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Review article

Investigating the error sources of the online state of charge estimation methods for lithium-ion batteries in electric vehicles

Yuejiu Zheng[a,b,*], Minggao Ouyang[b,**], Xuebing Han[b], Languang Lu[b], Jianqiu Li[b]

[a] College of Mechanical Engineering, University of Shanghai for Science and Technology, Shanghai 200093, PR China
[b] State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing 100084, PR China

HIGHLIGHTS

- SOC estimation methods are reviewed with general merits and demerits.
- New perspective with focus on error analysis of SOC estimation methods is proposed.
- Using error flow charts to analyze SOC error sources from models to algorithms.
- Choosing more reliable and applicable SOC estimation methods is discussed.
- Future development of the promising online SOC estimation methods is suggested.

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ABSTRACT

Sate of charge (SOC) estimation is generally acknowledged as one of the most important functions in battery management system for lithium-ion batteries in new energy vehicles. Though every effort is made for various online SOC estimation methods to reliably increase the estimation accuracy as much as possible within the limited on-chip resources, little literature discusses the error sources for those SOC estimation methods. This paper firstly reviews the commonly studied SOC estimation methods from a conventional classification. A novel perspective focusing on the error analysis of the SOC estimation methods is proposed. SOC estimation methods are analyzed from the views of the measured values, models, algorithms and state parameters. Subsequently, the error flow charts are proposed to analyze the error sources from the signal measurement to the models and algorithms for the widely used online SOC estimation methods in new energy vehicles. Finally, with the consideration of the working conditions, choosing more reliable and applicable SOC estimation methods is discussed, and the future development of the promising online SOC estimation methods is suggested.

1. Introduction

With the increasing focus on the environmental protection and energy conservation, new energy vehicles (NEVs) have been extensively investigated during the past decade. Among various types of NEVs, hybrid electric vehicles (HEVs), Plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) are the most popular [1,2]. They all implement the battery-motor system as the auxiliary or the main power source (HEVs, PHEVs and FCEVs) or the unique power source (BEVs) [1]. Lithium-ion batteries (LiBs) are now the most promising batteries to construct the battery-motor system owing to their favorable performances in energy density, lifespan and energy efficiency. Battery management system (BMS) is essentially required to keep LiB packs working safely and efficiently [3].

Sate of charge (SOC) estimation is generally acknowledged as one of the most important functions in BMS and is thus widely studied by academia and industry. However, a consensus has not been reached on the definition of SOC [4]. SOC is generally defined as the ratio between the available capacity and the reference capacity [3–6]. The reference capacity commonly refers to the current maximum capacity the battery can release at a constant current rate and a specific ambient temperature as the manufactory suggests. Hence, the reference capacity is almost invariant if the time scale is small and battery ageing is accordingly ignored. Unfortunately, when LiBs work in various ambient temperatures and with different current rates, we get different available

* Corresponding author. College of Mechanical Engineering, University of Shanghai for Science and Technology, Shanghai 200093, PR China.
** Corresponding author.
E-mail addresses: yuejiu.zheng@gmail.com (Y. Zheng), ouymg@tsinghua.edu.cn (M. Ouyang).

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capacities [7]. If the above definition is used, SOC could be different when the current rate and the ambient temperature change.

Nevertheless, because SOC represents a charge "state", the working condition theoretically has no influence on SOC if LiBs are not charged or discharged. It means that if the battery SOC is 50% at room temperature, it should remain 50% at −10 °C. It also implies that when a LiB cannot deliver power at −10 °C, its SOC could be greater than 0. This is not weird because one may confuse the concepts between SOC and state of function (SOF, also known as state of power, SOP) which indicates the power can be released from the battery at the current situation.

We believe SOC definition having no relevance to the working conditions could be more reasonable. From the battery point of view, the main reaction at the negative electrode is

$$\mathrm{Li}_x\,\mathrm{N} \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftarrows}} x\mathrm{Li}^+ + xe^- + \mathrm{N} \tag{1}$$

where N is the active negative electrode material and x represents Li amount in the negative electrode. Similarly, the main reaction at the positive electrode is

$$y\mathrm{Li}^+ + ye^- + \mathrm{P} \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftarrows}} \mathrm{Li}_y\mathrm{P} \tag{2}$$

where P is the active positive electrode material and y represents Li amount in the positive electrode. The change of Li amount in the positive electrode is proportional to that in the negative electrode. Therefore, the Li amount in the negative electrode x can be used to measure battery SOC [8,9]. For the electrodes, the Li amount should be in the range that no Li deposition happens due a high Li amount x in the negative electrode (noted as $x_{\max}$), and also no positive electrode distortion due to a high Li amount y in the positive electrode (which means a low Li amount x in the negative electrode, noted as $x_{\min}$) [10]. The reference battery capacity can be defined as the electric charge of the electrons released from $x_{\max}$ to $x_{\min}$ in equation (1). And when the Li amount is x, SOC can then be calculated as

$$SOC = \frac{x - x_{\min}}{x_{\max} - x_{\min}} \tag{3}$$

Equation (3) also suggests that the exact SOC definition from the battery point of view has no relevance to the environment, but is directly related to the Li amount in the negative/positive electrode.

However, we are not able to measure the Li amount, neither can we exactly know the maximum and minimum Li amount. Though the Doyle-Fuller-Newman model can be used to estimate Li amount, it is usually too complicated for online applications. Fortunately, this model points out that, for the same battery system, when the LiB is discharged to the cut-off voltage at a specific condition (such as 1/3C[1] at 25 °C, and given sufficient time for a stable polarization in the LiB), the distribution of the lithium concentration on the positive and negative electrodes is almost unchanged. It means that the Li amount in the negative electrode is approximately constant when it reaches the cut-off voltage with a constant current discharge of 1/3 C at 25 °C. The Li amount can then be considered as the minimum value $x_{\min}$ allowed by the manufacturers. When the LiB is charged, the similar result happens and the Li amount reaches the maximum value $x_{\max}$. Therefore, from the engineering point of view, the rated capacity is the capacity when the Li amount increases from $x_{\min}$ to $x_{\max}$ in the negative electrode. Hence, the Li amount from x to $x_{\min}$ in the negative electrode can also represent the capacity discharged to the cut-off voltage with a constant current discharge of 1/3 C at 25 °C. Correspondingly, SOC should be defined as the ratio between the available capacity at the standard discharge and the reference capacity. The "available capacity" in the SOC definition should be defined as the capacity discharged to the cut-off voltage with a constant current discharge of 1/3 C at 25 °C rather than an "available capacity" that may vary with temperature and current.

Accurate SOC estimation in NEVs has many advantages:

(1) Parameters of the LiB modeling change with SOC. An accurate SOC can provide accurate parameters according to the SOC-parameter look-up tables, and thereby the model can better simulate the LiB.
(2) For all types of NEV battery systems, accurate SOC estimation can prevent the battery from over-charge and discharge, and therefore ensures the battery system safety, extends battery life and makes use of the limited energy more efficiently.
(3) For BEVs and PHEVs in pure electric drive mode, accurate SOC estimation can support the accurate estimation of the driving range.
(4) For BEVs and PHEVs, better charging strategy, which may improve battery life, and efficient vehicle-to-grid strategies [11] could be developed with the knowledge of the accurate SOC.
(5) For FCEVs, HEVs and PHEVs in hybrid mode, accurate SOC estimation can be used for a more reasonable vehicle energy management strategy, which improves the efficiency of other power sources.
(6) SOC estimation of the single cells is an important indicator for balancing strategies, and an accurate SOC obviously makes balancing strategies work more effectively.

SOC cannot be directly measured, but we may calculate it according to its definition. For example, SOC can be calculated according to equation (3), if the coulometric titration technique is used to determine the Li amount x in the negative electrode. Nonetheless, this method will destroy the LiB. The available capacity can also be obtained at the standard discharge and then SOC can be calculated. This method is simple and reliable, but it destroys the original SOC and neither is it practical in real applications. As a result, plenty of SOC estimation methods were invented, and they were reviewed and compared in a few references [3–6,12–18].

Zhang et al. [13] had an early review on the SOC estimation methods, where six estimation methods were discussed, including fuzzy logic (FL), artificial neural network (ANN), extended Kalman filter (EKF) and so on. Waag et al. [5] classified the respective approaches in various groups with the focus on the strengths and weaknesses for the use in online BMS applications. They suggested that approaches still had to be extended and qualified further to be able to deal with aged batteries and under real conditions. Lu et al. [3] reviewed different SOC estimation algorithms with their advantages and disadvantages. They suggested that the Ampere-hour counting (AHC) method with correction by open circuit voltage (OCV) and SOC calibration was suitable for BEVs and PHEVs. The AHC combined with the algorithm of the adaptive control theory was suggested to be the most suitable method for HEVs. Kalawoun et al. [6] presented a review of methods and models used for SOC estimation. They introduced a novel classification of the existing SOC estimation methods. They believed SOC estimator based on directly measured input variables did not take into account the sensor noises. They also indicated methods based on closed-loop processing, like the Kalman filter (KF) and controller, were promising candidates, but the main difficulty of these methods was the parameter identification. Finally, they suggested that the machine learning techniques could provide an ideal SOC model. Cuma et al. [14] reviewed SOC estimation methods for different battery systems, including NiMH, lead acid, lithium polymer and lithium-ion batteries. They categorized the estimation methods into five groups, and listed their average errors indicated in publications. Li et al. [15] compared the Luenberger observer, EKF and sigma point Kalman filter (SPKF) for SOC estimation. Barillas et al. [16] further added the sliding-mode observer (SMO) for the comparison of SOC estimation. System performances in terms of the accuracy, estimation robustness against temperature uncertainty and sensor drift were discussed. Nejad et al. [17] presented a systematic review for lumped-parameter equivalent circuit models (ECMs) for

[1] $1/X$ C current rate indicates X hours for a complete discharge.