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Internal short circuit detection for battery pack using equivalent parameter and consistency method

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HIGHLIGHTS

- Theoretical foundation and practical method of ISCr detection are introduced.
- The influence of ISCr on cells' OCV and internal resistance has been discussed.
- The effectiveness of the ISCr detection method is validated through experiments.
- The specific time consumed to detect ISCr is compared.

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ABSTRACT

Internal short circuit (ISCr) detection of a battery is critical for preventing thermal runaway and enhancing electrical vehicle safety. In this paper, the electrical characteristics of the ISCr of a large format lithium ion battery are analyzed using the equivalent circuit model (ECM). An ISCr detection method is developed based on battery consistency within the battery pack. The ISCr detection method employs the recursive least square (RLS) algorithm based on the mean-difference model (MDM), which is derived from the ECMs consisting of the mean and difference value of cells' voltage and resistance. The algorithm first estimates the basic parameters of the MDM. Then the algorithm calculates the characteristic parameters, such as the differential of the voltage and the fluctuation function of the internal resistance, derived from the basic parameters of the MDM. These characteristic parameters obviously vary once ISCr occurs, thereby helping the battery management system to realize ISCr detection. The effectiveness of the ISCr detection method is validated through a series of experiments.

1. Introduction

Under the dual pressure of the energy crisis and environment pollution, the electrification of vehicular powertrains has become increasingly popular [1,2]. Lithium-ion batteries have a high energy density and a long cycle life, and they are frequently chosen as onboard vehicles energy storage devices [3]. However, Li-ion batteries have potential safety issues, the largest one of them being thermal runaway [4–11]. Thermal runaway of onboard vehicles Li-ion batteries can cause catastrophes because of which the occupants of the vehicle may suffer property loss and physical damage [12,13]. Therefore, researchers and designers are putting consistent effort to prevent the onboard vehicles thermal runaway of Li-ion batteries [14].

Internal short circuit (ISCr) in Li-ion batteries is regarded as one of the main reasons that lead to thermal runaway under practical conditions, given no crushing or any other irregular external factors occur [15]. The initial stage of ISCr in a Li-ion battery has few obvious indicators and is therefore difficult to identify [16]. Unfortunately, once there are visible indicators of ISCr, no effective countermeasures can be used to prevent the battery from thermal runaway. Therefore, the early detection of the ISCr based on the understandings of the ISCr mechanisms is critical for the BMS to prevent further damages caused by the thermal runaway.

Most recent approaches for ISCr detection are mainly provided

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by patents. Owing to the conventions of the patent writing, most methods presented in these patents lack of essential details, which made them difficult to be replicated. The ISCr detection methods in available patents can be classified into the following five categories:

a) Detecting ISCr by comparing the measured voltage or temperature value of the battery with the value predicted by the model [17–20];
b) Detecting ISCr by identifying the unusual voltage drop recovery of the battery [21,22];
c) Detecting ISCr by inspecting the on–off voltage or capacity of the battery [23,24];
d) Detecting ISCr by comparing the battery capacities calculated using different algorithms [25];
e) Detecting ISCr by battery pack consistency [26,27].

Equivalent circuit models (ECM) of batteries [28–30] have a relatively simple structure and an acceptable accuracy for practical applications. A cell with ISCr can be described by an ECM with a short circuit resistance parallel connected to a cell [31,32]. Using the ECM of ISCr, the electrical behavior of ISCr can be analyzed effectively. Besides, an external short circuit (ESCr) has similar ECM as ISCr, indicating that ISCr could be simulated using ESCr to acquire the electrical performance of ISCr [31].

The mean-difference model (MDM), which consists of the cell mean model (CMM) and the cell difference model (CDM), describes both, the cell's average condition and the differences within a battery pack [33]. The CMM can predict the average cell performance based on the assumption that cells have a favorable consistency and operate under similar working conditions. The CDM is applied to describe the variance among cells, i.e., cell voltage difference, OCV difference, and internal resistance difference etc. These variances are caused by the variance in the battery's capacity, internal resistance, and temperature, also especially can be caused by the ISCr discussed in this paper.

The features of ISCr will be more and more obvious along with the developing process of ISCr, which is associated with the diminishing of ISCr resistance. However, hard shorts or the late stage of ISCr, which have mΩ magnitude of short resistances, will lead to instant thermal accidents, and thereby the ISCr detection results will be meaningless due to no time margin for countermeasures. Soft shorts or the early stage of ISCr, such as shorts of 100/10/1 Ω, have remaining time for them to run into thermal accidents because of low heat generation power. Therefore, the detection results of the early stage of ISCr are more practical and could be used for alarm and countermeasures.

In this research, we aim to establish a method that can detect ISCr and validate the method through experiments. In Section 2, an ECM is used to discuss the theoretical foundation of the equivalent parameters and consistency-based ISCr detection method. The MDM and the recursive least square (RLS) algorithm are adopted to implement the proposed method, and a statistical approach is used for ISCr detection. In section III, a test bench is constructed and ESCr resistances of 100/10/1 Ω are applied to simulate ISCr, and the results of the experiments are presented. In Section 4, the ISCr detection results are presented and discussed. Finally, the conclusions of the entire study are presented in Section 5.

2. Theoretical foundations of equivalent parameter and consistency ISCr detection

2.1. Equivalent parameters

Most ECMs could be equivalently transformed into the electrical circuit presented in Fig. 1(a) if capacitive components are neglected. The voltage dynamics of the simple ECM in Fig. 1(a) are described by Eq. (1), where U is the measured voltage, E is the OCV, I is the current, and R is the internal resistance of the battery.

$$U = E - I \cdot R \tag{1}$$

When ISCr occurs in the battery, the ECM is supposed to change into the formation shown in Fig. 1(b), in which an ISCr resistance R_{ISCr} is connected in parallel to the original circuit. The ESCr of battery will have the same ECM. For the ECM presented in Fig. 1(b), the dynamics are described by Eq. (2), where U and I represent the measured voltage and current, respectively; I_R is the current conducted through the original internal resistance; and I_{ISCr} is the current conducted through the ISCr resistance.

$$\begin{cases} E - I_R \cdot R = I_{ISCr} \cdot R_{ISCr} \\ I_R - I_{ISCr} = I \end{cases} \tag{2}$$

Solving Eq. (2), we get I_{ISCr} as

$$I_{ISCr} = \frac{E - I \cdot R}{R + R_{ISCr}} \tag{3}$$

Then, by combining the expression of I_{ISCr} in Eq. (3) with Ohm's law, we prove that U and I in Fig. 1(b) are expressed as Eq. (4).

$$U = \left(\frac{R_{ISCr}}{R + R_{ISCr}} \cdot E\right) - I \cdot \left(\frac{R_{ISCr}}{R + R_{ISCr}} \cdot R\right) \tag{4}$$

Eqs. (1) and (4) have the same structure; the only difference is that in Eq. (4), E and R are replaced by $\frac{R_{ISCr}}{R+R_{ISCr}} \cdot E$ and $\frac{R_{ISCr}}{R+R_{ISCr}} \cdot R$, respectively. $\frac{R_{ISCr}}{R+R_{ISCr}} \cdot E$ is called the equivalent OCV (EOCV) and $\frac{R_{ISCr}}{R+R_{ISCr}} \cdot R$ is called the equivalent internal resistance (EIR), which are equivalent parameters, explained in the next sections.

2.2. Effect of ISCr

2.2.1. Parameter effect of ISCr

If the OCV and the internal resistance of a cell with ISCr are evaluated using the U and I data according to Eq. (1), EOCV and EIR will be obtained, complying with Eq. (4) who has same structure with Eq. (1), instead of the real OCV and the real internal resistance. EOCV and EIR are smaller than the real parameters because there is an additional scale factor $\frac{R_{ISCr}}{R+R_{ISCr}}$ that is smaller than 1. In this research, the phenomena that the evaluated EOCV and EIR in a cell with ISCr are smaller than the real parameters is called the parameter effect of ISCr.

Eqs. (5) and (6) express the differences between the equivalent parameters of a cell with ISCr and its real parameters due to the parameter effect of ISCr, where the negative symbols indicate that the equivalent parameters are smaller than the real ones.

$$\Delta E_{parameter} = \frac{R_{ISCr}}{R + R_{ISCr}} \cdot E - E = -\frac{R}{R + R_{ISCr}} \cdot E \tag{5}$$

$$\Delta R_{parameter} = \frac{R_{ISCr}}{R + R_{ISCr}} \cdot R - R = -\frac{R}{R + R_{ISCr}} \cdot R \tag{6}$$

According to Eqs. (5) and (6), if there is no ISCr which means $R_{ISCr} = \infty$, the value of both $\Delta E_{parameter}$ and $\Delta R_{parameter}$ will be zero no matter what value R has. If there is ISCr, the naturel change of R with battery aging which is usually positive will lead to more obvious $\Delta E_{parameter}$ and $\Delta R_{parameter}$. Therefore, the naturel changing of battery internal resistance R with battery aging will not have influence on $\Delta E_{parameter}$ and $\Delta R_{parameter}$ for batteries without ISCr, but will emphasize $\Delta E_{parameter}$ and $\Delta R_{parameter}$ for batteries with ISCr.