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Fault Diagnosis of Overcharge and Overdischarge of Lithium Ion Batteries

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The purpose of this study is to diagnose and analyse the overcharge and overdischarge fault of lithium ion battery. Through the dynamic simulation model, the phenomenon of overcharge and overdischarge fault for automotive lithium-ion battery (LIB) was discussed, and the fault diagnosis effect was summarized. The results of this study show that the fault diagnosis analysis of LIB can achieve good results. It is of certain application value for diagnosis of LIB with different parameters. Therefore, it's concluded that the overcharge and overdischarge faults of automotive LIB are likely to jeopardize the using effect of the batteries, which should attract more attention of relevant automobile manufacturers.

1. Introduction

The automobile is a tool in daily human travel, which not only consumes energy but also pollutes the environment in the course of use. To reduce the emission of harmful substances, many scholars at home and abroad have applied research on new energy vehicles, and the state departments have also issued relevant policies to guide the introduction and promotion of new energy vehicles. Relevant research shows that the promotion of new energy vehicles is inseparable from the power battery. The batteries used in new energy vehicles need not only have good performance, but also have economic and environmental protection, causing no pollution to the environment. Compared with other power batteries, lithium-ion battery (LIB) is one of high-tech batteries, with relatively high service life and power, which has an important impact on the promotion of new energy vehicles. With the rapid research of electric vehicles, LIB technology is also constantly developing, and many domestic and foreign automobile manufacturers have developed and applied LIBs. However, it may have large safety problems in the practical application process, which has a certain impact on the safety of car travel.

Therefore, in this paper, the common overcharge and overdischarge fault was taken as the example for fault diagnosis analysis. First, the LIB model and simulation model were studied and analyzed. Then the application effects of the two models were explored and the fault diagnosis of this study was summarized.

2. Literature review

Due to the early start, the US research on battery management systems is relatively mature. Representative examples are the battery management system developed by General Motors for EVI on electric vehicles and the SmartGuard system developed by Aerovironmevt (Chen et al., 2014). The EVI battery management system monitors the battery's current and voltage. It has high voltage protection and over discharge alarm functions. The SmartGuard system records battery history data and archives it. The overcharge behavior can be detected, and information about the worst state battery is provided. In 2010, Ford developed a pure electric vehicle remote monitoring system, which can collect and analyze the power battery working data in real time. Relevant information was reported in a timely manner, and the management strategy of the power battery management system was adjusted. The system helps to improve the performance of the power battery in terms of consistency, cycle life, harsh environmental adaptability and stability. Tesla Motors uses a three-stage battery management system (Chen et al., 2016). The layered approach is used to closely monitor

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multiple battery packs of thousands of lithium batteries. While ensuring the overall performance of the battery, its safety factor was greatly improved.

In Europe, research on battery diagnostic systems in Germany is a leader. The BADICOACH system developed by Werner Retzlaff and Mentzer Electronic GmbH, and the BATTMAN system designed by B.Hauck are the most representative. The BADICOACH system stores detailed battery data for the most recent discharge cycle. When judging battery performance, the wrong usage is quickly found. The BATTMAN system is unique in that it includes different battery packs. According to the management idea of common module and difference module, different types of power battery packs are managed by improving related software and hardware. Japan and South Korea have also made a lot of forward-looking research on battery management systems. Toyota Motor Corporation of Japan developed a hybrid electric vehicle battery management system, namely the Prius battery management system (Dey et al., 2016). Various battery related parameters such as temperature, voltage and current are monitored. Once a parameter is found to exceed the expected level, the system automatically generates the corresponding fault code. South Korea's Ajou University and Advanced Engineering Research Institute develop battery management systems. The communication between the thermal management, charging, security and other systems and the remote computer is strengthened, which further improves the feedback control.

An observer-based fault diagnosis method was proposed. The power battery current, voltage, and temperature are analyzed. The internal dynamics of the battery are estimated and potential faults are judged. A second-order partial differential equation is used to construct a lithium-ion battery model, and a fault diagnosis observer for distributed parameter systems is designed. Compared with traditional observers based on approximate ordinary differential equations, the accuracy of system fault diagnosis is improved. Aiming at the external short circuit of the battery pack, the change rate of battery voltage, current and temperature during the fault is studied, and the external short circuit diagnosis method is proposed. Conditions such as normal working conditions, overcharging, and over-discharging were separately studied (Feng et al., 2016). Based on the influence of the Randles equivalent circuit, an optimized battery model was established. Fuzzy logic is used for fault diagnosis. Aiming at the large variety of faults and complex state of large-scale battery system, an active diagnosis scheme based on discrete event system is proposed, and the fault diagnosis of finite state machine control system is adopted (Lamb et al., 2015).

In terms of the diagnostic technology of electric vehicle batteries, although the domestic start is relatively late, relevant enterprises, universities and scientific research institutions have invested a lot of efforts. Chery Automobile Co., Ltd. developed a remote real-time monitoring system for electric vehicles based on GPRS wireless communication network. The system integrates data acquisition, recording, diagnostic analysis and status alarm, which is beneficial to real-time monitoring and intelligent analysis of electric vehicle demonstration operation. The remote monitoring system developed by Dongfeng Motor Co., Ltd. and Tsinghua University has been successfully applied to the "Dongfeng Tianyi" pure electric logistics vehicle. In the system, real-time running data of the vehicle is acquired by the vehicle-mounted terminal, and transmitted to the remote monitoring center through the wireless network. The monitoring point performs vehicle fault determination and early warning based on the analysis and processing results of the data. BYD Co., Ltd. produced the electric car BYD Qin. On the basis of the energy and heat control of the traditional battery management system, the function of automatic equalization of the battery cells is increased, so that the performance of the battery at various stages is improved. Huizhou Yineng Electronics Co., Ltd. worked closely with Beijing Jiaotong University to improve and optimize the structure and function of the battery management system (Liu and He, 2017). The battery management system is designed for online fault diagnosis and location. With portable diagnostics and data storage, fault types and fault locations are effectively analyzed.

In terms of battery diagnostic theory, relevant research institutions have made progress. An automatic test and diagnosis method for electric vehicle power battery is proposed. The trend of voltage parameters, voltage difference, state of charge, temperature and temperature difference of the single cell was analyzed. The fault diagnosis of single cell is realized by comparing with the preset database. When the battery pack voltage changes greatly, the parameter changes quickly. To solve this problem, a battery parameter acquisition and control method for battery management system is proposed. The method converts the serial connection of the control unit of the battery module of the current battery management system into a parallel mode. The parameter sampling of a plurality of battery module control units is synchronously implemented to avoid parameter differences caused by different parameter acquisition times of the plurality of battery module control units (Sidhu et al., 2015). An early diagnosis method for battery pack performance failure is proposed. The battery pack is allowed to stand, charge and discharge for two cycles before leaving the factory. According to the collected voltage data and temperature data, the fault condition of each single battery in the battery pack is judged, and the unqualified single battery is replaced in time, so that the quality of the factory battery pack is guaranteed. Based on the state of charge (SOC) and state of health (SOH) of the cells, the equivalent SOC and SOH of each battery module and the entire battery are gradually estimated. According to the working state of the entire battery pack, whether an overdischarge phenomenon occurs is diagnosed. Based on the observer theory, a fault diagnosis strategy based on Longberg observer and learning observer is proposed. The strategy first divides the battery pack fault system into two subsystems. Then, the Longberg Observer and the Learning Observer are designed separately. The Longberg Observer is used to detect and separate battery faults, and the learning observer is used to update the separated faults online, thus achieving synchronous separation and estimation of battery faults. The proposed battery fault diagnosis system analyzes the collected power battery status signals. When a specified number of state signals continuously exceed the preset value range within a predetermined time, the battery is judged to be malfunctioning. According to the relationship between the preset fault signal and the fault type and fault level, the type and level of the fault currently occurring are determined (Yan et al., 2016). Relevant information is sent to the fault handling module for effective processing to ensure safe operation of the power battery.

In summary, the current battery fault diagnosis is mainly to detect battery voltage, current, temperature and other parameters. According to this, most of the faults are concentrated in capacity reduction, internal resistance increase, short circuit, and poor cell uniformity in the battery pack. There are few troubleshooting studies on overcharging and overdischarging. Only a few references refer to this part of the study. A method of monitoring voltage or estimating SOC is taken. In fact, there are many factors that cause changes in battery voltage and SOC. The above diagnostic studies only stay on the surface of the fault and lack the identification of specific internal causes. Therefore, it is necessary to conduct further analysis and research on the overcharge and overdischarge fault diagnosis of the battery.

3. Methods

3.1 Establishment of lithium-ion battery model

The power battery is a key component of the electric vehicle, and the battery model describes the external characteristics of the battery. Therefore, it is of great significance to study the battery model. On the one hand, in the process of battery design and manufacturing, simulation of the battery can significantly reduce battery testing time and optimize product performance. In the system simulation research of electric vehicle, battery simulation is an indispensable and important part. On the other hand, in order to improve the energy efficiency of the battery, extend its service life, and ensure safety, it is necessary to effectively manage the charge and discharge processes of the power battery system. The battery management system (BMS) not only monitors the battery voltage, current, and temperature etc., but also obtains state variables such as battery SOC and SOH. The ideal battery model should include the following features: it can systematically reflect the operating characteristics of the battery; the complexity is not high; the state equation is easy to be established and calculated; it is feasible. According to the above battery model analysis, taking the internal resistance characteristics, voltage characteristics and capacitance characteristics of LIBs into account, the second-order resistance-capacitance (RC) equivalent circuit model was established by combining the advantages of the GNL model and the Thevenin model (Fig.1).

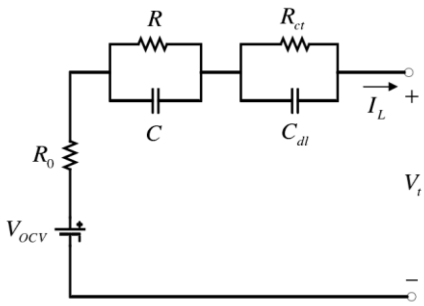

Figure 1: Second-order RC equivalent circuit model

In the equivalent circuit shown in Fig.1, according to Kirchhoff's voltage law, the voltage across capacitance C is calculated as:

$$\dot{V}_c = \frac{V_c}{RC} + \frac{I_L}{C} \quad (1)$$

The experimental subject used in this paper was a lithium-ion battery manufactured by A123 Systems, and the specific model was APR18650M1A. The specific parameters of the battery are: rated capacity 1.1Ah, nominal voltage 3.3V; charging limit voltage 3.65V, that is, when the open circuit equilibrium voltage reaches 3.65V, the SOC value of the battery can be considered as 1; the discharge cutoff voltage is 2.0V, that is, to discharge the battery, if the terminal voltage drops to this value, the load must be disconnected to stop discharging, otherwise, the battery will over discharge. At this time, the battery SOC is considered to be 0. The experimental system includes the lithium ion battery, constant current electronic load, experimental circuit board, data acquisition card, and notebook computer. The constant current electronic load is used for constant current discharge of the battery. The experimental circuit board is composed of sampling resistor and pulse discharge resistor. The function of the sampling resistor is to convert the discharge current signal into a voltage signal, and the pulse discharge resistor is used for the pulse discharge test of the battery. The data acquisition card collects the current and voltage signals in the experiment and sends it to the computer. The data acquisition card and the computer are connected via a USB data cable. (The battery discharge experiment system is shown in Fig.2 below)

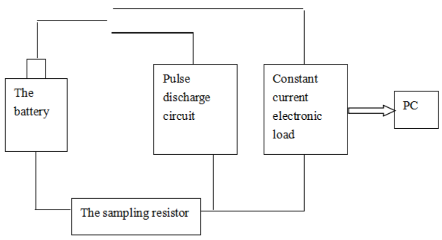

Figure 2: Battery discharge test system

The constant current discharge was applied to the battery at the discharge current of 1A, and each discharge time was set to be 300s. The battery discharge data was recorded during this period. The load was disconnected and held it for more than 20 minutes until the battery voltage didn't change significantly. At this time, the open circuit balance voltage was measured. Then, the battery was pulsed and it was allowed to stand for a period of time after each pulse discharge to bring it to equilibrium. The above steps were repeated until the battery voltage dropped to the discharge cut-off voltage of 2.0V. Table 1 lists some measured data, including the open circuit balanced voltage value of the lithium-ion battery at different SOC values during the constant current discharge process.

Table 1: Voltage values measured in each static stage of the experiment

OCV (V)	SOC
3.6051	1
3.3468	0.924243
3.3229	0.848485
3.3147	0.772728
3.2994	0.621214
3.2891	0.545456
3.2715	0.469699
3.2486	0.318185
3.2180	0.242427
3.1823	0.166670
2	0

Because of the highly non-linear relationship between the open-circuit voltage and the charge state of the battery, the high-order polynomial function used in this paper fits the relationship between OCV and SOC. (OCV-SOC curve parameter values are shown in Table 2 below)

Table 2: OCV-SOC curve parameter values

k_0	k_1	k_2	k_3	k_4
2	1865	-8903	1.823e+0.4	-2.087e+0.4
k_5	k_6	k_7	k_8	k_9
1.465e+0.4	-6497	1810	-304.9	28.74

3.2 Design of lithium-ion battery fault diagnosis model

The battery fault is reflected in the change of the internal battery parameters. When the battery is overcharged or overdischarged, the system parameters such as the resistance and capacitance of the battery will change accordingly. Therefore, the related fault model can be established by overcharging and overdischarging the battery and then obtaining battery parameters under different fault conditions. Because of the limited experimental conditions, the internal parameters of the LIB in the overcharged and overdischarged states was cited from the literature. The ohmic internal resistance R0 and the internal resistance R, Rct of the lithium ion battery both show an increasing trend in the overcharge and overdischarge states, and the increase in the overcharge is greater than the over-discharge; the polarization capacitances C and Cdl gradually decreases with the increase in the number of over-discharge cycles, but rapidly increases in the over-discharge state. The parameters after 18 over-discharge cycles were selected as the overdischarge fault model of the lithium ion battery. The parameters after 6 overcharge cycles were selected as the over-charge fault model of the LIB. To make contrast, the parameter after one overdischarge cycle was used to simulate the fault-free mode of the lithium-ion battery. The specific parameters of Kalman filter for different models are shown in Table 3.

Table 3: parameters of kalman filter model

model	R_0 (Ω)	C (F)	R (Ω)	C_{dl} (F)	R_{ct} (Ω)
normal	0.0503	0.1922	0.0051	0.8213	0.0126
The overcharge	0.1661	0.0007	0.4907	0.0140	0.1833
A put	0.0623	0.2590	0.0054	2.9430	0.0081

4. Results and discussions

4.1 Model simulation verification

To evaluate the performance of the lithium-ion equivalent circuit model, it can be modeled and simulated, and then the simulated results were compared with the experimental results to make judgment based on their difference. Matlab is an abbreviation of Matrix Lab. It is convenient for user algorithm development, numerical calculation, and data analysis. Simulink is a software package for dynamic system modeling, simulation, and analysis. Its graphical interactive environment enables users to build the block diagram model of system quickly with no need to write any code. LIB simulation model mainly consists of three parts: SOC calculation module, parameter updating module, and output voltage calculation module. The battery SOC is calculated using the ampere-hour accumulation method: SOC (0) represents the initial state of charge of the battery, Cn is the rated capacity of the battery, and I represent the charge and discharge current; coulombic efficiency is also expressed, by taking 1 for charge and 0.98 for discharge. The parameter updating module obtains the corresponding open circuit voltage value by looking up the table according to the OCV-SOC function relationship established above for the current SOC value of the battery. In particular, each element in the battery equivalent circuit, including voltage source, internal resistance, and capacitance, is related to SOC and temperature. The voltage deviation at the initial stage and the final stage of discharge is large, and the maximum error is about 0.052V. The voltage measured at voltage platform period and model simulated voltage are matched relatively high, with the error fluctuating within plus or minus 0.04V. The rated voltage of the lithium ion battery used in this paper is 3.3V, so the maximum absolute error of the model simulation voltage is about 0.052V, accounting for 1.576% of the rated voltage.

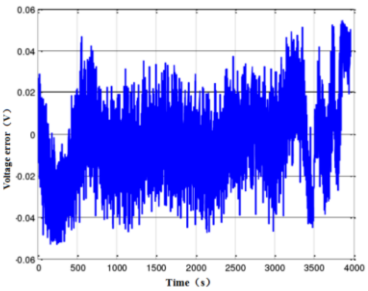

Figure 3: Model voltage error of the constant current transport mode

The trend of measured voltage was basically consistent with the simulated voltage. In the initial stage of discharge, the deviation between the battery model voltage and the measured voltage underwent a relatively fluctuating process: it gradually increased at the beginning and gradually decreased after reaching the maximum value of 0.049V; After reaching zero, it was increased in the opposite direction to about 0.02V, and then it was slowly decreased again. As the discharge continued, the model voltage error gradually stabilized, remaining slightly over 0.01V. The maximum absolute voltage error of the model simulation was about 0.049V, accounting for 1.485□of the rated voltage. Therefore, the established battery simulation model has good performance.

4.2 Model fault diagnosis and analysis

This paper simulates the continuous occurrence of different fault conditions in the battery at the discharge current of 1A. The simulation duration lasted a total of 2,400 seconds, which is divided into four equal time periods. The initial 600 seconds and the last 600 seconds have the same battery status all in the fault-free condition. Assuming that for a certain period, the battery only shows one of the fault types. In the initial 600 seconds and the last 600 seconds, the voltage curve of the normal model coincides with the measured voltage curve, while the voltages of the overcharge and overdischarge models are far from the measured voltage. From 601 to 1,200 seconds, the overcharge model is close to the measured terminal voltage curve, while the terminal voltage of the normal model and over-discharge model shows a deviation from the measured value. From 1,201 to 1,800 seconds, the overdischarge model voltage curve agrees with the measured voltage, while the normal model and over-charge model seriously deviate from the measured voltage curve. The residuals of the normal model are almost zero during the first 600 seconds and the last 600 seconds; the rest of the period is far from zero. The residual of the overcharge model approaches zero during 601 to 1,200 seconds, and its value has remained above 0.3V despite its decreasing process during 0-600 seconds; the residual of the over-discharge model approaches zero during the period of 1,201 to 1,800 seconds, although it tends to be zero and then gradually deviates, with the minimum value of about 0.1V.

5. Conclusions

During the application of automotive lithium-ion battery, the overcharge and discharge phenomenon will inevitably occur, which has a certain important impact on the normal use of battery. This paper mainly explores the overcharge and overdischarge issue in automotive ion batteries and also their impacts. The results indicate that the established battery dynamic simulation model in this study has good application effects and it is applicable to the simulation and analysis of LIB with different parameters. Besides, combined with the equivalent circuit model analysis, it is found that this model can effectively detect the failure of automotive lithium-ion battery, which has a certain positive effect on the safe use of automotive batteries.

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