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A Review on Safety Management Strategies: Theory and Practical Application of Lithium-Ion Power Batteries

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Abstract Battery safety in electric vehicles is a comprehensive engineering endeavor that requires meticulous consideration at every stage, including battery materials, battery pack design, and battery management systems (BMS). This review focuses on safety management strategies and practical applications of lithium-ion power batteries. The management of battery safety primarily encompasses charge and discharge safety, high-voltage safety, and thermal safety. Among these, charge and discharge safety management aims to prevent battery damage or safety incidents caused by overcharge or over discharge. High-voltage safety management involves detecting insulation faults, overcurrent, and other potential risks to prevent electrical hazards. Thermal safety management ensures individual battery cells, modules, and the battery pack maintain an optimal operating temperature range and uniform temperature distribution, thereby preventing thermal runaway.

Keywords Electric vehicle · Battery safety management · Lithium-ion battery · Safety regulations

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1 Power Battery Safety Regulations

1.1 International Regulations

In the field of power battery international standardizations, Organizations as ISO and IEC have launched standards for lithium-ion batteries, lead-acid batteries, alkaline batteries, and fuel cells in succession. America, Japan and South Korea have combined their own technological development paths and national conditions, established their own power battery standard system based on the requirements of ISO and IEC standards. The Table 1 below presents the safety testing standards for international lithium-ion power batteries.

1.2 Domestic Regulations

The in-progress standard in China is GB 38,031–2020- Electric vehicles traction battery safety requirements. Chinese power battery safety standards, starting from the automotive industry standard QC/T 743–2006-Lithium-ion batteries for electric vehicles [4], to the recommended standards GB/T 31,485–2015-Safety requirements and test methods for traction battery of electric vehicle [5] and GB/T 31,467–2015 [6], and finally to the national mandatory standard GB 38,031–2020 [7].

GB 38,031–2020 benchmarked international standards IEC 62,660–2 Part 2- Reliability and abuse testing, IEC 62,660–3 Secondary lithium-ion cells for the propulsion of electric road vehicles Part 3- Safety requirements, and has been upgraded to a mandatory standard based on industry needs. Table 2 presents the main power battery safety standards of GB 38,031–2020.

2 The Inequality of Lithium-Ion Batteries

The inequality of batteries can be attributed to two factors. Firstly, during the manufacturing process, variations in material composition and process issues lead to differences in the activation level, thickness, porosity, tab connections, and separators of battery electrode materials. Additionally, the solid electrolyte interface film near the electrodes during battery formation is random and can contribute to battery inequality. Secondly, during installation and use, factors such as temperature, ventilation conditions, self-discharge level, and electrolyte density in the battery pack can affect the voltage, internal resistance, and capacity, thereby increasing the inequality of these parameters among individual batteries.

At present, common positive electrode active materials for lithium-ion batteries include $LiCoO_2$, $LiNiO_2$, $LiMn_2O_4$, $LiFePO_4$, et al. The safety of positive electrode materials mainly includes thermal stability and overcharging safety. During

Table 1 International safety testing requirements for lithium-ion power batteries

Standard	Test items	Safety requirements
UL 1642	Squeeze, drop, vibration, acceleration, impact, falling hammer impact	No fire, no explosion, no leakage
	Short circuit, overcharge, over discharge	No fire, no explosion, the battery shell temperature below 150 °C during short-circuit test
UN38.3 [1]	Vibration, acceleration impact, falling hammer impact	No fire, no explosion
	Short circuit, overcharge, over discharge	No fire, no explosion, the temperature of battery shell below 150 °C during short circuit testing; Overcharge and discharge require no disassembly or combustion within 7 days
IEC 62,660–3-2022 [2]	Mechanical impact, squeezing	No fire, no explosion
	External short circuit, internal short circuit, overcharge, over discharge, high temperature test	No fire, no explosion
	High temperature and low temperature charge protection	The surface temperature of the battery is higher or lower than the operating temperature range of the battery, and it is not allowed to charge the battery under any charge current
ISO 12405–3-2014 [3]	Random vibration, mechanical impact, simulated collision, squeezing	No leakage, no rupture, no fire, no explosion
	Temperature shock, short circuit, overcharge and over discharge protection, thermal runaway	The battery system should maintain 100 Ω/V insulation without AC,. and maintain 500 Ω/V insulation with AC

overcharge process of lithium-ion batteries, the reaction equation is as follows.

$$Li_{0.5}COO_2 \rightarrow 1/6CO_3O_4 + 1/6O_2 + 1/2Li_{0.5}COO_2 \tag{1}$$

The consistency of capacity in practical applications is that the remaining amount of electricity in the battery during discharge is not equal, and the remaining amount of electricity in the battery can be expressed as follows:

$$C = C_0 - \int I_b(t)d(t) \tag{2}$$

Table 2 Power battery safety standards of GB 38,031–2020

Test Object	Test items	Safety requirements
Single cell battery	Overcharge	No fire, no explosion
	Extrusion	No fire, no explosion
Battery pack or system	Vibration, mechanical impact, simulated collision, squeezing	No leakage, shell rupture, fire or explosion, and no abnormal termination conditions are triggered. The insulation resistance after the test should not be less than 100 Ω/V, and there should be no fire or explosion after compression
	Thermal runaway	After the battery loses heat control and causes danger in the passenger area, a thermal event alarm signal should be provided 5 min before it occurs
	Over temperature and current protection, external short circuit protection, over charge and discharge protection	No leakage, no shell rupture, no fire or explosion, and no abnormal termination conditions are triggered. The insulation resistance after the test should not be less than 100 Ω/V

In the formula, C_0 is the initial capacity of the battery, and I_b is the discharge current related to time.

As shown in Fig. 1, the "barrel effect" shows that during charging, the middle battery has reached the cut-off voltage, while the left and right batteries are not fully charged. If there is no balanced control and safety management mechanism, continuing to charge the battery will cause the middle battery to overcharge and cause unnecessary safety accidents.

Currently, there are two approaches to address battery inequality: active equalization and passive equalization. Active equalization involves transferring energy from cells with higher energy to cells with lower energy or supplementing the energy of the entire pack to the lowest cell. Its advantages include high efficiency and minimal losses. Passive equalization, on the other hand, typically involves discharge the higher voltage cells through resistors, releasing energy in the form of heat, and allowing other cells to have more charge time. In this way, the overall system's energy is limited by the cell with the lowest capacity [8, 9].

In addition to the impact of battery inequality on battery charge safety, charge stations also affect battery charge safety. Due to space limitations, a brief overview is provided here. The reliability and security of the communication system in charge stations have a significant impact on the safety of electric vehicle charge. If the communication protocols between the vehicle and the charge station are mismatched or incompatible, the electric vehicle will not be able to initiate the charge process [10]. During the charge process, transmission or reception errors can lead to charge interruptions, overcharge, and the risk of fire in the electric vehicle or charge equipment. The aging and failure of components in charge equipment also affect charge safety [11–14].

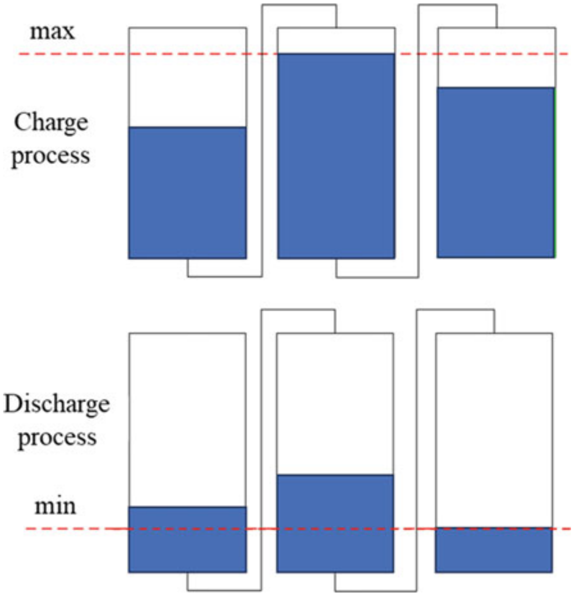

Fig. 1 The barrel effect of batteries (Charge and discharge process)

3 High Voltage Safety Management

High voltage inter-lock (HVIL) is a safety feature in electric vehicles that ensures the electrical integrity of high-voltage components and their connections to the high-voltage power lines by using low-voltage signals. When the Battery management system (BMS) detects an abnormal circuit open, it is necessary to promptly disconnect the high-voltage power to ensure the personnel safety and vehicle equipment operation [15, 16]. To ensure the safe use of batteries, monitoring the current inside the battery pack can provide short-circuit and over current protection. Current monitoring is commonly achieved using shunt resistors and Hall sensors. Shunt resistors offer high precision but introduce voltage drop and energy loss. Additionally, their resistance can vary with temperature, leading to measurement errors [17]. Hall sensors, on the other hand, offer advantages such as high accuracy and linearity, independent of electrical isolation devices, fast response time, and no voltage loss. Those are widely used for current monitoring inside power battery packs. Hall sensors should be installed before the main negative relay so that the current can be monitored regardless of whether the power battery is in a charge or discharge state. This arrangement is also based on the consideration of monitoring the current during the battery's self-heating process, as it is essential for ensuring the heating process safety [18].

Figure 2 shows lithium-ion power battery protection circuit model. Overcurrent protection is achieved by detecting the voltage across a sampling resistor caused by the discharge current and comparing it with the overcurrent threshold voltage. The overcurrent protection adopts a multi-level protection mode, firstly, the current

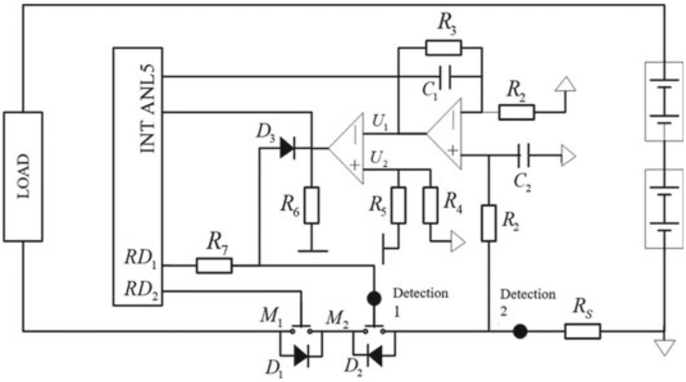

Fig. 2 A type of lithium-ion power battery protection circuit

I flowing through both ends of resistor R, converted to voltage through a current voltage conversion circuit.

$$U_1 = \frac{I R_S}{R_2}(R_2 + R_3) \tag{3}$$

In the formula, the voltage U_1 is sent to the I/O port ANL5, and after A/D conversion, it is compared with the overcurrent threshold voltage. When the value exceeds the overcurrent threshold voltage and the duration exceeds the corresponding overcurrent delay time, turned off the MOSFET at the overvoltage control end, and cut off the discharge circuit. Suitable resistor values are selected based on sampling accuracy and circuit power consumption considerations. To balance sampling accuracy and short-circuit protection response time, the values of capacitors should not be too large. Multiple levels of overcurrent protection with different threshold voltages and corresponding delay times are used, where larger threshold voltages have shorter delay times [19].

4 Thermal Runaway Warning

Regarding the warning of battery thermal runaway, it mainly focuses on monitoring and warning critical conditions when the battery experiences thermal runaway [20]. By monitoring temperature, smoke, and combining parameters such as voltage, current, and internal resistance, the occurrence of thermal runaway can be determined. By combining multiple parameters for warning, the reliability of the warning system Can effectively reduce false positives and improve system reliability.

Figure 3 shows the conventional practical application of battery thermal management development process.

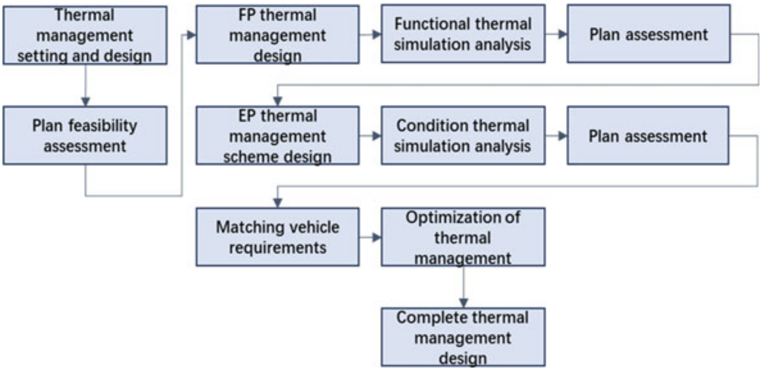

Fig. 3 Battery thermal management development and design process

When the battery operates at normal temperatures, its internal resistance decreases as the temperature rises. However, when the temperature exceeds the normal operating range and thermal runaway occurs, the internal resistance of the battery increases significantly. Srinivansan [21] proposed a thermal runaway warning method for lithium-ion batteries based on impedance phase rapid monitoring. The internal impedance of the battery is divided into amplitude Z and phase shift θ. the monitoring of internal battery temperature and prediction of thermal runaway can be achieved. Since a sudden change in internal resistance does not necessarily indicate thermal runaway, as the battery can experience changes in resistance due to external disturbances or poor contacts, it is necessary to combine multiple characteristic parameters for warning [22].

The characteristics of gases generated during battery thermal runaway are more suitable as the basis for early warning judgments. Research has shown that the detection sensors have advantages such as high reliability and low cost compared to other combustible gas sensors. Therefore, it has been determined that gas and temperature can serve as early signals for battery thermal runaway warning. In order to explore more effective warning methods, many scholars have combined multiple parameters for analysis, which can further enhance the safety and reliability of lithium-ion battery systems. For example, Ma Wei [23] built a warning system for lithium-ion batteries, it serves as a warning for thermal runaway, considering the temperature and voltage parameters in abnormal operating conditions. Wang Fang [24] concluded a warning method for thermal runaway of individual lithium-ion batteries based on temperature, smoke, and combustible gas data, using the Dempster-Shafer evidence theory, and implemented the warning of thermal runaway.

To conduct scientific research and engineering applications, simulation and experimental methods are commonly used, including ADVISOR based simulation platforms, hardware in the loop, and model in the loop experiments. Shown as in Fig. 4.

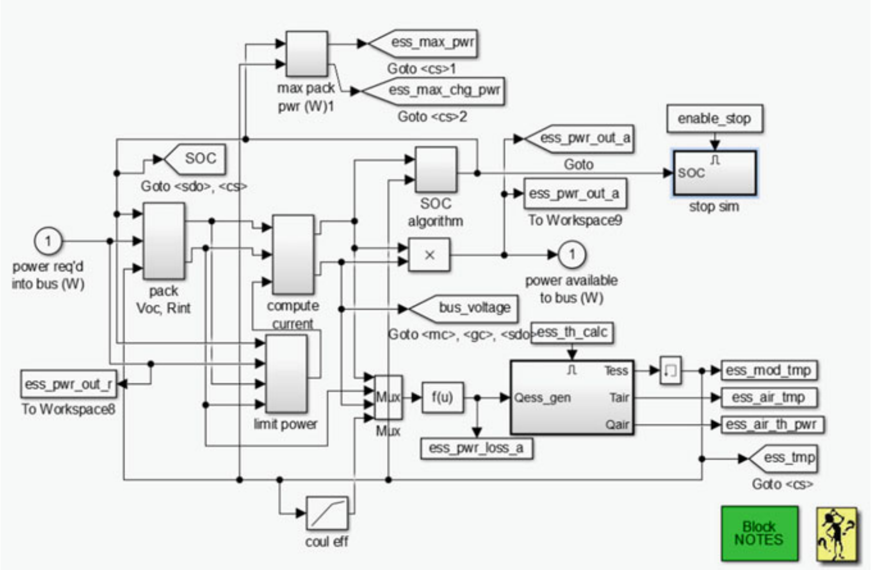

Fig. 4 Lithium-ion battery simulation model in ADVISOR

5 Conclusion

This article starts with the factors influencing battery safety and provides a detailed introduction to the safety management of electric vehicle batteries. Power batteries are complex systems combined electrochemistry, mechanics, heat, and control management. Those are closely interconnected, and failure in any aspect can have a significant impact on the safety of power batteries. To facilitate the understanding of lithium-ion power battery safety design methods, this includes battery selection, module assembly design, battery pack safety protection, and design strategies of lithium-ion battery safety management.

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