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Research on the Influencing Factors of Power Battery Range Degradation and Optimization Strategies

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Abstract: With the rapid popularization of the new energy vehicle (NEV) industry, power batteries serve as the core energy storage component of vehicles, and their range degradation has become a key pain point that restricts users' driving experience, affects vehicle service life, and hinders the high-quality development of the industry. During long-term charging and discharging and under complex operating conditions, power batteries experience problems such as irreversible capacity decline and reduced driving range, which not only increase users' vehicle costs but also lead to a series of problems such as battery scrapping and resource waste. Taking NEV power batteries as the research object, this paper systematically analyzes the core factors causing battery range degradation, including internal material characteristics, the external use environment, charge-discharge conditions, and operation and maintenance management. Combining the working principles of batteries with actual application scenarios, it puts forward all-round optimization strategies such as technical optimization, usage standards, and operation and maintenance upgrades, providing a theoretical reference and practical basis for improving the service life of power batteries, delaying range degradation, and promoting the sustainable development of the NEV industry.
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Keywords: new energy vehicles; power battery; range degradation; influencing factors; optimization strategies

1. Introduction

Against the background of the continuous advancement of the dual-carbon strategy and the electrification transformation of the automobile industry, China's NEV production and sales have ranked first in the world for many consecutive years, and market penetration has continued to climb. As the core power source of NEVs, the performance stability, range capability, and service life of power batteries directly determine the core competitiveness of vehicles. At present, lithium-ion power batteries have become the mainstream supporting battery for NEVs owing to their advantages such as high energy density, long cycle life, and excellent cost performance. However, in actual use, whether for household passenger cars or commercial NEVs, range degradation is common: the driving range of a new vehicle drops noticeably after 1-3 years of use, and the degradation problem is even more prominent under low-temperature environments, frequent fast charging, and harsh road conditions.

Power battery range degradation is divided into two types: reversible degradation and irreversible degradation. Reversible degradation can be recovered through standardized charging, environmental adaptation, and other means, whereas irreversible degradation is caused by internal structural damage to the battery and cannot be repaired; it is the core reason for battery scrapping and the sharp shrinkage of vehicle range. The range degradation problem not only reduces users' willingness to buy and use vehicles and triggers market consumption disputes, but also greatly increases the pressure of power battery recycling and restricts the reputation and long-term development of the NEV industry. Therefore, an in-depth exploration of the various factors affecting power battery range degradation and the formulation of scientific and feasible optimization strategies are of great practical significance for improving battery performance, extending battery life cycles, and improving users' driving experience.

2. Overview of the Working Principle of Power Batteries and Range Degradation

2.1 Core Working Principle of Power Batteries

The lithium-ion power batteries currently dominant in NEVs are mainly composed of four core components: the positive electrode, the negative electrode, the electrolyte, and the separator. Their working essence is the repeated de-intercalation and migration of lithium ions between the positive and negative electrodes: during charging, lithium ions are extracted from the positive electrode material, migrate through the electrolyte and separator to the negative electrode, and are intercalated into the negative electrode material, realizing the storage of electrical energy as chemical energy; during discharging, lithium ions are extracted from the negative electrode and flow back to the positive electrode, converting chemical energy into electrical energy to supply power for vehicle driving and on-board equipment. Under ideal operating conditions, the migration process of lithium ions is stable and reversible, and battery capacity can remain stable for a long time. However, during long-term cyclic use, various internal and external factors disrupt the ion migration balance, causing internal structural damage to the battery and reducing the number of effective lithium ions, ultimately manifesting as decreased battery capacity and range degradation.

2.2 Manifestations of Power Battery Range Degradation

Power battery range degradation is mainly reflected in two aspects. First, capacity degradation: as the number of charge-discharge cycles increases, the maximum available capacity of the battery continues to decrease, and the mileage a vehicle can travel with the same charge amount keeps declining. Second, performance degradation: the charge-discharge efficiency of the battery decreases and the internal resistance increases; the vehicle's acceleration performance and low-temperature range stability deteriorate. Even at full charge, the actual range is far lower than the rated range. According to degradation characteristics, it can be divided into temporary reversible degradation and permanent irreversible degradation. Reversible degradation is mostly caused by external factors such as ambient temperature and state of charge and can be

recovered after the conditions improve; irreversible degradation originates from the aging of internal materials and structural damage of the battery and is the core reason for the end of battery life.

3. Analysis of the Core Influencing Factors of Power Battery Range Degradation

3.1 Internal Material and Structural Factors (Fundamental Factors)

The aging of internal battery materials and structural damage are the core internal causes of irreversible range degradation and are inherent battery losses that cannot be completely avoided. First, positive electrode materials age and fail. Mainstream ternary lithium and lithium iron phosphate positive electrode materials, during long-term ion de-intercalation, experience problems such as lattice structure collapse, material dissolution, and shedding of active substances, resulting in a continuous decrease in the number of lithium ions available for reaction and a sharp decline in battery energy storage capacity. Among them, ternary lithium batteries have higher energy density but weaker positive electrode stability, and their degradation rate is relatively faster after long-term cycling; lithium iron phosphate batteries have a stable structure and a more gradual degradation rate, but their low-temperature performance is notably weak.

Second, the loss of negative electrode materials is prominent. Graphite negative electrodes are the mainstream negative electrode material of power batteries. During long-term charging and discharging, the repeated intercalation and extraction of lithium ions cause the volume of the negative electrode material to expand and crack, forming an irreversible SEI film on the surface. An overly thick SEI film increases the internal resistance of the battery, hinders ion migration, and consumes a large amount of active lithium ions, causing permanent loss of battery capacity. In addition, the shedding and pulverization of negative electrode materials directly destroy the internal reaction system of the battery and accelerate range degradation.

Finally, the failure of the electrolyte and separator aggravates degradation. The electrolyte is the carrier of ion migration; during long-term use, it undergoes decomposition, volatilization, and deterioration, leading to a decline in ion conduction efficiency. At the same time, impurities produced by electrolyte decomposition attach to the electrode surface and clog ion channels. As the core component that isolates the positive and negative electrodes and prevents short circuits, the separator experiences pore clogging and aging damage under long-term operating conditions, which not only reduces the charge-discharge efficiency of the battery but also aggravates internal battery losses and accelerates range degradation.

3.2 External Ambient Temperature Factor (Sensitivity Factor)

Ambient temperature is a key external factor affecting the range stability of power batteries. The optimal operating temperature of a battery is 25℃-35℃, and both high-temperature and low-temperature environments cause range degradation. In a low-temperature environment, the viscosity of the electrolyte increases substantially, the ion migration rate drops sharply, the internal resistance of the battery increases significantly, and charging and discharging are incomplete; a large number of lithium ions cannot complete effective migration, directly causing a sharp drop in the available capacity of the battery and a substantial shrinkage of vehicle range. At the same time, lithium precipitation is very likely to occur during low-temperature charging; lithium dendrites will pierce the separator and consume active lithium, causing permanent battery damage. Repeated use at low temperatures will continuously accelerate range degradation.

The damage of a high-temperature environment to the battery is more irreversible. High-temperature exposure in summer and long-time vehicle driving raise the temperature of the battery pack. High temperature accelerates electrolyte decomposition and electrode material aging, aggravates the thickening of the SEI film, and intensifies internal side reactions of the battery. Under long-term high-temperature conditions, the active substances of the battery are continuously consumed, and the capacity degradation rate rises substantially; in severe cases, safety hazards such as battery swelling and thermal runaway also occur, greatly shortening the service life of the battery. Relevant test data show that the annual degradation rate of power batteries used in high-temperature environments for a long time is more than 20% higher than that in normal-temperature environments.

3.3 Charge-Discharge Operating Conditions Factor (Core Human Factor)

Users' daily charging and discharging habits are the main human factor affecting the degradation rate of power batteries. Poor vehicle use and charging habits greatly accelerate battery loss. First, frequent fast charging aggravates battery degradation. DC fast charging relies on a large current to achieve rapid energy replenishment. During the charging process, the ion migration rate inside the battery is too fast, which easily leads to ion accumulation and precipitation; the electrode materials withstand severe stress changes, accelerating material aging and structural damage. For vehicles that rely on fast charging for a long time, the battery degradation rate is 1.5-2 times that of conventional slow charging.

Second, the harm of over-charging and over-discharging is significant. Storing at full charge and maintaining a 100% full-charge state for a long time keeps the battery in a high-voltage stress state for a long time, accelerating the aging of the positive electrode material and the decomposition of the electrolyte; while deep discharge driving, that is, charging only after the battery power is exhausted, causes excessive delithiation of the negative electrode material, triggering structural collapse and causing irreversible capacity loss. In daily vehicle use, frequent full charging and full discharging and parking in a depleted state are the main reasons for the rapid battery degradation of ordinary users.

In addition, high-intensity discharge operating conditions aggravate degradation. Frequent rapid acceleration, high-speed driving, and uphill heavy-load driving of the vehicle cause the battery to discharge continuously at a large current; the internal power load of the battery is too large and the ion reaction is intense, causing the internal resistance of the battery to rise rapidly and material loss to intensify. Long-term high-intensity vehicle use significantly shortens the cycle life of the battery.

3.4 Battery Operation, Maintenance, and Management System Factors

The battery management system (BMS) is the "intelligent steward" of power batteries; it is responsible for monitoring parameters such as battery temperature, voltage, current, and state of charge, and realizes charge-discharge protection, temperature regulation, and balancing control. If the accuracy of the BMS algorithm is insufficient or its control functions fail, the consistency of battery cells will become unbalanced. A power battery is composed of multiple cells connected in series and parallel. During long-term use, if the capacity and voltage of the cells deviate and cannot be balanced in time,

some cells will be over-charged or over-discharged, causing the performance of the entire pack to decline and accelerating overall range degradation. At the same time, a fault in the vehicle's battery thermal management system makes it impossible to precisely regulate battery temperature, causing the battery to remain in high-temperature or low-temperature conditions for a long time and aggravating loss. In addition, problems such as the lack of daily operation and maintenance, the failure of dust-proof and waterproof protection of the battery pack, and the aging of lines also indirectly affect battery performance and accelerate range degradation.

4.Optimization Strategies for Delaying Power Battery Range Degradation

4.1 Optimize Battery Materials and Production Processes to Reduce Inherent Degradation from the Source

Aiming at fundamental degradation problems such as internal material aging and structural damage of the battery, optimization is needed from the R&D and production ends to improve battery stability and durability. First, optimize the electrode material ratio and improve the formulations of ternary lithium and lithium iron phosphate positive electrode materials; through technologies such as doping and coating, enhance the stability of the positive electrode lattice structure and reduce material dissolution and collapse. Optimize the modification process of graphite negative electrodes to improve the anti-swelling and anti-pulverization capabilities of the negative electrode material, inhibit the formation of lithium dendrites, and reduce the loss of active lithium. Second, upgrade the electrolyte formulation and develop high-temperature-resistant, low-volatility, and highly conductive electrolytes to reduce the electrolyte decomposition rate, broaden the stable operating temperature range of the battery, and improve ion migration efficiency.

At the same time, optimize the battery production and packaging process to improve the pore uniformity and high-temperature resistance of the separator and eliminate separator clogging and damage; improve the internal packaging structure of the battery to enhance the heat dissipation efficiency and structural stability of the battery, reduce internal loss during cycling, and reduce the inherent degradation rate of power batteries from the source. In addition, the research and development of new energy storage batteries such as solid-state batteries and sodium-ion batteries can be vigorously carried out to break through the material bottleneck of traditional lithium batteries and fundamentally solve the range degradation problem.

4.2 Optimize the Battery Thermal Management System to Adapt to All Temperature Conditions

Aiming at the range degradation caused by temperature, it is necessary to upgrade the vehicle's battery thermal management system to achieve precise temperature control. On the one hand, optimize the active temperature control system and upgrade the liquid cooling, air cooling, heat dissipation, and preheating devices to improve the accuracy of battery temperature regulation and ensure that the battery works in the optimal range of 25℃-35℃. In a low-temperature environment, preheat the battery in advance through the preheating device to avoid ion precipitation and structural damage caused by low-temperature charging and discharging; in a high-temperature environment, dissipate heat and cool down quickly to inhibit the occurrence of internal side reactions of the battery and reduce the material aging rate.

On the other hand, optimize the structural design of the battery pack and add heat insulation and thermal insulation protective layers to reduce the impact of extreme external temperatures on the battery; through refined zoned temperature control, solve the problem of uneven temperature inside the battery pack, ensure that all cells work at a consistent temperature, improve battery consistency, avoid cell degradation imbalance caused by local overheating or overcooling, and extend the overall service life of the battery.

4.3 Standardize Users' Charging and Discharging Habits to Reduce Human-induced Loss

Scientific vehicle use and charging habits are a low-cost and effective means to delay battery degradation and extend range life. In terms of charging methods, adhere to slow charging as the main method and fast charging as a supplement; for daily commuting energy replenishment, give priority to AC slow charging, and use DC fast charging only in emergency scenarios to reduce the damage of large-current charging to the battery. In terms of the charging range, avoid full charging and full discharging; maintain daily charging in the healthy range of 20%-80%, and avoid long-term 100% full-charge storage and driving in a depleted state. When the vehicle is parked for a long time, keep the battery level at 50%-60% to effectively reduce battery stress loss.

In terms of vehicle operating conditions, develop calm driving habits, reduce frequent rapid acceleration, rapid deceleration, and high-speed high-intensity driving, and reduce the frequency of large-current discharge of the battery; when driving in low winter temperatures, preheat the battery in advance to avoid direct fast charging and aggressive driving at low temperatures; in summer, avoid long-time exposure of the vehicle to the sun and ventilate and cool down in time after parking to reduce high-temperature loss of the battery. Standardizing vehicle use habits can effectively reduce the irreversible degradation rate of the battery and greatly extend the service life of the battery.

4.4 Upgrade the Battery Management System and Strengthen Intelligent Operation and Maintenance Control

Optimizing and upgrading the BMS battery management system and improving the accuracy of intelligent control is an important technical means to delay battery degradation. First, optimize the BMS control algorithm to accurately estimate core parameters such as the battery SOC, cell voltage, and temperature, realize refined charge-discharge protection, and eliminate problems such as over-charging, over-discharging, over-current, and overheating of cells. Second, strengthen the battery balancing management function and, through active balancing technology, correct the capacity and voltage deviations of cells in real time, ensure the consistency of the entire battery pack, and avoid overall performance degradation caused by cell imbalance.

At the same time, build an intelligent battery operation and maintenance monitoring platform to collect battery operation data in real time, predict and warn of battery aging degree and hidden fault hazards, and promptly discover problems such as abnormal battery internal resistance, abnormal temperature, and cell degradation imbalance, so as to realize early detection and early maintenance. In addition, regularly carry out professional testing and maintenance of power batteries, clean dust from the battery pack, inspect line conditions, and repair minor performance losses to effectively delay range degradation.

5. Conclusion and Outlook

Power battery range degradation is the result of the combined action of multiple factors such as internal material loss, external environmental influence, human vehicle use conditions, and intelligent operation and maintenance control. Among them, material and structural aging is the fundamental internal cause; temperature conditions and poor vehicle use habits are the key triggers that accelerate degradation; and the imbalance of the battery management system is an important contributing factor. The range degradation problem not only affects the NEV user experience but also restricts the high-quality development of the industry. Through a systematic analysis of various influencing factors, this paper proposes all-round optimization strategies from four dimensions—material and process optimization, temperature control system upgrading, vehicle use habit standardization, and intelligent operation and maintenance strengthening—which can effectively delay power battery range degradation and extend battery service life.

With the continuous iteration of new energy technologies, power battery materials, thermal management systems, and intelligent control technologies will continue to be upgraded, and the R&D and application of new energy storage batteries will gradually break through the range degradation bottleneck. In the future, combining intelligent and digital technologies to achieve precise control of the full life cycle of power batteries, together with scientific guidance for users' vehicle use and a complete battery operation and maintenance system, will maximize the reduction of battery degradation loss and promote the NEV industry toward a more stable, more durable, and more sustainable direction.

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