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Adaptive state of charge estimator for lithium-ion cells series battery pack in electric vehicles

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HIGHLIGHTS

- A bidirectional resistor based lumped parameter equivalent circuit model is proposed.
- Cells imbalanced parameters are analyzed and used for cells filtering approach.
- Cells filtering approach for ensuring voltage/SoC balancing is proposed.
- Cells series connected battery pack model is built and evaluated by cell unit model.
- Battery pack's SoC is accurately estimated by AEKF-based method with unit model.

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ABSTRACT

Due to cell-to-cell variations in battery pack, it is hard to model the behavior of the battery pack accurately; as a result, accurate State of Charge (SoC) estimation of battery pack remains very challenging and problematic. This paper tries to put effort on estimating the SoC of cells series lithium-ion battery pack for electric vehicles with adaptive data-driven based SoC estimator. First, a lumped parameter equivalent circuit model is developed. Second, to avoid the drawbacks of cell-to-cell variations in battery pack, a filtering approach for ensuring the performance of capacity/resistance conformity in battery pack has been proposed. The multi-cells "pack model" can be simplified by the unit model. Third, the adaptive extended Kalman filter algorithm has been used to achieve accurate SoC estimates for battery packs. Last, to analyze the robustness and the reliability of the proposed approach for cells and battery pack, the federal urban driving schedule and dynamic stress test have been conducted respectively. The results indicate that the proposed approach not only ensures higher voltage and SoC estimation accuracy for cells, but also achieves desirable prediction precision for battery pack, both the pack's voltage and SoC estimation error are less than 2%.

1. Introduction

Energy crises, environmental issues and concerns regarding peaking oil production have promoted research into development of various types of electric vehicles (EVs), which has been established as one of the seven strategic emerging industries in China. In recent years, lithium-ion batteries have attracted special attention for EVs applications because of the high power density, high energy density and long lifetime [1,2]. In order to satisfy the operation voltage and traction power requirements of various EVs, low voltage lithium-ion cells are generally connected in series, parallel or series/parallels to construct a stable lithium-ion battery pack. In such applications, a battery management system (BMS) is critical for maintaining optimum battery performance and ensuring safety in EVs. The most important key function of the BMS is to monitor the State of Charge (SoC) from a model-based estimation algorithm for the cells strung lithium-ion battery pack [3–6]. Accurate SoC estimates improve the power distribution efficiency and extend the batteries' expected life greatly. Unfortunately, due to cell-to-cell variations in the battery pack, it is hard to model the battery pack accurately. As a result, accurate SoC estimation for battery pack remains very challenging and problematic.

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An assortment of techniques has previously been reported to measure or estimate the SoC of the cells or battery packs, each having its relative merits, as reviewed by Xiong et al. [7]. The most common method is the ampere-hour (Ah) integral/counting method, which is based on both current measurement and integration [8]. However, its performance is highly dependent on the measuring accuracy of current, and this open-loop calculation method can easily lead to accumulated calculation errors due to uncertain disturbances from the practice application and lack of necessary corrective resolution. Therefore, the method that is often recalibrated by the equilibrium open circuit voltage (OCV) method [6], the support vector based estimators [9], the artificial neural networks (ANNs) and fuzzy logic principle based estimations [10,11], sliding mode observer [12], the extended Kalman filtering (EKF) based estimators [13–17] and others [18,19]. Most of the methods have been widely used and made acceptable achievements in different applications.

A common drawback of the above methods for the battery packs is that the difference between each individual battery cell has been ignored and the work mainly focuses on estimating the SoC for a battery "cell". As we know, for the vehicular operation, due to the voltage and power/energy requirements, the battery systems are usually composed of up to hundreds of cells connected in series or parallel. The battery system has less available capacity when the cells in the battery pack are not balanced. Specifically, the weakest cell limits the discharge capacity of an imbalanced battery pack. During the discharge and charge operation, the weakest cell will reach the minimum discharge level and the maximum charge level before the rest of the cells [20,21]. As a result, this parameter variation among the cells makes "pack model" and "pack state" values hardly providing sufficient information, which at last affects the prediction precision of available energy and power and even damages the battery systems.

So for a reliable and accurate battery management, the BMS should calculate each individual cell's state and use the lowest SoC to avoid the over-discharge and use the highest SoC to avoid the overcharge condition. One possible solution is to design an estimator which works well for estimating single cell SoC, and to replicate the estimator N times to estimate all SoCs for the N cells in a battery pack [22]. However, due to limited computing ability of an automotive embedded system, it is hard to implement online calculations for N cells. Kim et al. [17] proposed a method to improve SoC estimation of a lithium-ion battery pack based on a screening process, which in some degree guarantees the uniformity of the cells, and makes it possible to be used in BMS. One of the limitations of the method is that, in actual operation, the method will reduce the acceptance proportion of tested cells, most of the cells have been eliminated, only two or three of twenty have been chosen. Another limitation is the variance threshold of the cells is not discussed, which is very important for improving the acceptance proportion. Last is the EKF-based SoC estimator is vulnerable to divergence from imbalanced cells behavior. Dai et al. [20] introduced a dual time-scale EKF based cells SoC estimation method with an "averaged cell" model. The result indicates the good performance of the algorithm. However, one of the limitations of the method is that, in actual using, the computation cost is higher. More importantly, there are some problems required to be solved before the dual-EKF applied to practical application. Roscher et al. [21] introduced a reliable state estimation of multi-cell lithium-ion battery systems, by which cell impedance and SoC variations could be detected precisely. However, the detailed process of how to determine the tunable correction gain was not discussed in the paper. In additional, this work also requires a prohibitive level of computation for battery systems. Plett [22] explored a cute method called "bar-delta filtering" which took advantage of the fundamental similarity between all series connected cells in a pack and could estimate SoC, resistance and capacity of each cell in a manner requiring only somewhat more computational effort than that for a single cell. Aiming at SoC estimation for lithium-ion battery pack of multi-cells in series, Liu et al. [23] proposed a minimal cell load voltage (V_{min}) of the battery pack based SoC estimation method. With EKF algorithm, the dynamic state estimation of SoC is realized. However, V_{min} model-based method ignored the problem of overcharge from the cell with maximum terminal voltage. Another limitation is "V_{min}" cell not always the cell with lowest capacity in the battery pack; as a result, the SoC prediction error will be larger in this situation.

In this study, aiming at reliable and accurate SoC estimation for lithium-ion battery pack of multi-cells in series, on one hand, based on the lumped parameter equivalent circuit model, the unit model is proposed and used for estimating the terminal voltage and state for cells having similar electrochemical characteristics: similar capacity, resistance and other characteristics. The unit model is also employed for estimating the battery pack's voltage and state; on the other hand, a systematic cells filtering approach is proposed for choosing cells with similar electrochemical characteristics, afterward the chosen cells are assembled to a series connected battery pack. Through the filtering process, the cells that have similar electrochemical characteristics are finally chosen, and each cell can be used as a unit model. This approach has the potential to eliminate the drawbacks of cell-to-cell variations and reduce the influence of EVs from the imbalanced battery cells and packs. As a result, the performance of the battery pack which has good capacity/resistance conformity can be described with a cell unit model. At last, we can use the unit model to estimate the state of the battery system. However, the filtering threshold is crux for improving the choosing intensity of the tested cells. Additionally, the adaptive extended Kalman filter (AEKF), which can improve the prediction precision by adaptively updating the process and measurement noise covariance, is applied to estimate the battery pack's SoC with the cell unit model.

The remainder of the paper is organized as follows. Section 2 shows the main imbalanced parameters of cells and the basic concept of the filtering approach, which is used for filtering the cells having similar electrochemical characteristics, and at last a detail flowchart for filtering approach is presented. In Section 3, a cells series connected battery pack model is build based on the cell lumped parameter equivalent circuit unit model and then the AEKF-based SoC estimator is proposed for estimating the state of battery pack through the unit model. Section 4 describes the cells test, as a case, a total of 20 lithium-ion polymer battery (LiPB) cells are used for carrying out the cells filtering process. Section 5 evaluates the estimation accuracy of AEKF-based battery SoC estimator for estimating the battery pack's terminal voltage and SoC. Specifically, in order to compare the SoC estimation accuracy for chosen cells series connected battery pack and the other cells series connected battery pack and to evaluate the filtering approach, the dynamic stress test-based comparative simulations are conducted and the estimation results suggest that the proposed approach is reliable. In the final section, some conclusions and final remarks are given.

2. Cells filtering approach

2.1. Cells inconsistent characteristic parameters

In general, the more numbers of the cells connected in battery systems, the greater of the difference exist in cells parameters. What's worse, the differences in cells' performance caused by the manufacturing chain coupling with the operation conditions of the