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Battery pack topology structure on state-of-charge estimation accuracy in electric vehicles

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ABSTRACT

Battery inconsistency are exacerbated by the resistance of inter-cell connecting plate (RICP) and the input impedance of battery voltage monitoring system (IIBVMS), both of which cannot be eliminated in a battery pack. Experiments show that the inconsistency distribution and SOC deviation in a battery pack is restricted by RICP and IIBVMS. In this paper, a “parallel-series” battery pack model is proposed and validated. The effects of RICP and IIBVMS on SOC deviation are analyzed. Results indicate that RICP causes unevenly current flowing through each in-parallel battery cell, and so the battery cell directly connected to the battery module posts presents the lowest SOC. In order to restrict SOC deviation to an acceptable level, the equivalent relation of the battery inconsistency caused by RICP to the inherent inconsistency is discussed. The reasonable matching RICP is then presented. IIBVMS causes different current leakage in each voltage sampling line. The closer the battery module connects to the positive terminal of a battery pack, the higher leakage current is. The different leakage current in each voltage sampling line exacerbates battery inconsistency and causes different initial SOC for each battery module. The relationship among the leakage current, the input impedance and the number of in-series battery modules are discussed. And an improved schematic diagram of battery module voltage sampling is further presented to lower the leakage current and to solve the sampling time delay caused by the multi-switch.

1. Introduction

Lithium ion batteries have attracted much attention by automobile manufacturers because of their high energy density and long cycle life. As an essential part of electric vehicles (EVs), the performance of a battery pack directly affects the vehicle range, acceleration performance, fuel economy, and energy recovery performance [1]. The basic parameter often used to describe the performance of a battery pack is the state-of-charge (SOC). SOC can provide the crucial information of a battery pack for regulating the design of dis/charging strategy [2]. However, a battery is a sealed chemical energy storage source, and the chemical energy information cannot be directly accessed. Thus, many algorithms for battery SOC estimation are proposed [3,4]. Generally, there are the current integration method combined with the open circuit voltage method [5], the Kalman filter method [6], the sliding mode observer method [7], the recursive least squares method [8] and the neural network method [9].

In application, a battery pack generally consists of hundreds of battery cells connected in parallel or series [10]. Due to inconsistent manufacturing processes and in-homogeneous operating environments, battery cells always have inherent variances which cannot be eliminated [11,12]. These variances result in SOC deviation between individual battery cell and battery pack. The methodology for single battery cell cannot be directly extrapolated to estimate the SOC of a battery pack. Researchers have concentrated on identifying the inconsistent battery cell by voltage difference, internal resistance difference or capacity difference [13–16]. They proposed many methods for battery pack SOC estimation. Dai [13] estimated the SOC of all individual battery cells in an in-series battery pack using a dual time-scale Kalman filtering method. Plett [14] realized battery pack SOC estimation by a ‘bar-delta filtering’ method. Zhong [15] presented a method for battery pack SOC estimation based on battery cell uniformity analysis. Zheng [16] proposed a battery pack SOC estimation method using a mean-different model.

Even so, the accuracy of SOC estimation is still unsatisfactory. In recent years, researchers have recognized that the factors affecting the accuracy of SOC estimation should also been detected. Li [17] pointed out that the initial SOC, coulomb efficiency and

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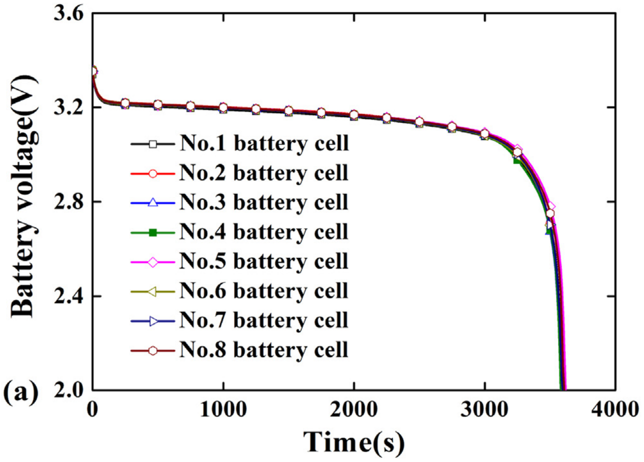
dis/charging efficiency were the most important factors. And the correlation between SOC and coulomb efficiency was in-depth investigated by Zheng [18]. Roscher [19] proposed that the open circuit voltage (OCV) characteristics including the very flat OCV curve and the pronounced hysteresis phenomena was another critical aspect. Plett [14] thought that the current bias caused by the sensor error also needed be considered. Meanwhile, an "enhanced self-correcting" (ESC) model involving the OCV characteristics was involved in the paper. The battery pack topology structure also enlarges the SOC estimation error. Bruen et al. [20] pointed out that the battery inherent inconsistency caused different current flowing through in-parallel battery cell, which led to the SOC deviation among in-parallel battery cells. To solve this problem, Kim et al. [21] introduced a screening process for the improved SOC balancing of battery packs. Through the screening process, the battery cells that have similar electrochemical characteristics were selected.

The distribution of battery inherent inconsistency caused by inconsistent manufacturing processes was considered fitting the normal distribution in previous researches. We chose eight GH–10 Ah $LiFePO_4$ battery cells (3.2 V, 10Ah) for testing. Firstly, the eight battery cells were discharged with 1C (C = battery capacity/1 h) constant current respectively at 25 °C. The measured results, shown in Fig. 1(a), showed that the deviation among them was within 15 mV. Subsequently, the eight single battery cells were connected in-parallel to form a battery module and the battery module posts were connected with No. 1 battery cell. Then, the battery module was discharged with 1C constant current at 25 °C. Our constant current discharge tests showed that the battery voltage decreased gradually from No. 1 to No. 8 battery cell at the same moment. The voltage inconsistency of an in-parallel battery cell presented regular variations, as shown in Fig. 1(b). By analyzing the structure of the battery pack, we found that the resistance of inter-cell connecting plate (RICP) and the input impedance of battery voltage monitoring system (IIBVMS) would restrict the distribution of battery inconsistency. However, previous studies seldom focus on this topic.



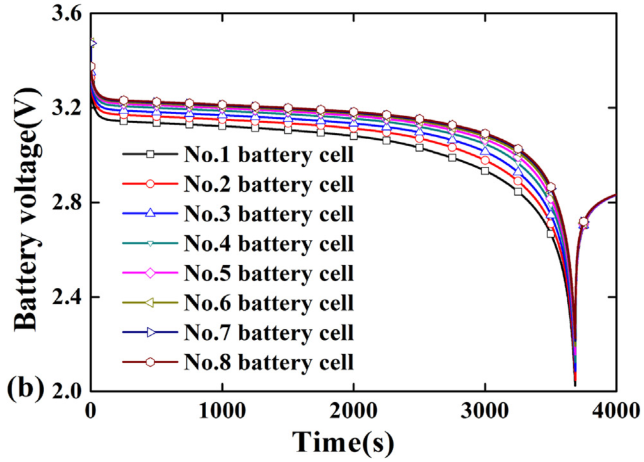


Fig. 1. (a) Voltage-to-time curves for eight battery cells. (b) Voltage-to-time curves for an in-parallel battery module.

In reality, it is difficult to differentiate the battery inconsistency exacerbated by RICP and IIBVMS from the battery inherent inconsistency using experimental methods. Simulation has been found to be an effective methodology to reveal the impacts of RICP and IIBVMS on SOC deviation. Many battery models for capturing the dis/charging behaviors of a battery have been proposed. As a compromise between accuracy and feasibility, the equivalent circuit models have been adopted [22]. Tarun [23] stated that a first or a second RC block equivalent circuit model was feasible and provided sufficient accuracy. Wang [24] proposed that a first RC block equivalent circuit model could be used to describe the dynamic and the steady state characteristics of a battery under testing conditions.

In this paper, a single battery cell model according to the first RC block equivalent circuit model is developed. Subsequently, a "parallel-series" battery pack model is built to verify the effectiveness of the developed single battery cell model. Based on developed battery models, the influence of RICP and IIBVMS on SOC deviation is then discussed. Finally, some rules are suggested to lower the battery inconsistency caused by RICP and IIBVMS.

2. Battery model development

2.1. Battery cell model development

Fig. 2 shows a first RC block equivalent circuit model, where C is the battery capacity, V_{oc} represents OCV, R_0 is the ohmic internal resistance, R_1 and C_1 denote the polarization resistance and capacitance. I is the battery current, V represents the terminal voltage. The critical parameters, C, V_{oc}, R_0, R_1 and C_1, are related to SOC, temperature and current [23].

To perform the simulation, tables describing the relationship of these parameters to SOC, temperature and current need be pre-established and pre-calibrated. The input parameters of the tables, temperature and SOC, are acquired empirically by the following methods. The temperature is evaluated by the energy conservation law and the SOC is estimated by the standard current integration method.

Based on the above tables and methods, each element in the first RC block equivalent circuit model is built separately with the Simscape language. Fig. 3 gives the specific modeling process for R_0

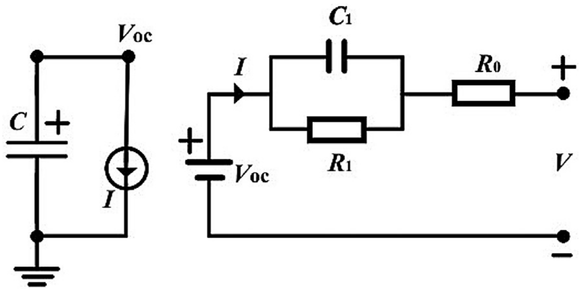


Fig. 2. The first RC block equivalent circuit model.