

IoT Based Battery Management System: A Comprehensive Analysis of Lithium-ion Battery and Advances in Technology

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Abstract: Efficient energy storage management is essential for ensuring the safety, reliability, and longevity of rechargeable battery systems. This paper presents the design and implementation of an Internet of Things (IoT)-based Battery Management System (BMS) using an Arduino microcontroller. The proposed system monitors critical battery parameters such as temperature, voltage, and charging/discharging current in real time to maintain safe operating conditions. State of Charge (SOC) is estimated using the Coulomb counting method, while the Constant Current–Constant Voltage (CCCV) technique is employed to evaluate the State of Health (SOH) of the battery. Battery data are transmitted to the Thing Speak platform for cloud-based storage, remote monitoring, and analysis. The developed BMS provides a cost-effective and scalable solution for modern energy storage applications.

Keyword: Battery Management System (BMS), Internet of Things (IoT), Energy Storage Systems, State of Charge (SOC), State of Health (SOH).

I. INTRODUCTION

Battery Management Systems (BMS) play a vital role in modern energy management by improving battery performance, ensuring operational safety, and enabling efficient and sustainable energy utilization. By reducing dependence on fossil fuels, BMS technology supports energy sector stabilization and enhances grid competitiveness, particularly in response to the intermittent nature of renewable energy sources. A BMS performs detailed technical analysis of dynamic energy storage behavior within batteries, taking into account battery-specific characteristics such as chemistry, capacity, and operating conditions [1].

The operation and analysis of a BMS are based on key parameters including terminal voltage, current, charging characteristics, State of Health (SoH), capacity, and temperature. Variations in voltage and current often serve as early indicators of electrical abnormalities, while significant temperature fluctuations may trigger protective cutoffs to prevent thermal runaway. Changes in cycle count provide insights into charging and discharging

efficiency, and when combined with temperature and current data, can reveal capacity degradation. Metrics such as SoH and capacity play a crucial role in maintenance decision-making by identifying batteries that may require servicing or decommissioning [2].

The growing importance of BMS technology is driven primarily by the rapid adoption of electric vehicles (EVs) and large-scale energy storage systems, both of which demand advanced battery monitoring and control. Additionally, the widespread use of rechargeable batteries across consumer electronics has accelerated the need for continuous technological innovation in BMS solutions. These factors collectively contribute to the steady expansion of the global BMS market, as illustrated in Fig. 1 [3].

Despite extensive research, conventional BMS approaches exhibit several inherent limitations related to compatibility, performance, cost, scalability, reliability, security, and maintenance. Traditional systems often suffer from hardware constraints that restrict monitoring accuracy and system efficiency. High initial costs and limited accessibility further hinder widespread adoption, particularly for small-scale manufacturers and decentralized energy systems. Moreover, conventional BMS architectures frequently lack the flexibility required to adapt to emerging technologies and evolving energy demands. Security vulnerabilities, including data privacy concerns and susceptibility to cyberattacks, also pose significant barriers to deployment [4].

To overcome these challenges and unlock the full economic and operational potential of BMS, Internet of Things (IoT) technology has emerged as a highly promising solution. IoT-based BMS frameworks leverage wireless connectivity, real-time data acquisition, advanced analytics, and predictive modeling—often supported by machine learning techniques—to enhance energy efficiency and extend battery lifespan. IoT integration enables proactive maintenance, remote monitoring, and real-time decision-making, transforming BMS from a standalone control unit into a responsive and interconnected energy ecosystem capable of supporting sustainable and adaptive energy infrastructures [5]. Wireless communication technologies are fundamental to IoT-enabled BMS operation. Protocols

such as Wi-Fi provide high-speed data transmission for real-time monitoring, while Low Power Wide Area Network (LPWAN) technologies like LoRa are particularly suitable for remote or harsh environments. These communication methods ensure reliable data exchange with minimal power consumption and fault tolerance. However, integrating IoT with BMS introduces challenges related to system compatibility, performance optimization, cost efficiency, scalability, reliability, and cybersecurity, all of which must be addressed to achieve effective deployment [6].

The selection of appropriate IoT hardware is another critical consideration in BMS design, as illustrated in Fig. 2. Factors such as compatibility with system requirements, communication capabilities, power consumption, and scalability must be carefully evaluated. Among available wireless technologies, LoRa stands out due to its long communication range, low energy consumption, and high scalability. These characteristics make it well suited for battery-powered BMS applications deployed in large industrial facilities or geographically dispersed locations, where conventional communication methods may be impractical or unreliable.

Recent research has explored advanced concepts such as digital twins for EV battery systems, integrating IoT, cloud computing, artificial intelligence, and multi-layer modeling to enhance battery design, monitoring, and operational management [7]. While digital twin technology offers promising solutions for optimization and sustainability, challenges remain regarding cost justification and practical implementation in industrial settings [8]. Wireless Battery Management Systems (WBMS) have also gained attention for their potential to overcome the limitations of wired BMS architectures. Surveys of WBMS highlight their benefits while emphasizing the need for further research to address issues related to reliability, security, electromagnetic interference, and cost-effectiveness, particularly in high-power lithium-ion battery systems [9]. Additionally, recent developments in modular IoT-based BMS designs demonstrate improved fault tolerance and deployment flexibility; however, scalability and integration with future technologies remain open challenges [10]

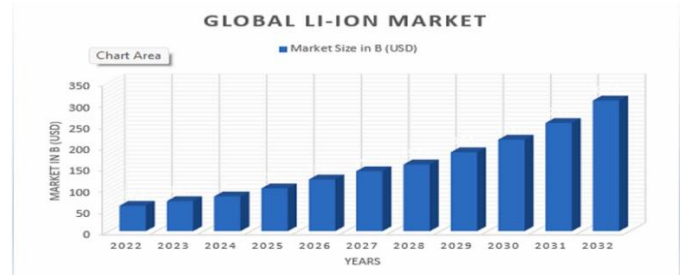


Fig. 1 Global LI-ION Market

II. LITERATURE SURVEY

This section presents an overview of recent research on Energy Management and Smart Home Systems, with a focus on IoT-based solutions.

In one study, an IoT-enabled automated temperature and humidity monitoring and control system was developed using a Raspberry Pi. The system collects temperature and humidity data, which are then transmitted to the internet for real-time monitoring and control [11]. Another research work implemented an IoT-based energy management system using temperature and light intensity sensors. The sensor data is relayed to an Arduino microcontroller, which regulates appliance usage as required. Additionally, a Raspberry Pi3 calculates the total power consumption of each appliance over time and visualizes the results through graphs generated from data collected via Hall sensors, which are transmitted wirelessly over Wi-Fi. The system stores graphical data showing power consumption versus time for appliances under different climatic conditions on a cloud server [12].

In the domain of battery management, an IoT-based BMS was developed to detect hydrogen gas emissions from batteries while monitoring essential battery parameters such as health, power quality, and power factor. Cloud and IoT integration enhances the system by enabling more efficient data analysis. Moreover, a GPS tracker is incorporated to monitor vehicle location, allowing rapid assistance if necessary [3]. A comprehensive BMS has also been proposed that continuously monitors key battery parameters and actively balances the cells within a battery pack. This system employs an embedded MSP430 microprocessor for monitoring and control, demonstrating its applicability in everyday electrical systems by improving efficiency, power quality, and overall performance [14][15].

The performance of sensors, processors, and communication modules within the BMS has been evaluated for accuracy and reliability. To further improve battery monitoring, a MATLAB-based State of Charge (SOC) estimation method called Co-estimate was implemented on a hardware battery testbed. Comparison between simulation results and hardware implementation demonstrated the feasibility and effectiveness of this method. The proposed hardware architecture is also suitable for implementing Co-Estimation in electric vehicle applications [16].

Furthermore, IoT and PLC-based energy management solutions have been explored for Virtual Power Plants (VPPs) in a unified electricity market. In this system, forecasts of university loads and solar generation for the day-ahead (DA) market are used to optimize energy distribution. The system automates supply and load management using PLCs and Raspberry Pi, which send control signals to relay switches. PLC programming is accomplished via the Node-RED platform, enabling seamless monitoring and control for optimal energy utilization.

Collectively, these studies demonstrate the potential of integrating IoT, microcontrollers, PLCs, and cloud computing in energy management systems and smart home applications. The research highlights improvements in real-time monitoring, predictive analytics, energy efficiency, and reliability, establishing a strong foundation for future innovations in intelligent energy systems.

III. METHODOLOGY

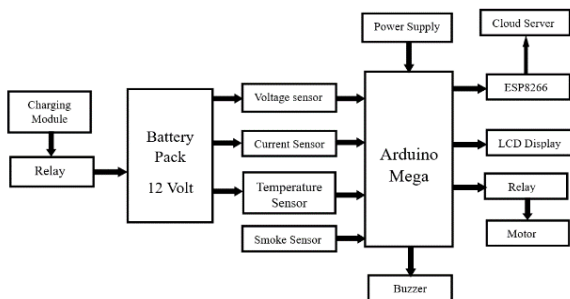


Fig.2 Block diagram of IoT based battery management system.

1. Battery Pack Design

A 12 V lithium-ion battery pack is designed using cylindrical lithium-ion cells, each with a nominal voltage of 3.7 V and a capacity of 3.4 Ah. Among the common battery pack configurations, two arrangements are

typically considered: nPmS and mSnP. In this work, the nPmS configuration is selected due to its inherent advantages in cell balancing. This configuration allows natural balancing between cells within a module, reducing complexity and minimizing balancing issues. Additionally, the nPmS structure is well suited for high-power applications such as electric vehicle battery systems.

2. Circuit Design

The BMS hardware is designed to monitor and protect the battery pack effectively. Voltage sensors are used to measure the voltage of individual battery cells, while a current sensor monitors the overall charging and discharging current. Temperature sensors are integrated to track thermal conditions and prevent overheating. Relays are employed to control the charging and discharging paths, ensuring safe operation under various conditions. Protective components such as resistors, capacitors, and diodes are included to provide signal filtering, electrical stability, and circuit protection.

3. Embedded Programming

An Arduino microcontroller serves as the central processing unit of the BMS. Embedded software is developed to continuously acquire voltage, current, and temperature data from the sensors. Based on these measurements, the system calculates important battery metrics such as total pack voltage, State of Charge (SoC), State of Health (SoH), and thermal status. Safety limits are predefined for overcharging, deep discharging, overcurrent, and excessive temperature. When abnormal conditions are detected, the system automatically activates protective actions to prevent battery damage.

4. IoT Integration

To enable remote monitoring and data analysis, the BMS is integrated with an IoT platform using wireless communication modules such as ESP8266 or ESP32. The system connects to a Wi-Fi network and periodically uploads sensor data—including voltage, current, and temperature—to the cloud. Secure communication protocols are implemented to ensure reliable data transmission and to allow authorized remote control of the charging and discharging processes.

5. User Interface and Remote Access

A user-friendly web or mobile interface is developed using the IoT platform's tools. This interface allows users to view real-time battery information, track historical data, and receive alerts during fault conditions. Users can also configure system parameters remotely, improving usability and operational flexibility.

four-cell lithium-ion battery system and deployed for real-time monitoring and evaluation through the IoT dashboard

Table. 1 Parameter Analysis of Battery

Parameter	Rated / Nominal Value	Safe Operating Range	Monitored Purpose
Battery Voltage	3.7 V (Li-ion cell)	3.0 - 4.2 V	Overcharge and deep discharge protection
Battery Capacity	2500 mAh	80% - 100% of rated	SOC and SOH estimation
Charging Current	1 C	0.5 C - 1 C	Safe and efficient charging
Discharging Current	1 C	≤ 2 C	Load and stress monitoring
Battery Temperature	25 °C	0 - 45 °C (charge), -20 - 60 °C (discharge)	Thermal safety
State of Charge (SOC)	100 %	20 - 100 %	Energy availability tracking
State of Health (SOH)	100 %	≥ 80 %	Aging and degradation detection
Internal Resistance	50 mΩ	≤ 100 mΩ	Performance and fault diagnosis
Gas Concentration	0 ppm	≤ Threshold limit	Leakage and hazard detection
Communication Delay	< 100 ms	≤ 200 ms	Real-time monitoring reliability

IV. RESULTS ANALYSIS

The performance of the proposed IoT-based Battery Management System is demonstrated through the experimental results illustrated in the corresponding figures. Figure 3(a) depicts real-time electrical measurements obtained during system operation,

including the voltages of individual battery cells, the total battery pack voltage, and the associated charging or discharging current. Monitoring cell-level voltages enables the identification of voltage imbalance among cells, which is critical for maintaining uniform charge distribution and extending battery lifespan. The pack voltage, when analyzed alongside current profiles, reflects the overall energy flow and operating mode of the system. Furthermore, variations in current provide insight into load demand and charging efficiency under different conditions. Together, these measurements validate the system's capability to accurately track electrical parameters, support safe operation, and ensure reliable performance of the battery pack throughout charging and discharging cycles.

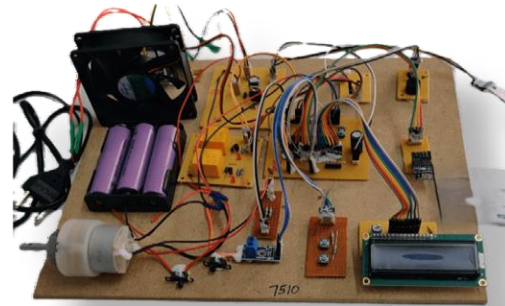


Fig. 3(a) Real-time monitoring of cell voltages

Figure 3(b) illustrates a broader set of operational and safety parameters continuously monitored by the system, including discharge rate, battery temperature, remaining charge percentage, detected gas concentrations, and the computed State of Charge (SOC). Real-time monitoring of these variables provides a comprehensive understanding of battery health, usage patterns, and thermal behavior. Tracking temperature and gas levels is particularly critical for ensuring operational safety, as abnormal variations may indicate overheating, cell degradation, or the onset of hazardous conditions. In addition, observing discharge characteristics and SOC trends supports accurate energy management and helps prevent over-discharge or excessive load conditions. Collectively, the continuous assessment of these parameters enhances system reliability,

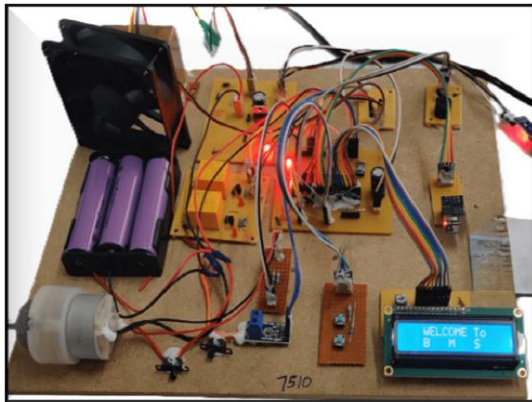


Fig. 3(b) Real-time monitoring of battery system

Figure 4 shows the data visualization obtained from the ThingSpeak IoT platform. The cloud-based graphs display both real-time and historical trends of key battery parameters, supporting remote monitoring and detailed performance analysis. This visualization capability enhances user awareness and enables timely decision-making for battery management and maintenance.

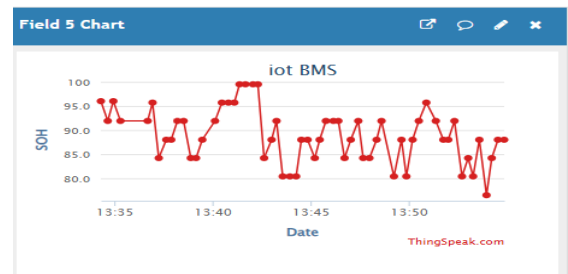
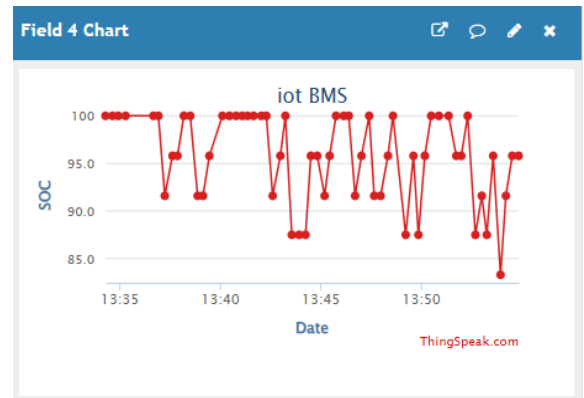
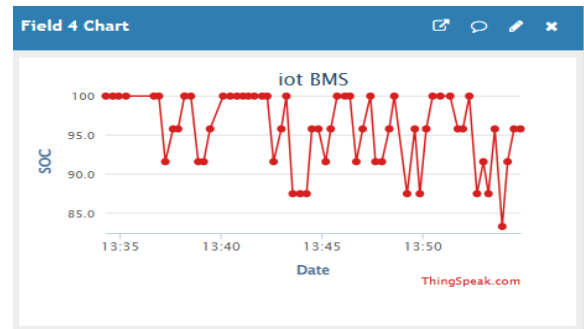
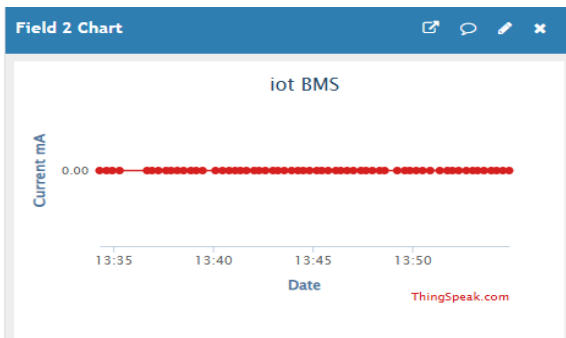
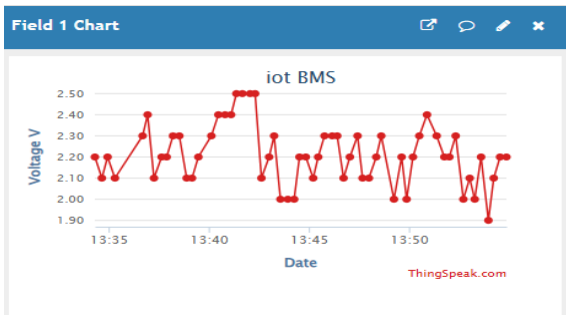


Fig. 4 Thing speak server data



V. RESEARCH DIFFICULTIES AND GAPS

Technical Difficulties

Battery management is challenging due to the non-linear behavior of lithium-ion batteries, where SOC and SOH vary with temperature, load conditions, and aging, making accurate modeling difficult. Reliable sensing is also critical, as electrical noise and high-voltage environments can introduce measurement errors that affect safety and cell balancing. Communication delays in IoT systems may limit timely responses to critical conditions, while limited processing capability of low-power controllers restricts the use of advanced analytics. Additionally, harsh operating environments and the need to scale from small battery units to large battery packs further increase system complexity.

Research Gaps

Despite extensive research on IoT-based battery monitoring, security remains an underexplored area. Many existing systems lack robust protection against cyber threats, leaving them vulnerable to malicious attacks that could intentionally overcharge, discharge, or disable battery packs.

Another notable gap is the absence of standardized communication protocols. The lack of universal standards makes interoperability between IoT-BMS hardware from different manufacturers difficult, limiting system integration and large-scale deployment.

Most current research emphasizes cloud-based data processing, with limited attention given to edge computing approaches. There is a need for strategies that process time-critical safety data locally while transmitting long-term health and performance trends to the cloud, thereby improving response time and reliability.

Integration with smart grid infrastructure is also insufficiently addressed. While significant progress has been made in BMS design, fewer studies explore how IoT-enabled BMS can interact with Vehicle-to-Grid (V2G) systems to support grid stability and efficient energy distribution.

Long-term system reliability is another area requiring further investigation. Many studies rely on short-term laboratory testing or simulations, resulting in a lack of real-world performance data that demonstrates how IoT-based BMS solutions perform over extended operational lifetimes, such as a decade-long automotive use case.

Finally, the energy consumption of IoT components themselves is often overlooked. In smaller battery systems, the power required for continuous sensing, processing, and wireless data transmission can significantly impact overall battery efficiency, reducing the net benefit of the monitoring system.

VI. CONCLUSION

This paper presented the design and implementation of an IoT-based battery monitoring system for electric vehicle applications, aimed at enabling continuous online monitoring of battery performance and degradation. The primary objective of the study was to demonstrate the practical feasibility of integrating embedded hardware with IoT technologies for real-time

battery condition assessment.

The developed system consists of a battery monitoring hardware unit and a web-based user interface for data visualization. Key battery parameters, along with time and location information, are transmitted over the internet. The integration of a GPS module allows the system to identify vehicle coordinates and display location data through a mapping application, enabling remote tracking of battery status.

The proposed system architecture supports future enhancements, such as the development of a dedicated smartphone application for user-friendly monitoring and battery degradation alerts. Communication reliability can also be improved by adopting wired networking solutions, such as Ethernet, as an alternative to cellular-based connectivity.

IoT-based battery monitoring systems offer significant advantages, including real-time observation, predictive maintenance capabilities, improved battery lifespan, enhanced user experience, and optimized charging strategies. Remote monitoring and control features make the system particularly suitable for fleet management applications. However, challenges related to system cost, data security, network reliability, false alarms, and integration with existing vehicle systems must be carefully addressed. Implementing robust cybersecurity measures is essential to protect sensitive battery and location data transmitted wirelessly.

Overall, the study confirms that IoT-enabled battery monitoring is a viable and effective solution for tracking battery performance degradation in electric vehicles. The proposed system provides a scalable foundation for future smart mobility and intelligent energy management application

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