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A method for the estimation of the battery pack state of charge based on in-pack cells uniformity analysis

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HIGHLIGHTS

- Build a method for battery pack SOC estimation.
- Analyze the effect of the uneven cells problems to the pack SOC.
- The SOC is estimated with consideration of different balance control strategies.
- The UPF method is used to estimate the SOC to improve the accuracy.

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ABSTRACT

The state-of-charge (SOC) is a critical parameter of a Li-ion battery pack. Differences among in-pack cells are inevitable and can change the total capacity of a pack and the remaining available capacity. Because the traditional methods for the estimation of the SOC of a pack did not consider the difference among the cells and the impact of balance control, we developed a new method that accounts for these problems. To accurately estimate the pack SOC, we establish the relationship between the parameters of the pack and those of in-pack cells under different balance control strategies. This paper also studies the two different types of connections of a battery pack: in series and in parallel. Based on the model of the first over-charged cell and that of the first over-discharged cell, the estimation of the SOC of a battery pack is realized by the Unscented Particle Filter (UPF) algorithm. A simulation experiment verified the method for the estimation of the SOC for a battery pack based on actual data and proved that an accurate estimation value can be obtained by the method.

1. Introduction

With the development of electric vehicles and smart grids, lithium-ion batteries are becoming widely used as large-scale energy storage systems. As we know, to meet the requirements of high-energy and high-power applications, a battery system is usually composed of hundreds or thousands of cells through series and parallel electrical connections. An accurate estimation of the SOC of a battery system will enable the protection of the battery pack from being over-discharged or over-charged and thereby extend the service life [1].

Many methods currently exist to estimate the SOC of cells or battery packs in real-time, with the primary methods being the current integral method [1], the neural network model method [2], the fuzzy logic method [3] and the battery model-based method. The current integral method is simple to implement and is often used with correction by open circuit voltage. In the battery model-based method, the battery model is first established, and then an algorithm such as the Kalman Filter (KF) [4], Extended Kalman Filter (EKF) [5], Unscented Kalman Filter (UKF) [6,7], Particle Filter (PF) [8] or Unscented Particle Filter (UPF) [9], is used to estimate the SOC. These approaches have been widely studied in many reports in the literature, and most of them have achieved acceptable results.

However, the methods discussed above, usually do not take into account the difference between each individual cell when calculating the SOC of the entire pack. The in-pack cell with the lowest available capacity will determine the available capacity of the entire pack, because that cell will be the first to be completely discharged during the discharging of the pack. Similarly, the charging of the pack will stop when the in-pack cell with the highest available capacity is full, even though the other cells are still not fully charged. Hence, uneven cells problem will limit the total capacity and remaining available capacity of the pack and thus affect the SOC of the entire battery pack.

Differences among the in-pack cells are inevitable, mainly because of the production process used and the external environment

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effects [10]. The variations in the individual cells are primarily the cell total capacity, internal resistance and the initial value of the SOC [11]. A battery management system (BMS) with a balance control unit addresses the uneven cell problem. Unfortunately, different balance control strategies may have different impacts on the uniformity. The estimation of the SOC of the battery pack should take this BMS-related factor into consideration.

Some research studies already exist on the estimation of the pack SOC that consider the cell-to-cell variation. Liu [12] developed a battery model based on the lowest voltage and the EKF algorithm to estimate the pack SOC. The author only studied the case where the lowest voltage limited the discharging of the battery pack and did not consider the fact that the highest voltage limited the pack charging. Plett [13] proposed a new method to estimate each in-pack cell SOC, resistance and capacity based on bar-delta filtering, which took advantages of the similar states among the in-pack cells. Dai [10] explored a method to estimate the pack average SOC first, and then the divergences between each individual cell and the "averaged cell" were analyzed to obtain the estimation of the SOC of all the cells. Plett and Dai both analyzed the uneven cells problem and each proposed a valid method to estimate the SOC of the in-pack cells, but they did not discuss in detail the pack SOC.

In this study, we establish the relationship between the pack parameters (SOC and total capacity) and the parameters of the in-pack cells with consideration of the different balance control strategies. Because the first over-discharged cell (denoted by B1) and the first over-charged cell (denoted by B2) limit the total available capacity of the pack, the relationship becomes simplified, and the pack SOC can be represented by the parameters of B1 and B2. In this study, the SOC of B1 and B2 are determined by the UPF algorithm with their corresponding battery models, and then the pack SOC can be calculated based on their relationship.

The paper is organized as follows. In Section 2, the definition of the pack SOC is first described, and then we analyze the relationship between the parameters of the pack and those of the in-pack cells. The relationship is studied with different electrical connections and with different balance control strategies. In Section 3, we present a common battery model for B1 and B2. In Section 4, the UPF algorithm is applied to estimate the SOC of B1 and B2. Using the parameters of B1 and B2, the pack SOC is calculated. In Section 5, simulations based on UPF algorithm are used to verify the accuracy of the estimation of the pack SOC.

2. Estimation of the SOC of a battery pack

2.1. Definition of the single-cell SOC

The cell SOC reflects residual capacity as a percentage of some reference. The cell SOC is defined as the ratio of the remaining capacity to the total capacity [14]. The SOC can be expressed as the following equation:

$$SOC(t) = SOC(t_0) + \frac{\eta_c \int_{t_0}^{t} i(\tau)\mathrm{d}\tau}{C_N} \tag{1}$$

where $i(\tau)$ represents the value of current (defined to be positive for charging and negative for discharging), η_c represents the Coulombic efficiency, C_N represents the total capacity, and $SOC(t_0)$ represents the SOC value at time t_0.

2.2. Theoretical analysis of the SOC of a battery pack

The battery pack, as Fig. 1 shows, is usually composed of several battery units in series and/or parallel electrical connection. To meet the demand of large capacity systems, a battery unit usually

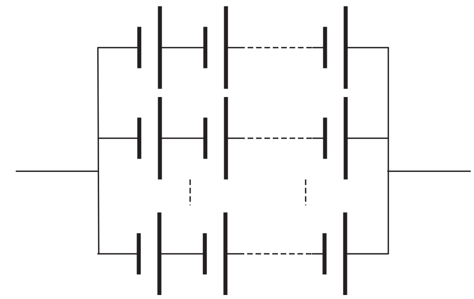

Fig. 1. Battery pack system.

consists of several cells in parallel. Because a self-balancing characteristic exists for cells connected in parallel, the battery unit can be regarded as a single cell with a higher capacity, and the relationship between battery units and the pack can be converted into the relationship between the in-pack cells and the pack. The BMS manages the batteries by estimating the pack SOC, performing balance control and charge–discharge control, and communicating with the external electronic devices. Similar to the definition of the SOC of a single cell, the battery-pack SOC can also be defined as the ratio of the remaining available capacity of the pack to the total capacity of the pack. To analyze the relationship between the pack SOC and the parameters of in-pack cells, the pack is analyzed for two situations: series connection and parallel connection.

2.2.1. Series connection

When the cells are in series, the SOC and total capacity of each cell are denoted by SOC_i and C_i, respectively, where $i \in \{1, \ldots N_s\}$. The BMS has a role of balancing the cell-to-cell variation, which results in the changes to the SOC of the in-pack cells, so the estimation of the pack SOC should take the balance control into consideration. The different balance control strategies [15], no balance, passive balance and active balance, will be discussed below.

2.2.1.1. Without balance control. The battery pack capacity is the sum of the minimum cell capacity that can be charged and the minimum remaining cell capacity that can be discharged [16]. The minimum chargeable cell capacity $\min_{1 \leqslant j \leqslant N_s}((1 - SOC_j)C_j)$ (denoted by C_{min_c}) is the maximum capacity of the pack that can be charged. The minimum remaining cell capacity $\min_{1 \leqslant i \leqslant N_s}(SOC_i C_i)$ (denoted by C_{min_r}) is the maximum capacity of the pack that can be discharged. Thus, the total capacity of the pack is:

$$\begin{aligned} C_{pack} &= \min_{1 \leqslant i \leqslant N_s}(SOC_i C_i) + \min_{1 \leqslant j \leqslant N_s}((1 - SOC_j)C_j) \\ &= C_{min\_r} + C_{min\_c} \end{aligned} \tag{2}$$

The SOC of the pack is:

$$SOC_{pack} = \frac{C_{min\_r}}{C_{min\_r} + C_{min\_c}} \tag{3}$$

Assume that a pack consists of three cells connected in series. As shown in Fig. 2, the cells exhibit different values of the initial SOC, internal resistance and total capacity. The pack operates without balance control. When the pack is fully charged, the SOC of the 3# cell is 100% and the total capacity of the pack is equal to the current minimum remaining capacity of cells. When SOC_{pack} is 100%, according to Eq. (3), we can infer that C_{min_c} is 0% and the total capacity of the pack is C_{min_r}, which is the minimum remaining cell capacity. So the total capacity of the fully charged pack, as shown in Fig. 2, is the remaining capacity of the 2# cell. We defined the minimum remaining cell capacity in the fully charged pack as $c_{\min}$, the corresponding cell SOC as SOC_{cell} and the total capacity