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Battery Management System for Electric Vehicles

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***Abstract*— In recent years, Electric Vehicles (EVs) have gained significant importance due to increasing environmental concerns and the need for sustainable transportation. Unlike conventional vehicles, EVs rely completely on battery systems for their operation. However, managing these batteries efficiently is a complex task because they are sensitive to parameters like voltage, temperature, and current. Improper handling can lead to reduced performance, faster degradation, or even dangerous situations such as overheating and fire.**

To overcome these challenges, a Battery Management System (BMS) is used. The BMS acts as an intelligent control unit that continuously monitors and manages the battery pack. It ensures that all battery cells operate within safe limits and perform efficiently under different conditions. This research paper provides a detailed understanding of BMS, including its working, functions, architecture, and importance in EVs.

The paper also discusses advanced concepts such as State of Charge (SOC), State of Health (SOH), and thermal management, which are essential for improving battery life and reliability. Additionally, it highlights current challenges and explores future technologies like AI-based BMS and wireless communication systems. Overall, this study emphasizes that a well-designed BMS is critical for the safety, performance, and long-term sustainability of electric vehicles.

I. INTRODUCTION

Electric vehicles (EVs) have emerged as an effective and environmentally friendly substitute for conventional vehicles powered by internal combustion engines. The growing adoption of EVs is largely influenced by the need to lower carbon emissions, reduce environmental pollution, and decrease reliance on non-renewable fossil fuels. A major component of an EV is its battery pack, commonly built using lithium-ion cells, which provides electrical energy for vehicle operation and supporting systems. Although lithium-ion batteries offer advantages such as high energy density and improved efficiency, they are highly sensitive to operating conditions including excessive temperature, overcharging, deep discharging, and aging effects. If these factors are not properly controlled, the battery may experience reduced performance, accelerated degradation, safety hazards, and a shorter service life. Therefore, an advanced monitoring and control system is essential to ensure reliable and safe battery operation in electric vehicles.

A Battery Management System (BMS) is designed to manage and protect the battery pack by continuously supervising important parameters such as cell voltage, current, and temperature. The BMS ensures that the battery operates within predefined safe limits and helps prevent issues such as overheating, short circuits, overcharging, and over-discharging. It also estimates important battery conditions, including State of Charge (SOC), which indicates the remaining energy available, and State of Health (SOH), which reflects the overall condition and aging status of the battery. In addition, the BMS performs cell balancing to maintain uniform voltage levels among individual cells, improving battery efficiency and extending operational lifespan.

The system further communicates real-time battery information to the vehicle control system for efficient energy utilization and performance management. As electric vehicle technology continues to evolve, the development of reliable and intelligent BMS solutions remains essential for improving vehicle safety, efficiency, durability, and user confidence in electric mobility.

II. LITERATURE REVIEW

1. The rapid growth of Electric Vehicles (EVs) has led to significant research in battery technologies and their management systems. Since the battery is the core component of an EV, many researchers have focused on improving battery performance, safety, and lifespan through efficient Battery Management

Systems (BMS). Over the years, various studies have explored different aspects of BMS, including state estimation, thermal management, cell balancing, and system architecture. In earlier research, the main focus was on understanding battery behaviour and developing mathematical models to estimate important parameters like State of Charge (SOC). One of the widely studied methods is the Kalman Filter-based approach, which provides more accurate SOC estimation compared to simple techniques like Coulomb counting. Researchers found that accurate SOC estimation is essential for efficient battery usage, as it helps in preventing overcharging and deep discharging, which can damage the battery. However, these methods still face challenges when operating under dynamic conditions such as varying temperatures and load changes.

2. As battery technology advanced, researchers began focusing on State of Health (SOH) estimation, which indicates the aging condition of the battery. Studies have shown that battery degradation is influenced by multiple factors such as temperature, charge-discharge cycles, and current rates. Various techniques, including machine learning models and data-driven approaches, have been proposed to improve SOH prediction. These methods help in estimating the remaining useful life of the battery, allowing timely maintenance and replacement.

3. Another important area of research is cell balancing. Due to manufacturing variations, individual cells in a battery pack do not behave identically. Over time, this leads to imbalance, which reduces the overall efficiency and capacity of the battery. Researchers have developed both passive and active cell balancing techniques to address this issue. Passive balancing is simple and cost-effective but wastes energy as heat, whereas active balancing is more efficient as it redistributes energy among cells. Recent studies suggest that advanced active balancing techniques can significantly improve battery performance, especially in large battery packs used in EVs.
Thermal management has also been a major focus in BMS research. Batteries generate heat during operation, and improper temperature control can lead to performance degradation or safety hazards such as thermal runaway. Researchers have explored different cooling methods, including air cooling, liquid cooling, and phase change materials. Among these, liquid cooling systems are found to be more effective for high-performance EVs, as they provide better heat dissipation. Modern BMS systems integrate thermal management with real-time monitoring to maintain optimal temperature conditions.

4. In recent years, the integration of Artificial Intelligence (AI) and Machine Learning (ML) into BMS has gained significant attention.AI-based models can analyse large amounts of data and predict battery behaviour more accurately than traditional methods. For example, machine learning algorithms are used to improve SOC and SOH estimation, detect faults, and optimize battery performance. These intelligent systems can adapt to changing conditions and provide real-time decision-making, making BMS more efficient and reliable.

5. Another emerging trend in research is the development of Wireless Battery Management Systems (WBMS). Traditional BMS uses complex wiring to connect different components, which increases system weight and reduces reliability. WBMS eliminates the need for wiring by using wireless communication, thereby simplifying system design and improving scalability. Researchers haveshown that WBMS can reduce system complexity and enhance performance, especially in large battery packs.

6. Despite these advancements, several challenges still exist in BMS technology. Accurate state estimation under varying conditions remains difficult, and advanced systems often increase the overall cost of EVs. Thermal management and scalability are also major concerns, especially for high-capacity battery systems. Therefore, ongoing research is focused on developing cost-effective, accurate, and scalable BMS solutions.

7. In conclusion, the literature review shows that significant progress has been made in BMS technology, but there is still scope for improvement. Future research is expected to focus on intelligent, adaptive, and energy-efficient BMS systems that can meet the growing demands of electric vehicles while ensuring safety and reliability. Literature review

III. PROBLEM STATEMENT AND IDENTIFICATION-

3.1Problem Statement-

With the fast growth of electric vehicles (EVs), battery systems have become the most important part of modern transportation. EV batteries need to offer high performance, long life, and safe operation in different conditions like temperature changes, changing loads, and repeated charging and discharging. However, managing these complex battery systems is a big challenge.

One key problem is that EV battery packs consist of hundreds or even thousands of individual cells connected together.

These cells are not exactly the same because of manufacturing differences and how they are used. Over time, this causes imbalance among the cells, where some cells may get overcharged while others stay undercharged. This imbalance lowers the overall efficiency of the battery and can cause long-term damage.

Another big issue is keeping the battery safe.

Batteries are very sensitive to factors like voltage, current, and temperature. If these factors go beyond safe levels, it can lead to overheating, degradation, or dangerous conditions like thermal runaway, which could cause fires or explosions. Without proper monitoring and control, making sure the battery works safely is very hard.

Getting accurate estimates of battery parameters like State of Charge (SOC) and State of Health (SOH) is also a big challenge.

These values can't be measured directly and must be estimated with algorithms. But things like temperature changes, aging, and changing loads make it hard to get accurate estimates. Also, thermal management remains a big concern, especially in high-capacity batteries used in EVs. Too much heat during operation can reduce battery life and performance. Managing this heat efficiently without making the system more complex or expensive is a tough task.

Therefore, the main problem is designing an efficient Battery Management System that can ensure safety, improve performance, keep cells balanced, and provide accurate monitoring under all operating conditions.

Solving these challenges is essential for the reliable and large-scale use of electric vehicles.

3.2Problem Identification-

The key issues identified in current Battery Management Systems include:

1. Inaccurate State Estimation
- Difficulty in precisely estimating SoC and SoH under varying load and environmental conditions
- Limitations of traditional estimation methods (e.g., Coulomb counting, simple models)

2. Cell Imbalance
- Uneven charging/discharging among cells in a battery pack
- Leads to reduced efficiency, capacity loss, and potential safety hazards

3. Thermal Management Challenges
- Inefficient monitoring and control of temperature distribution
- Risk of overheating and thermal runaway

4. Aging and Degradation
- Lack of effective prediction models for battery degradation over time
- Difficulty in estimating Remaining Useful Life (RUL)

5. Real-Time Monitoring Limitations
- Delays or inaccuracies in data acquisition and processing
- Limited integration with IoT or smart monitoring systems

6. Scalability Issues
- Difficulty in managing large battery packs (e.g., in electric vehicles or grid storage)
- Increased system complexity and cost

7. Safety Concerns
- Insufficient fault detection (over-voltage, under-voltage, short circuits)
- Limited early warning systems

8. Cost and Complexity
- Advanced BMS solutions can be expensive
- Trade-off between performance and affordability

IV. OBJECTIVES

The primary aim of the Smart Battery Management System (BMS) based on the ESP32 controller is to ensure safe, reliable, and efficient operation of the battery pack through continuous monitoring and intelligent control functions. The system is designed to measure important battery parameters such as voltage, current, and temperature with the help of the INA219 voltage/current sensor and the LM35 temperature sensor. These measurements are used to evaluate the operating condition of the battery and to estimate the State of Charge (SOC), allowing effective utilization of the available battery energy.

Another important objective of the system is to enhance battery protection by identifying abnormal operating conditions such as excessive temperature rise, low-voltage conditions, and other battery-related faults. Whenever unsafe conditions are detected, the system automatically isolates the load using a relay mechanism to prevent damage to the battery and connected devices. In addition, a buzzer is activated to provide immediate fault indication and alert the user.

The Smart BMS also aims to provide real-time monitoring and user-friendly visualization of battery parameters through a 16×2 LCD display. To support remote supervision and IoT-based applications, the ESP32 enables wireless communication through Wi-Fi and integrates with the Blynk platform for live data monitoring. Overall, the proposed system focuses on improving battery safety, operational efficiency, reliability, and service life, making it suitable for electric vehicle and energy storage applications.

V. THEORETICAL BACKGROUND

A Battery Management System is an essential component in electric vehicles, responsible for monitoring, controlling, and protecting the battery pack to ensure safe and efficient operation. EVs commonly use lithium-ion batteries due to their high energy density, long cycle life, and good performance characteristics. However, these batteries are sensitive to operating conditions such as voltage, current, and temperature, which necessitates the use of an advanced BMS.

The core function of a BMS is to estimate key battery parameters, particularly State of Charge (SoC) and State of Health (SoH). SoC represents the remaining charge in the battery and is typically estimated using methods such as Coulomb counting, open-circuit voltage (OCV), and model-based approaches. SoH indicates the overall condition and aging level of the battery, which is influenced by charge-discharge cycles, temperature variations, and usage patterns. Accurate estimation of these parameters is crucial for reliable battery performance and longevity.

Another important aspect of BMS operation is cell balancing. In a battery pack, multiple cells are connected in series and parallel configurations. Due to manufacturing inconsistencies and operating conditions, individual cells may exhibit different voltage levels, leading to imbalance. Cell balancing techniques, either passive or active, are employed to equalize the charge across cells, thereby improving efficiency and extending battery life.

Thermal management is also a critical component of the BMS. During operation, batteries generate heat, especially under high load conditions such as rapid acceleration or fast charging. Excessive temperature can degrade battery performance and may lead to safety hazards like thermal runaway. Therefore, the BMS continuously monitors temperature and employs cooling or heating mechanisms to maintain optimal operating conditions.

In addition, modern BMS designs incorporate fault detection and protection mechanisms to ensure safety. These include monitoring for over-voltage, under-voltage, over-current, and short circuit conditions. Advanced systems also integrate communication protocols, such as Controller Area Network (CAN), to enable real-time data exchange between the BMS and other vehicle control units. Recent advancements in BMS technology involve the use of intelligent algorithms, including machine learning and model-based techniques, to improve the accuracy of state estimation and enable predictive maintenance. These approaches help in early detection of faults, estimation of remaining useful life, and optimization of battery performance.

Overall, the theoretical foundation of a BMS combines principles from electrical engineering, control systems, thermal management, and data analytics to ensure safe, efficient, and reliable operation of electric vehicle batteries.

Cell balancing is another important theoretical concept in BMS design. In a multi-cell battery pack, small differences in cell characteristics lead to unequal charge distribution. This imbalance reduces the overall usable capacity and may cause overcharging or deep discharging of certain cells. Passive balancing dissipates excess energy as heat, while active balancing redistributes energy between cells using capacitors, inductors, or converters. Active balancing is more efficient but also more complex and costly.

Thermal management plays a vital role in ensuring battery safety and performance. Electrochemical reactions inside batteries generate heat during operation, especially under high load conditions such as acceleration, hill climbing, and fast charging. If the temperature exceeds safe limits, it can lead to thermal runaway, causing irreversible damage or safety hazards. Therefore, BMS integrates temperature sensors and cooling systems (air cooling, liquid cooling, or phase change materials) to maintain optimal thermal conditions.

Safety management is another key theoretical aspect. The BMS protects the battery pack from abnormal conditions such as over-voltage, under-voltage, over-current, short circuits, and external faults. It uses relay switches, fuses, and electronic control circuits to isolate faults and prevent system failure. Additionally, diagnostic algorithms are used to detect early signs of failure and trigger protective actions.

Modern BMS architectures also incorporate communication systems such as Controller Area Network (CAN), Local Interconnect Network (LIN), or wireless communication protocols. These enable data exchange between the battery system and other vehicle control units, such as motor controllers and energy management systems. This

integration is essential for coordinated vehicle operation and energy optimization.

Recent advancements in BMS technology focus on intelligent and predictive systems using artificial intelligence (AI) and machine learning (ML). These techniques improve the accuracy of battery state estimation, enable predictive maintenance, and help in forecasting battery degradation trends. Model-based approaches such as equivalent circuit models (ECM) and electrochemical models are also widely used to simulate battery behaviour under different conditions.

Overall, the theoretical background of EV Battery Management Systems is based on principles from electrochemistry, electrical engineering, control systems, thermodynamics, and data-driven

5.1. Methodology / Approach

The goal of this research is to look into, examine, and assess different battery management strategies and optimization methods that can help improve the safety, dependability, and overall performance of next-generation electric vehicle (EV) battery systems.

Since the study mainly uses existing literature, simulation studies, and industry standards, the approach focuses on a thorough review, comparison, and combining of current findings rather than creating or testing actual physical prototypes.

5.2. Research Approach

This paper uses a qualitative and analytical method, following these steps: Comprehensive Literature Review Carry out a detailed review of academic papers, technical standards, and industry reports that focus on:

Battery monitoring and state estimation techniques, such as State of Charge (SOC), State of Health (SOH), and State of Power (SOP).

Thermal management and safety systems, such as liquid cooling, phase-change materials, and thermal runaway prevention.

Advanced battery management system (BMS) designs that aim for sustainability and efficiency, like AI-driven predictive analytics, cloud-connected BMS, and cell balancing methods.

The materials reviewed will be grouped based on the system level: cell-level, module-level, and pack-level solutions.

Comparative Analysis

Do a detailed comparison of various BMS methods in terms of:

-Accuracy of estimation, response time, and how complex the calculations are.

-How well they can be integrated with EV designs, such as lithium-ion, solid-state, and sodium-ion batteries.

-The costs, complexity, and safety concerns when these systems are used on a large scale.

-This comparison will help highlight the trade-offs between performance, reliability, and battery lifespan.

Case Study Evaluation

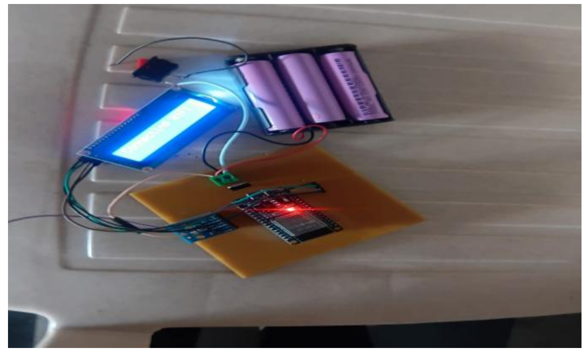
-Look at existing simulation and real-world studies, like BMS for high-capacity EV battery packs, real-time SOC estimation under different driving conditions, or AI-optimized thermal management in test environments.

-Highlight how these approaches work under varied conditions such as high temperatures, fast charging, and different driving patterns.

Gap Identification
-Find out where there are research and implementation gaps, such as:
-Lack of standardization in managing mixed-cell battery packs with different chemistries.
-Insufficient models for optimizing dynamic cell balancing and thermal control.
-Limited real-world data for training AI models that predict battery degradation.
-These gaps will form the basis for suggesting future research directions.
Proposed Framework
Develop a conceptual Intelligent EV BMS Framework that includes:
- A hybrid state estimation system that uses both model-based and data-driven methods.
- AI-based algorithms for thermal and charge management that help with dynamic load balancing and predictive safety control.
- Pack-level energy cooperation models that use distributed diagnostics for detecting and isolating faults.
The framework is designed to be practical for high-energy-density EV systems while ensuring safety and performance.

5.3. Scope of the Study
This research does not involve building or testing a physical battery pack for EVs.
Instead, it focuses on analyzing secondary data from existing literature, simulations, and industry reports. The study is limited to BMS algorithms and thermal-safety strategies relevant to EV batteries, where increasing range, lifespan, and safety are major challenges. The methodology combines technical innovation with safety and economic sustainability.

5.6. Expected Contribution
By following this methodology, the paper aims to:
- Provide a detailed comparison of BMS and battery optimization approaches for EVs.
- Identify key challenges and opportunities for improving battery safety, longevity, and efficiency.
- Suggest a scalable and hybrid framework that can guide future research and the practical implementation of intelligent EV battery systems.
- Contribute to achieving safer, longer-lasting, and more sustainable electric mobility in line with global goals for clean transportation.



VI. MITIGATION TECHNIQUES

As electric vehicle (EV) battery systems advance with higher energy density, quicker charging, and longer driving ranges, safety and thermal stability have become major concerns.
The growing need for high-performance batteries, combined with varying operating conditions, increases the risk of degradation, overheating, and failure within the battery pack. To tackle these issues, researchers are creating advanced estimation methods, thermal management solutions, and AI-driven predictive control systems to build safer and more dependable EV
battery systems. Each strategy targets a different part of the battery system, from monitoring individual cells to optimizing the whole pack. Together, these techniques help ensure reliable and efficient energy storage for EVs.

6.1. Battery State Estimation Techniques
State estimation involves accurately determining the internal condition of battery cells to ensure safe and effective operation.
Key methods include:
- SOC Estimation: Determines the remaining charge using Coulomb counting, Kalman filtering, or neural network models. This is crucial for predicting how far an EV can travel.
- SOH Estimation: Tracks the battery's aging and capacity loss by analyzing impedance and cycle data. It is important for maintenance and warranty management.
- Thermal State Monitoring: Detects temperature differences within the pack using distributed sensors and thermal modeling to prevent thermal runaway.
- Multi-Parameter Estimation: Combines SOC,

SOH, and SOP for a full health check and better decision-making.

While these methods help improve reliability, they face challenges like real-time accuracy, handling sensor noise, and managing computational demands in large battery packs.

6.2 Thermal and Safety Management Design

To reduce safety risks and thermal problems, the battery system should be built with active protection in mind.

Techniques include:

- Active Thermal Management: Liquid or refrigerant-based cooling systems that keep the temperature of cells uniform during charging and discharging.
- Passive Thermal Management: Use of phase-change materials (PCMs) or thermal pads to absorb extra heat without extra power use.
- Cell Balancing Strategies: Both passive and active balancing to make sure charge is evenly distributed and prevent overcharging of individual cells.
- Fault Detection and Isolation: Real-time monitoring of voltage, current, and temperature to find issues and automatically isolate faulty cells.
- These methods help lower failure risk while maintaining high performance and battery lifespan.

6.3 AI and Machine Learning-Based Battery Optimization

Artificial Intelligence (AI) and Machine Learning (ML) are valuable tools for improving battery performance and safety in EVs.

AI-Driven SOC/SOH Prediction: Predictive models forecast how batteries will degrade and how long they will last under different load and temperature conditions.

Reinforcement Learning (RL): Used to adjust charging profiles and thermal control settings for better efficiency and less degradation.

Federated Learning (FL): Allows multiple vehicles to learn from each other without sharing sensitive battery data, which helps protect privacy and cut down on cloud computing loads.

AI for Thermal Runaway Prediction: Neural networks can detect early signs of thermal runaway from sensor data and trigger safety actions.

However, AI techniques need large labeled datasets, edge computing power, and strong safety testing before they can be widely used.

6.4 Hybrid Mitigation Strategies

A single-layer solution alone cannot fully ensure safe and effective EV battery operations.

Thus, an integrated hybrid mitigation strategy is necessary.

Accurate State Estimation ensures reliable cell-level monitoring.

Thermal and Safety Management reduces risks at the pack and system levels.

AI-Driven Optimization offers adaptability and predictive control across the system.

Together, these methods create self-diagnosing EV battery systems that balance safety, performance, and lifespan.

The ultimate aim is to build smart, resilient battery systems that support global electric mobility and sustainability goals.

VII. CHALLENGES AND LIMITATIONS

Even though a Battery Management System (BMS) is crucial for making sure batteries in electric vehicles work safely and efficiently, it still has several real-world challenges and limitations that can affect how well it performs and stays reliable.

These issues come from the complicated way batteries behave, the different environmental conditions they face, and the requirements for system design.

7.1 Battery Estimation

One big challenge in BMS is estimating battery parameters accurately, especially State of Charge (SOC) and State of Health (SOH).

These are not measured directly but are calculated using math models and algorithms. However, battery behavior is very complex and changes based on many things like temperature, current, aging, and how the battery is used. Because of this, it is hard to get precise estimates under normal operating conditions. Even small mistakes in estimation can lead to wrong decisions, which can hurt battery performance and safety.

7.2 Cell Imbalance

Another key limitation is the imbalance of cells within the battery pack.

In an electric vehicle battery, many cells are connected together, and due to differences in manufacturing or aging, each cell may act differently. Over time, some cells might charge or discharge faster than others, causing imbalance. While BMS uses balancing techniques to fix this, achieving perfect balance is tough, especially in large battery packs. Poor balancing can lower overall efficiency and make the battery last shorter.

7.3 Thermal Management

Thermal management is also a major challenge in BMS design.

Batteries produce heat when they are being charged or discharged, and if this heat is not controlled properly, it can cause overheating and even dangerous situations like thermal runaway. Creating an effective cooling system that keeps the temperature in check without making the system too complicated or expensive is a big challenge. In extreme weather conditions, keeping the temperature safe becomes even harder.

74 Complexity and Cost

Another limitation is the complexity and cost of BMS hardware and software.

A modern BMS needs many sensors, controllers, communication systems, and protection circuits. Features like real-time monitoring, data processing, and predictive analysis add more complexity. This leads to higher costs for making and maintaining the system, which can affect how affordable electric vehicles are.

7.5 Power Consumption

Power consumption by the BMS itself is another issue. Since the BMS keeps running to monitor the battery's condition, it uses energy from the battery. Although the power it uses is not very high, it can still affect overall efficiency, especially in systems where energy saving is very important.

7.6 Reliability

Reliability and fault detection can be tough challenges. The BMS has to detect problems like sensor malfunctions, short circuits, or unusual battery behavior in real time. But it's not always simple to spot these issues quickly and correctly, especially when several factors are involved. If fault detection fails, it can lead to serious safety problems.

7.7 Communication and Data Handling

Another challenge is communication delays and managing data within the system. The BMS talks to various parts of the vehicle using protocols like CAN. In big battery systems, dealing with large volumes of data in real time can be tough. Any delay or mistake in communication can affect how well the system works and makes decisions.

7.8 Scalability

Scalability is also a problem, especially in high-capacity battery systems used in electric vehicles.

As the number of cells increases, so does the complexity of monitoring and controlling each one. Making a BMS that can handle large battery packs without affecting performance is a big challenge.

7.9 Aging and Degradation

Finally, aging and degradation of battery cells create long-term challenges for BMS operation. As batteries age, their characteristics change, making it harder for the BMS to accurately estimate parameters and maintain performance. Adapting the system to these changes requires advanced algorithms and continuous calibration.

VIII. CONCLUSION

In summary, the Battery Management System is one of the most important parts of electric vehicles since it directly affects battery safety, performance, and how long it lasts.

A well-designed BMS ensures the battery stays within safe limits by constantly monitoring key factors like voltage, current, and temperature. It also protects the battery from harmful situations such as overcharging, over-discharging, and overheating. Through features like cell balancing and state estimation, the BMS keeps the performance of all battery cells consistent and provides important information about the battery’s condition. This not only improves efficiency but also boosts the overall reliability of the electric vehicle.

However, the study also shows that BMS technology still has several challenges, including accurate parameter estimation, thermal management, system cost, and complexity.

Solving these issues is crucial for the continued growth of electric vehicles and for increasing their use worldwide.

With ongoing progress in technology, especially in

areas like artificial intelligence, wireless communication, and data analysis, future BMS systems are likely to become more intelligent and efficient.
These improvements will help in better predicting battery behavior, early fault detection, and efficient energy use.
In the long run, developing advanced and affordable BMS solutions will play a key role in achieving sustainable transportation and reducing reliance on fossil fuels.
Therefore, ongoing research and innovation in this field are necessary to fully realize the potential of electric vehicle technology.

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