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Local cell temperature monitoring for aluminum shell lithium-ion battery based on electrical resistance tomography

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ABSTRACT

This paper presents an approach for the local the cell temperature monitoring of an aluminum shell lithium-ion battery cell by electrical resistance tomography, which has a great potential to analyze the correlation of apparent resistivity, local cell temperature and residual capacity. To determine this correlation, a flexible sensor was first designed, and the Wenner configuration was applied in the measurements. The investigated temperatures ranged from −20 °C to 70 °C. The results showed that the apparent resistivity had an exponentially increasing trend as the temperature increased. The effect of the residual capacity was further investigated. It is found that a lower residual capacity resulted in a lower apparent resistivity, which intensified as the temperature decreased. A comprehensive equation was developed to determine the local cell temperatures. Images of the apparent resistivity distribution under cell discharge further revealed the feasibility of the method. Finally, the proposed equation was applied to evaluate the cell core temperature which was compared with the surface temperatures from external sensors.

1. Introduction

Lithium-ion battery (LIB) cell has been considered as one of the most promising and competitive power battery cells especially for electric and hybrid vehicles due to its high capacity density and long cycle life [1]. However, with the extensive application of LIB cells, the subsequent safety problems focusing on cell thermal runaway have captured people's attention in recent years.

Thermal runaway is regarded as the main cause of LIB cells catching on fire and exploding [2]. However, the flammability of the electrolyte, the rate of charge and/or discharge, and the engineering of the battery pack are commonly thought to be related to the tendency of LIB cells to catch on fire and explode [3,4]. These factors can potentially cause the battery pack to rupture, ignite, or explode when exposed to high temperatures or when short circuit. Therefore, high temperature and short circuit conditions are more likely to trigger thermal runaway, and short circuits could result in an abrupt increase of cell internal temperatures further affecting the entire thermal environment. In addition, the adjacent cells may also then heat up and fail and in some cases, can cause the entire battery pack to ignite or rupture. Ultimately, solutions for thermal runaway are dependent on the ability to measure the internal cell temperature of an LIB cell.

The temperature measurements of LIB cells have been investigated by researchers in recent decades. However, those studies rarely concentrated on the internal cell temperature but rather on the surface temperature of the cell. Currently, surface temperature monitoring has been well addressed by using external sensors, i.e. thermocouples,

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resistance temperature detectors (RTDs) and newly fiber Bragg sensors [5]. Nevertheless, incidence of thermal safety problems remains at a high level because of the obvious inequality between the internal cell temperature and the surface temperature. On one hand, as the life span reduces gradually, aging of the internal cell material is accelerated, which can cause an inhomogeneous distribution of internal cell temperature. On the other hand, the battery would be operated under a larger discharge rate and a narrower space for release of excess heat, which directly causes the thermal runaway especially as the energy capacity and the size of the LIB cell increases. Therefore, it is imperative to explore novel methods to evaluate the internal temperatures of LIB cells.

Mathematical modelling was first proposed to investigate the thermal behavior and estimate the core temperature as described in previous research [6–13]. However, the validation of the cell model in experiments is usually complicated because the experimental set-ups are highly sophisticated even on the laboratory scale. Some other non-destructive methods for internal temperature measurements were proposed by other authors [14–16]. Fleckenstein et al. [14] investigated thermal characterizations of battery cells and determined the temperature via heat conductivity and the specific heat capacity of an LIB cell with Thermal Impedance Spectroscopy (TIS) method. Srinivasan et al. [15] proposed Electrochemical Impedance Spectrum (EIS) method, and explored the correlation between the internal cell temperature and the phase angle of the electrochemical impedance at a certain frequency. Subsequently, Schmidt et al. [16] suggested an appropriate measurement frequency and investigated the sensitivity of the method on temperature considering the state of charge (SOC). EIS method is based on the impact of temperature on the SEI resistance changing, which increases the accuracy of the temperature measurement without setting up additional external sensors and wires.

Due to the thermal inertia of LIB cell, significant time delay of thermal transmission from inside to outside will occur especially with the growing battery cell sizes and increasing power demands. The increase of the local temperature in different areas of the LIB cell may be 10 °C or even more, which commonly induces thermal runaway. Therefore, the local temperature monitoring inside an LIB cell is necessary for cell safety. However, although the currently existing methods may have an effective evaluation of internal cell temperature on average, the local temperatures inside an LIB cell still cannot be accurately measured, thus some others novel methods need to be adopted and applied.

Electrical Resistance Tomography (ERT) is a non-intrusive industrial visualization technology that takes voltage measurements around the periphery of a domain to determine the apparent resistivity distribution inside. This technology has been studied and applied for many years in geophysical surveys [17], concrete structure investigations [18], two-phase flow detections [19] and medical inspections [20]. However, the application of the ERT technique for evaluating the internal battery structure is still a new concept. As we know, the resistivity of any conductors not only depends on material properties but also on the temperature, and the resistivity of most metal conductor has a linear relationship with temperature in a certain range [21]. Based on this, for an LIB cell, composed of some complex material units, e.g., organic electrolyte, electrodes, SEI, etc., the local cell temperatures can be determined by the apparent resistivity distribution measured by the ERT technique. So far, the authors have preliminarily investigated and evaluated the ERT method on steel shell LIB cells using simple measuring devices [22]. The feasibility of the ERT method to detect the distribution of the internal cell apparent resistivity has been validated, and real-time changes of the apparent resistivity with temperature can be reflected directly with a profile image. However, there are still gaps which remain to be filled. Firstly, the preliminary work only obtained a single profile map of certain regions inside the cell not represent the entire cell body. Secondly and more importantly, a further understanding of the apparent resistivity change with temperature will be beneficial to the real time monitoring of the local cell temperatures.

Therefore, our goal is to determine the correlation of local temperatures and the apparent resistivity distribution. For this purpose, a flexible sensor device was elaborately designed, and the apparent resistivity measurements were performed on a commercial aluminum shell LIB battery cell (10 A h). The research was carried out considering three aspects: exploration, improvement, and evaluation. The correlation of local cell temperature and apparent resistivity was determined and improved by residual capacity. Furthermore, three LIB cells in parallel connection were investigated in operation mode. The multi-zone inversion images of apparent resistivity at different discharge times were reconstructed and the method was applied to determine the core temperature of the middle LIB cell compared with the measured surface temperatures.

2. Theory

2.1. Measurement principle

For the ERT survey, an electrode configuration should be applied for apparent resistivity measurements. The most common configurations are the pole–pole, pole–dipole and dipole–dipole arrays, as shown in Fig. 1. The pole–pole and pole–dipole arrays usually require one or two electrodes placed at infinity. As for an LIB cell, it is impossible to set up this kind of electrode due to the limited size of the cell body. As a result, dipole–dipole arrays would be more suitable for LIB cells. Especially when the scale factor $n = 1$ for the dipole–dipole array, a typical Wenner configuration with an inter-electrode distance a is proposed. With the advantage of the higher data sensitivity in the horizontal direction, the Wenner configuration is chosen to be utilized in this study. After conducting the voltage measurements, the apparent resistivity ρ can be theoretically calculated as

$$\rho = K\Delta U/I. \tag{1}$$

where I is the exciting current amplitude, ΔU is the measured voltage difference of electrodes M and N, and K is