

A novel active equalization method for lithium-ion batteries in electric vehicles



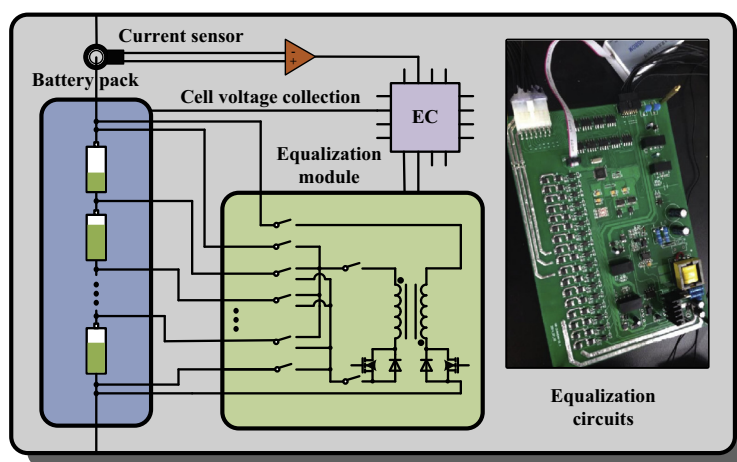
Yujie Wang, Chenbin Zhang, Zonghai Chen^{*}, Jing Xie, Xu Zhang

Department of Automation, University of Science and Technology of China, Hefei 230027, PR China

HIGHLIGHTS

- Build an active equalization method for lithium-ion batteries.
- A bidirectional transformer topology is introduced for active equalization.
- The PF method is used for cell SOC estimation to eliminate drift noise of current.
- The SOC based equalization algorithm is analyzed with different SOC bounds.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:

Received 3 September 2014
Received in revised form 26 January 2015
Accepted 27 January 2015
Available online 25 February 2015

Keywords:

Lithium-ion battery
Cell inconsistency
Active equalization
Remaining capacity estimation
Equalization algorithm

ABSTRACT

Cell inconsistency is inevitable due to manufacturing constraint. Therefore, cell equalization is essentially required. In this paper, we propose a novel active equalization method based on the remaining capacity of cells which is feasible for lithium-ion battery packs in electric vehicles (EVs). The cell models are established based on a combined electrochemical model of lithium-ion batteries. The remaining capacity and state-of-charge (SOC) of cells are observed at the beginning of equalization. The particle filter (PF) method is employed to estimate the cell SOC during equalization in order to eliminate the drift noise of the current sensor. The first high-SOC cell discharge (FHCD) and first low-SOC cell charge (FLCC) equalization algorithms are proposed and compared with 1% and 3% SOC bounds, respectively. The validation experiment results have shown that the proposed algorithm is suitable for equalization of lithium-ion batteries in EVs.

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1. Introduction

Anxieties of environment deterioration and global energy resources depletion force traditional vehicles to be cleaner. Electric

^{*} Corresponding author. Tel.: +86 055163606104.
E-mail address: chenzh@ustc.edu.cn (Z. Chen).

vehicles (EVs) are gradually accepted by people as they are zero-emission and environmentally friendly transports. In EVs, hundreds to thousands of cells are connected in series and parallel to provide sufficient power. Inconsistencies in cells are concerned due to the inconsistent manufacturing process and the inhomogeneous operating environment [1]. Significant degradation of maximum release capacity, energy density and life cycles can be observed

after pack construction due to cell variations [2]. Therefore equalization technology is necessary for the energy or battery management system (EMS/BMS).

In recent years, the equalization topologies and algorithms for lithium-ion battery packs are studied in order to mainly keep the remaining capacity of the cells balanced and extend their lifetime [3–8]. The equalization topologies can be divided into two main groups: passive equalization methods and active equalization methods. The fixed shunting resistor method is one of the most common used passive method which uses a resistor in parallel with each individual cell. The current is partially bypassed from the cells in order to limit the cell voltage. Therefore current is continuously bypassed and battery energy is continuously wasted through this method. The active equalization methods are proposed which use external circuits to actively transport the energy among cells [3,4].

Regardless of the equalization topologies, appropriate equalization algorithms are required to maximize the equalization efficiency. According to the literatures [5–9], the equalization algorithms can be divided into two categories: voltage based and state-of-charge (SOC) or capacity based equalization algorithms. Voltage based equalization algorithms [5–7] are extensively adopted in most real-time systems. The SOC based equalization algorithms [8,9] require accurate remaining capacity and cell SOC estimation which is more suitable for lithium-ion batteries. This is because the charge/discharge curves of lithium-ion batteries are nonlinear, a small voltage variation may have a large capacity inconsistency especially at the flat charge/discharge plateau. Many methods have been proposed in literatures for accurate SOC estimation. Plett [10–12] applied the EKF method for SOC estimation and believed that high-fidelity cell models are required to estimate accurate SOC. He et al. [13] proposed a new working model that takes the drift current as a state variable to eliminate the effects of drift noise in SOC estimation. Zhong et al. [9] analyzed the relationship between the pack SOC and the in-pack cells under different equalization conditions and proposed a method for battery pack SOC estimation. Liu et al. [14] developed a temperature-compensated battery model and employed a dual particle filter for SOC estimation. More researches on accurate SOC estimation can be found in our previous works [15–20].

Along this paper, a novel active equalization method is proposed for the lithium-ion batteries in EVs based on the

SOC-Particle Filter (SOC-PF) algorithm. This paper is organized as follows: In Section 2, 12 series of LiFePO₄ cells are chosen from an urban electric bus. The cell inconsistencies are analyzed with a dynamic charging current profile. In Section 3, a bidirectional active equalization topology is first introduced. We subsequently propose a SOC based equalization algorithm based on particle filter. In Section 4, the first high-SOC cell discharge (FHCD) and first low-SOC cell charge (FLCC) equalization algorithms are proposed and compared with 1% and 3% SOC bounds, respectively. The numerical results have shown that the proposed algorithms are suitable for equalization of lithium-ion batteries in EVs.

2. Lithium-ion cell inconsistency analysis with dynamic charging current profile

In EVs, equalization circuits are used to discharge the cells with higher SOC to the battery pack and charge the cells with lower SOC from the whole battery pack to extend range and avoid early cut off. Identification of cell voltage and SOC inconsistency for lithium-ion battery pack is challenging due to the relatively flat SOC-OCV curves of lithium-ion cells compared to other kinds of batteries [1]. We experimentally investigate the cell voltages of 12 series IFP1865140-type cells from an urban electric bus which are developed by Hefei Guoxuan High-Tech Power Energy CO. Ltd. of China. The cells are selected to compose a small battery pack for experimental investigation with the nominal capacity of 12.5 A h. The dynamic charging current profile is shown in Fig. 1(a). Fig. 1(b) shows the pack SOC which is determined by the maximum remaining capacity cell during charging and minimum remaining capacity cell during discharging.

As can be seen from Fig. 1(c) and (d) the cell charging voltages (CCVs) of 12 series cells are different during the charging process. The average of maximum voltage difference during charging and resting are 15 mV and 5 mV. It is worth noting that the total voltage variation from 20% to 80% SOC is usually under 0.2 V. Meanwhile, the dynamic voltage varies dramatically when the charging current changes. The CCVs based equalization method is easy to cause over-equalization due to the flat OCV curve and voltage plateaus in large SOC ranges. Therefore we propose a SOC based equalization algorithm which is more applicable to lithium-ion batteries.

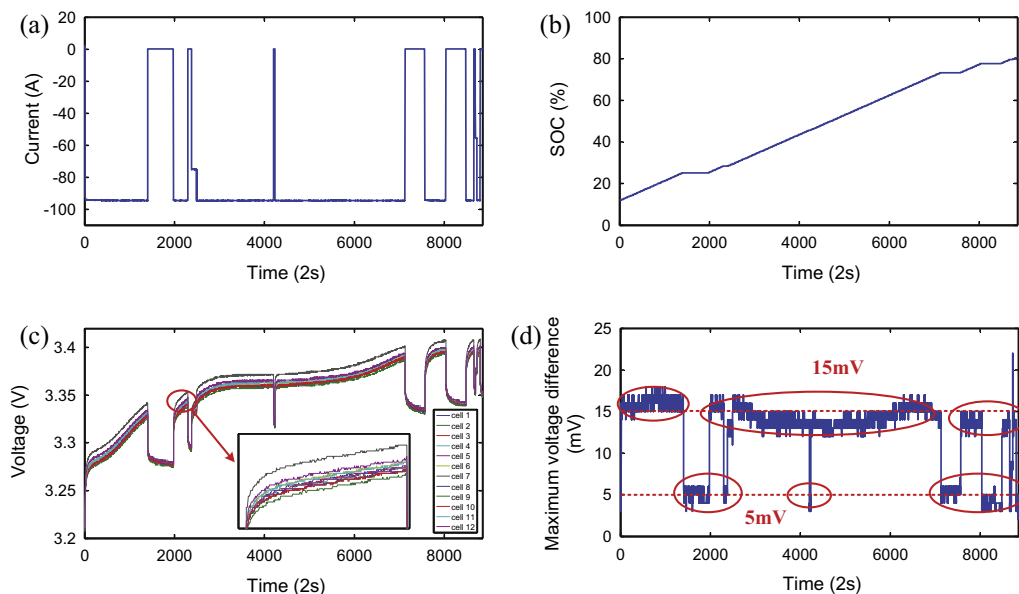


Fig. 1. Lithium-ion battery charging experiments: (a) dynamic charging current. (b) Pack state-of-charge. (c) CCVs of 12 series batteries. (d) Maximum voltage difference of the 12 series cells.

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