Current Trends and Technological Progress of Battery Management Systems for New Energy Vehicles

Zhuoyi Xiao*

School of Mechanical and Materials Engineering, North China University of Technology University, Beijing, 100043, China

Abstract. Driven by low-carbon development and carbon neutrality goals, new energy vehicles represent the main path for automotive industry change and strategic progress. Since battery problems like overcharging and over-discharging hurt safety and service life, the Battery Management System (BMS) has become a key research and development focus. Acting as the brain of the energy storage unit, the BMS monitors important parameters, manages temperature, and improves economic operation. Currently, global research combines advanced sensors and smart algorithms to make systems more reliable. While some international developments lead in real-time monitoring, significant progress has been made in distributed architecture and balance control through cooperation between universities and companies. Analysis shows that these management modules are moving toward a future with high precision, better intelligence, and smooth coordination in different environments. Finally, the improvement of these systems remains necessary for the sustainable use of electric power and the prevention of heat risks in modern transportation.

1 Introduction

Traditional gasoline vehicles use high energy and cause significant pollution, failing to meet modern low-carbon demands. New energy vehicles, with their zero-emission advantages, have become the core focus for industrial transformation under global "dual carbon" goals. For China, developing new energy vehicles is crucial for industrial upgrading. As battery technology advances, the Battery Management System (BMS) faces complex technical challenges, making it a key area for research.

Reliable BMS operation is essential to ensure safety and efficiency, as overcharging and over-discharging severely reduce battery lifespan. The BMS performs three main tasks: monitoring voltage, current, and temperature to ensure safety; managing thermal conditions to improve efficiency; and coordinating with energy systems to optimize operation.

Modern BMS units integrate sensors, controllers, and smart algorithms. Research in the United States remains highly advanced; for example, a BMS designed for EVI electric vehicles manages 26 cells to extend cycle life through thermal and fault management [1].

---

* Corresponding author: yizhuoxiao@outlook.com

Furthermore, AEVM has developed systems for real-time parameter tracking and data storage [2]. In China, significant progress has been achieved through university-enterprise cooperation. The "Chaoyue 2" hybrid vehicle by Tongji University utilizes a two-level distributed BMS architecture, where a master unit coordinates six sub-units via CAN bus communication [3]. Additionally, the BMS developed by Huizhou E-power and Beijing Jiaotong University has achieved widespread application and recognition [4].

This paper focuses on the core charging, discharging, and balancing modules of the BMS. It analyzes solutions for improving parameter accuracy and system stability, covering both master-slave hardware topologies and integrated software control. By synthesizing these results, this study clarifies the technical framework of current BMS applications to provide a clear reference for future research.

2 Fundamental theory and characteristics of BMS control modules

2.1 Definition Items and core functionalities

2.1.1 Electric charging and electric discharging management module

This module acts as the main unit for energy adjustment. Its core work is to watch key parameters, including voltage, current, temperature, State of Charge (SOC), and State of Health (SOH). Therefore, through changing charging and discharging ways in a dynamic manner, it stops capacity reduction and safety dangers that are caused by overcharging or over-discharging, hence making sure energy is used in an efficient way.

2.1.2 Balance-realizing module

This module is of essential importance for raising battery pack consistency and putting off capacity decline. It makes use of voltage equalizers to control potential differences among single cells. Therefore, by making the charging and discharging progress of each cell in synchronization, it reduces imbalances, hence improving the whole cycle life and safety of the battery pack.

2.1.3 Heat control component group

The thermal management module carries out regulation on the operating temperature of the battery pack for the purpose of guaranteeing safety and longevity. By means of monitoring temperature distribution, it keeps the electrochemical environment inside a most optimal range. Therefore, this process carries out prevention of thermal runaway and degradation, and hence it makes sure that the battery carries out efficient operation under various environmental conditions.

2.2 Operation mechanisms of control modules

2.2.1 Charge and discharge regulation control

The system makes use of electrochemical models to carry out real-time estimation of State of Charge (SOC). Therefore, through analysis of these states, the module carries out regulation of current flow for the purpose of preventing overcharging in the charging phase.

During discharge, hence, the BMS carries out current limitation in accordance with load demands and cell health to avoid over-discharging.

2.2.2 Balance rule of equalization

This module carries out monitoring of single battery cell voltages for the purpose of detecting inconsistent situations. Therefore, as the balancing logic shows, passive balancing methods release surplus energy from high-voltage cells in the form of heat, while active balancing methods make use of capacitors or inductors to carry out energy transfer from cells with higher capacity to cells with lower capacity.

2.2.3 Principle of thermal management control

Temperature sensors carry out monitoring of thermal situations throughout the battery pack. Therefore, in accordance with heat transfer principles, the system starts passive cooling through structural dissipation or active cooling through phase-change materials; thus, it maintains optimal temperature ranges and hence guarantees the overall safety of the system.

3 Creation of new things and precise control of BMS charge and discharge technology

3.1 Shortcomings of traditional charging and discharging operations

The constant current constant voltage (CC-CV) mode, as a classic traditional scheme for power battery charging and discharging control, has exposed significant technical limitations under the complex and variable actual working conditions of new energy vehicles, with its core defects concentrated in two key issues: SOC estimation deviation and delayed response to working conditions. The control logic and SOC estimation method of this mode are both designed based on ideal steady-state working conditions, using fixed constant current charging thresholds, constant voltage cut-off conditions, and a static voltage-SOC mapping relationship for power judgment.

However, in actual usage scenarios, the corresponding relationship between the open-circuit voltage (OCV) and SOC of the power battery will undergo nonlinear drift due to the coupling influence of multiple factors, including the increase in internal resistance caused by battery cycle aging, the change in polarization characteristics caused by drastic changes in ambient temperature, and the transient impact of large currents caused by frequent acceleration and deceleration. Traditional static estimation models cannot correct these dynamic variables in real time, resulting in SOC estimation errors exceeding 10% under extreme working conditions. This not only causes user-perceived range prediction inaccuracies such as false power and exaggerated range labels, but also indirectly triggers dangerous working conditions such as overcharging and overdischarging due to incorrect power judgment, accelerating battery capacity degradation and even inducing thermal runaway risks. At the same time, the control parameters of the CC-CV mode are preset fixed values, lacking the ability to dynamically adapt to sudden changes in vehicle working conditions.

When the vehicle faces scenarios with frequent switching of power demands such as rapid acceleration, high-speed climbing, and start-stop in congested sections, traditional systems cannot quickly adjust the charging and discharging current and voltage thresholds according to the real-time state of the battery such as temperature and internal resistance and health status. Combined with the serial link delay of sensor collection, controller operation, and actuator response in traditional BMS, the adjustment of the charging and discharging strategy has a delay of several seconds, leading to a serious disconnection between the energy supply rhythm and the vehicle power demand. This not only aggravates invalid energy consumption and battery temperature rise accumulation, but also affects the smoothness and safety of the vehicle's power output. These inherent limitations make the traditional CC-CV mode no longer able to meet the high-precision and high dynamic response requirements of high-specific-energy power batteries and intelligent new energy vehicles for charging and discharging control.

3.2 Technology progressions in SOC estimation measurement

SOC estimation mainly contains lookup-table methods, ampere-hour integration, and model-based approaches. Therefore, a key progress is the improved open-circuit voltage method, which defines the functional relationship fSOC-EMF in order to turn SOC estimation into an EMF problem, as demonstrated in Equation (1) [5].

$$\begin{cases} \frac{dUc_p}{dt} = -\frac{Uc_p}{R_pC_p} + \frac{I}{C_p} \quad p = 1,2 \\ \frac{dUc_0}{dt} = \frac{I}{C_0} \\ U_O = Uc_0 + Uc_1 + R_0I \end{cases} \tag{1}$$

In order to make accuracy better, the Adaptive Forgetting Factor Recursive Least Squares (AFFRLS) algorithm deals with data saturation problem that exists in traditional methods, and it can reach approximately 1% error [6]. Moreover, thus the combined AFFRLS-MIASRCKF algorithm applies adaptive square-root cubature Kalman filtering so as to keep robustness when complex driving cycles are under way, with RMSE being in the range of 1% to 3% [7]. Fig. 1 shows the estimation workflow.

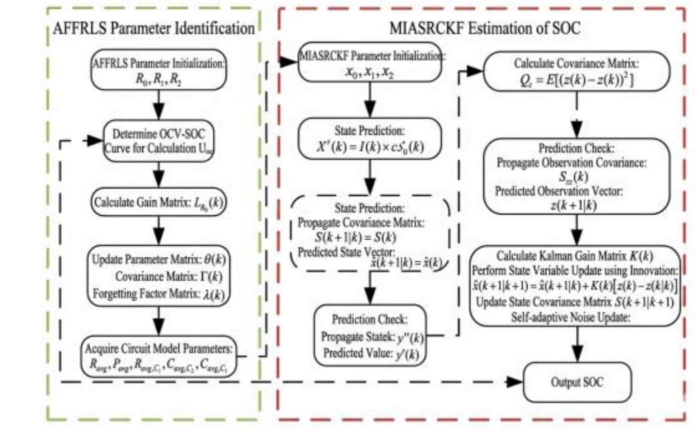

Fig. 1. Workflow of estimation for the AFFRLS-MIASRCKF algorithm.

Advanced technologies also contain Variational Bayesian Quantum Particle Filtering, which carries out dynamic adjustment of noise parameters for achieving better convergence [8]. Additionally, data-based methods and deep learning models catch non-linear dynamic characteristics; hence, they realize cooperative SOC and SOH estimation under different thermal and load conditions.

4 Progress of electricity storage cell equalization technique

4.1 Categorization of equilibrium-maintaining technique

Balancing technology is divided into passive and active two types. Passive balancing mainly makes use of switched-resistor circuits; although it is simple and low-cost, it has the problem of large energy consumption, thus it can only be applied to low-capacity situations. Active balancing has become the main stream for middle-to-high-level application scenarios because of its bidirectional energy transfer ability. Main active topologies contain capacitive type, inductive type (85%–90% efficiency, ideal for new energy vehicles), transformer-based type (providing high electrical isolation for grid-side storage), and hybrid schemes (reducing balancing time by more than 28%).

4.2 Active balance structure framework

Active balancing topologies are mainly classified into single-layer and multi-layer structures, as it is shown in Fig. 2.

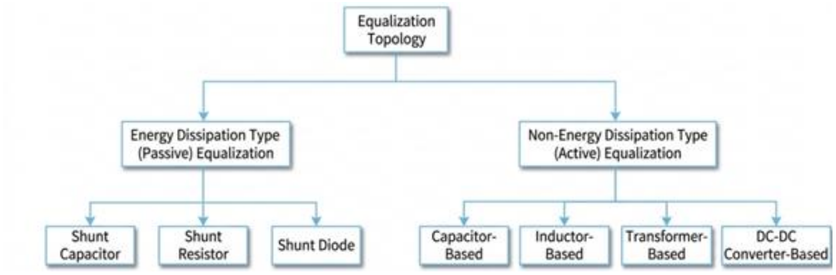

Fig. 2. Balance circuit topological structure.

4.2.1 Single-layer arrangement of connection structure

Single-layer structures make use of direct energy transfer action among cells. A multi-output transformer topology is introduced in related research [9], which is famous for high speed and simplicity without needing complex closed-loop control. Therefore, transformer manufacturing inconsistencies and winding limitations restrict its scalability. A bidirectional Buck-Boost converter [10], being a typical adjacent-cell balancing topology, is put forward in another research. Although it can realize bidirectional energy flow with strong scalability, thus its efficiency falls in a big way over long transfer paths, making it not suitable for long cell strings. Additionally, a flying-inductor topology for direct cell-to-cell balancing is presented by certain studies [11]. Despite its fast response speeds, the large quantity of switches and diodes raises control complexity and reduces system stability when cell numbers increase. Hence, overall, single-layer structures have difficulties with long transfer paths and bad hardware scalability, which limits their application in high-performance electric vehicles.

4.2.2 Multi-layer structure of network layout

For multi-layer configuration, it designs one dual-layer active balancing topology [12]. It makes use of compact, high-efficiency bidirectional Buck-Boost converters to conduct intra-module balancing, and applies fast, flexible multi-winding transformers to realize intermodule balancing. However, the fixed transformer parameters bring limit to system scalability and reliability. Therefore, a modular active balancing system has been developed, and its structure is shown in Fig. 3 [13].

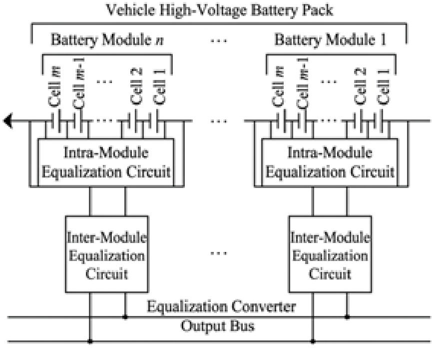

Fig. 3. System of two-stage balancing [13].

4.3 Passive balance technology

Passive balancing realizes cell conformity via the method of "peak shaving"; usually, it applies parallel power resistors to disperse surplus energy in the form of heat. Therefore, due to its mature state, academic research mainly centers on small-scale performance optimizations instead of structural reconstructions [14].

Most business BMS chips coming from firms such as TI, Renesas, and ADI have integrated passive balancing functions. Therefore, because internal heat limits exist, external circuits are usually needed for more high balancing currents. Domestic leading enterprises like BYD and CATL have built large patent collections in this field. Hence, notably, Aopu New Energy developed a centralized, power-adjustable circuit [15]. By letting multiple cells use resistors together, this design optimizes space and heat emission and at the same time makes adjustable power output possible.

4.4 Balancing technologies' contrastive analysis

Passive and active balancing have big difference in energy management and usage scenario. Passive balancing releases surplus energy as heat through parallel resistors; its simple structure and low expenditure make it perfect for mass-produced, cost-sensitive, or small-size battery systems. Therefore, active balancing applies transformers or converters to realize lossless energy transfer. Despite its higher complexity and cost, hence its more excellent efficiency in controlling large-scale pack inconsistencies make it the necessary selection for high-performance electric vehicles.

5 Conclusion

Under the background of global "dual carbon" targets, the Battery Management System (BMS) still holds critical status for industrial innovation. Therefore, this research proves that high-precision SOC estimation, which uses deep learning and improved OCV methods, can effectively solve estimation errors under complicated working conditions. Hence, as Fig. 3 have shown, the two-stage modular active balancing system has obvious superiorities compared with traditional single-layer topologies, thus realizing lossless energy transfer.

Complicated state monitoring and modular load balancing act as the fundamental basis for easing the key problems of mileage worry and safety worries. High-accuracy SOC state estimation not only precisely predicts residual electric quantity to relieve user confusion which is brought by incorrect mileage display but also improves dynamic electric power distribution. At the same time, all-round heat control and multi-dimension battery balance methods, from the origin, hold back the danger of heat out-of-control. These technique leaps give a definite industry direction for BMS producing factories: realizing algorithm unity to raise the compatibility of control logics, and combining hardware systems to make energy conversion efficiency get maximum promotion. This two-direction mutual promotion pushes the BMS to change from a only protection device into an intelligent, cooperating energy management center.

Therefore, hence, the development of BMS toward high accuracy, intellectualization, and mutual coordination is the core power machine that pushes the green transportation energy system to move toward sustainable, high-quality development.

References

1. X. Jing, Analysis and research on power batteries for new energy vehicles. Mechanical Management and Development **33**, 151-152 (2018)
2. L. Ma, Research and development of battery management system for energy storage, Master Thesis, Taiyuan University of Technology (2018)
3. J. Cao. Design of electric forklift battery management system and battery simulator based test system, Master Thesis, Zhejiang University (2021)
4. S. Xu, C. Hou, S. Yang. A lithium-ion battery management system suitable for large-capacity energy storage technology. Energy Storage Science and Technology **5**, 69-77 (2016)
5. H. Zhang. Research on lithium battery SOC estimation based on improved open circuit voltage method, Master Thesis, Anhui University of Science and Technology (2025)
6. T. Ouyang, P. Xu, J. Chen, J. Lu, N. Chen, Improved parameters identification and state of charge estimation for lithium-ion battery with real-time optimal forgetting factor. Electrochimica Acta **353**, 136576 (2020)
7. B. Wang. Lithium battery SOC estimation based on AFFRLS-MIASRCKF algorithm, Master Thesis, Anhui University of Science and Technology (2025)
8. M. Ren. Lithium battery SOC estimation based on variational Bayesian quantum particle filtering, Master's Thesis, Xi'an University of Technology (2025)
9. M.Y. Kim, C.H. Kim, S.Y. Cho, G.W. Moon, A cell selective charge equalizer using multi-output converter with auxiliary transformer, in Proceedings of the 8th International Conference on Power Electronics - Ecce Asia. Jeju, South Korea, May 30-June 03 (2011), pp. 310-317
10. P. Barrade. Series connection of supercapacitors: Comparative study of solutions for the active equalization of the voltages. Rivista Europea Di Diritto Pubblico **23**, 381-407 (2002)
11. S. Yarlagadda, T.T. Hartley, I. Husain, A battery management system using an active charge equalization technique based on a DC/DC converter topology. IEEE Transactions on Industry Applications **49**, 2720-2729 (2013)
12. T. Wang. Research on power battery double layer active equalizer based on multi-input transformer, Master Thesis, Jinan: Shandong University (2017)

13. C. She, T. Cai, P. Wei, et al. Research on decentralized logic equalization system for power battery and its equalization strategy. Journal of Power Supply **17**, 153-162 (2019)
14. L. Pan. Design of passive balancing controller in BMS chip, Master Thesis, Harbin Institute of Technology (2022)
15. Aopu (Shanghai) New Energy Co., Ltd. A centralized power-adjustable BMS passive balancing circuit: CN202110832571.1 (2021)