

Analysis of Fault Diagnosis and Safety Protection Technologies for New Energy Vehicle Battery Systems

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Abstract

With the rapid growth in the number of new energy vehicles on the road, the safety and reliability of lithium-ion power battery systems have become a major focus of attention. This paper systematically analyzes typical failure modes in power battery systems, summarizes their multi-source, coupled, and progressive characteristics, and identifies internal short circuits as the core factor triggering thermal runaway. Building on this, the paper reviews three categories of fault diagnosis methods-based on parameter monitoring, mathematical-physical models, and data-driven approaches-and compares their respective application scenarios and limitations. It then elaborates on comprehensive protection strategies covering graded early warning, thermal runaway suppression, high-voltage electrical safety, and regulatory compliance. Finally, the paper discusses technical bottlenecks such as the trade-off between diagnostic real-time performance and accuracy, as well as the scarcity of fault samples, and outlines future development directions including vehicle-cloud collaboration and digital twins. This paper aims to provide a technical reference for fault diagnosis and safety protection in power battery systems.

Keywords

New Energy Vehicles; Lithium-Ion Power Batteries; Fault Diagnosis; Safety Protection; Thermal Runaway

1. Introduction

Driven by the global energy transition and the “dual carbon” goals, the new energy vehicle industry continues to grow at a rapid pace, and lithium-ion power batteries have become the mainstream on-board energy storage solution. According to statistics from the Ministry of Public Security, by the end of 2025, China’s new energy vehicle fleet will reach 43.97 million units. With the rapid growth of the fleet, safety incidents caused by power battery system failures have become frequent,

posing a serious threat to the safety of drivers and passengers. Data indicates that in 2025, battery-related hazards accounted for 68% of all fire incidents involving new energy vehicles nationwide. Early fault diagnosis currently relies primarily on “post-event” alarms triggered by voltage and temperature thresholds, making it difficult to achieve early warning. In recent years, model- and data-driven diagnostic methods, as well as safety protection technologies such as aerogel insulation and tiered early warning systems, have become research hotspots. The national standard GB 38031-2020 has already specified requirements for thermal runaway testing. However, existing research often focuses on individual technologies, lacking a systematic overview of the complete chain encompassing failure mechanisms, diagnostic methods, and protective strategies. To address this, this paper analyzes the issue from three dimensions-failure modes, diagnostic technologies, and safety protection-to summarize failure characteristics, compare the applicability of various diagnostic methods, elaborate on tiered early warning and thermal runaway containment strategies, and discuss technical bottlenecks and future directions. The aim is to provide a technical reference for the safety design and fault diagnosis of power battery systems.

2. Analysis of Typical Failure Modes and Causes in Power Battery Systems

2.1. Failure Mechanisms at the Cell Level

Internal abnormalities within the cell itself are the primary source of safety risks in power battery systems. Among these, internal short circuits are the most dangerous; they occur when abnormal contact develops between the positive and negative electrodes, triggering a localized high current and rapidly generating high temperatures. Common causes of internal short circuits include: lithium dendrites precipitating on the negative electrode surface and penetrating the separator under conditions of overcharging, low temperatures, or high-rate charging; metal particles or electrode burrs left over from the manufacturing process piercing the separator under vibration; structural deformation of the cell caused by external impact; and separator aging and brittleness due to long-term use. Additionally, lithium plating is a phenomenon that cannot be overlooked; it often occurs during low-temperature or high-rate charging, where lithium ions fail to insert into the graphite layers and instead deposit on the anode surface, causing both capacity degradation and creating a potential hazard for internal short circuits. The solid electrolyte interphase (SEI) forms during the battery’s initial charging cycle and normally provides a passivating protective layer. However, under high-temperature, overcharging, or prolonged cycling conditions, the SEI may undergo abnormal growth or rupture. The former increases internal resistance and consumes active lithium, while the latter generates heat and repeatedly regenerates, potentially leading to thermal runaway.

2.2. Typical Malfunctions of the BMS System

The Battery Management System (BMS) performs critical functions such as status monitoring, logical decision-making, and control execution; if it fails, the entire battery system loses its protective barrier. Sensor failures manifest as drift, loss, or a severe decline in the accuracy of voltage, current, or temperature readings, which can lead to incorrect state estimation and thermal management failure. At the actuator level, the main negative relay is prone to two types of failures: sticking or failure to close. If the relay sticks, the high-voltage circuit remains energized even after the vehicle has been powered down, posing an electric shock risk; if it fails to close, the vehicle cannot be powered up and driven normally. More subtle issues include control strategy flaws and software vulnerabilities. For example, errors in State of Charge (SOC) estimation can lead to overcharging or over-discharging, while improperly set fault alarm thresholds, programming logic errors, or controller crashes can render the BMS ineffective in hazardous situations.

2.3. Thermal Management System Failure

The primary function of the thermal management system is to maintain the battery pack temperature within the optimal range of 15-35°C. A failure in this system directly disrupts the battery's thermal equilibrium. When the cooling system fails, heat dissipation capacity decreases, causing heat to rapidly accumulate within the battery pack. As temperatures continue to rise, this accelerates electrochemical side reactions. In cold environments, if a positive temperature coefficient (PTC) heater or film heater in the heating system fails, the battery cannot be effectively preheated. This not only significantly reduces charging efficiency but also greatly increases the risk of lithium plating on the anode. Even if the cooling and heating components are fully functional, an improperly designed thermal management system can cause significant temperature inconsistencies within the battery pack. Cells that remain in high-temperature zones for extended periods will age prematurely, becoming a weak link that limits the overall lifespan and safety of the battery pack.

2.4. Electrical Connection and Insulation Failures

The reliability of connectors and external circuits directly affects the electrical safety of power batteries. Bolt connections are prone to gradual loosening under continuous vibration. When high currents pass through, severe localized overheating can occur at the loose points, causing minor damage such as burning of the connection surfaces or, in severe cases, igniting surrounding materials. At the same time, insulation between high-voltage components and the vehicle chassis may be compromised due to vibration-induced wear, aging of insulating materials, or coolant leaks. This can cause insulation resistance to drop to dangerous levels, potentially leading to electrical leakage or even short circuits. Such faults typically develop slowly and are difficult to detect in their early stages, but they can escalate

rapidly once they worsen. Therefore, proactive prevention through regular inspection of connection torque and insulation resistance is essential.

2.5. Patterns and Characteristics of Failure Evolution

Based on the analysis of the four categories of failures described above, the failure behavior of power battery systems exhibits three distinct characteristics. First is multi-source failure: failures can originate from internal electrochemical processes, such as lithium plating or the breakdown of the solid-electrolyte interface (SEI) film, or from external factors such as loose electrical connections, thermal management failures, or software control defects, involving multiple physical domains including electrical, thermal, mechanical, and chemical aspects. Second is coupling: different failure types trigger and exacerbate one another in a chain reaction. An initial anomaly often leads to secondary failures, creating a positive feedback loop that ultimately accelerates system failure. Third is gradual progression: The vast majority of failures are not sudden but develop gradually from minor initial anomalies, such as micro-short circuits, widening local temperature differentials, or slight loosening of connection points. This provides a valuable window of opportunity for early warning and intervention. A precise understanding of these characteristics is the logical starting point for effective fault diagnosis and system protection design.

3. Analysis of Power Battery System Fault Diagnosis Technologies

3.1. Diagnostic Approaches Based on Real-Time Monitoring of Operating Parameters

In the field of battery fault diagnosis, directly utilizing measurable operating parameters for condition assessment is the most traditional and easily implementable method. Among these, fixed-threshold comparison strategies establish safety limits for characteristic parameters such as voltage, current, and temperature; when measured values exceed the preset range, an alarm is immediately triggered. While this method responds quickly, it often fails to identify faults until they have progressed to a relatively severe stage, making it a lagging protective measure. In contrast, trend analysis focuses on the temporal evolution of these parameters. For example, monitoring the rate of cell voltage decline while the vehicle is stationary can sensitively detect self-discharge anomalies in the early stages of micro-short circuits, thereby issuing early warnings before the fault deteriorates rapidly. Each strategy has its own focus; in practical applications, the two are often combined, with the threshold method serving as baseline protection and trend analysis serving as proactive early warning, jointly enhancing the timeliness and reliability of diagnostics.

3.2. Fault Diagnosis Techniques Based on Mathematical and Physical

Models

This diagnostic approach involves constructing mathematical models that reflect the internal or external response characteristics of the battery, comparing the model outputs with actual measurement values, and identifying faults based on residual signals. It represents a diagnostic method with a clear underlying mechanism. Electrochemical models, based on porous electrode theory and concentrated solution theory, can precisely describe internal processes such as lithium-ion concentration distribution and potential changes. While they offer high diagnostic accuracy, their complex equations and numerous undetermined parameters make real-time operation difficult under the constraints of limited onboard computing resources. Equivalent circuit models, on the other hand, use ideal components such as resistors, capacitors, and voltage sources to approximate the battery's external voltage-current response. With a simple structure and parameters that can be updated online via recursive least squares or Kalman filtering, they have become a hot topic in current research on in-vehicle fault diagnosis. In practical applications, equivalent circuit models combined with state observers (such as extended Kalman filters) can effectively detect typical faults such as internal short circuits and abnormal state-of-charge.

3.3. Intelligent Diagnostic Strategies Based on Big Data Learning

With the widespread adoption of vehicle-to-everything (V2X) technology and the massive accumulation of battery operational data, the automatic extraction of fault features using data mining and machine learning algorithms has become a key area of development. Traditional machine learning methods, such as support vector machines and random forests, can achieve intelligent identification of various fault types by constructing high-precision classifiers through supervised training on large amounts of battery data collected under both normal and fault conditions. Deep learning methods go a step further by employing deep architectures such as convolutional neural networks or long short-term memory (LSTM) networks to automatically extract abstract features from raw time-series data, eliminating the need for manual design of complex feature engineering. They are particularly adept at handling complex diagnostic problems characterized by strong nonlinearity and severe mutual coupling, such as the early evolution of internal short circuits and multiple fault couplings. Although deep learning models involve significant computational overhead, they can be deployed in the cloud and work in tandem with on-board real-time diagnostics, providing a powerful tool for the precise early warning of power battery system failures.

4. Analysis of Safety Protection Technologies for Power Battery Systems

4.1. Fault Classification and Tiered Response Mechanism

To minimize the risks posed by faults, a multi-level early warning system must be established based on the urgency of the fault and its potential consequences, with the battery management system automatically executing corresponding control actions. Level 1 warnings correspond to minor anomalies, such as increased cell voltage deviations or local temperature differences exceeding set values. In such cases, the system moderately limits output power while issuing a warning via the instrument panel. A Level 2 warning corresponds to more severe deviations, such as voltage exceeding the charging upper limit or temperature approaching the material's tolerance limit. In this case, the BMS significantly reduces power output, initiates forced cooling or heating compensation, and triggers audible and visual alarms. Level 3 alerts correspond to extremely dangerous conditions, such as severe voltage overshoot, a sudden drop in insulation resistance, or confirmed thermal runaway. In such cases, the system must immediately trip the main circuit relay to de-energize the high-voltage system and trigger an external alarm to guide personnel evacuation. This tiered, closed-loop management strategy not only avoids secondary risks caused by sudden power cuts but also decisively isolates the source of danger in critical moments.

4.2. Thermal Runaway Suppression and Isolation Measures

When a single cell experiences thermal runaway, preventing the spread of heat to adjacent cells is key to controlling the scale of the incident. Filling the spaces between cells with highly efficient thermal insulation materials, such as silica aerogel felt or mica composite panels—which have a thermal conductivity of less than $0.02 \text{ W}/(\text{m}\cdot\text{K})$ —can significantly delay heat transfer. This is complemented by a directional pressure relief design, which incorporates guide channels in the battery pack housing to direct high-temperature ejecta in a predetermined direction, preventing direct impact on adjacent cells. Phase-change materials can be arranged around the cells to absorb large amounts of latent heat through their melting or solid-solid phase-change processes; for example, paraffin-based composite phase-change materials can achieve a phase-change enthalpy of over $150 \text{ kJ}/\text{kg}$, helping to reduce the local temperature rise rate. Furthermore, the battery pack housing employs a fire-resistant sealed structure that effectively prevents the spread of flames and high-temperature gases into the passenger compartment or the external environment, thereby buying valuable time for occupants to evacuate.

4.3. High-Voltage Electrical Safety and Insulation Protection Design

In addition to thermal safety, electrical safety is also a critical component of the protection system. The high-voltage interlock circuit monitors the on/off status of all high-voltage connectors; if a disconnection is detected, it immediately triggers an alarm and performs a power-down operation. The online insulation resistance monitoring device continuously measures the resistance between the high-voltage

system and the vehicle chassis; when the resistance drops below a safety threshold (e.g., below 100 Ω/V), it is determined that insulation has failed, triggering protection. The active discharge circuit utilizes power resistors to discharge residual busbar capacitance to below 60 V within seconds following a collision or emergency power-down, preventing electric shock to rescue or maintenance personnel. Together, these electrical safety measures form a second line of defense against leakage, short circuits, and electric shock incidents.

4.4. Industry Standards and Engineering Compliance Requirements

The implementation of safety protection technologies must comply with the mandatory requirements of relevant national and international standards. National Standard GB 38031-2020 stipulates that, following thermal runaway in a single power battery cell, the battery pack or system must not catch fire or explode, and must provide at least 5 minutes of escape time during thermal propagation testing. GB/T 31485-2015, in turn, establishes test methods and evaluation criteria for safety under abuse conditions such as overcharging, short-circuiting, crushing, and needle penetration. UN Regulation R100 provides detailed provisions regarding the electrical safety of electric vehicles, including insulation resistance, water and dust resistance ratings, and high-voltage labeling. During product development, the effectiveness of protective designs must be verified through simulation and real-vehicle testing to ensure compliance with the aforementioned standards and to obtain certification from third-party testing organizations.

5. Current Technical Bottlenecks and Development Trends

Although significant progress has been made in power battery system fault diagnosis and safety protection technologies, several key challenges remain in engineering applications. First, there is an inherent trade-off between the real-time performance of diagnostic algorithms and model accuracy: high-fidelity electrochemical models impose a heavy computational load, making it difficult to run them in real time on automotive-grade chips, while simplified models are prone to false negatives or false positives. Second, data-driven methods rely heavily on a large number of labeled fault samples. However, severe faults occur infrequently during actual vehicle operation, resulting in scarce data and insufficient model generalization capabilities. Third, safety protection measures (such as multi-layer thermal insulation and active pressure relief) increase the weight and manufacturing costs of battery packs, conflicting with the vehicle's requirements for lightweight design and cost-effectiveness. Fourth, diagnostic reliability in scenarios involving multiple coupled faults remains suboptimal; existing methods struggle to simultaneously handle multiple concurrent anomalies such as internal short circuits, loose connections, and sensor drift.

Looking ahead, the following directions hold promise for overcoming these

bottlenecks. Vehicle-cloud collaborative diagnostic architectures are gradually becoming mainstream: the onboard BMS performs rapid threshold assessments and lightweight model computations, uploads key data to the cloud, where complex deep learning models conduct in-depth analysis, and then transmits the diagnostic results back to update the onboard strategy. Digital twin technology constructs a virtual model that runs in sync with the physical battery, simulating internal electrochemical-thermal-mechanical coupling processes in real time to predict fault evolution paths and enable virtual validation. Advancements in smart battery concepts-such as embedding fiber-optic grating sensors or microcapsule self-healing materials within battery cells-are expected to fundamentally enhance the intrinsic safety of batteries. Additionally, the potential of large language models in time-series data processing and anomaly pattern recognition is gaining attention; in the future, these models could be used to automatically parse massive amounts of operational logs, reducing reliance on manually designed rules.

6. Conclusions

This paper systematically analyzes the typical failure modes, diagnostic techniques, and safety protection strategies for lithium-ion power battery systems in new energy vehicles. The results indicate that power battery system failures exhibit multi-source, coupled, and progressive characteristics, with internal short circuits being the core factor triggering thermal runaway. Diagnostic technologies are evolving from threshold-based judgment toward trend analysis and the integration of model-driven and data-driven approaches. Trend analysis methods can enable early warning of micro-short circuits, and deep learning methods demonstrate significant advantages in handling complex nonlinear faults; however, challenges related to on-board real-time performance and data dependency still need to be addressed. Safety protection requires the establishment of a comprehensive system that integrates multi-level early warning, thermal runaway containment, electrical safety design, and compliance with standards. Measures such as aerogel insulation and directional pressure relief can effectively delay the escalation of incidents. This paper is primarily based on literature analysis and does not include experimental validation. Future work could involve comparative testing of diagnostic methods using public datasets and exploring the in-vehicle deployment of lightweight models.

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