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# System state estimation and optimal energy control framework for multicell lithium-ion battery system

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## HIGHLIGHTS

- Employed a dual-scale EKF based estimator for in-pack cells' SOC values.
- Proposed a two-stage hybrid state-feedback and output-feedback equalization algorithm.
- A switchable balance current mode is designed in the equalization topology.
- Verified the performance of proposed method under two conditions.

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## ABSTRACT

Cell variations caused by the inevitable inconsistency during manufacture and use of battery cells have significant impacts on battery capacity, security and durability for battery energy storage systems. Thus, the battery equalization systems are essentially required to reduce variations of in-pack cells and increase battery pack capability. In order to protect all in-pack cells from damaging, estimate battery state and reduce variations, a system state estimation and energy optimal control framework for multicell lithium-ion battery system is proposed. The state-of-charge (SOC) values of all in-pack cells are firstly estimated using a dual-scale extended Kalman filtering (EKF) to improve estimation accuracy and reduce computation simultaneously. These estimated SOC values provide specific details of battery system, which cannot only be used to protect cells from over-charging/over-discharging, but also be employed to design state-feedback controller for battery equalization system. A two-stage hybrid state-feedback and output-feedback equalization algorithm is proposed. The state-feedback controller is firstly employed for coarse-grained adjustment to reduce equalization time cost with large current. However, due to the inevitable SOC estimation errors, the output-feedback controller is then used for fine-grained adjustment with trickle current. Experimental results show that the proposed framework can provide an effectively estimation and energy control for multicell battery systems. Finally, the implementation of the proposed method is further discussed for the real applications.



## 1. Introduction

Lithium-ion batteries (LIBs) are widely used in energy storage systems for their high-energy density, long service life and environmental friendliness. An assortment of researches about LIBs have been proposed in recent years. For instance, Zheng et al. [1] presented a co-estimation method to estimate state of charge (SOC), capacity and resistance by trinal PI observers. Weng et al. [2] proposed a new framework based on incremental capacity analysis to monitor state of health (SOH) on-board for battery packs. Wei et al. [3] developed a novel technique which integrated the Frisch scheme based bias compensating recursive least squares (FBCRLS) with a SOC observer for enhanced model identification and SOC estimation. Since one single cell has limited voltage and capacity, hundreds or thousands of cells are series/parallel-connected to meet high-energy and high-power application requirements, which coupled with a series of safety, uniformity and durability issues [4]. In order to maintain optimum battery performance, a battery management system (BMS) is critical for battery system [5]. The safety, discharge efficiency and cycle life of the battery are the most important issues in the development of electric vehicles (EVs) and hybrid electric vehicles (HEVs) [6]. However, due to the inconsistency of in-pack cells, the battery SOC must be considered for each battery cell individually. The

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available capacity of the battery pack will also be reduced. Furthermore, various operating conditions among different cells, such as the environmental temperature, external stress state will apparently increase inconsistency among the series-connected cells along with the battery operating time, which will result in premature cells degradation and safety hazard [7]. Therefore, every in-pack cells' SOC should be estimated firstly to monitor the battery charging and discharging operations, and optimal energy controller must also be designed to balance inconsistency of in-pack cells, which will improve energy efficiency and extend their service life.

In recent years, an assortment of techniques has been proposed in order to achieve accurate battery SOC estimation [8]. The most common method is the ampere-hour (A h) counting method, which is based on both current measurement and integration [9]. However, its performance is highly dependent on the initial SOC value and the measuring accuracy of current. The method that is often recalibrated by the open circuit voltage (OCV) method [10], the support vector based estimators [11], the fuzzy logic principle [12] and artificial neural networks [13] based estimation and the extended Kalman filter (EKF) based estimators and others [14–16]. However, a common drawback of the above methods is that the work mainly focuses on SOC estimation issues of single cell and the differences among individual battery cell have been ignored. To overcome this problem, Zhong et al. [17] developed a new definition for pack SOC considering the difference among the cells and the impact of balance control. However, in order to maintain optimum battery performance and ensure safety in EVs/HEVs, all in-pack cells' SOCs must be available. The simplest solution is to develop an estimator which works well for estimating single cell SOC, and to duplicate the estimator N times to estimate all SOCs for a battery string with N cells [18]. Nevertheless, it is a heavy task for micro-controller to estimate SOC value of each individual cell using accurate estimator at each sampling time. For the sake of simplifying the SOC estimation of all in-pack cells, an assortment of possible solutions has previously been proposed in the past few years. Dai et al. [19] has developed a method based on EKF which uses the current and "average cell" voltage to determine the battery pack's average SOC at first, and thereafter incorporate the performance divergence between the "average cell" and each individual cell to generate the SOC estimation for all cells. Zheng et al. [20] has proposed a mean-plus-difference model for battery pack, where the mean model represented the whole pack and difference model investigated inconsistency among every single cell. The above cases have made valuable contributions for battery pack SOC estimation considering the battery inconsistence in a pack. To reduce computation cost and ensure reliable operations, Sun et al. [21] have explored a dual-scale cell SOC estimation approach for series-connected battery pack which uses the filtering process to select the cell to represent the whole behavior of battery pack, and uses micro time scale to estimate the SOC of the selected cell and macro time scale for the unselected cells. This approach could effectively reduce computational complexity. However, for reliable and accurate battery management, the BMS should use the lowest SOC to avoid over-discharging and the highest SOC to avoid over-charging. Besides, the highest and lowest SOC can be used as input of state-feedback controller of equalization system. Therefore, to estimate all in-pack cells' SOCs accurately, especially the highest and lowest SOCs, a dual time scales based cell SOC estimation approach for series-connected battery pack is employed in this paper. The micro time scale is used to estimate the highest and lowest SOC values. Namely, these SOCs are estimated at each sampling interval. The macro time scale is used to update other cells' SOCs which are estimated for a certain longer sampling intervals. Through the dual time scales, the computation cost can be greatly reduced.

Despite the state estimation issues of all in-pack cells, the energy imbalance phenomena will result in available capacity loss and rapid decline in cycle life of battery pack. Therefore, equalization systems have been designed in order to prevent imbalance phenomena and to optimize the energy allocation. A number of equalization topologies have been proposed to balance battery energy, as reviewed in Ref. [22]. Among them, the non-dissipative equalization topologies employ no dissipative charge-shutting elements or voltage/current converters to move energy from one cell to another, which are featured with lower energy loss and thus have attracted much attention. A bidirectional flyback transformers-based equalization topology is employed in this paper. Furthermore, appropriate equalization algorithms must be constructed based on the equalization topology. According to the different control objectives, these algorithms can be divided into two categories, i.e. output-feedback control and state-feedback control. Output-feedback control algorithms target the consistent terminal voltages [23,24], which are most feasible to realize because the voltages are directly measured. However, the output-feedback algorithms cannot eliminate the inconsistency of inner impedance. Cells with higher impedance among all of the cells included will reach higher terminal voltages during charging and lower terminal voltages during discharging. Analogously, cells with lower impedance will reach higher terminal voltages during discharging and lower terminal voltages during charging. Besides, the effect of inconsistency of inner impedance will expand when the balance current become large. The state-feedback algorithms target the consistent SOCs [25,26], whose benefit is that all the cells' SOCs are equivalent to the pack's SOC when each cell's SOC is consistent. Thus, the cells are allowed to fully charged/discharged at the same time, by which the inconsistency of impedance and the battery aging caused by different depth of discharge (DOD) of each cell can be eliminated. Unfortunately, the SOC estimation errors are inevitable. Aiming to reduce balance time and improve energy efficiency, a two-stage hybrid state-feedback and output-feedback equalization algorithm is proposed in this paper. The state-feedback controller is firstly employed for coarse-grained adjustment to reduce equalization time cost with large current, and the output-feedback controller is then used for fine-grained adjustment with trickle current to suppress the effects of battery inner resistor and inevitable SOC estimation errors. What's more, a switchable balance current mode is designed in the proposed topology, where the discharge/charge current can be switched by the primary and secondary series resistances of flyback transformers.

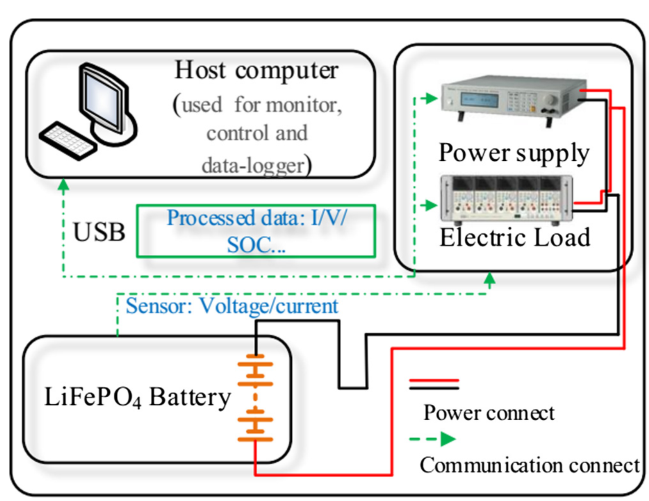


**Fig. 1.** Battery test bench.