Exploration of Key Technologies in Electric Vehicle Battery Management Systems

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Abstract:

Battery Management System (BMS) serves as a vital bridge connecting the battery pack, overall vehicle system, and the electric motor in electric vehicles (EV). BMS conducts real-time monitoring of parameters such as voltage, current, and temperature, by integrating with the sensors within the power battery, enabling comprehensive management of the EV's electric system. The primary role of BMS is to prevent overcharging and over-discharging of the batteries during application, to balancing the individual cells within the battery pack, to enhance overall efficiency, and to extend the battery pack's lifespan. BMS continuously monitors the operational parameters of individual cells and the entire battery pack, such as voltage, current, and temperature, while engaging in real-time communication via a bus interface with the vehicle's monitoring system and on-board chargers. This communication is critical for maintaining the overall safety performance of the battery pack. In summary, as the core of the battery system, BMS plays a significant role in electric vehicles, and exploring the key technologies of BMS is of utmost importance. This paper delves into two main sections: an overview of BMS categories and functions, and an analysis of critical BMS technologies.

Keywords:

Electric vehicle; BMS; Shunt-Based Current Sensor.

1. Overview of BMS Categories and Functions

1.1 Basic Categories of BMS

BMS can be categorized based on the topology of connection structures into centralized, modular, master-slave, and distributed.

① Centralized BMS: All individual cells are located within a single encapsulation module, with a bundle of wires extending from the module (N+1 wires for N individual cells), and each wire is separately connected to each cell. Centralized BMS offers advantages such as a compact structure, cost-effectiveness, and ease of maintenance.

② Modular BMS: BMS is divided into multiple identical sub-modules, and encapsulated wires connect to each different modules inside the battery. Modular BMS inherits the advantages of centralized BMS and has the advantages of simple connectivity between BMS sub-modules and cells, proximity of sub-modules to the cells, and ease of expanding BMS sub-modules.

③ Master-Slave BMS: Consisting of a master module and multiple identical slave modules, the master module is responsible for computation and communication, while the slave modules measure the voltage of cells. Master-slave topology has a lower manufacturing cost and combines most of the advantages of modular topology.

④ Distributed BMS means electronic components are directly installed on the circuit board along with the detected cells. Distributed BMS also offers the advantage of simple connections. The structures of centralized, modular, master-slave, and distributed BMS are illustrated in Figure 1.

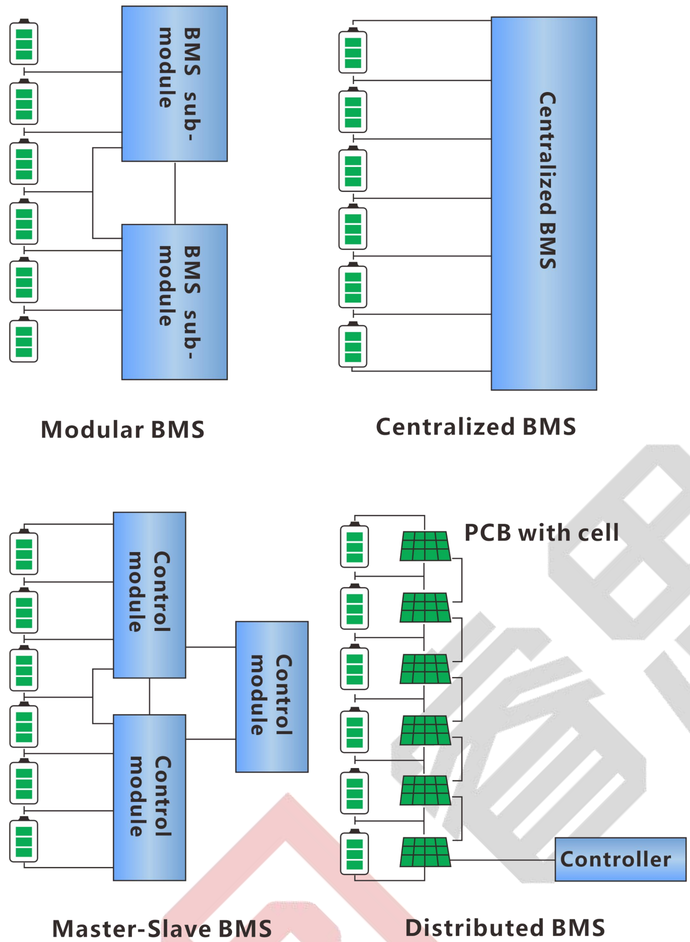

Figure 1: Different Structures of BMS

BMS can also be categorized into BMS analog system (simple system) and BMS digital system (complex system), based on the type of processing system.

① The BMS analog system refers to the use of analog circuits (such as analog comparators, amplifiers, differential circuits) to process the voltage of cells. This type of system is simple in design and easy to implement. However, it cannot measure the capacity of cells. It can only detect which cell is low-voltage but cannot measure the exact value of that cell's voltage.

② The BMS digital system can accurately monitor the voltage, temperature, and other factors of each cell and process the aforementioned states of cell into digital signals. The basic structure diagrams of the analog system and the digital system are respectively shown in Figure 2 and Figure 3.

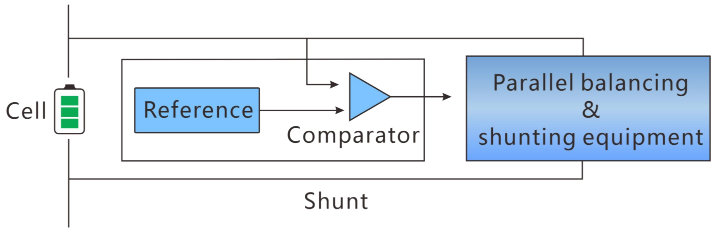

Figure 2: Structure Diagram of Analog System

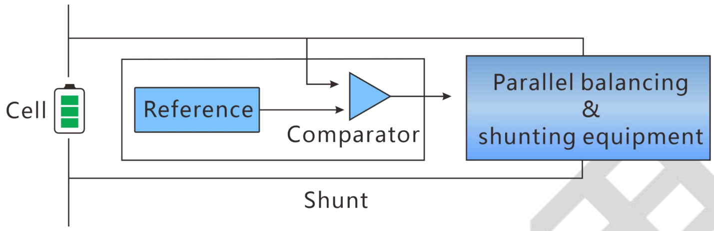

Figure 3: Structure Diagram of Digital System

1.2 Basic Functional Modules of BMS

1.2.1 Constant Current and Voltage Charging Module

The constant current and voltage charging module is a device used for standardized battery charging. Constant voltage and constant current represent two operating modes: constant current mode (CC mode) and constant voltage mode (CV mode). In CC mode, the charging device outputs a fixed charging current to the battery pack, and the charging voltage gradually increases during the entire charging process. CV mode refers to when the battery pack is nearly fully charged and the battery voltage becomes stable, the charger maintains a constant charging voltage. During the subsequent charging process, the charging current exponentially decays until the battery is fully charged.

1.2.2 Shunting Module

The function of the " Shunting Module" is to balance the battery pack. The module is connected in parallel with individual cells. When cells are fully charged, the module diverts partial or all of the charging current to prevent the batteries from overcharged state.

1.2.3 Monitoring Module

The function of the "Monitoring Module" is to monitor parameters of cells, and it does not have the ability to actively control charging or discharging. Its functions typically include:

① Measuring the voltage of each individual cell.

② Measuring the current and temperature of the battery pack.

③ Compiling data.

④ Calculating or assessing the state of the battery pack, such as State of Charge (SOC).

⑤ Displaying results.

⑥ Providing warning functions.

1.2.4 Control Module

The Control Module implements closed-loop control upon receiving the voltage of each individual cell. The control module cannot cut off the battery pack's current but can send instructions to other devices such as chargers or loads to reduce or disconnect the battery pack's current as needed.

1.2.5 Balancing Module

The Balancing Module function is to maximize the performance of the battery pack by managing the imbalance among individual cells within the battery pack. It has communication capabilities and can transmit data to other parts of the system. The wiring configuration of the balancing module allows it to control the charging power supply and discharge load.

1.2.6 Protection Module

The Protection Module function is similar to the balancing module, but it includes an additional switch to disconnect the current. It is more suitable for managing smaller batteries.

2. Analysis of BMS Key Technologies

2.1 Measurement Technologies

2.1.1 Voltage Measurement Technology

The primary function of BMS is data collection and signal measurement, including individual cell voltage, individual cell temperature, battery module temperature, and battery pack current. Voltage signals are acquired by analog multiplexers, read by an analog-to-digital converter and transmitted to the processor.

There are generally three voltage measurement structures: discrete voltage measurement, single-level multiplexing voltage measurement, and differential multiplexing voltage measurement. Specifically, in the discrete voltage measurement structure, a distributed BMS can directly measure the voltage of individual cells, and the battery pack is usually powered by the individual cells themselves during voltage measuring. In the single-level multiplexing voltage measurement structure, the BMS can measure the battery tap voltage and calculate the voltage difference between two taps as the individual cell voltage. In the differential multiplexing voltage measurement structure, the BMS can simultaneously use both methods to measure the voltage at both ends of the individual cell and calculate the voltage difference as the individual cell voltage. The three voltage measurement structures are illustrated in Figure 4.

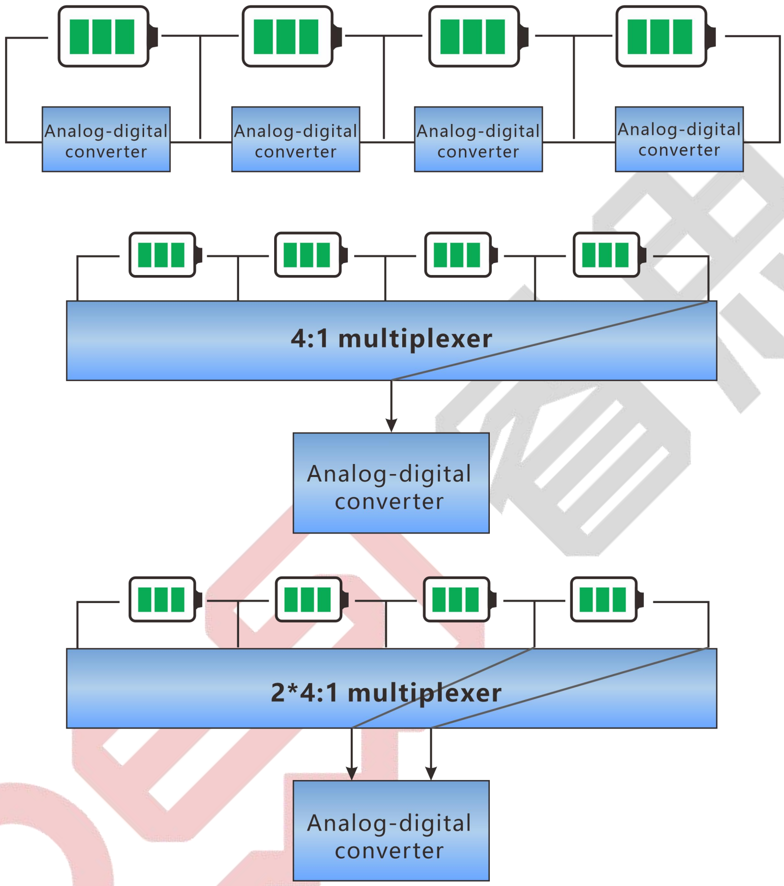

Figure 4: Structure Diagrams of Three Kinds of Voltage Measurement Structures

2.1.2 Temperature Measurement Technology

Temperature measurement technology is significant for ensuring the stable operation of batteries. Most individual cells have their discharge capacity limited during a specific ambient temperature range. Therefore, in some temperature-uncontrollable and motional application scenarios, it is necessary to monitor the temperature of individual cells to ensure regular operation. Batteries can also heat up due to internal issues like individual cell damage or external problems such as poor power contacts, necessitating temperature measurement devices to send warning signals to the system. In distributed BMS, each sub-module is equipped with sensors, which are convenient not only to measure cell temperatures but also to monitor the functionality of balancing modules.

Different types of BMS have different applications and requirements for temperature measurement technology. Digital BMS may not have an absolute requirement for temperature monitoring, whereas distributed BMS can measure the temperature of each individual cell. Non-distributed BMS can only measure the temperature of batteries or battery modules. Regarding the placement of temperature sensors, if BMS sensor probes are limited , they should be distributed at the locations where temperature changes are most significant.

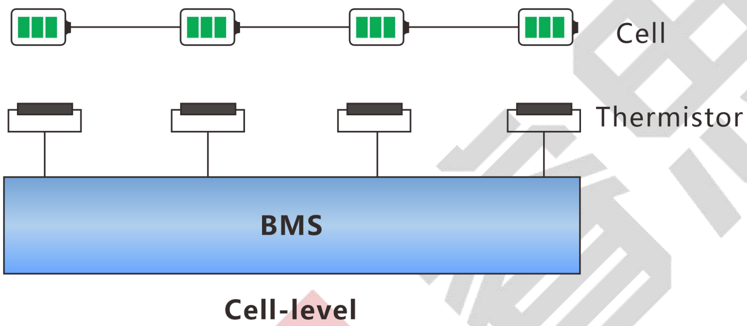

Figure 5: Structure Diagram of Cell-Level Structure

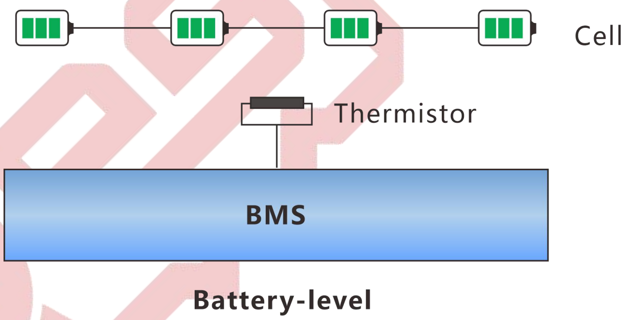

Figure 6: Structure Diagram of Cell-Level Structure

2.1.3 Current Measurement Technology

Current measurement technology enables the BMS to have additional functionalities： It helps prevent individual cells from exceeding the safe level due to continuous discharge, calculates the internal direct current resistance of individual cells, and measures the voltage at individual cell terminals, etc. Presently, there are mainly two types of devices used for current measurement: shunt-based current sensor and current sensor based on the Hall effect. The structure diagrams of shunt-based current sensor and Hall effect current sensor are respectively illustrated in Figure 7.

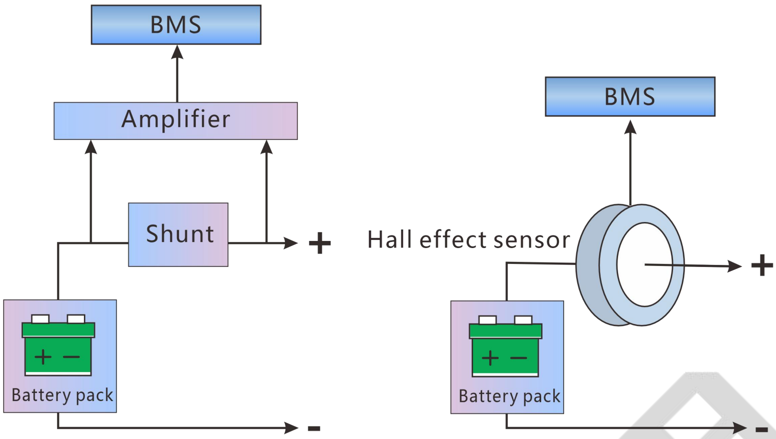

Figure 7: Structure Diagrams of Shunt-Based Current Sensor and Hall Effect Current Sensor

The shunt-based current sensor is a high-precision and high-power resistor. The current from the battery pack passes through the shunt resistor, generating a voltage drop; The high-current Hall effect sensor is a ring-shaped module, and the cable carries current passing through the ring-shaped module. The low-current Hall effect sensor is an integrated circuit with two power terminals, and the current flows through the integrated circuit. Comparison of characteristics between shunt-based current sensor and Hall effect sensor as in Table 1:

Comparison between Shunt-Based Current Sensor and Hall Effect Current Sensor				
Feature	Shunt-Based Current Sensor	Hall Effect Current Sensor		
		Open Loop	Close Loop	Fluxgate
Accuracy	High, 0.1%~0.05%	Low, 1%~5%	High, 1%~0.1%	
Response Speed	Fast	Fast	Medium	
Measurement Range	<1000A	<1000A, but saturation should be considered, as magnetic materials may be permanent magnetized		
EMI	None	None	High	
Overcurrent Capability	Strong	Weak, should include magnetic saturation		
Power Consumption	High	None		
Temperature Drift	Medium	None		
Cost	Low	Low	High	
Zero Drift	None	Yes		
Advantages	High accuracy, strong anti-interference, low cost	Low cost	High accuracy, low TCR	

Table 1: Comparison between Shunt-Based Current Sensor and Hall Effect Sensor

Figure 8: Shunt-Based Current Sensor

2.2 Management Technologies

BMS can be divided into three management technologies: protection, balancing, and thermal management. Protection ensures that the battery always operates within the Safe Operating Area (SOA). Balancing maximizes the capacity of battery pack, while thermal management controls the environmental temperature to keep the battery operating in the safe area. State of Charge (SOC) is used to reflect the remaining capacity of the battery. It represents the ratio of the remaining charge of the battery to its rated capacity under certain discharge rate conditions. The mathematical expression is as follows:

$$SOC = Qt / Q \times 100\%$$

In the expression: Qt represents the remaining charge, and Q represents the rated capacity.

2.2.1 Protection Management

① Request for Disconnection:

When SOC is at or near the limited conditions, BMS will reduce or stop the use of the battery pack by controlling the external system through the monitoring module and and balancing module. To implementation of the above function, firstly detect the linear change values, then send the switch signals. These signals include: Discharge Current Limit (DCL), Charge Current Limit (CCL), Low Voltage Limit (LLIM or LVL), and High Voltage Limit (HLIM or HVL). The structure diagram of request for disconnection is shown in Figure 9.

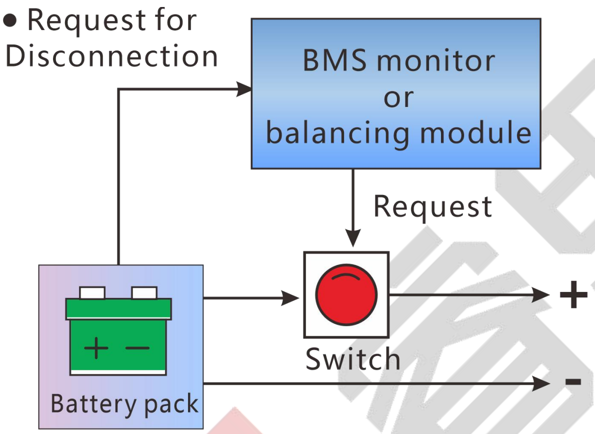

Figure 9: Structure Diagram of Request for Disconnection

② Direct Disconnection:

The protection module will cut off the battery current to prevent the battery pack from operating outside the safe operating area. The protection module does not rely on other systems. It directly controls the current flowing through it by switches. Regardless of the protection technology used in the BMS, it must ensure that it operates properly at maximum current and voltage. The structure diagram of direct disconnection is shown in Figure 10.

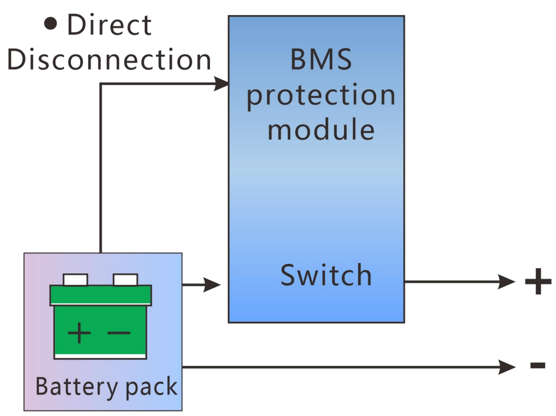

Figure 10: Structure Diagram of Direct Disconnection

2.2.2 Balancing Management

Due to factors such as production issues or usage wear, the charges of individual cells can be various within a battery pack. If the differences are not addressed, it can gradually increase with use. The overall capacity of the entire battery pack is determined by the cell with the lowest charge, like the "barrel principle". Therefore, to maintain good consistency among each cell, it's necessary to balance the cells, aiming the uniform charge levels of all cells.

Balancing technology ensures that individual cells are in the balanced state in terms of charging and discharging. There are commonly two types of balancing techniques: active balancing and passive balancing. Passive balancing is to discharge to resistors, which is simple and reliable, effectively addressing cell inconsistency but leading to energy waste.

Active balancing achieves balance through methods like peak shaving and energy transfer. There are four main active balancing techniques: capacitor balancing, inductor balancing, transformer balancing, and DC-DC balancing. Active balancing offers advantages such as high energy efficiency and fast balancing but comes with challenges including complex circuits, higher costs, and higher failure rate, leading to significant technical barriers. Active and passive balancing are depicted in Figure 11.

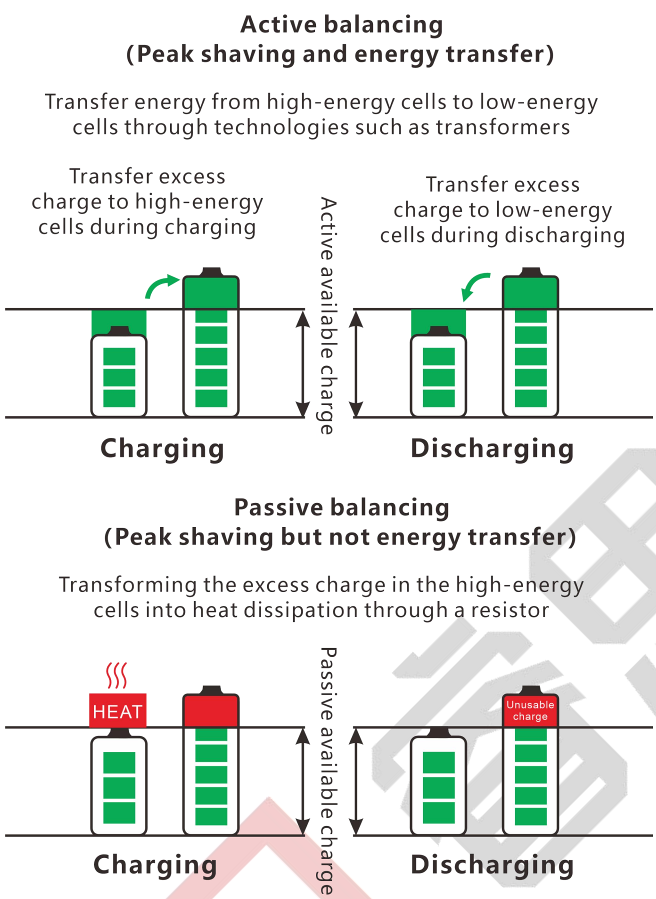

Figure 11: Active and Passive Balancing

The advantages and disadvantages of active and passive balancing are shown in Table 2:

Technology	Passive balancing	Active balancing
Cost	Low	High
Solution	Simple	Complex
Reliability	High	Low
Balancing component	Resistor	Capacitor, inductor, transformer, DC-DC
Balancing method	Power dissipation	Energy transfer
Efficiency	Low	High
Balancing current	100 ~ 500mA	1 ~ 10A
Applied battery	Lithium iron phosphate battery	Ternary polymer lithium battery
Price	Passenger vehicle: around 5000 CNY	20000-30000 CNY
Risk	Passive balancing generates thermal energy. If the balancing current is too large, there will be difficulties of heat dissipation and poses safety hazards; If the balancing charge is low, it faces the problem of low efficiency, and the balancing time is too long.	Active balancing achieves energy transfer, resulting in high electricity utilization rate, high efficiency, and fast balancing. However, the structure of active balancing circuits is complex, resulting in high costs, high failure rates, and high technical barriers.
Example	Laef, Zotye, Zhidou, Model S, most EV buses	Chevrolet Volt, SAIC Motor, BYD

Table 2: Advantages and Disadvantages of Active and Passive Balancing (Andrea, 2018)

2.2.3 Thermal Management

Due to the inherent properties of battery materials, especially lithium-ion batteries, both excessively high and low temperatures can adversely affect regular operation. High temperatures can affect the reliability of the battery's network architecture and reduce its load life. Conversely, working at excessively low temperatures can reduce the material's activity, available capacity, and battery efficiency. Specifically, thermal management primarily employ three methods: preheating, heat dissipation, and temperature balancing.

Preheating refers to the process of heating the battery when its temperature is detected to be below a specified value. It is to prevent the battery from operating at low temperatures where its regular performance may be compromised, and to avoid safety incidents. Specifically, charging a battery at a low temperature can lead to internal short circuits because the battery's capacity diminishes at low temperatures, which can result in a risk of momentary over-voltage. Conversely, the discharge capability of the battery is limited at low temperatures. Therefore, it is necessary to raise and maintain the temperature of the battery when operating in cold conditions.

Heat dissipation refers to the effective cooling of the battery when its temperature is relatively high to prevent the occurrence of thermal runaway incidents. Production issues and usage wear can lead to partial overheating of the battery, triggering a series of exothermic reactions, even various thermal runaway events in severe cases. Depending on the source of cooling, heat dissipation can be classified into passive and active cooling. Based on the heat transfer medium, it can also be categorized into three cooling forms: air cooling, liquid cooling, and cooling by PCM (Phase Change Materials). Structure diagrams of an air cooling system and a liquid cooling system are illustrated in Figure 12 and 13.

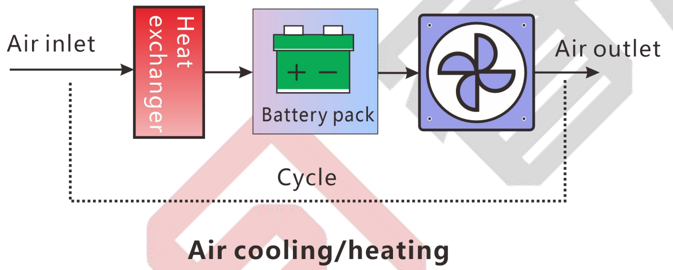

Figure 12: Structure Diagram of Air Cooling System

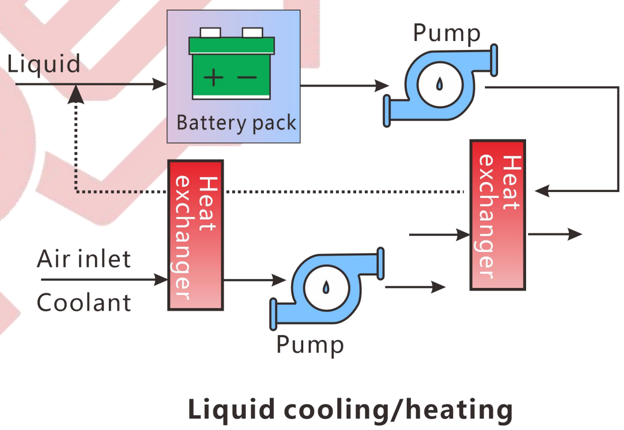

Figure 13: Structure Diagram of Liquid Cooling System

Temperature balancing refers to reducing temperature differences within the battery pack, suppressing the formation of regional hotspots, preventing rapid degradation of cells in high-temperature areas, and improving the overall lifespan of the battery pack. The ideal operating temperature for batteries typically is between 20 to 30°C. Temperatures that are too high or too low can lead to a fast degradation of battery lifespan.

2.3 Evaluation Technologies

The evaluation function of the BMS includes state of charge (SOC) and depth of discharge (DOD). Based on the values of SOC and DOD, it's possible to estimate the remaining usage time of the battery and remaining driving distance. However, with present technological means, directly measuring the SOC of a battery pack remains challenging. There are currently only two estimation methods: voltage conversion and current integration. Voltage conversion relies on the inherent characteristics of battery materials. During discharging, there is a certain linear relationship between battery voltage and capacity. Therefore, at specific stages of battery capacity, voltage can be converted into battery capacity. However,the correspondence between voltage and battery capacity is not entirely linear. The accuracy of this estimation method is not very high. As a result, voltage conversion is rarely used as an only method in practical applications.

Current integration, also known as Coulomb counting, refers to the process of integrating battery current to obtain a relative value of its charge. Coulomb counting is a highly precise method for converting battery capacity. However, there are two limitations:

① The leakage current from individual cells that doesn't pass through the current sensor is not included in the calculation.

② Drift in the measurement of battery current can result in SOC changes over time.

Coulomb counting is particularly suitable for lithium-ion batteries because of its low leakage of current. In the case of lead-acid batteries, the battery voltage decreases linearly during discharging. Therefore, using a voltmeter as an indicator of SOC is a viable option. In practice, a technical combination of Coulomb counting and voltage conversion is often employed, to provide a reasonable solution for estimating the DOD of the battery. A schematic diagram of estimating DOD by combining current integration and voltage conversion is illustrated in Figure 14.

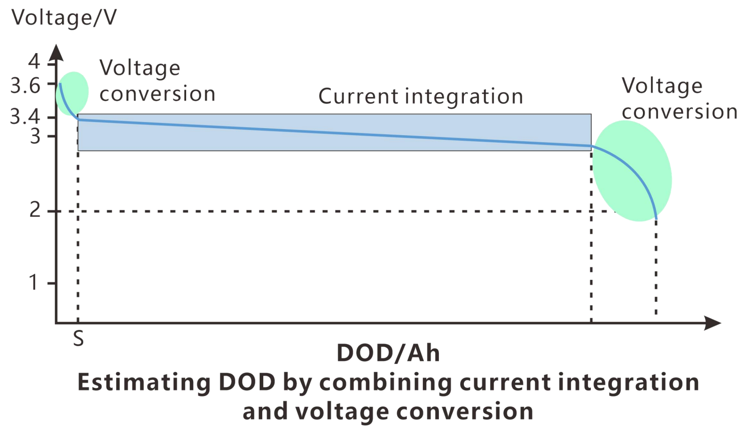

Figure 14: Schematic Diagram of Estimating DOD by Combining Current Integration and Voltage Conversion

Summary of Functional Technologies is shown in Figure 15.

Technologies		Descriptions
Measurement technologies	Battery measurement	Measurement & analysis of battery voltage Measurement & analysis of battery current Measurement & analysis of battery temperature
	SOC/SOH measurement	SOC evaluation SOH evaluation High precision capacity integration
Management technologies	High voltage safety management	High voltage interlock loop High voltage isolation monitoring High voltage disconnection evaluation
	Battery safety management	Overcharge/over-discharge protection Overcurrent/overtemperature/low-temperature protection Multi-evaluation of failure protection Dual failure detection
Balancing technologies	Balancing management	Balancing based on voltage mode Balancing based on time mode Balancing based on SOC of cell Active/passive balancing
Other technologies	Other functions	Low cost & power consumption Historical data recording Cascade flexible expansion CRC number verification

Figure 15: Summary of Functional Technologies

Enterprise Profile:

C&B Electronics is a manufacturer of Shunt-Based Current Sensor. C&B Electronics internally manages the entire process from raw materials to current sensor production. C&B Electronics utilizes highly automated full-industry-chain production to supply diverse products in bulk to customers. Testing and measurement solutions are also available for customers, including automated testing and measurement equipment, to meet the demand for efficient measurement and calibration.

CB series current sensors are developed by Advanced Measurement Center (AMC) of C&B Electronics. AMC is a team of sophisticated experts with experiences in materials, hardware, algorithms, automation, reliability, etc. The goal in current phrase for RESI is to meet the most demanding requirements for precision current measurement through proprietary core technologies, by developing the current sensors ranging from tens of amperes to thousands of amperes, covering most precision current measurement applications, including electric vehicles, energy storage, green power generation, measurement, testing, and industrial applications.

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