Interval method for an efficient state of charge and capacity estimation of multicell batteries

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ABSTRACT

Concerning large battery systems, the estimation of pack state of charge and state of health remains a challenging problem which needs to be solved under limited computational resources of a battery management system. Instead of multiplicating the existing model-based techniques for individual cells, a novel method is proposed which aims at effectively and reliably determining the pack conditions for cells connected in series. In order to realize an accurate estimation, definitions of pack SOC and pack capacity are carefully studied first. Due to the fact that a battery pack is usually restricted by the two cells with maximum and minimum voltage during the charging and discharging process, respectively. The investigated approach computes the battery SOC by considering the voltage limit of a battery pack, regardless the number of cells. In this way, a trade-off between the accurate knowledge of all cells and the real-time capability is presented. In order to fulfill the task of verification, different approaches such as simulation with modeled cell variation, offline validation with measured data, and online test with a battery module are conducted. The state estimation for battery pack show convincing results in the entire operating range, while the computational complexity can be significantly reduced.

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1. Introduction

Lithium-ion batteries provide a high energy and a high power density compared to other technologies such as lead-acid or nickel-metal hydride, making them preferable for a variety of devices from portable electronics to electric vehicles. Single battery cells operate in a specific voltage range depending on the various active materials which are typically metal oxides ($LiCoO_2$, $LiMn_2O_4$) or metal phosphates ($LiFePO_4$) on the positive and graphite on the negative electrode. Furthermore, single battery cells have limitations in terms of charging and discharging current. Therefore, it is necessary to provide a large number of cells to fulfill the specifications. For this purpose, cells are usually connected in series[1] to provide the desired system voltage. The high voltage configuration (up to 400 V with around 100 cells in series) can match the voltage range of power electronics for an efficient operation, reduces the overall battery current, and therewith the

wire cross-section. Among the key features of battery systems, a reliable and safe application of energy storage is primarily important. To achieve these goals, advanced algorithms for battery monitoring, including state of charge (SOC) and state of health (SOH) estimation are increasingly required.

In the field of state estimation for a single cell, a number of methods ranging from Coulomb counting to open-circuit voltage (OCV) based estimation approaches are proposed [4–6]. These techniques are often used in combination with other techniques due to the fact that the SOC-OCV characteristic changes only slightly over the battery lifetime. Model-based approaches such as Kalman filtering [7–10] and particle filtering [11,12] are further applied to take the various uncertainties of the estimation into account. In addition, battery states can also be determined by methods of machine learning. In [13,14], monitoring algorithms using support vector machines and artificial neural networks are investigated. Such approaches rely on a training process associated with battery input and output variables and can result in high computational costs.

Concerning a large battery system with a low-cost battery management system (BMS) and the existence of cell-to-cell variation, efficient algorithms for monitoring the pack conditions have to be applied. In [34], a state estimation accuracy of 5%-8% is
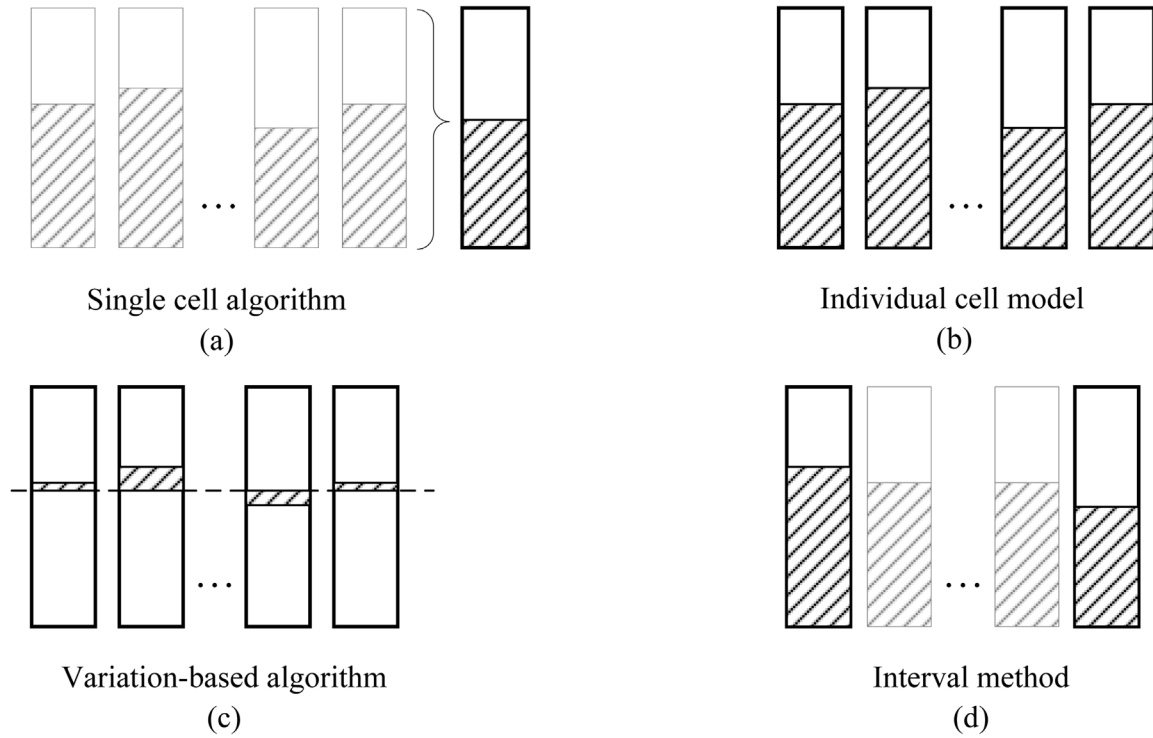

Fig. 1. Classification of state estimation for multicell battery systems.

demanded for the usage in electric vehicles, the accuracy of estimation design in this work is specified to less than 5% for battery pack estimation.

In this work, an efficient method for on-line battery state of charge and capacity estimation is proposed. In case of series connection,[2] the approach computes the pack states by considering the voltage limit of a battery pack, regardless the number of cells. A trade-off between the accurate knowledge of all cells and the real-time capability is presented. The paper is organized as follows: Section 2 provides an overview over existing techniques for battery state estimation. Their advantages and disadvantages are discussed. Additionally, motivation for a new approach is given. In Section 3, key issues and the various mathematical definitions for a battery pack are elaborated, considering the cell variations in a battery pack. Section 4 focuses on the development of the proposed algorithm for pack estimation. The experimental details and the corresponding results are discussed in detail in Section 5. Finally, Section 6 provides a summary of the contribution.

2. Existing algorithms for pack estimation

As mentioned above, critical aspects that must be considered in a battery system are cell-to-cell variations and limited computing resources of the battery control unit. The former exist inherently and can be caused by several factors, either intrinsic (mainly due to the tolerances in manufacturing process [1]) or extrinsic (caused by variations in cell operating conditions, such as local current density [2] and temperature inhomogeneity [3] within a battery pack) to the cell properties. As a result, cells are primarily imbalanced in the cell voltage, impedance, SOC, and capacity. In order to prevent the battery from critical operating conditions and to improve battery pack performance, effective algorithms for

detecting pack states need to be studied. In Fig. 1, possible estimation approaches for large battery systems are shown, which can be divided into four groups.

- In the simplest case, the entire energy storage system can be treated as one single cell (Fig. 1(a)) with a high voltage and a large capacity [15]. Estimation approaches used for single cells can be thus directly implemented. Due to the fact that the approach is not able to describe the cell variations and to identify the single cell operation range, further techniques for multicell state estimation are developed, most of which provide the solution for the consideration of single cell characteristics.

- As an improvement, individual cell models can be applied separately for each cell in a battery pack [16,17] and estimation approaches are thereafter multiplicated to a battery system, as shown in Fig. 1(b). Though this method can achieve the best performance in terms of estimation accuracy, the disadvantage is that this requires high computing power since the model parameters must be optimized for each cell. Especially for estimation algorithms such as sigma point Kalman filter [8] and particle filter [11], when additional particles are computed to reconstruct the SOC, the computational effort is scaled up at the same time. Due to the increasing functions per control unit, optimization on computational efficiency has become more demanding.

- The algorithms of the third group illustrated in Fig. 1(c) focus on the variations between the multiple cells. In [18], cell inconsistency of a Li_2MnO_4 pack is studied, where the battery average SOC is estimated at first and SOC variations are achieved based on the OCV difference. However, the characteristic map of delta SOC-OCV needs to be established offline. Furthermore, approaches proposed in [19–21] take the difference of internal resistance into account. As a result, voltage deviations between cells can be presented more precisely by the SOC differences. However, the disadvantage is that the computational effort is

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[2] Cells connected in parallel are not considered in this work.