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A Review on Real-Time Battery Management Systems for Two-Wheeler Electric Vehicles with Cell-Level Monitoring and Protective Alarming

Mr. Kharat Sagar Balasaheb, Mr. Sarwade Aniket Kailas,
Ms. Wale Yogita Kisan, Ms. Pawar Harshada Santosh
Department of Electrical Engineering
Amrutvahini College of Engineering Sangamner

Abstract: *The rapid adoption of electric vehicles has significantly increased the demand for efficient and reliable energy storage systems. Among various energy storage technologies, lithium-ion batteries have emerged as the preferred choice for electric two-wheelers due to their high energy density, long service life, and superior charging characteristics. However, the safe operation of lithium-ion batteries remains a major challenge because they are highly sensitive to overcharging, deep discharge, excessive current flow, and abnormal temperature rise. These conditions can negatively affect battery performance, reduce operational life, and create serious safety risks.[1][2] A Battery Management System (BMS) plays a vital role in monitoring, protecting, and optimizing battery operation. Modern BMS technologies provide continuous supervision of cell voltage, current, temperature, State of Charge (SOC), and State of Health (SOH) while ensuring safe operation through various protection mechanisms[3][4]. Recent advancements in communication technologies, Internet of Things (IoT), Artificial Intelligence (AI), and cloud-based monitoring have further enhanced the capabilities of battery management systems[8][9]. This paper presents a comprehensive review of Battery Management Systems used in electric two-wheeler applications. Various battery monitoring techniques, cell balancing methods, fault diagnosis approaches, thermal management strategies, and intelligent battery management technologies are analyzed. The paper also discusses current research challenges and future developments that can improve the safety, efficiency, and reliability of electric vehicle battery systems.*

Keywords: Battery Management System, Electric Vehicle, Lithium-Ion Battery, Cell Monitoring, Thermal Management, State of Charge, Cell Balancing, Fault Diagnosis, Electric Two-Wheeler

I. INTRODUCTION

The transportation sector is experiencing a major transformation due to growing environmental concerns, increasing fuel prices, and the global demand for sustainable mobility solutions. Electric vehicles (EVs) have emerged as an effective alternative to conventional internal combustion engine vehicles because they offer reduced emissions, improved energy efficiency, and lower operating costs. Among various EV categories, electric two-wheelers have gained significant popularity, particularly in developing countries such as India, where they represent a large share of daily transportation.[1][2].

The performance and reliability of an electric vehicle are highly dependent on its battery system. Lithium-ion batteries have become the preferred energy storage technology because of their high energy density, lightweight construction, low self-discharge rate, and long cycle life[3][4]. Despite these advantages, lithium-ion batteries require careful monitoring and control during charging and discharging operations. Improper operating conditions such as overcharging, over-discharging, excessive current flow, and temperature rise can lead to battery degradation, reduced efficiency, and safety hazards including thermal runaway

To address these challenges, Battery Management Systems (BMS) have become an essential component of modern electric vehicles[5][6]. A BMS continuously monitors important battery parameters and ensures that the battery operates within safe limits. It also provides protection against abnormal operating conditions, improves battery utilization, extends battery life, and enhances overall system reliability.

In recent years, significant advancements have been made in battery management technologies. Researchers have explored various approaches involving intelligent control algorithms, wireless communication systems, Internet of Things (IoT) platforms, Artificial Intelligence (AI), machine learning techniques, and cloud-based monitoring solutions. These developments have improved the accuracy of battery monitoring and enabled predictive maintenance capabilities for electric vehicle battery systems.[8][9][10]

This review paper examines the fundamental functions of Battery Management Systems and discusses recent developments in battery monitoring, fault diagnosis, thermal management, cell balancing, and intelligent battery management techniques. The objective is to provide a comprehensive understanding of current BMS technologies and identify future research opportunities for electric two-wheeler applications.

II. NEED FOR BMS IN ELECTRIC TWO-WHEELERS

Electric two-wheelers have become an important part of modern transportation because of their low operating cost, reduced environmental impact, and suitability for urban mobility. However, the performance of these vehicles depends heavily on the condition and efficiency of the battery pack. Lithium-ion batteries, although highly efficient, are sensitive to electrical, thermal, and mechanical stresses[3][5]. Therefore, an effective Battery Management System (BMS) is essential for ensuring safe and reliable battery operation.

Electric two-wheelers are frequently subjected to varying operating conditions such as rapid acceleration, stop-and-go traffic, steep road gradients, and changing environmental temperatures. These conditions cause fluctuations in battery current and temperature, which can accelerate battery degradation if not properly monitored. A Battery Management System continuously supervises battery parameters and prevents operation beyond safe limits.

One of the primary functions of a BMS is protection against overcharging and over-discharging. Excessive charging voltage may cause lithium plating, internal heating, and permanent cell damage. Similarly, deep discharge can reduce battery capacity and shorten battery life. The BMS ensures that each cell operates within its recommended voltage range, thereby improving battery longevity.

Temperature monitoring is another critical requirement. During charging and discharging, batteries generate heat due to internal resistance and electrochemical reactions. If excessive temperature rise remains undetected, it may lead to thermal runaway[10][24], which is one of the most serious safety concerns associated with lithium-ion batteries. Modern BMS units utilize temperature sensors to continuously monitor thermal conditions and activate protective measures whenever abnormal temperatures are detected.

Cell balancing is equally important in multi-cell battery packs[4][31]. Due to manufacturing tolerances, aging effects, and operating variations, individual cells may develop different voltage levels over time. This imbalance can reduce the overall usable capacity of the battery pack and increase the risk of cell failure. A Battery Management System helps maintain voltage uniformity among cells through balancing techniques, thereby improving performance and extending service life.

In addition to protection and monitoring functions, modern Battery Management Systems provide diagnostic capabilities that enable early detection of potential faults. Advanced communication technologies allow real-time battery information to be displayed through mobile applications, cloud platforms, and vehicle control systems. These capabilities enhance user awareness and simplify maintenance activities.

Therefore, Battery Management Systems have become indispensable for electric two-wheelers by ensuring battery safety, improving energy utilization, extending battery lifespan, and enhancing overall vehicle reliability.

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III. FUNDAMENTALS OF BATTERY MANAGEMENT SYSTEMS

A Battery Management System (BMS) is an electronic control system responsible for monitoring, protecting, and optimizing the operation of rechargeable battery packs. It acts as the intelligence layer between the battery cells and the vehicle's electrical system. The primary objective of a BMS is to ensure safe operation while maximizing battery performance, efficiency, and service life.

A typical Battery Management System consists of voltage sensing circuits, current sensors, temperature sensors, microcontroller units, communication modules, balancing circuits, and protection devices. These components work together to monitor battery conditions and execute protective actions whenever abnormal operating conditions are detected.

A. Voltage Monitoring

Voltage monitoring is one of the most important functions of a BMS[5]. Individual cell voltages are continuously measured to ensure that no cell exceeds its maximum charging voltage or falls below its minimum discharge voltage. Accurate voltage monitoring helps prevent overcharging and deep discharge, both of which can significantly reduce battery life and compromise safety.

B. Current Monitoring

Current monitoring enables the BMS to measure charging and discharging currents flowing through the battery pack[5]. Excessive current can generate excessive heat and damage battery cells. Current sensing also plays an important role in calculating battery capacity utilization and energy consumption during vehicle operation.

C. Temperature Monitoring[10][24]

Temperature has a direct impact on battery performance, efficiency, and safety. Most Battery Management Systems use temperature sensors positioned at strategic locations within the battery pack. These sensors continuously measure thermal conditions and enable the system to take corrective actions if temperature limits are exceeded.

D. State of Charge Estimation

State of Charge (SOC) indicates the remaining available energy within a battery and is commonly expressed as a percentage.[1][21][22] Accurate SOC estimation helps drivers understand the available driving range and supports efficient energy management. Various methods such as Coulomb Counting, Open Circuit Voltage (OCV) estimation, Kalman Filtering, and Artificial Intelligence-based techniques are commonly used for SOC estimation.

E. State of Health Estimation

State of Health (SOH) represents the overall condition of a battery relative to its original performance[3][25]. As batteries age, their capacity gradually decreases and internal resistance increases. SOH estimation techniques help predict battery degradation and support preventive maintenance strategies.

F. Cell Balancing

Cell balancing is a process used to equalize the charge level among individual cells within a battery pack. Two major balancing methods are commonly employed:[4][31]

Passive Balancing:Excess energy from higher-voltage cells is dissipated as heat through balancing resistors.

ActiveBalancing:Energy is transferred from higher-charged cells to lower-charged cells using capacitors, inductors, or power electronic converters.[31]

Active balancing generally provides higher efficiency but requires more complex hardware and control algorithms.

G. Fault Detection and Protection

Battery Management Systems continuously monitor operating conditions and activate protective mechanisms whenever abnormal situations occur[2][26]. Common protection functions include:

- Over-voltage protection
- Under-voltage protection
- Over-current protection
- Short-circuit protection
- Over-temperature protection

• Under-temperature protection
• Reverse polarity protection

These protection mechanisms improve battery safety and reduce the likelihood of catastrophic failures.

H. Communication and Data Management

Modern Battery Management Systems support various communication protocols such as CAN, UART, RS-485, Bluetooth, and wireless communication technologies. These interfaces enable data exchange between the battery pack, vehicle controller, [11][29]cloud servers, and user applications. Advanced communication systems support remote monitoring, predictive maintenance, and intelligent energy management.

Through the integration of monitoring, protection, balancing, estimation, and communication functions, Battery Management Systems have become a critical technology for ensuring the safe and efficient operation of electric vehicle battery packs.

IV . OBJECTIVES

- To study lithium-ion battery characteristics and associated safety challenges.
- Review recent Battery Management System technologies.
- Analyze SOC and SOH estimation techniques.
- Compare thermal management and balancing strategies.
- Identify research gaps and future directions..

V. LITERATURE SURVEY

1. Intelligent Real-Time Battery Management System for Electric Two-Wheelers Using IoT and Machine Learning

Author: Patil et al. (2024)

Patil et al. (2024) developed an intelligent Battery Management System specially designed for electric two-wheelers by integrating Internet of Things (IoT) technology and machine learning algorithms. The proposed system used distributed controllers for monitoring individual cell voltage and temperature in real time. Machine learning models were applied to predict battery abnormalities and health conditions before major failures occurred. The system also included cloud connectivity, enabling remote monitoring, data logging, and fault diagnostics through wireless communication. The researchers observed that predictive monitoring improved battery health estimation accuracy by approximately 12% compared to conventional BMS methods. The study demonstrated that IoT and AI technologies can significantly improve battery safety, reliability, and maintenance efficiency in compact EV applications.[1]

2. Cell-Level Fault Diagnosis and Protective Alarming in Lithium-Ion Battery Packs for Electric Vehicles

Author: Zhang and Liu (2023)

Zhang and Liu (2023) proposed an advanced fault diagnosis and protective alarming system for lithium-ion battery packs used in electric vehicles. Their research focused on detecting internal short-circuit faults at the cell level using a dual-threshold alarming mechanism based on impedance monitoring and thermal sensing techniques[2]. The developed system provided both early-warning alarms and emergency shutdown protection to prevent battery damage and thermal propagation. The architecture also supported automatic isolation of faulty cells to enhance overall pack safety. Experimental results showed that the proposed method reduced severe fault occurrences by nearly 30% in high-density battery systems. This research highlighted the importance of real-time fault monitoring and intelligent protective alarming in ensuring safe operation of EV battery packs.

3. Review of Thermal-Runaway Monitoring and Early-Warning Techniques in Lithium-Ion Batteries

Author: Yin et al. (2023)

Yin et al. (2023) presented a comprehensive review of thermal-runaway monitoring and early-warning techniques for lithium-ion batteries used in electric vehicles. The study discussed different indicators of thermal runaway such as temperature rise, voltage deviation, gas generation, and impedance variation. The authors analyzed various sensing technologies and emphasized the use of multi-sensor data fusion for improving detection accuracy[3]. Artificial Intelligence-based classification methods were also explored for identifying abnormal battery behavior in real time. The researchers found that combining voltage, temperature, and gas sensing techniques reduced false alarm rates by approximately 20% and improved the reliability of protective alarming systems. The study provided valuable guidance for selecting sensors and designing safe battery monitoring systems for EV applications.

4. A Comprehensive Review of Active Cell Balancing Techniques for Electric Vehicle Battery Packs

Author: Ashraf et al. (2025)

Ashraf et al. (2025) conducted a detailed review of active and passive cell balancing techniques used in electric vehicle battery packs. The paper compared different balancing topologies such as switched-capacitor, inductor-based, and converter-based balancing systems in terms of balancing speed, efficiency, thermal performance, and implementation cost.[4] The authors observed that active balancing methods improved usable battery capacity by 5–8% while reducing heat generation and improving overall pack efficiency.

5.Artificial Intelligence Based State of Charge and State of Health Estimation for Lithium-Ion Batteries

Author: Lipu et al. (2023)

Lipu and co-authors investigated the application of Artificial Intelligence techniques for estimating State of Charge (SOC) and State of Health (SOH) in lithium-ion batteries. Machine learning models[23] including Artificial Neural Networks, Deep Neural Networks, and Long Short-Term Memory algorithms were analyzed. The researchers reported that AI-based estimation methods achieved higher prediction accuracy under varying load and temperature conditions compared to conventional estimation techniques. The study demonstrated the growing importance of intelligent algorithms in modern Battery Management Systems.[23]

6.Wireless Battery Management Systems for Electric Vehicle Applications

Author: Kim et al. (2024)

Kim et al. developed a wireless Battery Management System architecture that eliminated traditional wiring harnesses between battery modules. Wireless communication was used to transfer battery information including voltage, temperature[28], and balancing status to a central controller. The proposed system reduced system complexity, vehicle weight, and installation costs. Experimental validation confirmed reliable communication performance under different operating conditions. The study highlighted the future potential of wireless battery monitoring technologies in electric mobility applications.

7.Digital Twin Based Battery Monitoring and Predictive Maintenance

Author: Wang et al. (2024)

Wang et al. proposed a Digital Twin framework for lithium-ion battery monitoring and predictive maintenance. The digital[27] model continuously synchronized with real-time battery operating conditions and predicted battery degradation trends using historical and real-time data. The system enabled accurate estimation of remaining useful life and improved maintenance planning. Results demonstrated that Digital Twin technology can enhance battery reliability while reducing maintenance costs and unexpected failures.

8.Cloud-Based Battery Analytics and Fleet Monitoring Systems

Author: Sharma et al. (2025)

Sharma et al. introduced a cloud-based battery monitoring platform designed for electric vehicle fleet management. The system collected battery information from multiple vehicles and stored it on cloud servers for centralized analysis. Advanced analytics tools were used to identify battery degradation [29]patterns, charging behavior, and operational anomalies. The platform provided real-time alerts and predictive maintenance recommendations to fleet operators. The study concluded that cloud-connected Battery Management Systems can improve operational efficiency and battery utilization in large-scale EV deployments.

9.Advanced Thermal Management Techniques for Lithium-Ion Battery Packs

Author: Chen et al. (2024)

Chen et al. investigated advanced thermal management techniques for lithium-ion battery packs used in electric vehicles. The study compared air cooling, liquid cooling, phase change materials, and hybrid cooling systems. Experimental results showed that liquid cooling provided superior temperature uniformity and improved battery life under high-load operating conditions. The authors concluded that effective thermal management is essential for maintaining battery safety and performance in modern electric vehicles.

10. Machine Learning-Based Fault Prediction in Battery Management Systems

Author: Singh et al. (2024)

Singh et al. proposed a machine learning-based fault prediction framework for Battery Management Systems. The model utilized historical battery data, voltage variations, current patterns, and temperature profiles to predict possible battery failures[24]. The developed system achieved high prediction accuracy and enabled early fault detection before critical battery degradation occurred. The study demonstrated the potential of artificial intelligence for enhancing battery reliability and reducing maintenance costs.

11. Internet of Things Enabled Smart Battery Monitoring System

Author: Kumar et al. (2023)

Kumar and co-authors developed an IoT-enabled battery monitoring platform for electric vehicle applications. The system used wireless sensors and cloud connectivity to collect and analyze[31] battery parameters in real time. Users could access battery information remotely through mobile applications and web interfaces. The researchers observed improved battery monitoring capabilities and enhanced user awareness through continuous remote supervision.

12.Review of State of Charge Estimation Methods for Lithium-Ion Batteries

Author: Hannan et al. (2023)

Hannan et al. presented a comprehensive review of State of Charge estimation methods used in Battery Management Systems. The study analyzed Coulomb Counting, Open Circuit Voltage, Kalman Filter, Fuzzy Logic, and Artificial Intelligence-based estimation techniques. The authors found that hybrid estimation approaches combining multiple methods produced higher accuracy under dynamic operating conditions. The review highlighted the importance of accurate SOC estimation for reliable battery operation.

13.Battery Health Monitoring Using Deep Learning Techniques

Author: Zhao et al. (2024)

Zhao et al. investigated deep learning techniques for battery health monitoring and degradation prediction. Various neural network models were trained using battery cycling data collected under different environmental conditions. Results indicated that deep learning algorithms could accurately estimate battery health and remaining useful life. The study demonstrated that advanced data-driven techniques can significantly improve battery diagnostics and maintenance planning.

14.Wireless Communication Architectures for Battery Management Systems

Author: Park et al. (2024)

Park et al. reviewed wireless communication technologies used in Battery Management Systems including Bluetooth, ZigBee, Wi-Fi, and CAN-based wireless architectures. The study focused on communication reliability, power consumption, security, and implementation challenges. The researchers concluded that wireless communication can reduce system complexity and improve scalability in large battery systems while maintaining reliable monitoring performance.

15.Cybersecurity Challenges in Smart Battery Management Systems

Author: Ahmed et al. (2025)

Ahmed et al. explored cybersecurity risks associated with connected Battery Management Systems. The study identified potential threats including unauthorized access, communication attacks, data manipulation, and system disruption. Various security frameworks and encryption methods were evaluated to protect battery data and communication channels. The authors emphasized that cybersecurity will become increasingly important as Battery Management Systems become more connected through IoT and cloud platforms.

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VI. DISCUSSION RELATED TO PROPOSED BATTERY MANAGEMENT SYSTEM

The literature reviewed in this study demonstrates that Battery Management Systems have become one of the most important technologies in modern electric vehicles[1][5][7]. As lithium-ion batteries continue to dominate the electric mobility sector, the need for intelligent monitoring, protection, and control systems has increased significantly. Researchers have proposed various techniques to improve battery safety, efficiency, and operational reliability.

One of the common observations from the reviewed studies is that continuous monitoring of voltage, current, and temperature remains the foundation of every Battery Management System[5][10]. These parameters directly influence battery performance and safety. Accurate monitoring enables the system to identify abnormal operating conditions at an early stage and initiate corrective actions before serious failures occur.

Several researchers have focused on cell-level fault detection and protective alarming mechanisms[2][26]. Their findings indicate that early detection of voltage imbalance, excessive temperature rise, and abnormal current flow can significantly reduce the risk of battery damage and thermal runaway. The implementation of intelligent fault diagnosis techniques improves system reliability and enhances user safety.

Recent developments in Artificial Intelligence and Machine Learning have further expanded the capabilities of Battery Management Systems[22][23]. AI-based algorithms have shown promising results in State of Charge (SOC) estimation, State of Health (SOH) prediction, and fault classification. Compared to conventional methods, intelligent algorithms provide better accuracy under dynamic operating conditions and varying environmental factors.

The reviewed literature also highlights the growing role of Internet of Things (IoT) technology in battery management applications[11][29]. IoT-enabled systems allow real-time monitoring, remote diagnostics, and cloud-based data analysis. These capabilities improve maintenance planning and provide users with continuous access to battery performance information. Such features are becoming increasingly important as electric vehicles become more connected and data-driven.

Cell balancing remains another critical aspect of battery management[4][31]. Researchers have demonstrated that maintaining uniform charge distribution among cells improves battery efficiency and extends battery lifespan. While passive balancing techniques are simple and economical, active balancing approaches offer better energy utilization and improved overall performance. The selection of an appropriate balancing method depends on application requirements, cost considerations, and system complexity.

Another emerging area identified through the literature survey is Digital Twin technology. Digital Twins create virtual representations of physical battery systems and continuously update their behavior using real-time operational data[27]. This approach enables predictive maintenance, performance optimization, and accurate degradation forecasting. Although still in the early stages of implementation, Digital Twin technology has significant potential for future Battery Management Systems.

Based on the reviewed studies, it can be concluded that the future of Battery Management Systems lies in the integration of intelligent algorithms, wireless communication technologies, predictive analytics, and advanced monitoring techniques. The combination of these technologies will contribute to safer, more efficient, and more reliable battery systems for electric two-wheeler applications.

VII. RESEARCH GAP

Although several research studies have been conducted on Battery Management Systems for electric vehicles, many existing systems focus primarily on high-end electric cars and large battery packs. Limited research is available specifically for compact, cost-effective Battery Management Systems designed for electric two-wheelers. Many conventional systems also lack real-time monitoring capabilities and user-friendly diagnostic features suitable for daily vehicle operation. While advanced BMS technologies based on Artificial Intelligence, Machine Learning, and Internet of Things (IoT) platforms provide improved prediction accuracy and fault diagnosis capabilities, they often increase implementation cost and system complexity, limiting their adoption in economical electric two-wheelers. Therefore, there is a growing need for Battery Management Systems that combine accurate cell-level monitoring, real-time fault

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detection, protective alarming, intelligent diagnostics, and affordability. **Future research should focus on developing practical, reliable, and cost-effective BMS solutions that can meet the safety and performance requirements of electric two-wheeler applications under diverse operating conditions[22][23]**.

VIII. CONCLUSION

Battery Management Systems have become an essential component of modern electric vehicles, particularly in lithium-ion battery-powered electric two-wheelers. As the demand for electric mobility continues to grow, ensuring battery safety, reliability, and efficiency has become increasingly important. This review examined recent developments in Battery Management System technologies, including battery monitoring, cell balancing, fault diagnosis, thermal management, State of Charge estimation, State of Health prediction, and intelligent control strategies.

The literature indicates that continuous monitoring of battery voltage, current, and temperature is fundamental for maintaining safe battery operation and extending battery lifespan. Various studies have demonstrated that advanced fault detection techniques, thermal management approaches, and cell balancing methods can significantly improve battery performance while reducing the risk of battery failures. Furthermore, the integration of Artificial Intelligence, Machine Learning, Internet of Things, and cloud-based monitoring platforms has enhanced the capabilities of modern Battery Management Systems by enabling predictive maintenance, real-time diagnostics, and intelligent decision-making.

The review also revealed that although significant progress has been achieved in Battery Management System research, challenges related to implementation cost, estimation accuracy, thermal safety, communication reliability, and practical deployment in electric two-wheelers still exist. Emerging technologies such as Digital Twins, wireless battery monitoring, and data-driven battery analytics are expected to play a major role in the future development of intelligent battery management solutions.

Overall, an effective Battery Management System is critical for improving battery safety, operational efficiency, and long-term reliability in electric vehicles. Continued research and technological advancements in this field will contribute to the development of smarter, safer, and more sustainable electric mobility solutions for future transportation systems.

"The future of Battery Management Systems lies in the integration of intelligent monitoring, predictive analytics, and cost-effective technologies that enhance both battery safety and vehicle performance."

IX. FUTURE SCOPE

The rapid advancement of electric vehicle technology is expected to drive significant developments in Battery Management Systems over the coming years. Future Battery Management Systems will move beyond conventional monitoring and protection functions toward intelligent, predictive, and self-adaptive battery management solutions.

One of the most promising research areas is the integration of Artificial Intelligence and Machine Learning algorithms for advanced battery diagnostics[22][23]. These technologies can improve the accuracy of State of Charge (SOC) and State of Health (SOH) estimation while enabling early fault detection and predictive maintenance. Intelligent algorithms can analyze large volumes of battery data and identify degradation patterns before performance deterioration becomes critical.

The application of Internet of Things (IoT) technology is also expected to expand in Battery Management Systems[11][29]. IoT-enabled battery platforms can facilitate real-time monitoring, remote diagnostics, and cloud-based data analysis. Such capabilities will allow vehicle owners, fleet operators, and service providers to monitor battery performance continuously and take preventive actions when necessary.

Digital Twin technology represents another emerging research direction[27]. By creating a virtual representation of a physical battery system, Digital Twins can simulate battery behavior, predict future performance, and support intelligent decision-making. The integration of Digital Twins with Battery Management Systems has the potential to improve battery reliability, optimize maintenance schedules, and extend battery life.

Wireless Battery Management Systems are also gaining attention as a future alternative to conventional wired architectures[28]. Wireless communication can reduce wiring complexity, decrease vehicle weight, simplify installation, and improve system scalability, particularly in large battery packs.

Future research is expected to focus on improving thermal management strategies through[24] advanced cooling techniques, smart thermal prediction models, and multi-sensor monitoring systems. These developments will help prevent thermal runaway events and enhance battery safety under demanding operating conditions.

Another important area of future development is battery cybersecurity. As Battery Management Systems become increasingly connected through cloud platforms and wireless communication networks, protecting battery data and communication channels from cyber threats will become essential.

Furthermore, the development of low-cost and highly reliable Battery Management Systems specifically designed for electric two-wheelers remains an important research priority. Future solutions should aim to balance performance, safety, intelligence, and affordability to support the widespread adoption of electric mobility.

Overall, future Battery Management Systems are expected to become more intelligent, connected, and autonomous, contributing significantly to safer, more efficient, and sustainable electric transportation systems.

"The integration of Artificial Intelligence, IoT, Digital Twin technology, and predictive analytics will define the next generation of intelligent Battery Management Systems."

REFERENCES

[1]. Patil, S., Deshmukh, A., and Kulkarni, R., “Intelligent Real-Time Battery Management System for Electric Two-Wheelers Using IoT and Machine Learning,” International Journal of Electric Vehicle Technology, vol. 12, no. 3, pp. 145–154, 2024.

[2]. Zhang, Y. and Liu, H., “Cell-Level Fault Diagnosis and Protective Alarming in Lithium-Ion Battery Packs for Electric Vehicles,” IEEE Transactions on Transportation Electrification, vol. 9, no. 2, pp. 221–230, 2023.

[3]. Yin, X., Chen, W., and Zhao, P., “Review of Thermal-Runaway Monitoring and Early-Warning Techniques in Lithium-Ion Batteries,” Journal of Energy Storage, vol. 68, pp. 107–119, 2023.

[4]. Ashraf, M., Khan, S., and Verma, D., “A Comprehensive Review of Active Cell Balancing Techniques for Electric Vehicle Battery Packs,” Renewable and Sustainable Energy Reviews, vol. 190, pp. 113–128, 2025.

[5]. Mulpuri, R., Sharma, K., and Patel, J., “Smart Battery Management System with Predictive Maintenance and Safety Alarming for Electric Vehicles

[6]. Singh, R., Mehta, P., and Gupta, A., “Real-Time Fault Detection and Adaptive Control in Battery Management Systems Using Edge AI,” International Journal of Smart Grid and Clean Energy, vol. 11, no. 4, pp. 278–286, 2022.

[7]. Deshmukh, V. and Rao, S., “Design and Implementation of Low-Cost Distributed BMS for Electric Two-Wheelers,” Journal of Power Electronics and Energy Systems, vol. 17, no. 2, pp. 95–103, 2023.

[8]. Bhaskar, T., Nair, P., and Reddy, M., “Data-Driven Thermal Anomaly Detection in Large Battery Packs,” Energy Reports, vol. 8, pp. 5412–5423, 2022.

[9]. Lipu, M. S. H., Hannan, M. A., and Hussain, A., “AI-Enhanced Battery Management System for Electric Vehicles,” Energies, vol. 16, no. 7, pp. 3115–3130, 2023.

[10]. Fan, J., Wang, L., and Zhou, Y., “Fault Diagnosis for Lithium-Ion Battery Packs Based on Relative Entropy and SOC Estimation,” Applied Energy, vol. 356, pp. 121–132, 2024.

[11]. Mulpuri, R., Naidu, V., and Kumar, P., “An Intelligent Battery Management System with End-Edge-Cloud Connectivity: A Perspective,” IEEE Internet of Things Journal, vol. 12, no. 1, pp. 144–156, 2025.

[12]. El Fallah, A., Karim, M., and Benali, H., “Advanced State of Charge Estimation Using DNN, GRU and LSTM Models for Lithium-Ion Batteries,” Applied Sciences, vol. 14, no. 2, pp. 722–735, 2024.

[13]. Krishna, P., “An IoT-Based Predictive Model for Improved Battery Management,” International Journal of Advanced Engineering Research, vol. 15, no. 5, pp. 88–97, 2024.

[14]. Manas, R., "Designing a Battery Management System for Electric Two-Wheeler Applications," Journal of Electrical and Electronics Engineering, vol. 10, no. 6, pp. 201–209, 2023.
[15]. Farman, A., "AI-Enhanced Battery Management Systems for Electric Vehicles
[16]. Andrioaia, D., Popescu, R., and Mihai, S., "Predictive Maintenance System to RUL Prediction of Li-Ion Batteries," Journal of Energy AI, vol. 9, pp. 100–112, 2025.
[17]. Panasonic Corporation, "Panasonic 26650 Lithium-Ion Cell Datasheet," Panasonic Energy Solutions, Japan, 2023.
[18]. Daly Electronics, "Smart BMS User Manual and Technical Specifications," Shenzhen Daly Electronics Co. Ltd., China, 2024.
[19]. N. Omar, M. Daowd, O. Hegazy, and J. Van Mierlo, "Lithium Iron Phosphate Based Battery – Assessment of the Aging Parameters and Development of Cycle Life Model," Applied Energy, vol. 113, pp. 1575–1585, 2014.
[20]. Hannan, M. A., Hoque, M. M., Mohamed, A., and Ayob, A., "Review of Energy Storage Systems for Electric Vehicle Applications,"
[21]. K. Liu, Y. Shang, Q. Ouyang, and W. Widanage, "A Data-Driven Approach With Uncertainty Quantification for Predicting Future Capacities and Remaining Useful Life of Lithium-Ion Batteries," IEEE Transactions on Industrial Electronics, vol. 68, no. 4, pp. 3170–3180, 2021.
[22]. X. Hu, F. Feng, K. Liu, L. Zhang, J. Xie, and B. Liu, "State Estimation for Advanced Battery Management: Key Challenges and Future Trends," Renewable and Sustainable Energy Reviews, vol. 114, 2019, Art. 109334.
[23]. M. S. H. Lipu, M. A. Hannan, A. Hussain, P. J. Ker, M. M. Hoque, and T. F. T. K. Sarker, "Artificial Intelligence Based Battery Management System for Electric Vehicles: A Review," Energies, vol. 16, no. 7, 2023.
[24]. M. Ghalkhani and S. Habibi, "Review of the Li-Ion Battery, Thermal Management, and AI-Based Battery Management System for EV Application," Energies, vol. 16, no. 1, Art. 185, 2023.
[25]. J. Meng, L. Cai, D. I. Stroe, G. Luo, and R. Teodorescu, "Lithium-Ion Battery State-of-Health Estimation for Electric Vehicle Batteries Using Machine Learning," Energy, vol. 202, 2020.
[26]. R. Xiong, J. Tian, H. Mu, and C. Wang, "A Systematic Model-Based Degradation Behavior Recognition and Health Monitoring Method for Lithium-Ion Batteries," Applied Energy, vol. 207, pp. 372–383, 2017.
[27]. S. S. Madani, M. H. Amini, and A. Y. Abdelaziz, "Artificial Intelligence and Digital Twin Technologies for Next-Generation Battery Management Systems: A Review," Batteries, vol. 11, no. 8, 2025.
[28]. H. Kim, S. Park, and J. Lee, "Wireless Battery Management Systems for Electric Vehicle Applications: Design Challenges and Opportunities," IEEE Access, 2024.
[29]. V. Sharma, R. Gupta, and P. Nair, "Cloud-Based Battery Analytics and Fleet Monitoring Systems for Electric Mobility," Energy Reports, 2025.
[30]. X. Yin, W. Chen, and P. Zhao, "Review of Thermal Runaway Monitoring and Early-Warning Techniques in Lithium-Ion Batteries," Journal of Energy Storage, vol. 68, 2023.
[31]. F. Feng, X. Hu, J. Liu, L. Lin, B. Liu, and M. Ouyang, "A Review of Equalization Strategies for Series Battery Packs: Variables, Objectives, and Algorithms," Renewable and Sustainable Energy Reviews, vol. 116, 2019