

Smart grid load management driven by IoT-based Arduino R4 controller

Abdallah Hussein,

Khaled Abojlala

a.hussein@eng.misuratau.edu.ly

kh.Abojlala@eng.misuratau.edu.ly

Electrical and Electronic Engineering
Faculty of Engineering, Misurata University Misurata, Libya

Article information	Abstract
<p>Key words</p> <p><i>load management, PV panel, battery, smart grid, Arduino, Internet of Things.</i></p> <p><i>Received 22 04 2026, Accepted 06 05 2026, Available online 07 05 2026</i></p>	<p>The increasing global demand for renewable energy and the critical need for efficient power management have made the development of innovative load management solutions necessary. This paper proposes an Internet of Things (IoT)-based Arduino R4 controller for load management in a smart grid. The system is designed to optimise energy consumption by providing real-time monitoring and control over the renewable energy sources and the utility grid. The technical approach involves integrating the Arduino with current and voltage sensors to track the power of PV, battery, utility grid and load consumption. Collected data is then transmitted to a cloud platform for detailed analysis and visualisation, supporting better decision-making and efficient load management. The monitoring components for the proposed system are low-cost and readily available on the market.</p>

I. Introduction

Traditional power grids often struggle to handle growing energy demands, leading to inefficiencies, power outages, and increased operational costs. To mitigate these problems, smart load systems have been developed to provide intelligent energy, enabling the monitoring, control, and optimisation of usage to reduce wasted power and enhance overall system efficiency [1,2].

The smart systems are applicable for monitoring and controlling renewable energy sources and electrical loads across various scales, including residential homes, commercial businesses, and large-scale utility grids. By integrating sensors, smart controllers, and cloud platforms, the system empowers users to manage their energy consumption more effectively and ultimately reduce energy costs [3].

Early smart grid load management systems used PLCs and centralised control, which were effective but costly, inflexible, and unsuitable for small-scale or residential use [4-7]. The use of non-open-source software like LabVIEW further increased costs [8-11]. In contrast, IoT-based microcontrollers such as Arduino, ESP8266/ESP32, STM32, and Raspberry Pi offer low-cost, flexible solutions with local data processing, wireless communication, and easy integration with cloud and mobile platforms, improving scalability while reducing overall system cost [1,3,12]. Moreover, this paper develops a simple, low-cost, and high-performance IoT-based solution for managing three power sources: solar panels, a battery storage system, and a backup utility grid connection.

II. Research System Design

A. The proposed IoT for smart grid management

Fig. 1 presents a block diagram of the proposed smart grid system, which integrates a photovoltaic (PV) panel, a battery, and the utility grid to supply domestic loads. The system acquires electrical data from the PV panel, battery, and utility grid using voltage and current sensors. An Arduino microcontroller uses an IoT protocol to collect and process the sensor data, which is then transmitted to and stored on a cloud server. A web-based, open-source platform serves as a cloud database and visualisation tool, enabling users to access the data via a smartphone application.

The IoT system continuously monitors key parameters of the smart grid that influence load management in real time through online platforms. This enables continuous tracking of PV generation, battery state of charge, and grid power availability, thereby enhancing system analysis, performance evaluation, and efficiency.

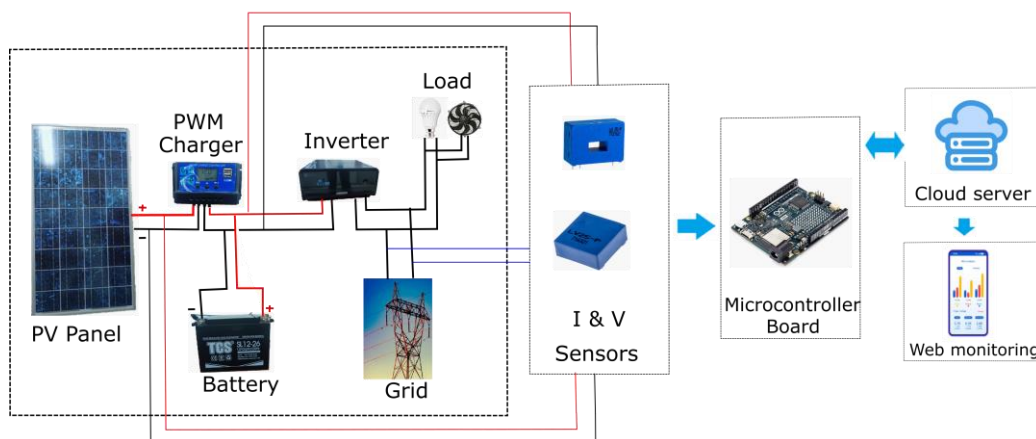


Figure 1. Block diagram of a proposed IoT-based smart grid system.

B. Application programming interface (API) and display unit

Continuous data collection requires a graphical or visual interface that can be accessed remotely and viewed in real time using a smartphone. The proposed system uses the open-source Adafruit IO platform as the application programming interface (API) for its display unit. Data is sent and received using the API through the MQTT protocol, while the smartphone application, developed using the React Native framework, serves as an interface

that allows users to monitor network data and control connected devices. The application uses the HTTP protocol to interact with the application programming interface (API).

III. Experimental Setup

In this study, multiple current and voltage sensors are used to measure the currents, voltages, and power outputs of the solar PV system, battery, and utility grid. The data gathered from these sensors is transmitted wirelessly to a cloud server using IoT communication protocols and is subsequently visualised through the Adafruit IO platform.

The main objective of the proposed system is to develop a simple, low-cost, and high-performance IoT-based solution for load management in a smart grid, with a particular focus on small-scale photovoltaic (PV) installations operating under both on-grid and off-grid conditions. Therefore, careful selection of sensor and controller hardware is essential to minimise cost while maintaining high accuracy in data acquisition.

The following low-cost sensors are used to quantify the electrical parameters:

- LV25-P voltage sensors are employed to measure the voltages of the PV system, battery, and utility grid. They have a measuring range from 10V to 500V, making them suitable for low and medium voltages.
- LA25-P current sensors with a measuring range from 0-25 A, which are utilised to measure the currents supplied by the PV system, battery, and utility grid.

The Arduino R4 controller is selected as the main processing unit for the data acquisition system due to its low cost, low power consumption, and high computational performance. In addition, the Arduino controller offers several useful features, including a built-in Wi-Fi module, numerous ADC input ports, and a simple programming environment.

The open-source IoT platform Adafruit IO is employed as a cloud database and data visualisation tool, providing interactive graphs and dashboards while keeping the system low-cost, accessible, and easy to develop. This integration between hardware and software aims to create a practical model for load management in a smart electrical network, based on real data and active consumer participation.

A. Hardware design

The proposed electrical smart grid was designed to have multiple energy sources, and the load is managed using an Arduino R4 controller supported by IoT technology. This grid integrates a utility grid and a PV system of a solar panel, a charge controller, a storage battery, and an inverter.

Integrated measurement and monitoring units were also designed, including sensors to measure the voltage and current for the photovoltaic panel, battery, and utility grid. The control unit collects data from these sensors in real time, processes it, and then makes operational decisions (connect/disconnect) based on a pre-defined load management strategy. Fig. 2 illustrates the practical circuit used in this study.

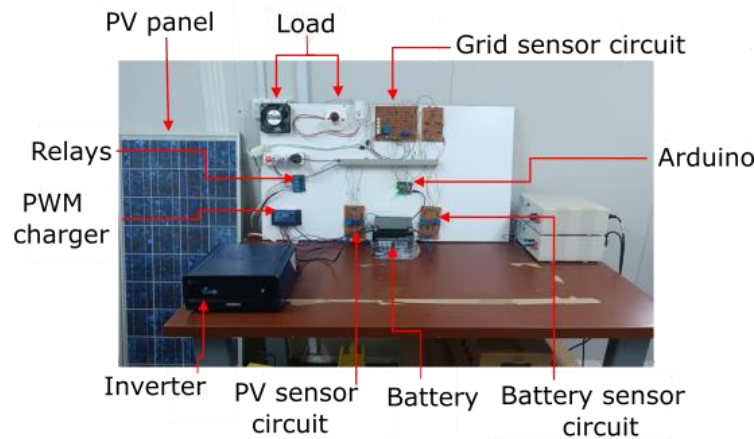


Figure 2. Experimental setup of the proposed system.

B. Hybrid grid system

In the proposed design system, the PV system consists of an 80W monocrystalline PV panel, a 10A PWM solar charge controller, a 12V 26Ah battery for energy backup, a load with a total daily energy consumption of 133 Wh/day, and the utility grid of 220V.

C. Sensing units

1. Current and voltage sensor circuit for PV

The current sensor with a maximum operating range equal to 5A (short circuit current of PV) was used in the design. While the proposed system's voltage sensor is designed to read the maximum value of the output voltage equal to 21.9V provided by the PV when the system is in open circuit.

The waveforms of the voltage and current sensor circuits output of a PV panel are shown in Fig. 3. The two observed waveforms indicate the real-time operating condition of the PV panel. The signals are conditioned to safe voltage levels before being input to the Arduino R4 for processing. These signals are used for power calculation, system monitoring, and load management.

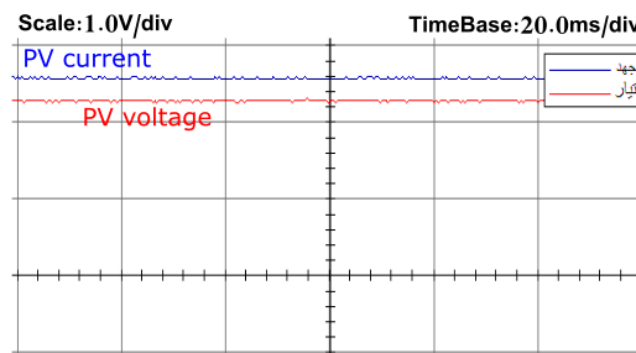


Figure 3. Waveforms of current and voltage sensor circuits for PV panel.

D. 2. Current and voltage sensor circuit for battery

The current sensor for the battery was designed with a maximum operating range equal to 5A (short circuit current of PV), assuming that the maximum current produced by the PV panel is

fully employed to charge the battery. Since the PV system uses a battery with a nominal voltage of 12 V, and its voltage can rise to about 15 V when fully charged, the input of the voltage sensor was designed to accommodate this upper limit. This ensures accurate measurement and protects the controller during voltage monitoring.

The voltage and current sensor circuit outputs of the battery are illustrated in Fig. 4. The analysis of these waveforms provides insight into the battery's real-time electrical operating conditions. The signals are conditioned to safe voltage levels before being input to the Arduino R4 for processing. These signals are employed for instantaneous power computation, state-of-charge monitoring, and load management.

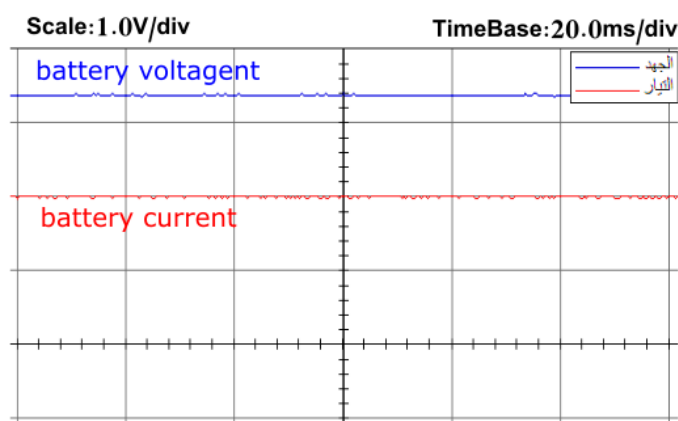


Figure 4. Waveforms of current and voltage sensor circuits for battery.

E. 3. Current and voltage sensor circuit for utility grid

The sensor circuit was designed based on the maximum current drawn by the load, where the total load power is 35 W (133 Wh/day) at a grid voltage of 220V. Since the connected loads are designed to operate at a voltage of 220 volts, this value was adopted as the basis for designing the voltage sensor.

The voltage and current sensor outputs of the utility grid connection are shown in Fig. 5. The simultaneous observation of these waveforms provides real-time information on the grid's electrical operating conditions.

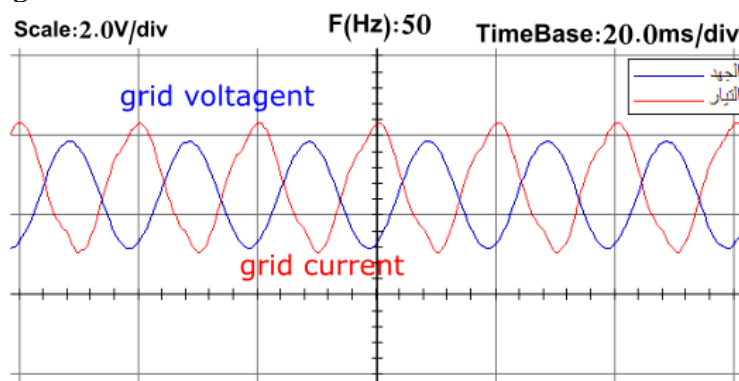


Figure 5. Waveforms of current and voltage sensor circuits for the utility grid.

The signals are conditioned to safe voltage levels before being input to the Arduino R4 for processing. They can be used for instantaneous power calculation, grid performance monitoring, load management, and protection control.

F. 4. Phase shift measurement circuit

Since the system loads are inductive by nature, determining the consumed power requires calculating the phase shift between voltage and current. The design converts the analogue signals of voltages and currents into digital square signals, where positive values are represented as one and negative values as zero. Then, the operational amplifier subtracts these signals to find the phase difference.

The output signal of the phase shift circuit shown in Fig. 6 is fed into a digital pin of the Arduino. This digital pin detects the time duration between zero crossing points of voltage and current signal waveforms using the **pulseIn** function, which is then used for the power factor measurements.

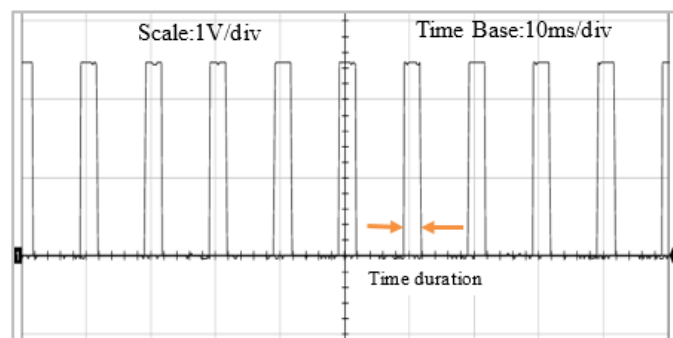


Figure 6. Output of the phase-shift measurement circuit.

G. Software design

H. Smartphone Application Design

The smartphone application is designed to provide an easy-to-use interface that allows the user to monitor various network parameters, which are read by the voltage and current sensors connected to the solar panels, the battery, and the utility grid, then processed and sent to the IoT platform (Adafruit IO) using the microcontroller (Arduino Uno R4). In addition, the application enables controlling the power sources by turning them on or off. This application serves as the link between the user and the IoT platform, which in turn connects the mobile application with the microcontroller.

I. Load management algorithm

Fig. 7 displays a flowchart of an IoT-based smart grid load management. The proposed monitoring system starts with monitoring the state of solar PV; if there is enough generated power, it is used to supply the load and charge the battery. On the other hand, if the power generated by the panel is insufficient to meet the load demand, the algorithm assesses the grid status in terms of availability and electricity cost. If the grid is unavailable or the cost is high, then the algorithm evaluates the battery's charge level. When the battery charge is above 50%, it supplies the load; if it is below 50%, the photovoltaic system is disconnected entirely, and the load is supplied from the main electricity grid.

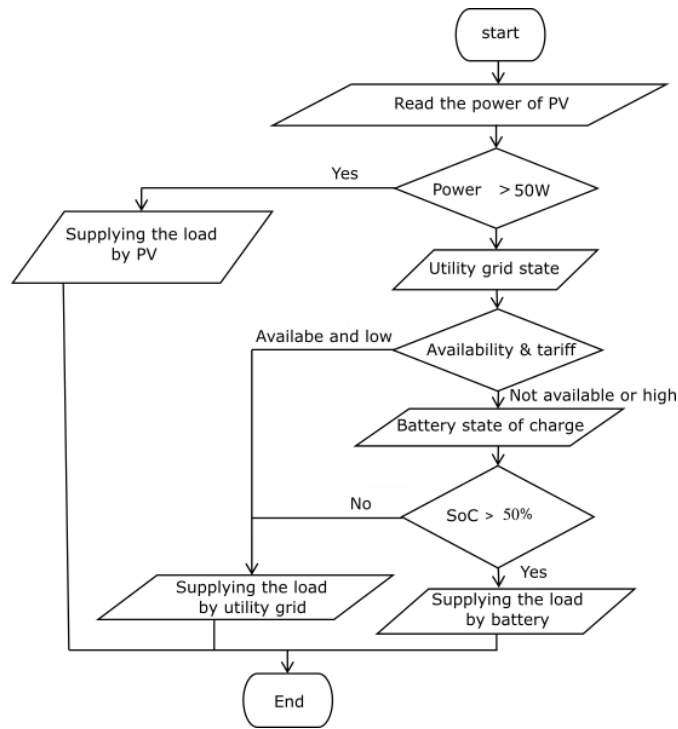


Figure 7. Flowchart of the proposed load management system.

IV. Results and Discussion

The measured values obtained using the designed systems were compared with the reference values acquired from the laboratory’s available equipment, specifically the LVDAC computer-based data acquisition and measurement system from LabVolt/Festo. The results presented in Table I include the reference values, the measured values, and the corresponding deviations, demonstrating that the designed system provides accurate measurements of voltage, current, power factor, and frequency at the smartphone. However, Potential work may incorporate statistical analysis based on multiple readings using metrics such as mean and standard deviation, as well as evaluating system performance over longer time periods to enhance the reliability of the results.

TABLE I. ACCURACY OF THE MEASURED ELECTRICAL PARAMETERS.

Measuring circuit	Electrical quantity	Measured value at smart phone	Reference value	Error %
PV	Voltage (V)	13.86	13.58	2.06
	Current (A)	2.79	2.75	1.45
	Power (W)	38.80	37.34	3.89
Battery	Voltage (V)	13.60	13.45	1.11
	Current (A)	-1.96	-1.98	1.01
Load	Voltage (V)	206.8	207.1	0.145
	Current (A)	0.135	0.133	1.5
	Power Factor	0.88	0.847	3.896
	Power (W)	24.12	23.2	3.97
	Frequency (Hz)	49.85	50.01	0.32

Upon launching the application, real-time data acquired from the microcontroller such as PV voltage, battery voltage and current, and load power factor, are displayed on the user interface. Additionally, graphical representations illustrate parameter trends (e.g., battery state of charge), with automatic updates based on the latest readings from the Adafruit IO platform.

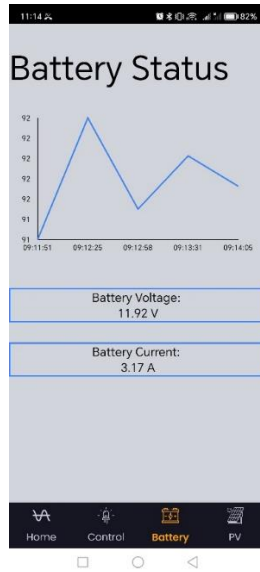


Figure 8. Battery dashboard

The graphical data for the smart grid load management obtained from the Adafruit IO IoT platform and the possible load management scenarios are as follows:

A. The power generated by the solar panel is greater than the load consumption

When sufficient solar irradiance is available, the electricity generated by the solar panels is free. It is therefore used to supply the loads. If the generated power exceeds the load demand (35W), the extra power is stored in the battery. Fig. 9 illustrates the power flow for this scenario.

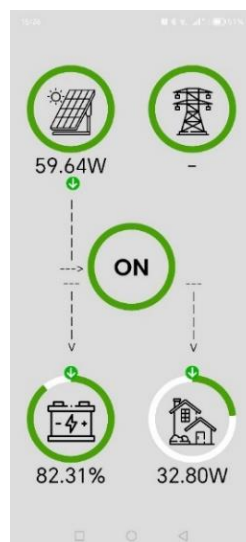


Figure 9. Power generated by the solar panel exceeds load consumption

B. Partial absence of sunlight during high electricity tariff periods or main grid outages.

The battery, provided its charge level is above 50%, primarily supplies the loads with energy, assisted by the solar panel. Fig. 10 shows the resulting power flow in this scenario.

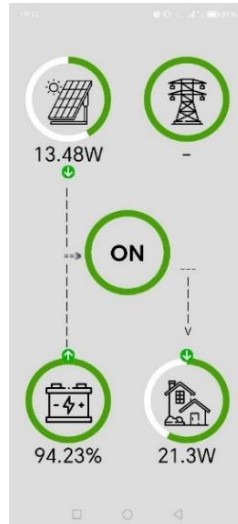


Figure 10. Partial absence of sunlight during high tariffs or main grid outages.

C. Partial absence of sunlight during low electricity tariff periods with main grid availability.

The main grid supplies the loads, while the power generated by the solar panel is directed to charge the battery. Fig. 11 shows the power flow in this case.

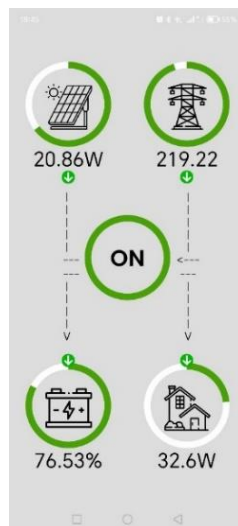


Figure 11. Partial absence of sunlight during low tariff periods with main grid availability.

D. Complete absence of sunlight or nighttime with main grid outage

The battery supplies the loads, provided its charge level is above 50%. Fig. 12 illustrates the power flow in this scenario.

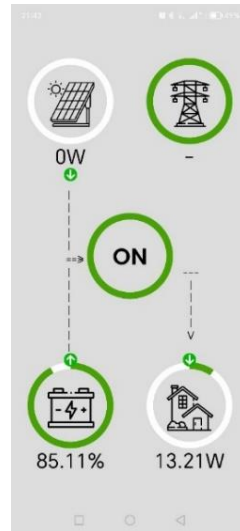


Figure 12. Complete absence of sunlight or nighttime with main grid outage.

E. Battery capacity falls below the design limit

During the design phase, the battery's depth of discharge was set at 50%. Therefore, when the battery charge drops below 50%, the photovoltaic system is either disconnected from supplying the loads, and the main grid supplies the loads. If the solar panel generates power, it is used to charge the battery. Fig. 13 illustrates the power flow in this scenario.

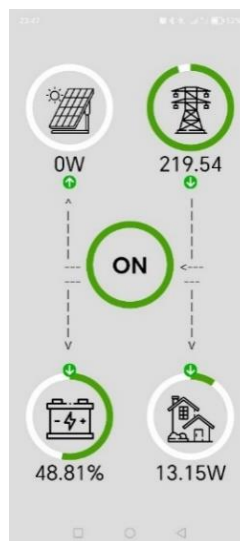


Figure 13. Battery capacity below the design limit.

V. Conclusion and Future Work

An IoT-based smart grid monitoring system was introduced in this paper. The output voltage and current of PV, battery and utility grid are all measured by the system. Moreover, the output voltages and the output currents are measured using LV25-P and LA25-P sensors, respectively. Additionally, the output power is calculated as the product of the measured voltage and current. The main controller of the system is the Arduino Uno R4 with built-in Wi-Fi, which collects and processes the sensor data, and then transmits and stores it in a cloud server. Web-based, open-source software functions as a cloud database and visualisation platform, allowing users to access the data through a smartphone.

An experimental setup is used to verify the proposed smart grid system load management based on IoT technology. The outcome clearly shows that the proposed system offers accurate results in monitoring and load management. The monitoring components for the proposed system are low-cost and readily available on the market.

The future work section has been expanded to highlight potential developments of the proposed system, including the integration of predictive algorithms for load demand and solar irradiance, the application of artificial intelligence techniques such as neural networks, and the adoption of reinforcement learning to enhance dynamic energy management decision-making.

Furthermore, a future integration framework can be envisioned, which may include acquiring real-time electricity tariff data through application programming interfaces (APIs) provided by utility service providers, via cloud-based IoT platforms, or through smart metering systems.

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إدارة أحمال شبكة كهربائية ذكية باستخدام متحكم أردوينو R4 معتمد على إنترنت الأشياء IoT

عبدالله حسين ، خالد أبو جلاله
قسم الهندسة الكهربائية والإلكترونية، كلية الهندسة، جامعة مصراته، ليبيا

الملخص

الطلب العالمي المتزايد على الطاقة المتجددة والحاجة الملحة إلى إدارة فعّالة للطاقة جعلاً من الضروري تطوير حلول مبتكرة لإدارة الأحمال بالشبكات الكهربائية. تقترح هذه الورقة نظام تحكّم يعتمد على إنترنت الأشياء (IoT) باستخدام متحكم أردوينو R4 لإدارة الأحمال في شبكة كهربائية ذكية. تم تصميم النظام بهدف تحسين استهلاك الطاقة من خلال توفير المراقبة والتحكم في الوقت الحقيقي لمصادر الطاقة المتجددة وشبكة الكهرباء العامة. تعتمد منهجية البحث على دمج متحكم أردوينو مع حساسات التيار والجهد لتتبع القدرة الكهربائية لكل من النظام الكهروضوئي الشمسي (PV)، والبطارية، وشبكة الكهرباء، واستهلاك الأحمال. بعد ذلك يتم إرسال البيانات المجمعة إلى منصة سحابية لإجراء تحليل مفصل وعرض للبيانات، مما يدعم اتخاذ قرارات أفضل وإدارة أكثر كفاءة للأحمال، كما أن مكوّنات المراقبة المستخدمة في النظام المقترح منخفضة التكلفة ومتوفرة في الأسواق.

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كهروضوئي، شبكة
ذكية، أردوينو، إنترنت
الأشياء