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Study on battery pack consistency evolutions and equilibrium diagnosis for serial- connected lithium-ion batteries

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HIGHLIGHTS

- Impact sensitivity of parameters variety on energy utilization ratio is analyzed.
- The law of SOC consistency evolutions is deduced for parameter variations.
- The OCV consistency model of the battery pack is proposed.
- The mapping between OCV and SOC distribution of the battery pack is established.

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ABSTRACT

The consistency among lithium-ion battery pack is an important factor affecting their performance. The paper analyzes the impact sensitivity of parameters consistency including capacity, internal resistance and state of charge (SOC) on energy utilization efficiency of the battery pack. It turns out that SOC variations is the most significant influence on battery consistency, and hence is employed as evaluation index to characterize battery consistency level. Then the SOC evolution is explored under four scenarios, and the result reflects that the columbic efficiency is associated with prominent accumulative effect on SOC divergence of the battery group in use. The OCV consistency model is established based on long-term battery data of two trolley buses. It is observed that the fitted results match with the operational data very well. Finally, the mapping relation between the OCV distribution and the SOC distribution of the battery pack using dichotomy method is proposed. The calculation error of battery pack energy utilization efficiency by using such method is within 1.5%, which can be used for battery equilibrium diagnosis and prognosis at a certain aging state.

1. Introduction

To deal with the energy crisis and environmental pollution, vehicle electrification is one of the effective approaches. Since lithium-ion batteries possess high energy density, high terminal voltage, long life and none memory effect [1,2], they are widely used as power sources in electric vehicles (EVs). With the prevailing application of lithium-ion batteries, the durability and safety for battery packs receive more and more attentions from researchers and engineers since the improper usage of batteries will shorten the battery life [3–6] and even sometimes cause severe fire hazards [7,8].

In the practical applications, batteries are usually series connected to form a high voltage battery group in order to meet the power and energy requirements. The inconsistency among battery cells is a key factor influencing the performance of battery packs. Battery inconsistency, which is also called cell to cell variations, origins from two main factors. One happens in the procedure of battery production [9–11], such as coating, ingredients and unevenness of impure contents of batteries which give rise to the difference in the battery initial performance like original capacity, resistance, coulombic efficiency and self-discharge rate. Although such differences are minute, huge variations will occur during the operation of batteries. For example, researchers in Ref. [12] reported that 48 cells from a mass production were tested under equal conditions but a 10% capacity range showed after 1000 cycles due to the production inconsistency. Another occurs in usage. Inconsistency of battery original performance will cause difference in equivalent current rate, SOC usage range among cells. On

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the other side, battery pack thermal distribution is always nonuniform, causing temperature variations among cells. The aforementioned factors will generate variations in SOC and aging (e.g. capacity fade, power fade) of the batteries [13]. The former will influence the utilization efficiency of the battery pack, the latter will impact the maximum available energy of the battery pack. In addition, both of them have an impact on the durability of battery packs. Experimental investigations on battery consistency have been implemented from various perspectives. In Ref. [14], Gogoana et al. reported that there is an additional 40% lifetime reduction when there is a 20% mismatch in the ohmic resistance for parallel connected batteries. During practical operation, the battery inconsistency becomes more and more severe because the temperature ingredient leads to different aging behaviors of batteries [5,6,15–17]. Su et al. [5] reported that batteries were more susceptible to temperature other than discharge current and discharge cutoff voltage. Susana et al. [15] compared the stability of the cathode material of lithium-ion batteries with blended cathode materials under 25 °C and 40 °C, and the experimental results showed that the elevated temperature is detrimental to the long term cycling stability of the cathode. Ganesan et al. developed an electrochemical-thermal coupled model for a battery pack to analyze the battery pack performance under various rates and temperatures. An additional 5% capacity loss of the battery pack was obtained when there is a temperature difference of 15 °C among the cells [18]. Before assembling the battery cells into a practical battery pack, batteries are usually connected in parallel in the first place. According to Ref. [19–21], either the internal resistance or the capacity mismatch would cause an unbalancing current distribution among parallel connected cells. These accelerate the capacity fade of a specific cell in the battery pack.

Battery inconsistency directly influences the energy and capacity utilization efficiency of a battery pack. Different approaches have been developed to reduce inconsistency before battery pack assembling [22,23]. In Ref. [22], experimental charge/discharge voltage signals were analyzed by using discrete wavelet transform-based feature extraction method to select batteries with similar electrochemical characteristics. Although the initial performance of the battery pack was guaranteed, the above method failed to predict the consistency divergence along with usage. For a battery pack without regularly maintenance and balancing, the capacity and energy utilization ratio will be affected by internal resistance [14,19], capacity [24], coulombic efficiency [25–27] and SOC [28] variations of battery cells during the operation. Generally speaking, there are two ways to investigate the impact of the battery pack way on inconsistency. One way is based on all individual cells [9,14,22,23,27,29,30] and another way is to just choose some representative cells in a pack [31]. Jiang et al. [30] developed a novel energy utilization efficiency evaluation method based on the distribution of the capacity. This method took into account the influence of capacity variations but neglected the internal resistance and SOC variations. Moreover, the capacities of all batteries are different in a battery pack. Schuster et al. [9,29] studied the correlation among capacity, the impedance, the researched evolution of capacity and the impedance distribution of battery cells during operation. The aforementioned approach could predict the inconsistency divergence based on experimental results obtained from lab, however, the impedance data was not available on board. Ouyang et al. [31] presented a battery pack capacity estimation method by determining the remaining charging and discharging electric quantities of batteries which are the firstly reached to charge and discharge cutoff voltages respectively. A merit of this method consists in one only needs to pay attention to two specific cells, but the estimation error could be large if the battery group only operates in a small SOC range. In applications, the commonly used battery pack SOC estimation method is to use current integration together with frequently calibration associated with OCV methods [24]. This would lead to a sudden drop or increase of the battery pack SOC when one specific battery voltage reaches beforehand to the cutoff conditions.

The previous studies have achieved notable progresses, but there are also some limitations. One weakness of the existed literature is without considering the online application evaluation and the prediction of battery inconsistency. Most researches analyze the battery inconsistency and its influence on battery packs based on the battery capacity and the impedance. However, it is difficult to measure the impedance on board. Moreover, the online capacity estimation errors of battery cells can be large if battery packs operate in a small and almost fixed SOC range - such as the working conditions of electric buses. Additionally, there is little literature which clearly states and predicts the battery pack performance along with the inconsistency evolution of the battery capacity, the internal resistance, SOC and the coulombic efficiency. Since only the battery voltage, the current and the temperature data are measured on board, effective methods to evaluate the battery pack consistency and predict how the consistency will evolve are urgently needed.

1.1. Contributions of the paper

The paper makes original contributions in the following aspects: (i) Sensitivity analysis of the impact of parameters consistency on energy utilization efficiency of the battery pack is performed. The SOC variation is the most significant influence on battery consistency, and hence is employed as evaluation index to characterize battery consistency level. (ii) The law of SOC consistency evolution is deduced for parameter variations of the capacity, the internal resistance, the columbic efficiency, and the initial SOC. Battery columbic efficiency shows prominent accumulative effect on SOC divergence of the battery group in use. (iii) Two OCV standard deviation models for describing the battery consistency are proposed based on the electric buses operating data, and L-M algorithms are used to identify the parameters. (iv) A mapping relationship between the OCV distribution and the SOC distribution of a battery pack is established by using dichotomy methods, and is applied for battery equilibrium diagnosis.

1.2. Organization of the paper

The rest of the paper is organized as follows. Section 2 introduced the theoretical analysis method of battery consistency. Detailed sensitivity analysis of the impact of the parameters consistency on energy utilization efficiency of the battery pack is described, and one conclude that SOC consistency is the most significant factor on energy utilization efficiency. Battery SOC consistency evolutions under four scenarios are discussed, which shows that columbic efficiency will lead to prominently accumulative effect on SOC divergence. The OCV consistency model of the battery pack and identification algorithm are introduced in Section 3 and the corresponding accuracy is demonstrated. The mapping relationship between the OCV distribution and the SOC distribution of the battery pack using dichotomy method is presented in Section 4. The proposed method is validated by experimental data. Finally, Section 5 summarizes the main findings of this paper and related open issues.

2. Theoretical analysis of battery inconsistency

2.1. Sensitivity analysis of parameters consistency to energy utilization efficiency

At a specified battery aging state, the distributions of parameters such as capacity, internal resistance and SOC will directly