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Hybrid battery management system using the internet of things

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Abstract:

The steadily increasing acceptance of battery technology has created numerous opportunities for identifying new technologies and methods to improve the performance and safety of batteries used in various applications, including electric vehicles and digital devices. The current study focuses on the interaction of hardware and software for recording and monitoring battery pack data. The battery management system uses IoT technology, a microcontroller, and sensors to collect voltage and temperature data from battery cells. The individual cell voltage reached approximately 4.2 volts and achieved a full charge of 99%, which was measured locally and displayed remotely on a mobile dashboard via an IoT server. The cells are charged in parallel, and the entire charging process for all cells is completed in about 10 minutes. The battery pack temperature was continuously monitored during charging and discharging, assisting in mitigating risks and improving battery lifespan through proper data. The battery management system's ability to monitor charging and discharging cycles and their performance allows for corrective actions and informed decision-making to ensure safe operation. Validation, testing, and demonstration of the effectiveness of the IoT-based hybrid-powered battery management system revealed its ability to detect battery performance issues and exchange data for disciplinary action. This creates a safe environment for the use of battery management systems in a variety of battery operations.

Keywords: Battery cell; Internet of things; Hybrid system; Battery management; Microcontroller

1. Introduction

In the current era, power management is crucial across all industrial sectors, including automotive, medical, and manufacturing [1, 2]. The increasing development and adoption of electric vehicles (EVs) have highlighted numerous challenges related to battery performance and safety [3]. Effective battery management is essential to address these issues, ensuring safety and extending the lifespan of batteries or battery packs [4]. Thus, battery management systems (BMS) play a vital role in maintaining the balance of charging and discharging cycles by leveraging prior experience, historical data, and advanced modeling techniques [5, 6]. Lithium-ion cells, commonly used in battery packs, are assembled into modules and connected in series to provide the required voltage for various applications [7]. The voltage and temperature of these batteries must be kept within specific ranges to ensure safe operation. Deviation from these ranges can lead to battery cell degradation or ignition. Typically, the voltage of a Lithium-ion battery cell should remain between 2.5 to 4.2 volts, and the temperature should be maintained between 40 °C and 60 °C to ensure safe operation [8, 9]. Several factors can affect battery cells, including cell age, overcharging, over-discharging, and load complexity [10]. Modern BMS must ensure battery packs function safely and report their status regularly. BMS can significantly extend battery cell life by monitoring the state of charge (SoC). Accessing real-time information on battery charging and discharging status enhances the safety and durability of battery cells [11].
Further, hybrid battery charging systems that integrate solar power with main power sources offer a robust solution

for maintaining reliable energy storage and supply [12, 13]. These systems combine renewable energy from solar panels with the dependable availability of main power sources, ensuring continuous power availability while optimizing battery performance and energy efficiency. During sunny periods, solar panels generate electricity, which is regulated by a charge controller and used to charge the battery bank. The charge controller ensures efficient and safe charging. When solar power is insufficient, such as during nighttime or cloudy days, the system automatically switches to the main power source to charge the batteries, ensuring a reliable power supply. Additionally, the inverter draws power from the battery bank to supply power to connected loads. The system can seamlessly transition between solar and main power sources to maintain an uninterrupted power supply.

A sophisticated monitoring system provides real-time data on energy production, consumption, and battery status, allowing for informed decision-making and system optimization [14, 15]. Effective battery management strategies further enhance system performance, making hybrid systems increasingly attractive for residential, commercial, and remote applications [16]. The integration of the Internet of Things (IoT) in battery management systems represents a significant advancement in optimizing battery performance, enhancing efficiency, and ensuring reliability [17, 18]. IoT-enabled BMS can monitor, control, and manage battery operations in real-time, leading to extended battery life, and enhanced safety. IoT is an advanced technology used across various fields today [19]. It involves the interconnection of physical components, embedded electronics, sensors, actuators, and network connections, allowing these components to gather and share data. IoT devices link physical components to the virtual world, enabling data access from any location. Using IoT systems, battery operations can be easily monitored and controlled remotely. Leveraging real-time data, predictive analytics, and remote management capabilities, IoT enhances the efficiency, reliability, and lifespan of battery systems across various applications [20, 21]. The integration of IoT in battery management not only improves operational efficiency but also contributes to broader goals of energy conservation and sustainability.

The main objective of the present work is to develop a hybrid battery management system using the Internet of Things. This approach aims to provide an efficient way to monitor battery parameters and improve battery durability. Regular monitoring of battery health parameters, such as voltage and temperature, can significantly boost battery performance. A microcontroller unit with a built-in Wi-Fi function is used to collect data and transmit it to the server. A display unit connected to the BMS monitors the current status of the sensors. A mobile application is developed to remotely monitor the current status of battery cells. Thus, the IoT-based BMS is being developed with the long-term goal of improving cost-effectiveness, safety, reliability, and optimal operation of battery energy storage systems.

2. Methodology

The proposed schematic diagram of the BMS model is presented in figure 1. It comprises photovoltaic solar panels, a main power source, a BMS system, a controller unit, and an IoT interface system. The solar panel generates a direct

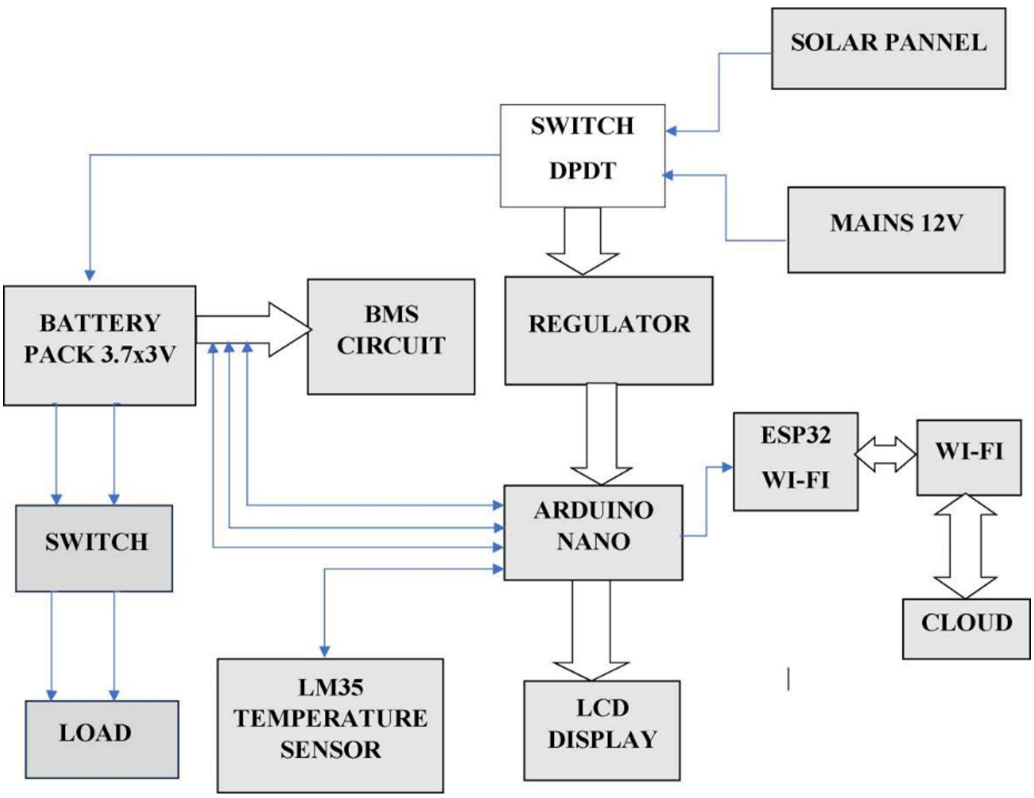

Figure 1. Schematic of battery management system.

voltage in the presence of sunlight, which is transmitted to charge the battery through a switch. When sunlight is insufficient, the main power source is available to charge the battery pack. The energy generated by the solar panel is stored in the battery pack and used as needed. The primary function of the battery management system is to detect and monitor the battery type, voltage, temperature, power consumption, state of charge, and charging cycle. The dedicated interface among the components provides real-time information to the end user regarding the status of the battery. To ensure safe operation, the BMS monitors factors such as temperature and voltage across the battery pack. It also tracks the state of health of the battery, indicating its charging and discharging status. Additionally, the BMS continuously monitors the temperature and manages the thermal effects on the battery pack. It measures the overall battery pack temperature and can activate the cooling system if the temperature exceeds a certain threshold, ensuring it remains within safe limits. An additional provision for thermal management has been integrated into the BMS unit. The BMS unit is connected to the central controller unit and the battery cells to facilitate continuous data exchange. It transmits battery parameters to the controller unit, enabling easy monitoring of the system's loading capability. The controller unit acts as the main interface between the BMS and IoT devices, exchanging data with the end user through the server. With this data, corrective actions can be taken to maintain optimal battery parameters, preventing issues such as overheating and leakage, and ensuring the safety of the battery cells. In battery technology, the rate at which a battery is charged or discharged about its nominal capacity is referred to as the "*C*-rate." It represents a multiple of the battery's rated capacity and determines the current flowing into or out of the battery. It can be expressed mathematically as:

$$I = C \times \text{Capacity} \tag{1}$$

where '*I*' is the current, *C* is the *C*-rate, and Capacity is the nominal capacity of the battery.

2.1 Simulation and hardware

The schematic circuit of the battery management and controlling unit is shown in figure 2. The circuit is implemented using proteus software to represent the working of a realistic BMS circuit and control unit. The BMS model incorporates all the electronic components, including the BMS circuit, controller unit, battery cell, temperature sensor, and Wi-Fi module. The battery specifications have been used in the present work such as Battery Type: Lithium-Ion Battery, Nominal Voltage: 3.7 V, Nominal Capacity: 2000 mAh, Anode Material: Graphite, Cathode Material: Lithium Cobalt Oxide ($LiCoO_2$), Electrolyte Material: Lithium salt dissolved in organic solvent. However, the IoT integration was implemented with the circuit to show interfacing with IoT components with the circuit diagram. The solar panel and main power source were connected to a double pole double throw switch based on the condition that the supply unit can be switched over and transmit voltage to the BMS circuit. The battery pack is charged through the BMS circuit as required by individual battery cells. Then, the battery voltages were gathered by the controller unit, and the same voltage status was displayed on the screen. Temperature sensors were used continuously to monitor the temperature of the battery pack. When the temperature of the battery exceeds the limit set in the controller unit, a cooling system can be switched on to avoid the overheating of the battery cell. The display unit in the circuit shows the individual battery cell voltage status and temperature of the battery pack. All sensing unit data is transmitted to the Arduino uno controller unit. Then the controller-recorded data is

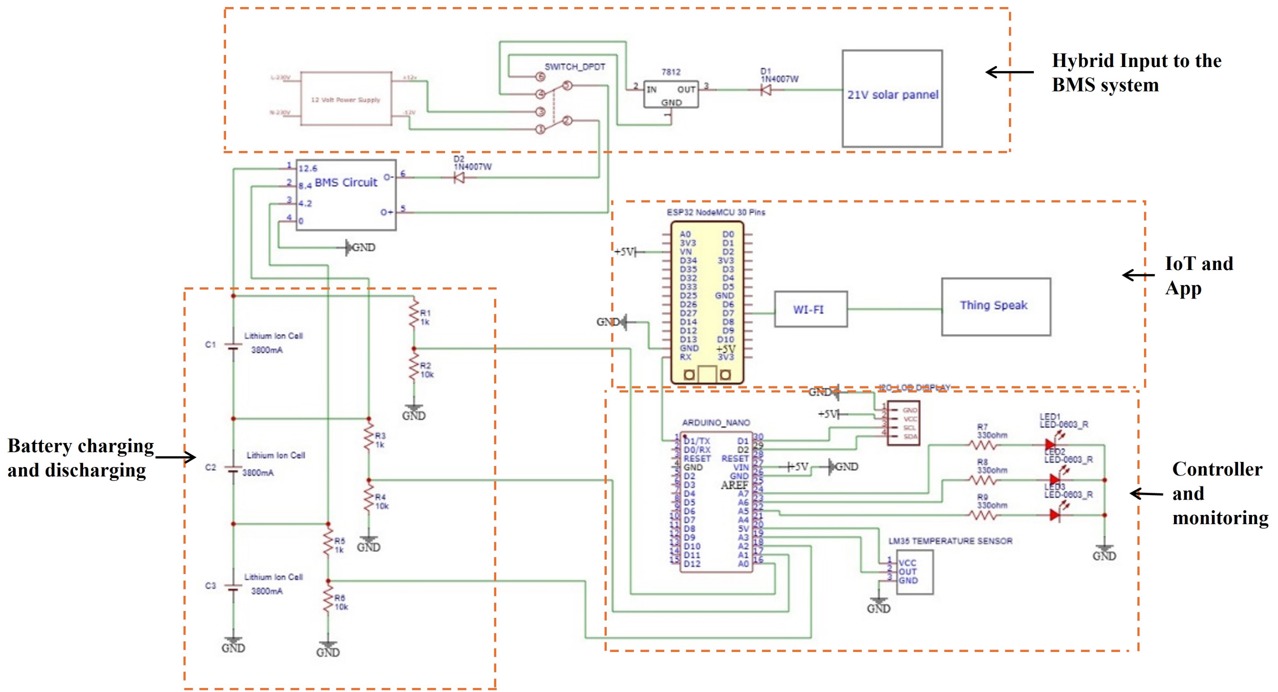

Figure 2. Schematic circuit of the BMS.

transmitted to ESP 32 through a Wi-Fi module using a serial connection. IoT cloud server is utilized to check the battery status remotely in their smartphone or computer.
The hardware components used to implement the experimental setup for battery data management included an Arduino Nano, ESP32, 12.6 V lithium-ion battery pack (with each cell having 4.2 volts), DPDT switch, 16x2 LCD, LM35 temperature sensor, and a 12 V solar panel. The main components of the battery management system are shown in figure 3. A voltage divider and BMS circuit were implemented to exchange the current and voltage values of the BMS system. Initially, the battery pack is charged by both the solar panel and the main power supply system, controlled via a double-pole switch. A hybrid energy system integrates multiple energy sources (e.g., solar, and batteries) to optimize energy generation, storage, and usage. On the other hand, a single-battery energy system relies solely on a single energy storage unit for its operations. In the current study, while the focus was primarily on monitoring the battery's SOC and temperature, the parameters of the solar energy system, such as solar panel output voltage and current, were also considered during the design and operation of the hybrid system. The LM35 temperature sensor is connected to the battery pack and the Arduino Nano controller. The controller converts the analog data of the voltage and temperature, and the individual cell voltages and battery temperature are displayed on the LCD screen. An I2C module was used to interface the controller unit with the display system. The sensor data is collected and transmitted to the Arduino Nano controller unit. The collected data is then transmitted to the ESP32 via the Wi-Fi module and subsequently to the Thing Speak server. The Arduino Nano Tx pin is connected to the ESP32 Rx pin, allowing the battery parameters to be displayed on the Thing Speak server. The Thing Speak server shows graphs of individual cell charging and discharging patterns using real-time data monitoring. To ensure a secure connection when transferring data between the ESP32 and the server, a unique authorization token is used, which is defined when registering an account on the Thing Speak mobile application. The data received from the server is shown on the digital dashboard.

3. Results and discussion

Battery management using a hybrid power supply and the Internet of Things has been implemented with various hardware and software components. The working prototype of the proposed battery management system is shown in figure 4. The hardware components were assembled after individually testing each part. Code was written to read sensor data, and a regulated circuit was used to control the switching device. The BMS system is powered by the main power source and a USB port connected to the controller

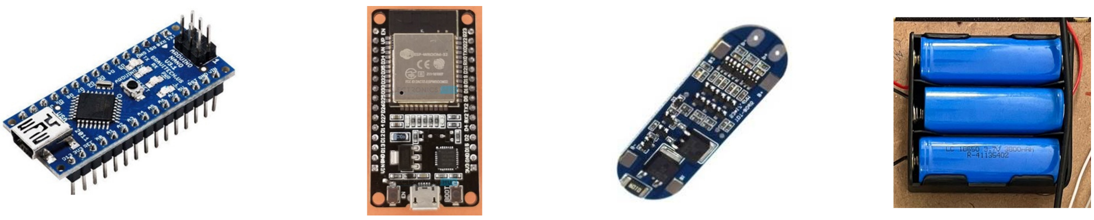

Figure 3. Main hardware component (a) Arduino Nano (b) ESP32 Microcontroller (c) BMS circuit (d) Li-ion Battery Pack.

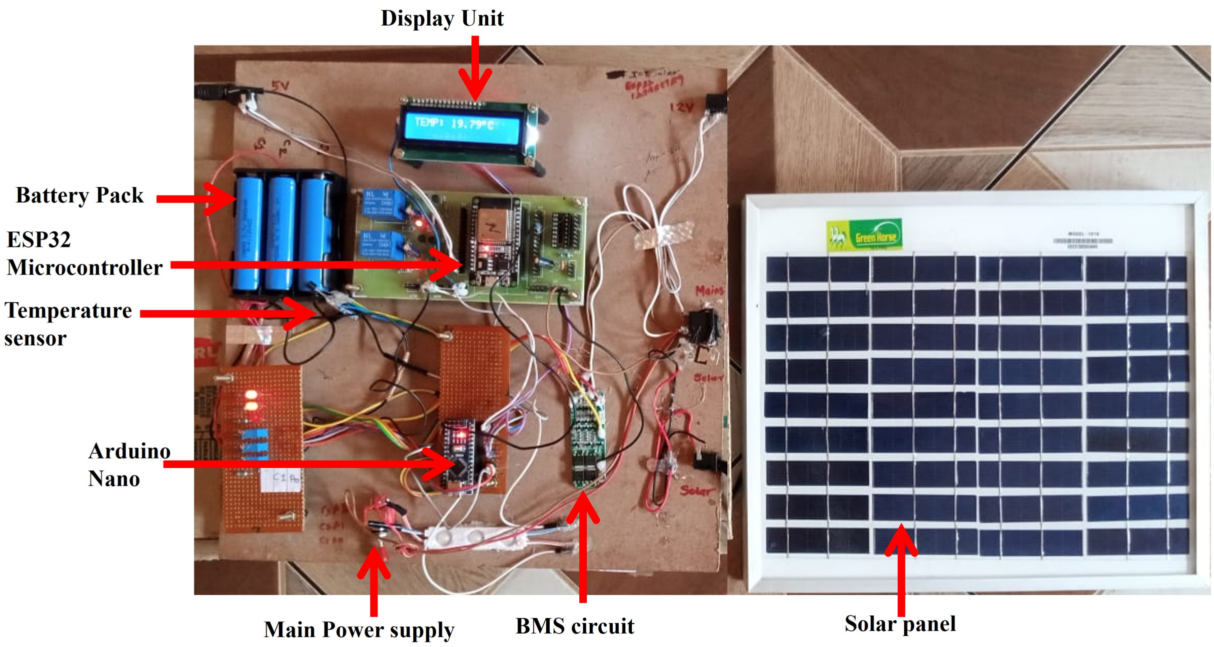

Figure 4. Working prototype of the battery management system.

and Wi-Fi module. Data collected from the controller and ESP32 is processed and linked to the Thing Speak server. Cell voltage and temperature are displayed on a mobile app and locally on an LCD screen. This data is continuously updated in real-time on the dashboard.
The battery information, including each cell's voltage and temperature, was continuously recorded and displayed. The BMS sensor data is displayed on an LCD, as shown in figure 5. The actual voltage of each cell was measured using a voltage sensor connected to each battery. The voltage sensor synchronized with the battery cell to measure the transition voltage. Similarly, a temperature sensor was connected to the battery, continuously monitoring the temperature and aiding in thermal management. This displayed data provides crucial battery information directly near the battery pack system.

Figure 5. BMS data were displayed on an LCD screen.

Table 1 shows the measured voltage of each battery cell as well as the system's difference in error during calibration. The voltage sensor detects the continuous voltage of the battery cell, and a multi-meter is used to verify the cell voltage before connecting the system. There was a percentage error in the voltage of individual cells. This error is an obvious phenomenon that occurs in all battery systems. As a result, proper calibration prevents fluctuation in the cells, and drastic voltage changes can shorten battery life.
The dashboard was meticulously designed to display all BMS information remotely, providing users with comprehensive and real-time insights into the battery's performance and condition. As depicted in figure 6, the mobile application dashboard allows users to view the voltage and temperature of each battery cell. The application effectively monitors the battery's condition as reported by the BMS model. Users can observe both the graphical and numerical representations of individual battery cell voltages and the overall temperature of the battery pack. This dual-format presentation ensures that users can quickly understand the battery's status, whether they prefer visual graphs or precise numerical data. The successful integration of the IoT with the BMS system exemplifies its deployment ability for end-user applications. The IoT interfacing allows for continuous monitoring and data transmission, ensuring that users are always informed about the battery's health and performance. This real-time information can be crucial for making informed decisions regarding the battery's usage, maintenance, and safety. In essence, the mobile application dashboard not only enhances the usability and accessibility of the BMS information but also represents a significant step towards more efficient and user-friendly battery management solutions.
Furthermore, the battery charging voltage levels of individual battery cells were continuously monitored and recorded. The server, via the IoT module, was able to read the charging voltages, as illustrated in figure 7. When the main power is turned on, each battery cell charges from its default voltage to a maximum of approximately 4.2 volts, achieving a full charge of 99%. The cells are charged in parallel, and the entire charging process for all cells is completed in about 10 minutes, as shown in figure 7 (a).
Similarly, when the load is activated, the discharging operation begins. The capacity of the battery cells decreases, meaning the voltage levels drop according to the load, as depicted in figure 7 (b). To ensure safe operation, the BMS unit sets limits for both the charging and discharging of the battery cells. An interlocking system ensures that during the charging process, discharging is disabled to prevent cell degradation and ensure safety. Furthermore, the system is designed to disconnect the battery cells from the charging supply once they are fully charged. During discharge, indications and precautions are provided to ensure that appropriate actions are taken by the user. The BMS also incorporates indicators for discharging levels, which prompt users to take necessary actions. The system's design includes future aspects such as monitoring the time taken for charging and discharging, understanding parameters that influence battery degradation, and other conditions that can help improve battery life and performance. By continuously gathering data on charging and discharging operations, the BMS can provide insights into the efficiency and health of the battery cells. This information is crucial for enhancing the overall performance and longevity of the batteries, making the BMS a vital tool for battery management.

Table 1. Battery cell voltage measurement.

Cell No	Battery cell voltage (V)	Multi-meter measurement (V)	Percentage error (%)
C1	4.18	4.00	4.50
C2	4.22	4.10	2.92
C3	4.05	3.99	1.50

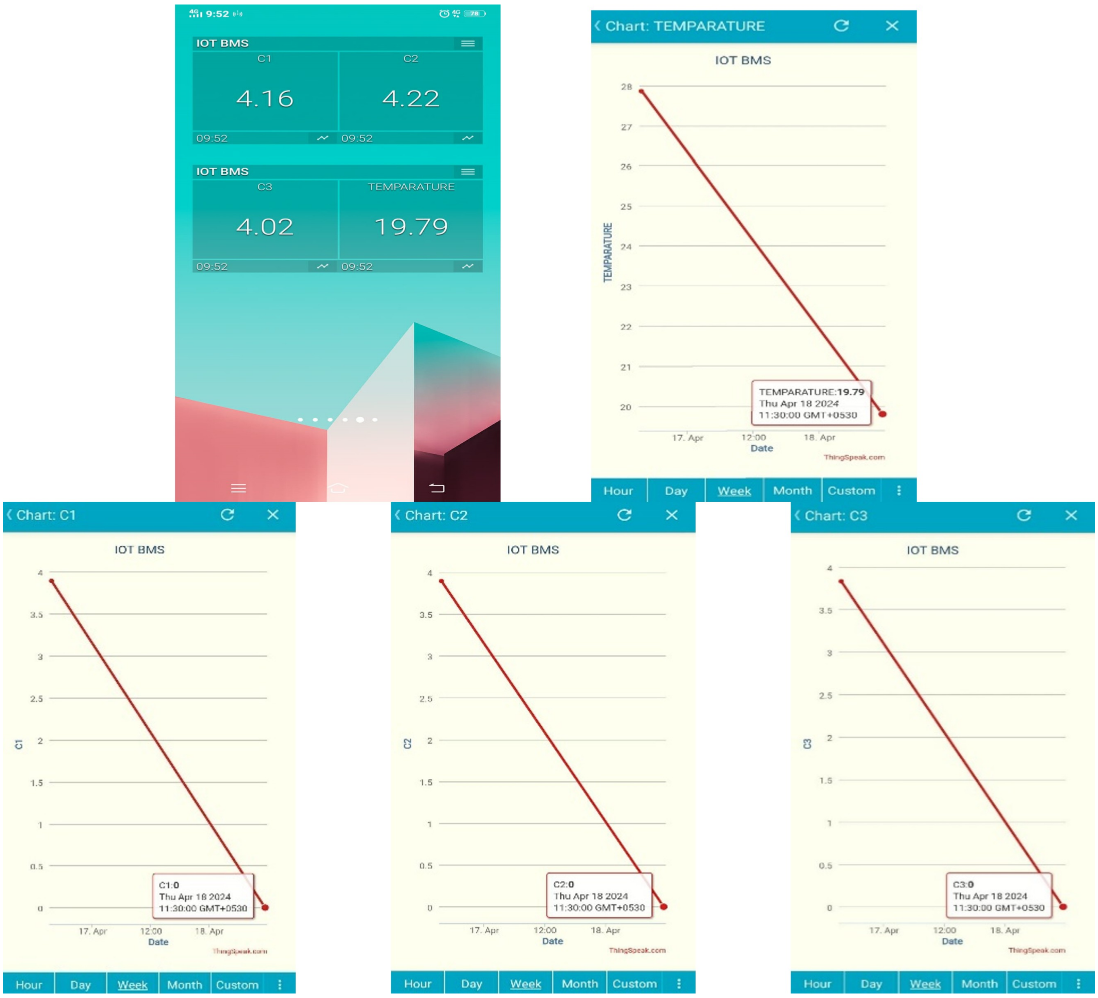

Figure 6. Battery status monitoring in the mobile dashboard.

In addition, temperature is a critical parameter in the BMS system. Overcharging or exposure to external heat can cause the battery to overheat, potentially leading to dangerous situations. Therefore, consistent temperature monitoring of battery cells is essential in any electrical battery system. During both the charging and discharging processes, the temperature of the battery cells is continuously monitored. Figure 8 illustrates the temperature variations of the battery pack during charging and discharging. It was observed that there is typically a fluctuation of about 7 °C to 8 °C during these processes. Overcharging or leaks in the battery cells can result in even higher temperatures, posing significant safety risks. To mitigate these risks, cooling systems are sometimes implemented to maintain optimal temperatures and prevent overheating. This consistent temperature monitoring ensures the safe operation of the battery system. High

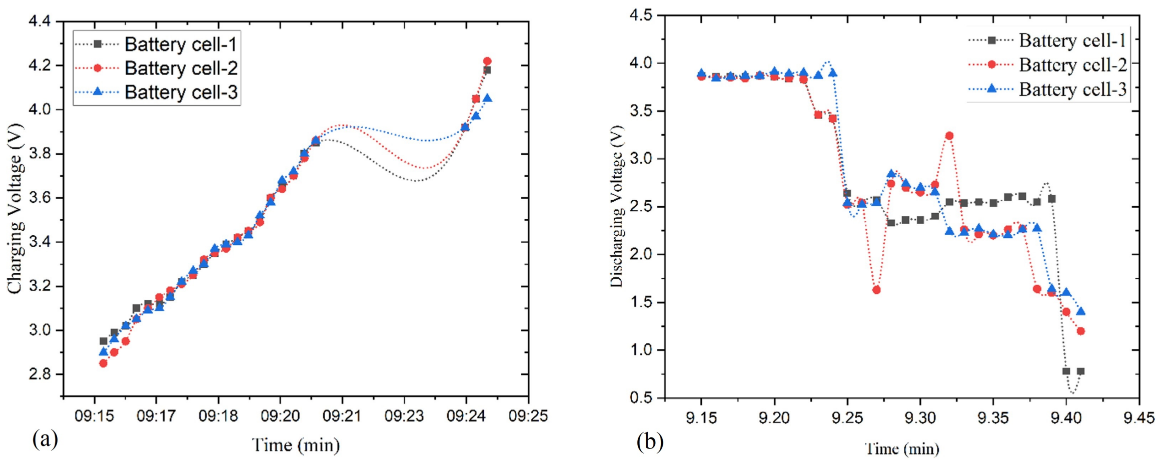

Figure 7. IoT server gathers the individual battery cell voltage during (a) Charging and (b) Discharging of the battery.

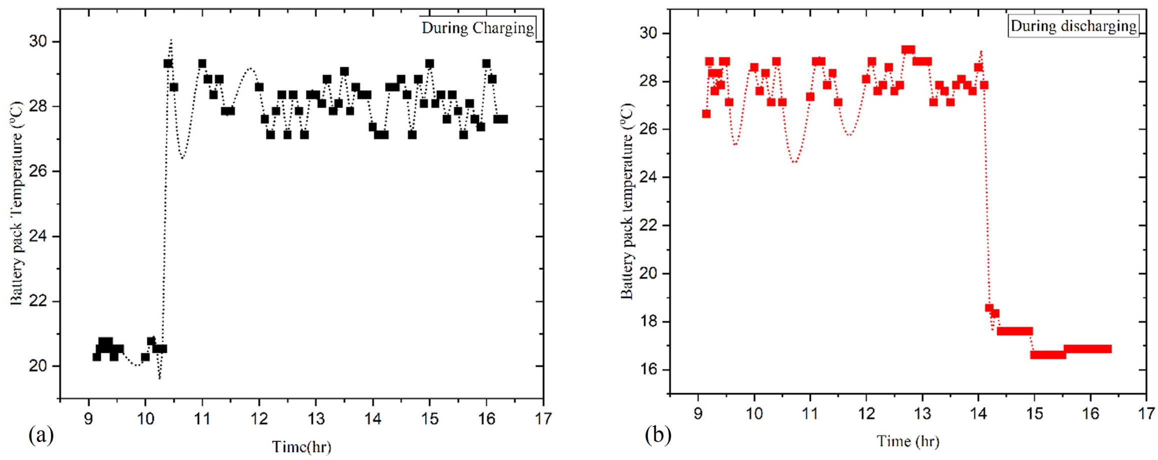

Figure 8. The server records the battery temperature during (a) Charging and (b) Discharging of battery voltage.

temperatures can compromise the integrity and safety of the battery, making it unsafe for further operation. Therefore, the inclusion of a cooling system in the BMS helps manage and dissipate excess heat, maintaining the temperature within safe limits.

The BMS thus plays a crucial role in all battery-operated systems by ensuring that temperature fluctuations are kept in check. This not only enhances the safety of the system but also extends the lifespan of the battery cells by preventing thermal degradation. The importance of a robust BMS cannot be overstated, as it safeguards the system against potential failures and hazards associated with temperature extremes.

4. Conclusion

The present study successfully implemented a battery management system utilizing the IoT to monitor and manage various parameters of a battery pack. The system employed a hybrid power source to support the BMS components and analyzed battery cells connected to the IoT device. Continuous monitoring of the cell voltage and temperature was achieved, with data displayed both locally and remotely. The integration of hardware and software facilitated effective data exchange and real-time monitoring of the battery cells. A dashboard was created to remotely access cell voltage and temperature, aiding in the comprehensive health monitoring of the battery cell. The individual battery cells, C1, C2, and C3, measured voltages of 4.18 V, 4.22 V, and 4.05 V, respectively. The overall measurement efficiency achieved was 99%. Further, the study observed that the charging time of the battery was shorter than the discharging time. Additionally, a noticeable temperature rise was observed during the charging phase, followed by a decrease during discharging. A temperature variation of 7 °C to 8 °C was recorded during prototype testing. The use of IoT technology proved beneficial for precise and remote access to individual battery data without information loss. This approach to BMS not only enhanced the protection of the battery cells but also ensured the safety of the overall system.

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Nomenclature

IoT	Internet of things
LCD	Liquid crystal display
OCV	Open circuit voltage
SOC	State of Charge
HEV	Hybrid Electric Vehicle
EV	Electric vehicle
BMS	Battery management system
BTMS	Battery thermal management system
DPDT	Double pole double through
ECM	Equivalent Circuit Model
ESP32	Espressif Systems 32-bit
Wi-Fi	Wireless fidelity
I2C	Inter-Integrated Circuit
LIB	Lithium-Ion Battery

Authors contributions
Authors have contributed equally in preparing and writing the manuscript.

Availability of data and materials
Data sharing does not apply to this article as no such datasets were generated or analyzed during the current study.

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

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