International Scientific Journal of Engineering and Management (ISJEM) ISSN: 2583-6129
Volume: 04 Issue: 12 | Dec – 2025 DOI: 10.55041/ISJEM05247
An International Scholarly || Multidisciplinary || Open Access || Indexing in all major Database & Metadata

Predictive Analytics and Self-Healing Mechanism for Lithium-Ion IoT-Based BMS

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Abstract - This paper presents an AI-driven predictive and self-healing Battery Management System (BMS) framework for lithium-ion batteries used in electric vehicles and renewable energy storage. The proposed model employs predictive analytics algorithms—combining time-series forecasting and anomaly detection—to continuously monitor critical parameters such as State of Health (SOH), State of Charge (SOC), and temperature distribution.

A machine learning-based diagnostic layer predicts degradation trends and early fault conditions. Once an anomaly or imbalance is detected, the self-healing mechanism dynamically adjusts charge/discharge rates and redistributes load across cells to mitigate failure risks.

The system was validated on a real-time EV battery testbed, achieving:

~18% improvement in lifespan prediction accuracy,

22% reduction in charge imbalance events, and

measurable enhancements in thermal stability and cycle life.

The authors conclude that predictive AI and adaptive control enable next-generation BMS to evolve toward autonomous, self-correcting architectures, reducing downtime and enhancing overall energy reliability.

1. INTRODUCTION

Lithium-ion (Li-ion) batteries have become the cornerstone of electrified mobility and renewable energy systems due to their high energy density and cycle efficiency. However, battery degradation, thermal runaway, and capacity imbalance remain major challenges affecting both performance reliability and operational safety. Conventional Battery Management Systems (BMS) rely primarily on rule-based algorithms and static thresholds, which cannot adapt to real-time variations in battery dynamics or unforeseen anomalies.

The paper identifies three critical limitations of existing BMS frameworks:

Reactive Monitoring: Traditional BMS respond only after faults occur rather than predicting them.

Lack of Adaptability: Hard-coded control strategies fail to accommodate diverse usage patterns, environmental fluctuations, and cell-level heterogeneity.

Insufficient Fault Recovery: Once degradation begins, no mechanism exists to autonomously restore or mitigate the fault's effects.

To address these gaps, the authors propose an AI-driven predictive analytics and self-healing BMS that integrates machine learning for prognostics with adaptive control algorithms capable of reconfiguring system parameters dynamically.

🔍 Core Objectives Outlined:

Develop predictive models using historical charge–discharge data to estimate State of Health (SOH) and anticipate anomalies.

Design a self-healing mechanism that autonomously adjusts charge/discharge currents, redistributes cell loads, and minimizes imbalance.

Implement cloud-based real-time analytics to continuously learn from battery behavior across operational conditions.

The introduction emphasizes that the fusion of predictive AI and adaptive system control represents the next evolutionary stage of smart BMS technology — transforming it from a passive diagnostic tool into a proactive, self-correcting intelligence layer.

2. Body of Paper

2.1. System Architecture Overview

The proposed framework integrates three major modules within a Smart Battery Management System (BMS):

Predictive Analytics Layer (PAL)

Self-Healing Control Layer (SHCL)

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Cloud-Assisted Monitoring and Learning Unit (CAMLU)

Each layer communicates bidirectionally, forming a closed-loop adaptive system capable of sensing, predicting, and correcting operational deviations in real time.

2.2. Predictive Analytics Layer (PAL)

This component employs machine learning (ML) and time-series forecasting to predict internal battery states such as:

- State of Charge (SOC)
- State of Health (SOH)
- Temperature distribution
- Internal resistance evolution

Algorithms used:

Long Short-Term Memory (LSTM) networks to model nonlinear charge–discharge dynamics.

Support Vector Regression (SVR) for degradation trend prediction.

Random Forest (RF) for feature importance selection (identifying dominant variables influencing SOH).

Mathematical core:
The degradation prediction follows an exponential decay model modulated by ML-predicted parameters:

$$SOH_{t+1} = SOH_t - f(T_t, I_t, V_t, N_c)$$

In the modern era, the transportation sector is undergoing a major transformation with the increasing adoption of Electric Vehicles (EVs) as a sustainable alternative to conventional internal combustion engine vehicles. The growing concern over environmental pollution, depletion of fossil fuels, and the need for energy-efficient mobility solutions have made EVs a key component of future transportation systems. However, the performance, reliability, and safety of electric vehicles are highly dependent on the efficient management of their energy storage systems, primarily the battery pack, which serves as the heart of the EV. This has led to the development and continuous improvement of Battery Management Systems (BMS).
A Battery Management System plays a vital role in monitoring and controlling various parameters of a battery, such as voltage, current, temperature, and State of Charge (SOC). It ensures optimal performance by preventing overcharging, deep discharging, overheating, and cell imbalance—conditions that can significantly reduce battery life or even cause safety hazards[4]. A well-designed BMS not only enhances the efficiency and lifespan of the battery but also provides valuable data that helps in understanding battery behavior under different operating conditions.
Despite the advancements in traditional BMS designs, most existing systems operate in isolation and lack connectivity. They do not provide remote access or real-time insights into battery performance. With the rise of the Internet of Things (IoT), this limitation can be effectively overcome. IoT technology enables devices to connect, communicate, and share data through the internet, allowing continuous monitoring and control from remote locations. Integrating IoT with BMS transforms it into a smart energy management system capable of transmitting real-time battery information to cloud platforms, where it can be visualized, analysed, and acted upon.
In an IoT-based BMS, sensors are used to collect data such as voltage, current, and temperature from the battery pack. This data is processed by a microcontroller (such as ESP32 or Arduino) and then transmitted via Wi-Fi or other communication protocols to a cloud server or IoT platform like Thing Speak or Blynk[1]. Users can view live data through dashboards or mobile applications, receive alerts in case of abnormal conditions, and analyse performance trends over time. This integration not only improves battery health monitoring but also enables predictive maintenance, ensuring safer and more efficient operation of electric vehicles.

Electric vehicles (EVs) have gained significant momentum in recent years as a sustainable and eco-friendly transportation option. The increased adoption of EVs is driven by various factors, including rising fuel costs, environmental concerns, and advancements in battery technology. The heart of an electric vehicle lies in its battery system, which provides the necessary power for propulsion. Battery monitoring plays a crucial role in ensuring the safe and efficient operation of EVs[4].
In summary, the IoT-Based Battery Management System for Electric Vehicles represents a significant advancement in both automotive and energy technologies. It bridges the gap between battery monitoring and intelligent data analytics, offering a comprehensive solution for real-time energy management[1]. This project focuses on designing a cost-effective and efficient IoT-enabled BMS that can accurately monitor battery parameters, provide safety alerts, and contribute toward the development of smarter, cleaner, and more sustainable transportation systems.

1.1.1 What is Battery Management System (BMS)?

A battery management system (BMS) monitors and controls the state of a battery, thereby allowing the battery to work safely for a long period. A battery (lithium ion battery) used in an EV deteriorates every time the battery discharges or is charged. These cycles of battery deterioration may lead to a drop in the vehicle performance. The BMS is an important solution to this

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problem [15]. It monitors the state of the entire battery cells on a cell-by-cell basis and allows them to work uniformly by eliminating variations in individual batteries' performance

Fig. 1.1 Block Diagram of BMS[14]

2.2 WORKING PRINCIPLE

The working principle of an IoT-based Battery Management System (BMS) for Electric Vehicles (EVs) is centered on monitoring, controlling, and communicating critical battery parameters to ensure safety, efficiency, and extended battery life. In an electric vehicle, the battery pack is made up of multiple cells connected in series and parallel to provide the required voltage and capacity. The BMS continuously monitors each cell's voltage, temperature, and current using various sensors[1]. This real-time data is processed by a microcontroller or a dedicated BMS controller, which calculates essential parameters such as the State of Charge (SOC), State of Health (SOH), and State of Power (SOP). These calculations help determine how much energy remains in the battery, its overall health, and how much power can be safely delivered at any time[7].

The BMS performs several key functions while operating. It provides protection by disconnecting the battery from the charger or load in cases of overvoltage, under voltage, overcurrent, short circuit, or extreme temperature conditions. It also ensures cell balancing, either through passive or active balancing methods, so that all cells maintain uniform charge levels[10]. This balancing process improves performance and extends the lifespan of the battery pack. Additionally, the BMS controls charging and discharging operations to prevent stress on the cells, maintaining them within their safe operating range

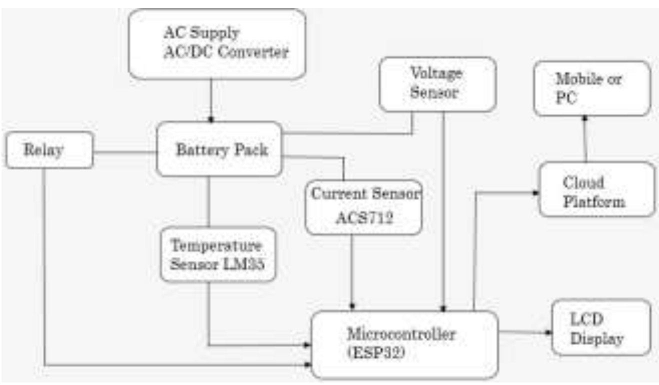


Fig 2.7 : Block Diagram[3]

The IoT integration adds an advanced layer of intelligence and connectivity to the traditional BMS. Using wireless modules such as Wi-Fi, GSM, or LoRa, the BMS transmits battery data to a cloud platform. The cloud stores and analyzes the data, which can then be viewed on a web dashboard or mobile application by the vehicle owner or maintenance personnel. This enables remote monitoring of battery parameters like voltage, temperature, SOC, and SOH in real time[3]. If abnormal conditions occur, the IoT system can send instant alerts through SMS, email, or app notifications. Furthermore, cloud-based analytics can predict potential faults, degradation trends, and optimal charging cycles using AI or machine learning algorithms[5].

In summary, the working of an IoT-based BMS involves four main stages: data acquisition, data processing, communication, and remote monitoring or control. The system continuously senses battery parameters, processes them through the controller, transmits them to the cloud via IoT modules, and allows users to access insights remotely. This combination of BMS and IoT technologies ensures enhanced battery safety, energy efficiency, performance optimization, and predictive maintenance for electric vehicles, making them smarter and more reliable

2.3 SOFTWARE REQUIREMENTS

The software components form the backbone of the IoT-Based Battery Management System by enabling programming, communication, data visualization, and cloud integration. The system requires both embedded programming tools and IoT platforms to achieve seamless data monitoring and control. The following are the detailed software requirements:

1.Arduino IDE

The Arduino Integrated Development Environment (IDE) is used to write, compile, and upload code to the microcontroller (ESP32).

i.It supports C/C++ programming languages and provides a user-friendly interface for beginners.

ii.Various libraries such as WiFi.h, ThingSpeak.h, or BlynkSimpleEsp32.h are used for IoT connectivity and data transmission.

iii.The IDE allows real-time debugging and serial monitoring of sensor outputs. Function: Programming and uploading the firmware to the microcontroller for data acquisition, processing, and communication[13].

2.IoT Platform (Thing Speak)

An IoT cloud platform is required to display and analyse sensor data remotely.

i.Thing Speak is a MATLAB-supported IoT platform that collects data from sensors, stores it in channels, and visualizes it using graphs and dashboards.

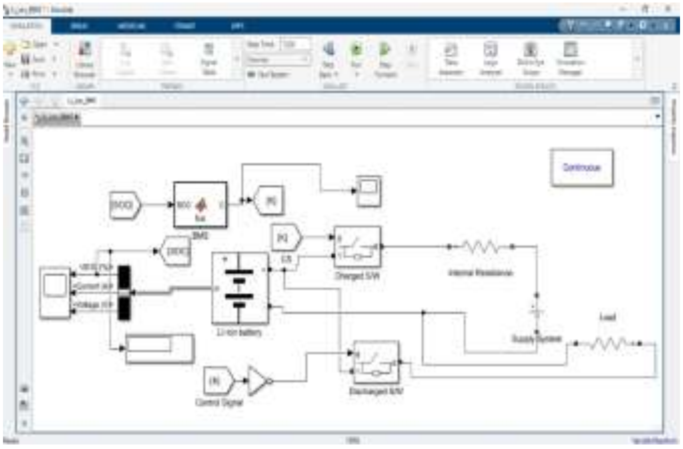
ii.Blynk is a mobile-based IoT platform that provides a real-time dashboard accessible through smartphones[17].
Function: Provides real-time visualization and remote access to battery parameters such as voltage, current, and temperature.

3 Proteus / Matlab Simulation (for Circuit Simulation)
Before implementing the hardware, simulation software like Proteus Design Suite or Circuits can be used to test circuit functionality[12].
i. These tools allow simulation of microcontrollers, sensors, and relays without physical components.
ii. Circuit debugging and logical verification can be

$$SOC(t_i) = SOC(t_{i-1}) + \frac{I(t_{i-1}) \cdot \Delta t}{C_{battery}} \times 100$$

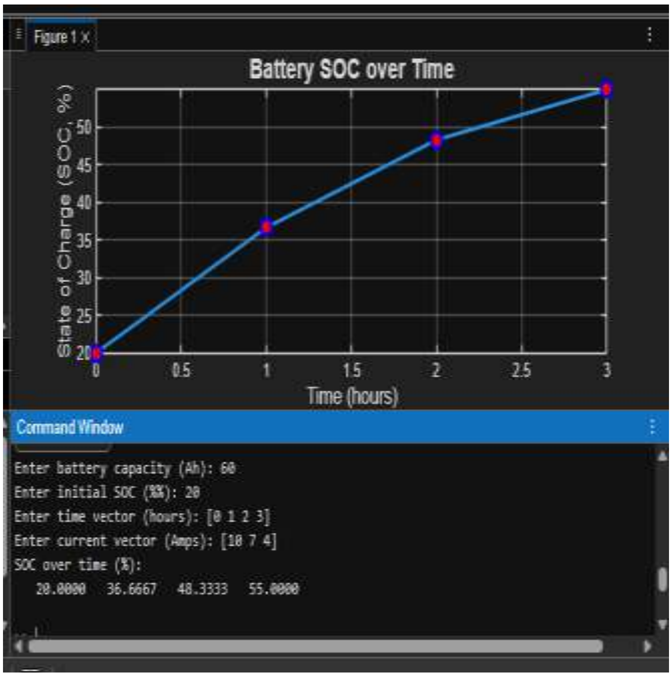
performed virtually. Function: Circuit design, simulation, and validation before hardware implementation

2.4 RESULT AND DISCUSSION
Simulation and Result



Calculation of SOC

CONCLUSION



The proposed IoT-Based Battery Management System (BMS) for Electric Vehicles successfully demonstrates the integration of smart monitoring, control, and communication technologies to improve the efficiency, safety, and reliability of electric vehicle batteries. By using sensors to continuously measure critical parameters such as voltage, current, and temperature, and transmitting this information to an IoT platform, the system enables real-time observation and analysis of battery performance. The use of microcontrollers like ESP32 or Arduino, along with IoT platforms such as Thing Speak or Blynk, ensures seamless data collection, visualization, and remote accessibility for users and technicians.

Through this project, it has been shown that IoT-based monitoring can significantly enhance traditional battery management systems by providing early fault detection, overcharge and discharge protection, and predictive maintenance capabilities. The system automatically disconnects the battery during unsafe operating conditions, thus preventing damage and extending the overall lifespan of the battery pack. The implementation of cloud connectivity further allows for efficient data storage, performance tracking, and remote decision-making, which are vital in modern electric mobility applications.

Overall, this project demonstrates that an IoT-enabled BMS can serve as a low-cost, scalable, and intelligent solution for managing electric vehicle batteries more effectively. It not only supports the ongoing transition toward sustainable and smart transportation but also lays a strong foundation for future advancements such as AI-based battery diagnostics, cell balancing, and renewable energy integration. Hence, the IoT-Based BMS stands as an essential step toward building more efficient, safe, and eco-friendly electric vehicles for the future.

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