the power system.

The overall costs of the proposed system are summarized in Table 2 in USD, which shows that the proposed IoT-enabled solar energy monitoring system with BESSs control can be installed into the power grid at a low cost. The proposed system costs 56.72 $, which is less than the solar energy monitoring system proposed in [33, 34], which costs more than 150 $. The lower cost is due primarily to the use of a low-cost MCU. Table 3 compares the costs of the controllers used in IoT-based solar energy monitoring systems in the literature. As shown in Table 3, all of the controllers listed cost more than the proposed ESP8266 MCU. Although microcomputers such as the Raspberry Pi and Beaglebone Black have a lot of processing power, they need external ADCs to take analog

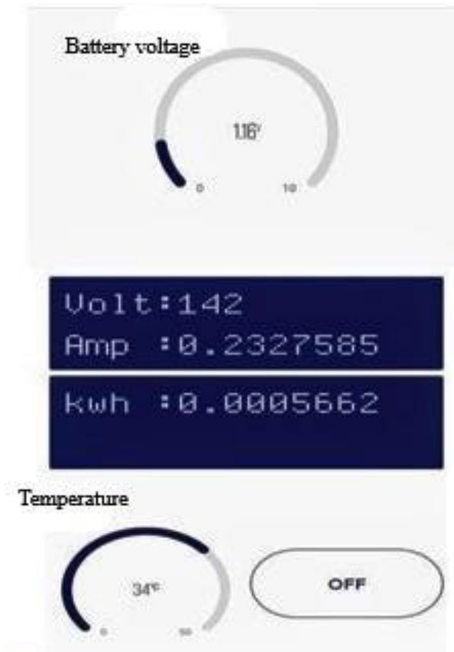

Fig. 10 App interface of the proposed solar system

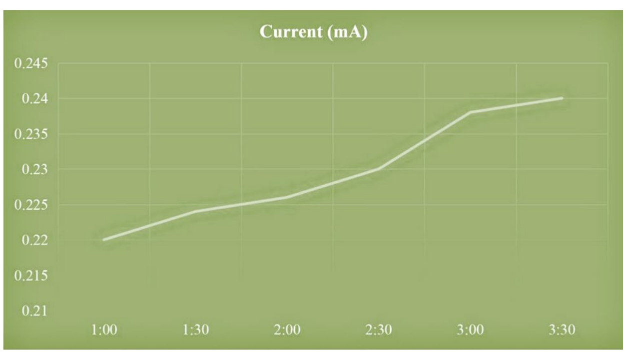

Fig. 11 Current values of the proposed system during a period

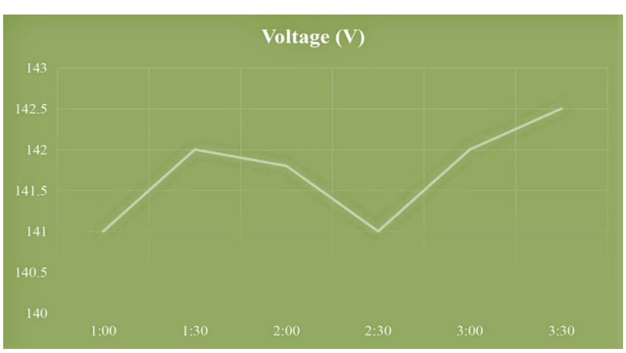

Fig. 12 Voltage values of the proposed system during a period

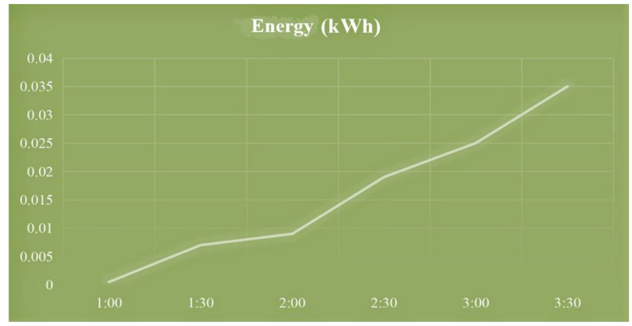

Fig. 13 Generated solar energy throughout a period

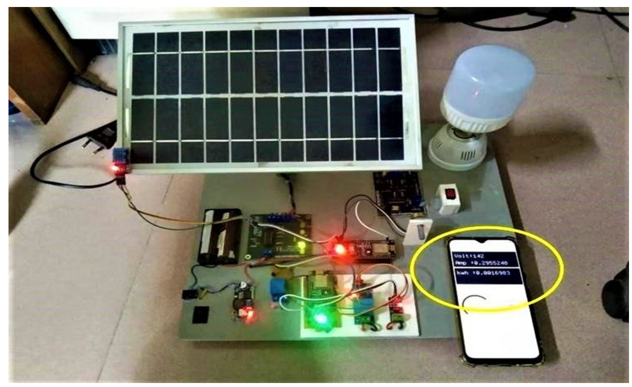

Fig. 14 App notification by the proposed system during low battery voltage level

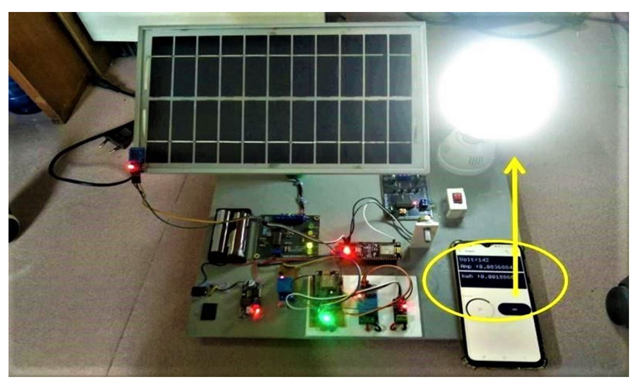

Fig. 15 Proposed solar energy monitoring system view during the load-off condition

measurements. They are also more expensive and consume more power than the proposed MCU ESP8266. The proposed ESP8266 MCU board, like Arduino boards, can be easily programmed using the Arduino IDE software. This low-cost MCU also provides wireless connectivity to the board as well as high computation capability. In addition, the proposed system makes use of the open-source Blynk

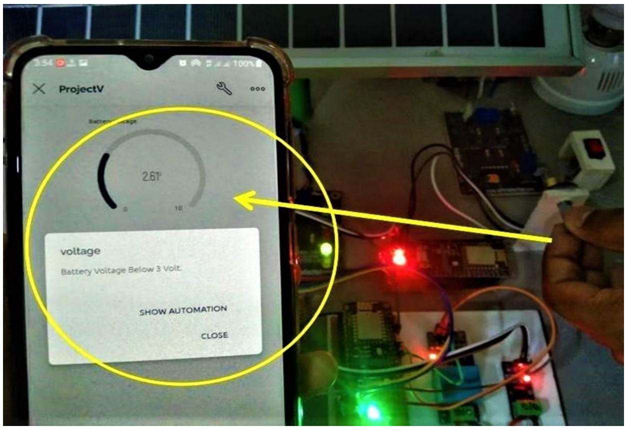

Fig. 16 Proposed solar energy monitoring system view during the load on condition

app for monitoring, visualization, and analysis of system data, which helps to reduce system costs. The Blynk app provides users with a user-friendly graphical user interface. Some solar energy systems in the literature used LABVIEW software [37, 38], which is a costly paid software. Therefore, the proposed Blynk app could be useful for low-cost IoT-based solar energy monitoring systems.

Conclusions

This article proposes an Internet of things (IoT)-enabled smart solar energy monitoring system to enhance the future smart grid's power quality and reliability with high levels of solar energy penetration. With the addition of IoT-enabled solar PV and storage, the power quality and reliability of the smart grid will be significantly increased. Additionally, the grid will be easier to manage, and resources will be able to produce a dispatchable power output as they become available. Storage is particularly important as a resource for regulation because it can react quickly, enabling the BESS to take solar PV power fluctuations into account. This system is economical. The primary advantage of implementing IoT in solar energy is that it allows for real-time monitoring of events from anywhere in the globe with access to all relevant data from a single central control panel. Users can learn about the solar system's temperature, current, voltage, and energy statistics by connecting their devices to a cloud network. For both on-grid (also called grid-tied) and off-grid solar energy systems, this technology can be useful for continually monitoring the system parameters.

Table 2 Cost summary of the proposed system

Sl. no.	Particulars	Specification	Qty	Unit price ($)	Total price ($)
01	Node MCU	ESP8266	2	5.45	10.89
02	Solar panel	10 Watt	1	10.15	10.15
03	Solar charge controller	–	1	2.31	2.31
04	Battery	3.7 V	2	0.92	0.92
05	Relay module	5 V	1	0.23	0.23
06	Buck converter module	LM2596	1	1.11	1.11
07	Current sensor	ACS712	1	2.58	2.58
08	Voltage sensor	ZMPT101B	1	3.23	3.23
09	Inverter circuit board	AC-DC	1	5.08	5.08
10	Transformer	1 Amp	1	1.29	1.29
11	Temperature sensor	DHT-11	1	4.62	4.62
12	Voltage regulator		1	2.77	2.77
13	Other				10.62
				Total	56.72

Table 3 A comparison of controllers used in IoT-based solar energy monitoring systems

Utilized controllers	Main features	Controller price ($)	References
Arduino Mega 2560	High processing power Low power consumption Integrated ADC An ethernet or GSM shield is required for wireless connectivity High I/O pins	38.72	[34, 39]
Arduino Uno	Low processing power Low power consumption Integrated ADC An ethernet or GSM shield is required for wireless connectivity Low I/O pins	27.60	[33, 40]
Raspberry Pi	Very high processing power High power consumption External ADC required Built-in Wi-Fi	35	[41, 42]
PIC 16F877	Low processing power Low power consumption Integrated ADC No built-in wireless connectivity	12.19	[43, 44]
BeagleBone Black	Very high processing power High power consumption External ADC required No built-in wireless connectivity	52.50	[45, 46]
ESP8266	High processing power Low power consumption Integrated ADCs Built-in Wi-Fi	5.45	Proposed

Data availability The article contains all of the necessary data and supporting information.

Declarations

Conflict of Interest The authors declare that they have no conflict of interest.

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