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Electrical behavior of overdischarge-induced internal short circuit in lithium-ion cells

Xin Lai, Yuejiu Zheng*, Long Zhou, Wenkai Gao

College of Mechanical Engineering, University of Shanghai for Science and Technology, Shanghai 200093, China

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A B S T R A C T

Lithium-ion cells connected in series are prone to be overdischarged, which may induce internal short circuit (ISC). In this study, the electrical behavior of overdischarge-induced ISC in NMC cells is analyzed. The performance of 11 new cells is tested, and these cells are then overdischarged to different depths. The electrical characteristics of these overdischarged cells are examined to assess the relationship between the ISC and depth of discharge (DOD). The cells are then rested for 100 days to assess the self-repair capability of overdischarged cells. The ISC is characterized by comparing the DOD with the capacity loss, leakage current, and ISC resistance. The degree of the ISC is found to increase nonlinearly with the DOD. A DOD of 120% or more can induce an irreversible ISC, and the electrical characteristics of severely overdischarged cells are similar to linear resistance characteristics. The self-repair behavior occurs in the cells with a DOD of less than 120% after a longtime rest and leads to a decrease in the degree of the ISC. The cyclic test results show that a higher DOD leads to a higher capacity decay rate. The electrical characteristics of the overdischarge-induced ISC are valuable in ISC identification and prediction.

1. Introduction

Lithium-ion batteries (LIBs) have been proven to be a reliable energy storage device. Among chemical power sources, LIBs are preferred choice, especially for portable electronic devices and electrical vehicles (EVs) [1–5], because of their long service life, high energy density, and minimal environmental impact. However, an important aspect that impedes the large-scale application of LIBs is their safety [6–9]. In recent years, many accidents involving EVs equipped with LIBs have been reported [10,11]. For example, five fire accidents involving Tesla Model S automobiles occurred over a period of 6 months, and a taxi made by BYD Company Limited caught fire during charging. Considerable effort has been devoted to investigating the reasons for the safety problem associated with LIBs. The safety performance of LIBs during operation has been found to be affected by several factors, especially in situations involving abuse [10,12–14], which can be classified into thermal abuse, mechanical abuse, and electrical abuse [15–17]. Overdischarge is a common form of electrical abuse, which has been reported to be extremely harmful because it induces internal short circuit (ISC) and accelerates capacity losses [5,18]. Therefore, it is necessary to investigate the characteristics of overdischarge and theirs impact on LIBs.

To maintain excellent cycle life and safety performance, LIBs must operate within a specified potential range. The potential of a single cell can be easily controlled under strict charging and discharging conditions. However, for numerous series-parallel connected cells, the accurate control of the voltage of each cell is challenging even when a battery management system (BMS) is used because of the inconsistency of cells in battery packs [19]. Therefore, one or more cells can easily overdischarge when tens to hundreds of cells are connected in series and parallel. These overdischarged cells may not be detected directly, which may lead to serious safety risks. Research has shown that overdischarge can induce ISC and accelerated aging without any mechanical destruction or the presence of foreign substances [3,11,18]. The occurrence of ISC in LIBs is becoming an issue of increasing concern because ISC considerably impact the safety and reliability of batteries [20–24].

Overdischarge is safer than overcharge because overdischarge does not cause thermal runaway as easily as overcharge. However, overdischarge may lead to the breakage of electrode materials,

* Corresponding author.
E-mail address: yuejiu_zheng@163.com (Y. Zheng).

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decomposition of the solid electrolyte interface (SEI), and dissolution of copper. Numerous studies have focused on the effects of overdischarge on the thermal and electrochemical properties of LIBs. Guo et al. examined the mechanism of the overdischarge process and overdischarge-induced ISC using scanning electron microscopy (SEM) and X-ray diffraction (XRD) [3]. Shu et al. conducted a comparative study of the overdischarge behaviors of three cathode materials ($LiFePO_4$, $LiMn_2O_4$, and $LiNiO_2$), and the results showed that the $LiFePO_4$ and $LiMn_2O_4$ cathode materials exhibited high structural stability during the overdischarge process [11]. Maleki et al. found that overdischarge might cause capacity losses and/or thermal stability changes, and they demonstrated that dissolved copper could migrate through the separator from the anode side to the cathode side and might cause an ISC [18]. Zhang et al. found that the capacity degradation of an overdischarged battery was caused mainly by the dissolution of the copper current collector and the deposition of Cu on the anode surface [25]. Erol et al. proved that impedance increased tremendously when a battery was either overcharged or overdischarged [26]. These studies have clarified the abuse tolerance behaviors and the electrochemical mechanism of overdischarged LIBs and provided guidance for designing voltage control strategies for BMSs and improving the reliability and safety of battery packs.

In practice, the detection of the electrochemical properties of cells is difficult. However, the electrical characteristics of cells can be detected and quantified in a BMS. For this purpose, it is vital to study the effects of overdischarge and overcharge on the electrical characteristics of cells. In this study, we investigated the electrical characteristics of NMC cells overdischarged to different degrees and the resulting degrees of the ISC. The overdischarged NMC cells were then rested for a long time (100 days) and then charged and discharged repeatedly. By comparing the changes in the capacity, short circuit resistance, and leakage current of these LIBs during cyclic charging and discharging processes, we were able to study the characteristics of overdischarged cells in detail. The results of this study provide guidance for the identification of ISC and the design of control strategies and algorithms for high-precision BMSs.

The remainder of this paper is structured as follows. The experimental flow and method are described in Section 2. In Section 3, the experimental results are discussed and analyzed to obtain the electrical characteristics of overdischarge-induced ISC of cells with different degrees of overdischarge. Finally, the conclusions drawn from the study and some closing remarks are presented in Section 4.

2. Experimental

2.1. Electrical representation of ISC

The electrical representation of ISC is shown in Fig. 1, where r

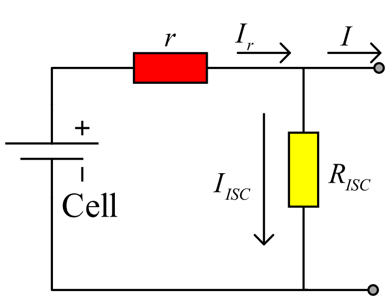

Fig. 1. Electrical representation of ISC.

and R_{ISC} denote the internal resistance and ISC resistance, respectivly, and I_r and I_{ISC} denote the currents of r and R_{ISC}, respectivly. For a normal cell, R_{ISC} is very large and I_{ISC} is equal to zero, so the current I is equal to I_r. For a cell with severe ISC, R_{ISC} is very small, the current I_r is entirely bypassed byR_{ISC}, so I is very small or zero and I_{ISC} is very large. That is, the leakage current of the cell is very large. The above analysis indicates that the ISC of the cell can be characterized by its electrical characteristics. In this study, the electric quantity loss, leakage current, and ISC resistance of the overdischarged cells with different degrees of overdischarge are compared; these parameters indicate the electrical behavior of the overdischarge-induced ISC.

2.2. Test bench

A commercial prismatic-pouch lithium-ion cell is tested in this study. The cathode material of the cell is NMC. The basic parameters of the cell are listed in Table 1. The experiments are performed on a test bench made by DIGATRON with a current range of −100 to +100 A and a voltage range of 0–60 V. The voltage accuracy is 1 mV and the current accuracy is ±0.1% of the full scale. The tested cells are placed in a temperature chamber (TEMI580, Dongguan Bell Company) to maintain the ambient temperature.

2.3. Test flow and method

The electric behavior of overdischarge-induced ISC with different degrees of overdischarge is examined by comparing the estimated results of the capacity loss, leakage current, and ISC resistance based on experimental results. The experimental process is illustrated in Fig. 2(c). The process consists of nine experimental steps and four main tests. The experimental steps and methods are described below.

(1) Basic performance test (Test Ⅰ): This test, which comprises a capacity test and a hybrid pulse power characterization (HPPC) test, is developed to assess the cell's basic performance. The capacity test is designed to determine the battery standard capacity. The test process is as follows. Place the cell in the temperature chamber at 25 °C for 3 h. Then, discharge the cell at a constant discharge current 1/3 C to 2.5 V. After waiting for 1 h, fully charge the cell using the constant current–constant voltage (CC–CV) method. In this method, the cell is charged at a constant current (1/3 C) until the voltage reaches 4.15 V, and then, the cell is charged at a constant voltage until the charging current falls to 1.6 A; then, charging is paused for 1 h. This process is repeated three times, and the mean value of the test capacity is chosen as the cell capacity. The HPPC test is designed to determine the open circuit voltage (OCV). In this test, a series of pulse power sequences are provided to the fully charged battery. Following one pulse power sequence, the cell is discharged to a state of charge (SOC) of 97.5% at 1/3 C and rested for 3 h before the next pulse power sequence is provided. The cell is tested at decrements of 2.5% SOC (10% when the SOC is less than 90%) until the cutoff voltage of 2.5 V is reached.

(2) Overdischarge test (Step 2): To overdischarge the cells to different degrees, the tested cell is connected in series with one auxiliary cell, and the voltage of all the cells is monitored, as shown in Fig. 2(a). The auxiliary cell is charged to 100% SOC, and the test cells are discharged to 0% SOC. Therefore, the test cell can be overdischarged to different degrees, which can be described by the depth of discharge (DOD). In this study, 11 new cells are discharged to DODs of 106%, 107%,