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Fault diagnosis and quantitative analysis of micro-short circuits for lithium-ion batteries in battery packs

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HIGHTLIGHTS

- A quantitative diagnosis method for the micro-short circuit fault of lithium-ion batteries is proposed.
- The remaining charging capacity is estimated using the charging cell voltage curve transformation.
- Estimated the leakage current and micro-short circuit resistance with low computational complexity.
- Verified the diagnosis method under a variety of charging strategies and battery ageing conditions.

ARTICLE INFO

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Battery pack
Battery management system
Short circuit
Charging cell voltage curve
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ABSTRACT

Micro-short circuit (MSC) of a lithium-ion battery cell is a potential safety hazard for battery packs. How to identify the cell with MSC in the latent phase before a thermal runaway becomes a difficult problem to solve. We propose a diagnosis method to detect the MSC according to the remaining charging capacity (RCC) variations between cells. When the charging cell voltage curve (CCVC) of the first fully charged cell is regarded as the benchmark, the RCC of each cell can be obtained by the CCVC transformation based on the uniform CCVC hypothesis. The accuracy of the RCC estimation method is validated under constant current and constant power charging experiments. The leakage current of the MSC cell can be obtained by the increase of the RCC after each charge, and it can be converted into the MSC resistance. We set up the battery pack system model with the MSC fault in Simulink® to verify the effectiveness of the method when the battery pack is charged up to different charge cutoff voltages. Through a series of experiments with external resistors, the adaptability of the MSC diagnosis method is further validated for the aged cell, multi-stage charging, and constant power charging.

1. Introduction

Because lithium-ion batteries has a lot of advantages, such as high energy and power density and long cycle life, they are favored by all kinds of electric energy storage devices [1–3]. However, lithium-ion batteries still cause security problems [4–6]. In 2016, a well-known smartphone (Samsung Note 7) was recalled and banned only after months of sale because the batteries sourced from two different suppliers had a faulty design and a manufacturing defect respectively [7,8]. The faulty design made electrodes on the top-right of the battery susceptible to bending. This weakened the separation between positive and negative tabs of the battery, thus resulting in short circuits [9]. For the manufacturing defect, the insulation tapes that should be covering the cells were missing and the battery had thin separator and protrusions inside the cell that resulted in damage of cathode and anode [9]. These cells then caught fire when both electrodes came into contact. Unfortunately, some spontaneous accidents with electric energy storage devices also occurred around the world in recent years [10]. It was found that these accidents were mostly caused by thermal runaway in the battery pack [11]. The internal short circuit (ISC) is considered to be the root cause of such thermal runaways [12,13].

A cell short circuit is caused by the connection of cell positive and negative in the case of a very small resistance for various reasons [14]. It contains the ISC and the external short circuit (ESC). The ESC is the most common case of cell abuse. In addition to the severe ESC when positive and negative connectors are directly shorted, the leakage of voltage measurement wiring, the equalization failure and other failures may also cause external micro-short circuit (MSC) [15,16]. Nail

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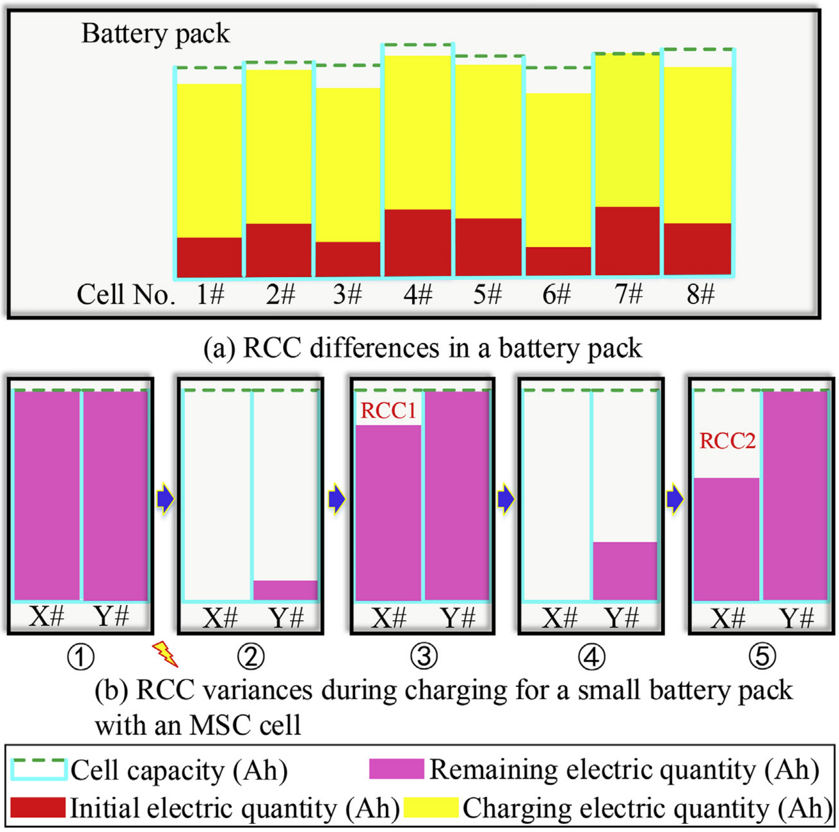

Fig. 1. A schematic diagram for the relationship between the RCC and the MSC. (a) RCC differences in a battery pack. (b) RCC variances during charging for a small battery pack with an MSC cell.

penetration, burning, extrusion and other violent acts can directly lead to severe cell ISC causing cell explosion or thermal runaway [17–19]. The internal MSC is generally caused by separator defects, part of electrodes drying, surface micro-thorns of electrode materials and so on in a cell [20,21]. In the cell production process, if current collectors and other raw materials have burr or dust precipitation, the separator will be easily destroyed. The internal MSC will be easily triggered because there are hidden dangers for the separator. Even for the cells without manufacturing defects, if the abuse occurs during use, such as over discharge/charge, ultra-high/low temperature or severe vibration, the lithium dendrites will form on the negative electrode surface, which may pierce the separator and further lead to internal MSC [22]. It is important to note that the internal MSC can develop over time both under normal use or abuse conditions. The increase of short circuit severity is often accompanied by the increase of the battery self-discharge rate and calorific value, leading to fire, and even thermal runaway and other serious problems [23]. Unfortunately, it is difficult to detect and predict the MSC because there is a long evolution process before the MSC eventually develops into the thermal runaway [10,24,25]. Though the probability of these failure events is estimated to be very low (1 in 5–10 million), the consequences of a cell failure due to a short circuit in a high energy battery system have the potential to be catastrophic [26]. Therefore, it is an urgent problem to detect the MSC cell during the incubation period of thermal runaway.

The MSC generally produces a large amount of heat at middle or late phase, so serious short circuit fault can be detected by thermal analysis. Ramadass et al. [27] utilized an infra-red imaging tool to analyze the ISC created in a lithium-ion battery and developed a controlled ISC test method to study several kinds of ISC. Fang et al. [28] built a 3D (Three-Dimensional) electrochemical-thermal model to study the ISC and found that the chance of thermal runaway can be reduced by either reducing the heat accumulation rate or shortening the temperature rise period through proper cell designs. Feng et al. [29] also built a 3D electrochemical-thermal model to simulate various ISC scenarios and explored the correlation between the measured voltage, current, and temperature data, and the ISC status. However, from a security standpoint, the temperature-aware level fault often means that thermal runaway has been formed.

In the field of battery management, the equivalent circuit model (ECM), the model-based fault diagnosis and the statistical approach are widely used. Chen et al. [15] established a simplified battery fault model and proposed a model-based fault diagnosis approach for detecting the ESC of lithium-ion batteries. Ouyang et al. [16] analyzed the electrical characteristics of the MSC using the ECM, and then constructed a detection method based on the equivalent parameters and battery consistency. Kim et al. [30] introduced a fail-safe design methodology for large-capacity lithium-ion battery systems using a short circuit response model. However, it is difficult to use some short-term state estimation results to quantitatively estimate the MSC fault, since the MSC has a long-term accumulation before it develops into thermal runaway. These methods can only identify the presence or absence of the fault, but cannot quantitatively evaluate the fault severity of the fault. Seo et al. [31] proposed a model-based switching model method to detect the ISC and quantitatively calculate the ISC resistance. However, the method needs to identify the battery model parameters and estimate the state of charge (SOC) of every cell in the diagnosis process, so the computational load is high for onboard device applications. As a result, there have been no effectively quantitative estimation method for the MSC fault reported.

This paper presents an MSC diagnosis method utilizing the uniform charging cell voltage curve (CCVC) hypothesis and the remaining charging capacity (RCC) variation. In the design of the method, both the long-time scale characteristic of the MSC and the availability of diagnosis algorithms for onboard vehicle applications are considered.