Comprehensive Analysis of Energy Storage System for Electric Vehicles

Zhenglin Mao *

Engineering and Technology College, Hubei University of Technology, Wuhan, China

* Corresponding Author Email: 1910732112@mail.sit.edu.cn

Abstract. There are many different applications for batteries, such as various new energy vehicles, such as electric vehicles (EVs) and hybrid electric vehicles (HEVs), etc. At the same time, an appropriate battery management system (BMS) is necessary to guarantee the battery's secure and dependable operation. When monitoring, managing, and maximizing energy storage systems, the battery module's performance is crucial. Equally crucial is the capability to detach the control module in abnormal circumstances. Initially, the power battery and BMS components of electric vehicles are covered in detail in this essay. The types and traits of various power batteries are initially described in this article. Besides, three state of charge (SOC) technologies—Ampere-hour (Ah), open circuit voltage (OCV) based, and model-based—are presented and reviewed, along with the role, composition, and key functions of BMS. Secondly, the hardware architecture and software architecture of BMS are explained in detail. Next, this paper analyzes and evaluates the advantages and disadvantages of different BMS architectures. Finally, this paper looks forward to the future development of BMS and predicts the main development directions of BMS in the future.

Keywords: Electric vehicles, power battery, battery management system, state of charge.

1. Introduction

Energy in any form is indispensable for global industry, however, due to the rapid development of industry, the world is facing the problem of excessive energy consumption, which has an impact on the environment. With the increasing demand for sustainable energy and zero-emission mobility, as well as global energy consumption has been rising gradually, efforts have been made to reduce CO2 and other greenhouse gas emissions on a global scale, supported by legislation and incentives [1]. Therefore, electric vehicles (EVs) are attracting attention as a low-carbon mode of transportation. Among them, traditional fuel vehicles account for the largest proportion of demand for fossil fuels such as oil, which is also accompanied by the increase of greenhouse gas emissions. Compared with fuel vehicles, the newly emerging new energy vehicles have significant advantages in all aspects, whether in fuel consumption or exhaust emissions. However, the performance and range of EVs are directly limited by battery technology, which also raises questions about their ability to replace internal combustion engines. In fact, many energy- or power-demanding application development is still hampered by the lack of highly effective, economically viable, and secure electric storage devices [2].

Power batteries play a vital role in EVs. As an energy storage device, it provides the required power and range for EVs, and Fig 1 is the electric vehicle schematic. An excellent power battery system can provide sufficient electric energy to enable EVs to meet the needs of daily use. At the same time, EV performance, acceleration performance, and charging efficiency are all directly impacted by the performance and quality of power batteries. Therefore, high-performance, high-reliability power batteries are essential to promote the development of the electric vehicle market. The continuous improvement and innovation of power battery technology will further enhance the performance and feasibility of EVs and promote the wide application of EVs.

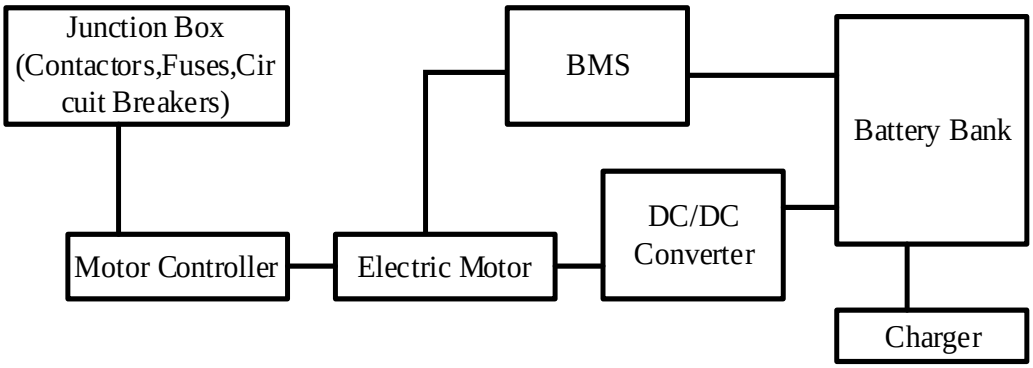


Fig. 1 Schematic electric vehicle (Photo/Picture credit: Original).

As the core energy storage device of EVs, batteries also have a wide range of application potential in other fields. Energy storage systems for EV batteries all play a significant part in the reuse of EVs, the construction of virtual power plants, and the support of microgrid systems to provide services for energy storage and dispatch. These potential application scenarios will promote the development of battery energy storage technology for EVs.

With the continuous breakthrough of science and technology, electric vehicle batteries have also benefited, its cell composition structure tend to be modular, the power battery is made up of several individual batteries connected in series and parallel and began to develop towards integration. Through reasonable design and electronic simulation optimization, the electric vehicle battery has formed battery management system (BMS) for management and control, which improves the management and control performance of the battery in all aspects. BMS is vital for batteries in EVs, it plays the role of monitoring, managing and protecting the battery. Initially, BMS monitors the status and performance of the battery, including battery temperature, voltage, current, and remaining capacity. Through real-time monitoring, BMS can ensure the normal operation of the battery and provide accurate battery status information. Secondly, BMS not just actively manages the operation of the storage device to extend its lifespan, efficiency, and safety but also gives the energy management system (EMS) unit precise estimates of the battery's condition [3]. Most important of all, BMS controls how the battery is charged and discharged, ensuring safe and efficient energy conversion and utilization. Through the strategy of controlling the battery charge and discharge current and voltage, BMS can increase the charging and discharging effectiveness of the battery and reduce energy loss. In summary, BMS are crucial to guaranteeing safety, extending life and improving performance, providing a solid foundation for the reliability, efficiency and sustainability of EVs.

At present, BMS of EVs is still in the development stage, in view of its importance to the development of the emerging electric vehicle plants, this paper introduces the core functions of existing power batteries and various BMS, as well as the advantages and disadvantages of different architecture models. Ultimately, the future development of BMS is summarized and analyzed. It is hoped that these studies can contribute to the further improvement and promotion of electric vehicle battery technology.

2. Power Batteries

Battery types are mainly divided into primary batteries and secondary batteries. The primary battery cannot be recharged due to its irreversible chemical reaction; the secondary battery can be recharged after the battery is discharged. Therefore, the current power batteries used in the field of electric vehicles mainly include the following categories:

Lead-acid battery has low energy density, large weight, and relatively short cycle life. This makes the application of lead-acid batteries in the field of electric vehicles relatively limited. However, these batteries still have certain applications in other fields, such as the starting battery of traditional internal combustion engine vehicles.

Nickel-cadmium batteries (Ni-Cd) are also used in electric vehicles but are gradually being replaced by lithium-ion batteries, this is owning to their heavier than lithium-ion batteries, smaller capacity and environmental pollution problems.

Nickel-metal hydride battery (Ni-MH) boasts an impressive longevity in terms of cycling and exhibits commendable resilience to elevated temperatures, but it also has certain self-discharge characteristics, which is caused by the diffusion of hydrogen in the battery. Improper storage conditions and prolonged parking may result in energy loss and may affect the performance of the battery. Its self-discharge rate is higher than that of lithium batteries but lower than that of lead-acid batteries.

Due to benefits including their high specific energy, high energy density, and low self-discharge rate in compared to other secondary batteries, Lithium (Li-ion) batteries are suited for EVs and hybrid electric vehicles (HEVs) [4]. Whereas, even if lithium batteries can maintain a high storage capacity when parked for a long time, there will still be a certain degree of self-discharge. However, there are also limitations to the widespread usage of lithium-ion batteries in automobiles because to their huge capacity and massive serial-parallel numbers, as well as concerns with cost, uniformity, safety, and durability [5].

Among them, lithium-ion batteries are currently the most mainstream and generally used power battery technology when it comes to electric automobiles, and through the continuous research and development and improvement of researchers, it has proven possible to create new lithium batteries with increased energy density, increased lifespan, and decreased cost. With the rise of the market for electric vehicles and the improvement of research and technology, more types of power battery technologies may appear in the future. Table 1 shows a comparison of the four types of battery quality.

Table 1. Comparison of different batteries

Types	Volumetric energy density (Wh/L)	Mass-energy density (Wh/kg)	Cycle index (cycles)	Self-discharge rate (months)	Environmental performance
Lead Acid	50-80	30-45	400-600	0	severe pollution
Ni-Cd	80-150	40-60	600-1000	25-30%	severe pollution
Ni-MH	100-300	60-80	800-1000	30-35%	eco-friendly
Li-ion	250-400	90-160	800-1200	6-9%	non-polluting

3. Key Technologies in Battery Management System

The battery management system is an electronic device that closely relates to batteries. It can perform tasks such as liquid leakage detection, heat management, battery balance management, alarm reminder, state of charge (SOC), discharge power calculation, and calculation of battery voltage, current, temperature, and other parameters. These calculations enable it to select the ideal current size for charging the battery. The controller area network (CAN) bus interface can be used to simultaneously connect it to the on-board controller, motor, energy control system, and on-board display system. Real-time communication can be achieved in this manner with the on-board controller, motor controller, energy control system, and on-board display system.

BMS is mainly composed of Battery Management Unit (BMU) master controller, Cell supervisor circuit (CSC) slave controller, circuit switching unit (CSU) equalization module, high-voltage unit (HVU) high-voltage controller, British thermal unit (BTU) battery status indication unit and global positioning system (GPS) communication module, from small to master-slave integrated architecture of power tools, electric bicycles, electric forklifts, intelligent robots, Internet of Things (IOT) smart homes, mild hybrid vehicles to master-slave separated electric vehicles (pure electric, plug-in hybrid), electric ships, etc., and then to the three-layer architecture energy storage system. Fig 2 below shows the architecture diagram of BMS electrical appliances.

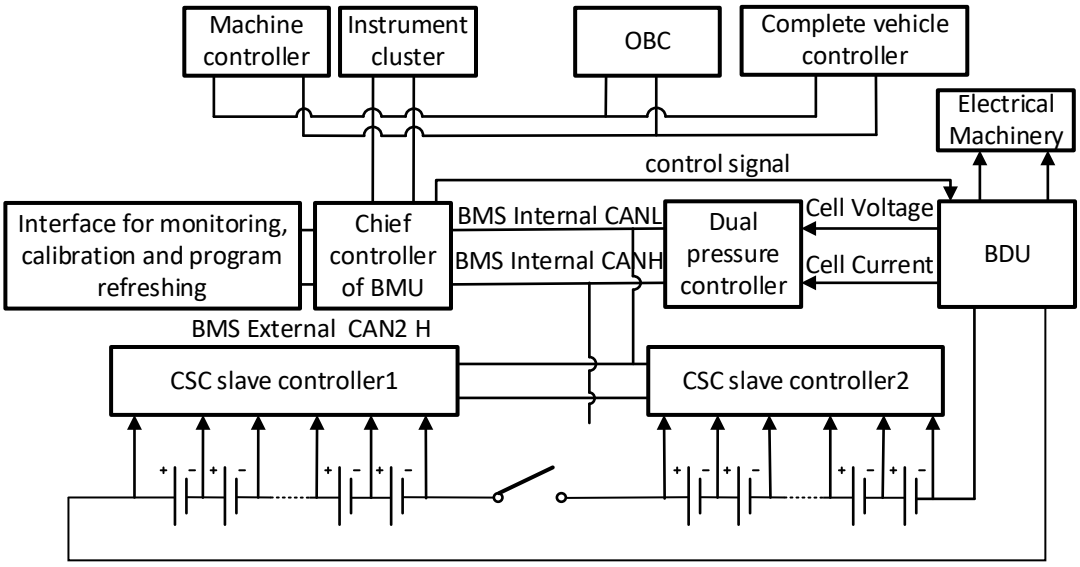


Fig 2 Electrical architecture of BMS [3].

3.1. Battery cell monitoring technology

Monitoring battery pack voltage, current, battery voltage, temperature, isolation, and interlocks are the main focus of BMS. The battery system may overvoltage due to a problem with the voltage regulator or battery charging mechanism. Overcharge can result in battery venting, while overvoltage and overcurrent might permanently harm the battery system. Since the emitted gases are flammable, this raises serious safety issues. Similarly, low voltage or current can seriously affect the performance of the battery. A crucial job for BMS is isolating central battery systems, especially for high-voltage systems. Current will flow through the body and result in death if a malfunctioning high-voltage battery system comes into contact with a human body. Another crucial job for BMS is temperature management. Heat and other anomalous issues that negatively impact the battery system can be produced by high temperatures [6]. If the temperature cannot be well controlled, then overheating of the battery may trigger a lot of chain reactions, so that the entire battery pack spontaneously ignites. To develop a strong working relationship with the BMS control module, this necessitates a fair configuration of the temperature sensor's position and frequency of use. The temperature of the inlet and outlet fluids is the main factor being monitored when determining the temperature of the battery pack's dissipation liquid, and the monitoring precision chosen is comparable to that of a single cell.

3.2. SOC estimation

The most crucial parameter in a BMS is SOC, which is used to quantify the remaining battery capacity as a percentage of total capacity under the same conditions [7]. Since SOC is the basis for everything else, accuracy and resilience, or error correction capabilities, are crucial. No amount of protection will make a BMS function correctly without an exact SOC because the battery will frequently be protected, let alone be able to last longer.

For a given battery capacity, an electric vehicle's driving range can be increased, and the battery pack's efficiency can be increased with greater SOC estimation accuracy.

The direct assessment approach and the model-based method are the two main ways that SOCs are evaluated. For the direct evaluation approach, SOC is primarily estimated using the Ampere-hours (Ah) or coulomb counting method and open circuit voltage (OCV) on the basis of direct measurement of battery current and voltage. SOC can be determined using Ah, which has the following formula:

$$SOC(k) = SOC(k_0) + \int_{k_0}^{k} \eta I(t)\,\mathrm{d}t \,/\, C_n \tag{1}$$

where SOC(k) is the known initial SOC and represents how well the battery is charged or discharged. I(t) stand for the current value, which is positive for charging and negative for discharging, and C stands for the battery's nominal capacity.

Ah is one of the most commonly used methods, but there are some problems when using Ah, such as cumulative errors. This method is high dependency on the current measurements, but the error will increase over time due to the lack of accuracy of the current sensors. In addition, it was previously mentioned that secondary batteries are subject to self-discharge, which can make it difficult to accurately determine the initial value of SOC in experiments.

As OCV is a linear function of SOC, it has become an effective and popular method to estimate SOC after allowing the battery to stand sufficiently [7]. Although it is convenient to operate and easy to implement, prolonged settling becomes a major limitation when evaluating SOCs.

However, it is mentioned in [6] that if the OCV can be gathered in real time, the SOC may be assessed while driving, which solves the difficulty. The model-based calculation method optimizes the online evaluation of the battery state of charge [7]. It should be highlighted that the model-based estimating approach is not just rely on real-time measured data, rather, it estimates or identifies the characteristic parameters using filtering or deft algorithms. It is, in essence, a development of the indirect approach [8].

3.3. Cell balancing technique

As the power battery of an electric vehicle consists of several batteries combined in series and parallel, but the factors such as current magnitude and temperature of each single battery cannot be exactly the same, because there are differences between them. So, it is necessary to equalize the battery pack by equalization technology, which is handled as follows [9].

In order to achieve the goal of balancing, passive balancing frequently uses resistance heat release to release the "extra power" of high-capacity batteries. The circuit is straightforward and dependable. The battery is less efficient despite being less expensive.

Efficiency can be increased by transferring more power to high-capacity cells during active balancing charging and to low-capacity cells during discharge, but this comes at a higher cost and with a more complicated circuit and lower dependability. Passive balancing may become less necessary if battery cell consistency improves in the future.

4. Architecture of Battery Management System

4.1. Hardware architecture

4.1.1 Centralized BMS

The centralized hardware architecture centralizes all electrical components on one board, including sampling chips for monomer voltage and monomer temperature. The majority of low-voltage HEVs have this type of configuration and use daisy-chain communication between the sample chip and the main chip. The advantage of this is that it is relatively simple and cost-effective; The disadvantage is that the wiring harness of single sampling is relatively long, resulting in the design of the sampling wire is more complicated, the long line and short line will cause additional voltage drop when equalizing, the wiring harness arrangement of the entire battery pack is also relatively troublesome, and the number of sampling channels is limited, which is suitable for smaller battery packs. Fig 3 below shows the schematic diagram of the centralized architecture.

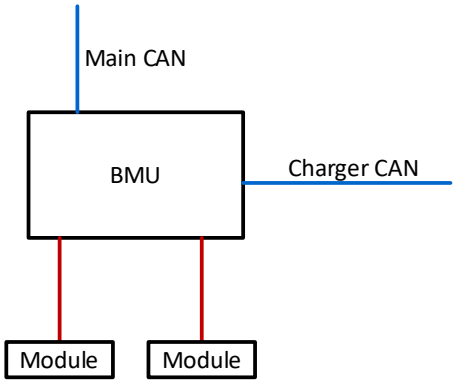


Fig 3 BMS with centralized architecture [3].

4.1.2 Distributed BMS

The distributed hardware architecture includes the motherboard and the slave board, where the motherboard is the BMU, and the slave board is the individual CSC sampling chips. Fig 4 illustrates the distributed schematic below. The advantage of this hardware architecture is that the process of module assembly can be simplified, the sampling harness is relatively easy to change, the wiring harness distance is uniform, and there is no problem of different voltage drop; the disadvantage is that the cost is high, additional motor controller units are required, and the independent CAN bus method is only to send the information of each module to BMS.

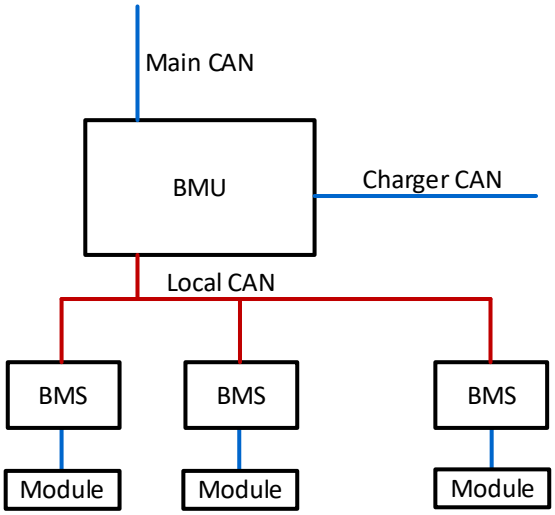


Fig 4 BMS with distributed architecture [3]

4.1.3 Comparison between different BMS architecture

Power tools, electric forklifts, electric low-speed vehicles (such as electric bicycles, electric motorcycles, electric sightseeing vehicles, etc.), and mild hybrid vehicles are examples of applications where centralized BMS is frequently used. These applications benefit from centralization's low cost, compact structure, high reliability, and low total cost. BMS hardware with centralized architecture can be divided into high-voltage areas and low-voltage areas. The high-voltage section is in charge of recording the voltage of a single battery, recording the system's overall voltage, and monitoring insulation resistance. The low-voltage area includes power supply circuits, CPU (Central Processing Unit) circuits, CAN communication circuits, control circuits, etc. BMS with distributed architecture is mostly used in plug-in hybrid and pure electric vehicles as a result of the ongoing development of passenger car power battery systems to high capacity, high total voltage, and big volume. However, centralized all battery modules are connected to a single BMS controller, which causes three types of problems. First, if that controller fails, the entire battery management system can fail, making the EVs unable to function properly. Secondly, BMS is also limited by the singularity of its connection when expanding. Increasing the number of battery modules may require

more complex wiring and larger controller capacity, increasing the cost and complexity of the system. Finally, since all battery modules need to communicate with a single BMS controller, this can lead to increased communication complexity and higher requirements for communication networks, including higher bandwidth and more reliable communication mediums.

The distributed BMS design may more effectively implement module- and system-level hierarchical management (Pack). Voltage detection, temperature detection, balance management (some will independently manufacture CSU units), and related diagnostic work are all carried out by the slave unit CSC for the monomers in the module; The HVU is in charge of keeping track of the battery pack's overall voltage, bus voltage, insulation resistance, and other conditions. Hall sensors or shunts can measure the bus current. Then, the main empty unit BMU receives the analyzed data and sends it to the CSC and HVU for further processing. This unit manages the internal and external communication networks as well as performing management tasks for the Battery State Estimate (BSE) evaluation, electrical system condition detection, contactor management, thermal management, operation management, charging management, and diagnostic management. The benefit of a distributed BMS architecture is that it can be effectively configured in accordance with the parallel and series designs of various battery systems, and that the wiring distance between the BMS and batteries is shorter, more uniform, and more dependable. It can also support larger battery system designs. The fact that distributed BMS better complies with the power battery system module design trend as a result of the widespread use of power battery systems in the automotive sector and the rise in output scale has also contributed to the widespread adoption of distributed BMS as a common application solution. Without a common module to serve as the foundation for industrialization, outdated electric models will be forced to replace their power batteries after several years of service due to a lack of spare parts, while power batteries retired from the automotive industry will be unable to be used to their full potential. To meet the demands of high space utilization, high reliability, and great adaptability, the standardized module must tightly integrate some battery management system operations (monomer status acquisition and management) with the battery. Consequently, the slave control unit CSC has over time evolved into one of the essential fundamental elements of the basic Module. However, Complex distributed architectures require the integration of independent BMS on each battery module, and each BMS needs to contain monitoring, control, and communication functions, which may require more sensor and circuit design. At the same time, in a distributed architecture, communication between each battery module needs to ensure coordination and synchronization. This may require more communication media and protocols to ensure reliable communication connections and ensure data consistency between different modules. All of these issues lead to increased hardware and communication complexity, which can make it more challenging to identify the battery module that is specifically in question. Troubleshooting and repair processes can be more complex and time-consuming (Table 2).

Table 2. Comparison between different BMS architecture

	Advantages	Disadvantages	Applications
Centeralized	Low cost, Compact High reliability	Failure can damage system Limited expansion Complex communication	Low-capacity Low total pressure Small-size scenarios
Distributed	High efficiency High reliability Highly adaptable	Complex design Harsh environmental conditions Inconvenient to maintain	Larger system designs

4.2. Software architecture

4.2.1 Charging management

The proper charging rate is essential for batteries since charging batteries too quickly can result in significant energy losses and temperature increases while charging batteries too slowly can significantly impact an electric vehicle's usage [10].

The battery can be slowly charged using an AC charging pile or a 220V power source via the automobile charger. Charging pile specs typically range from 16 to 64 amps, although they can also be charged using a household power supply. BMS can be activated using CC (connection confirm function) or CP (control pilot function) signals, but it must be made sure that it can fall asleep naturally following charging.

Fast charging is output direct current (DC) to charge the battery by the DC charging pile, which can achieve 1C or even higher rate charging, generally 45min can charge 80% of the charge. According to the Chinese national standard, the fast-charging process is more complicated and involves two versions in 2011 and 2015. The charging pile manufacturer's understanding of the technical details of the national standard process is unclear, which also presents a significant challenge to the vehicle charging adaptability. As a result, fast charging adaptability is a key indicator to measure.

4.2.2 Capabilities of estimation

The primary purpose of State of Power (SOP) is to determine the battery's current available charging and discharging power using the temperature and SOC lookup tables. The vehicle control unit (VCU) then makes decisions about how to operate the entire vehicle at the moment based on the provided power value. A combination of releasing battery capacity and protecting battery performance, such as partial power limiting before the cut-off voltage is reached, needs to be taken into account, which of course has an impact on the driving experience of the whole vehicle.

The state of health (SOH) ranges from 0 to 100% and is typically regarded as being below 80% once the battery can no longer be utilized. When employing capacity, the actual capacity of the present battery is evaluated using data from the battery operating process, and the ratio of the rated capacity is SOH. It may also be stated as a change in battery capacity or internal resistance. When the battery is degrading, accurate SOH will increase the accuracy of the estimation of the other modules.

State Of Charge, which is a component of the BMS'score control algorithm, describes the state of the battery's remaining capacity by primarily utilizing the Ah integration method and the Extended Kalman Filter (EKF) algorithm in combination with a variety of correction strategies (such as open-circuit voltage correction, full correction, correction at the end of charging, correction of the capacity under various environmental conditions, etc.).

The State of Energy (SOE) method has not been widely used in the market as of yet, and it often uses a simpler algorithm to look up a table and determine the ratio of the remaining energy to the maximum amount of energy that is now accessible. This function is mostly used to estimate the remaining range.

4.2.3 Fault detection and diagnosis

Different fault levels are distinguished for different battery performance conditions, and BMS and VCU will take different measures to deal with different fault levels, such as warning, power limitation, or severing the high voltage immediately. Data acquisition and logic errors, electrical errors (sensors and actuators), communication errors, and battery status errors are all examples of defects.

5. Future Outlook for BMS

At present, the development prospects of wireless BMS and cloud BMS are very clear, wireless BMS compared with traditional wired connection, reduce the use of cables and connectors, simplify the structure of the battery pack, can improve the overall efficiency and reliability. In addition, because the wireless BMS can achieve low power consumption and high scalability, the battery pack is more flexible and adjustable, adapting to the needs of different sizes and configurations. Cloud BMS is a big data platform that combines BMS monitoring and management functions to achieve the accumulation and analysis of battery life cycle data.

There are also many similarities between wireless BMS and cloud BMS. This is because they both involve the transfer and interaction of data to enable more advanced functions and services. It can be

said that wireless communication is the basis for realizing cloud BMS. Wireless BMS provides data collection, transmission and control, sending battery module information to the cloud, where it is processed, stored and analyzed. If the wireless BMS can transmit the battery data of the electric vehicle to the cloud system in real time, the cloud provides high-precision algorithms and advanced warning functions for the electric vehicle and identifies and evaluates the abnormal and fault signs of the battery by analyzing a large amount of real-time data and alerts the owner or driver and occupants in time, thereby reducing the risk of accidents and improving travel safety. Cloud-based BMS provides more timely and comprehensive information through remote monitoring and diagnostics, which can help car owners and manufacturers make more informed decisions.

In general, the future development direction of BMS is likely to focus on the combination of wireless BMS and cloud BMS technologies to build a smarter and more reliable electric vehicle BMS system.

6. Summary

The battery management system and electric car power battery's core technologies are examined in this study. Through the presentation of various types and features of power batteries, this study underlines the critical importance of a suitable BMS in ensuring the safe and reliable functioning of the battery. It also demonstrates BMS's capability to disconnect from the system in abnormal circumstances. Additionally, the fundamental function of BMS is introduced, along with an explanation of its capabilities, in monitoring, managing, and improving the energy storage system. The Ah method, OCV method, and model-based method are the three battery state estimate techniques that this study focuses on in terms of the fundamental operations of a battery management system. In addition, the advantages and disadvantages of alternative BMS architectures are also evaluated and analyzed. The hardware architecture and software architecture of BMS are also described in detail. This study concludes by anticipating the key future development direction of BMS and looking ahead to its future development. To sum up, this paper systematically introduces the key technologies of electric vehicle power battery and BMS based on the power battery and BMS of electric vehicle. It is an important reference for readers to understand the importance of battery management systems in electric vehicles and the different technology and architecture options. The prediction of the development direction of BMS in this paper will also provide readers with new perspectives and new thinking and let us look forward to greater development and innovation of BMS technology in the future.

References

[1] Y. Zhu, H. Wen, Q. Bu, X. Wang, Y. Hu and G. Chen. An Improved Photovoltaic Power Reserve Control with Rapid Real-Time Available Power Estimation and Drift Avoidance. IEEE Transactions on Industrial Electronics, 2023, 70(11): 11287-11298.

[2] S. Abada, G. Marlair, A. Lecocq, M. Petit, V. Sauvant-Moynot, F. Huet. Safety focused modeling of lithium-ion batteries: A review. Journal of Power Sources. 2016, 306: 178-192.

[3] H. Rahimi-Eichi, U. Ojha, F. Baronti and M. -Y. Chow. Battery Management System: An Overview of Its Application in the Smart Grid and Electric Vehicles. IEEE Industrial Electronics Magazine, 2013, 7(2): 4-16.

[4] J. Jaguemont, L. Boulon, Y. Dubé. A comprehensive review of lithium-ion batteries used in hybrid and electric vehicles at cold temperatures. Applied Energy, 2016, 164: 99-114.

[5] Languang Lu, Xuebing Han, Jianqiu Li, Jianfeng Hua, Minggao Ouyang. A review on the key issues for lithium-ion battery management in electric vehicles. Journal of Power Sources, 2013, 226: 272-288.

[6] Gabbar HA, Othman AM, Abdussami MR. Review of Battery Management Systems (BMS) Development and Industrial Standards. Technologies. 2021, 9(2):28.

[7] Liu, K., Li, K., Peng, Q. et al. A brief review on key technologies in the battery management system of electric vehicles. Front. Mech. Eng. 2019, 14: 47–64.

[8] Rui Xiong, Linlin Li, Jinpeng Tian. Towards a smarter battery management system: A critical review on battery SOH monitoring methods, Journal of Power Sources, 2018, 405: 18-29.

[9] GAO Zhennan, YANG Wei, LI Anqing. Research on BMS battery equalization method for electric vehicles. Southern Agricultural Machinery, 2020, 51(21): 20-21

[10] Zhonghao Rao, Shuangfeng Wang. A review of power battery thermal energy management. Renewable and Sustainable Energy Reviews, 2011, 15(9): 4554-4571.