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# State-of-charge inconsistency estimation of lithium-ion battery pack using mean-difference model and extended Kalman filter

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## HIGHLIGHTS

- MDM and EKF are applied to identify the SOC inconsistency.
- A gradually varying SOC inconsistency experiment is carried out for verification.
- The evaluated $\Delta SOC$ tracks the changing of actual value after a quick convergence.
- The method requires low computation effort.
- The method is robust and not limited by battery pack working conditions.

## ARTICLE INFO

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## ABSTRACT

State-of-charge (SOC) inconsistency impacts the power, durability and safety of the battery pack. Therefore, it is necessary to measure the SOC inconsistency of the battery pack with good accuracy. We explore a novel method for modeling and estimating the SOC inconsistency of lithium-ion (Li-ion) battery pack with low computation effort. In this method, a second-order RC model is selected as the cell mean model (CMM) to represent the overall performance of the battery pack. A hypothetical Rint model is employed as the cell difference model (CDM) to evaluate the SOC difference. The parameters of mean-difference model (MDM) are identified with particle swarm optimization (PSO). Subsequently, the mean SOC and the cell SOC differences are estimated by using extended Kalman filter (EKF). Finally, we conduct an experiment on a small Li-ion battery pack with twelve cells connected in series. The results show that the evaluated SOC difference is capable of tracking the changing of actual value after a quick convergence.

## 1. Introduction

With the air pollution and other damaging human activities, the environmental degradation is accelerating at an alarming rate. Electric Vehicles (EVs) have become a main trend in vehicle industry owning to environmental friendly [1,2]. As one of the most important component in EVs, battery pack is typically made up of hundreds of cells in series and parallel. The state-of-charge (SOC) inconsistency, which is the most prominently different feature compared with single cell, further impacts the power, durability and safety of the battery pack. For a series connected battery pack, the available consumed and chargeable capacity are determined by the minimum remaining available discharging and charging capacity among cells [3]. Hence, the inconsistency can lead to the decrease of the effective battery pack capacity. On the other hand, the lithium-ion (Li-ion) cell is often used in EVs owning to the high energy density, high power density, durability and environmental protection [4]. Unfortunately, Li-ion cell is sensitive to overcharge and overdischarge which may also originate from inconsistency. Therefore, improving the consistency of battery pack is very important and essential.

The most intuitive way is to improve cells uniformity of the battery pack, such as screening cells. Kim et al. [5,6] proposed a method for filtering cells which could enhance the similar electrochemical characters of battery pack. In the course of implications, however, even though the consistency of the cells has been guaranteed as far as possible initially, the performance of these cells will be gradually distinguished owning to different operating conditions (e.g., operate under different temperatures). Therefore, it is significant to study the SOC

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inconsistency estimation. As aforementioned, hundreds of cells are series connected in the battery pack, hence estimating each cell SOC is impractical. Recently, many efforts have been focused on this field. For instant, taking advantage of the similar characteristics of cells in the battery pack, Plett [7] introduced a method called bar-delta-filtering which estimated the pack-average state and parameters using a sigma point Kalman filter (SPKF) based on "bar filter" firstly, and then used N individual "delta filters" to estimate the differences between cell values and the battery pack average value. This method can furnish all cells SOC difference, resistance difference and capacity difference estimation respectively. However, the accuracy of the capacity difference estimation relies on the accuracy of the SOC estimation which is a challenge in the real application. Dai et al. [8] proposed a concise dual time-scale Kalman filtering method which used second-order RC model as the equivalent circuit model (ECM) for both *LiMn*$_2$*O*$_4$ battery pack and single cells. Next, with the model, the cell SOC differences were derived based on the mean SOC. This method attained a low SOC inconsistency calculation effort. Furthermore, for the purpose of achieving less random access memory (RAM) usage, they designed an ingenious dual time-scale implementation method and obtained remarkable results. However, the cell terminal voltage difference is derived from SOC difference, internal resistance difference and polarization resistance differences. If the terminal voltage difference is only considered to evaluate SOC difference, the estimated results credibility will decrease when the internal resistance difference needs to be considered. We have previously studied a mean-difference model (MDM) which adopted a cell mean model (CMM) for battery pack mean condition estimation and used a cell difference model (CDM) (which considered SOC difference and internal resistance difference) to identify the cell differences subsequently [9]. However, the least squares method introduced in our previous work [9] cannot be used under constant current working condition.

In this paper, based on the advantages of EKF, the SOC inconsistency estimation is further studied using MDM. A second-order RC model is selected as the CMM to equal mean feature of the battery pack and a hypothetical Rint model is employed as the CDM to simulate the cell differences with "mean cell". Then, the SOC inconsistency estimation of the battery pack is obtained by employing EKF. We further conduct an experiment on a small series connected battery pack in which different resistances are connected to the cells in parallel to simulate the constantly varying SOC inconsistency. The results show that the novel method evaluated SOC difference can track the changing of actual values after a quick convergence and requires low computation effort.

The remainder of this paper is organized as follows. Section 2 states the second-order RC model for CMM and the hypothetical Rint model for CDM. In Section 3, the EKF algorithm is employed to estimate mean SOC of the battery pack and SOC inconsistency of the cells. Then, the model parameters identification and the scheme of experiment are illustrated in section 4. Analytical results are expressed in section 5. Section 6 draws the conclusions finally.

## 2. Mean-difference model for battery pack

### 2.1. Cell mean model

It is important to note that the SOC inconsistency estimation is based on the sole CMM in a series connected battery pack. Therefore, it is worthy to achieve high mean SOC estimation accuracy by sacrificing some calculation effort. Reference [10–12] did some researches on the second-order RC model, and the results showed that the model was credible and could achieve a desirable SOC estimation accuracy. Our previous research indicated that second-order RC model had a good accuracy, but increasing the order of RC in ECM could not always improve model accuracy owning to over-fitting problems [13]. Therefore, we employ the second-order RC model as the CMM in this paper, as depicted in Fig. 1a. In the schematic diagram of the CMM, $R_0$ represents internal resistance of the "mean cell", parallel connected $R_D C_D$ and $R_T C_T$ are used to simulate the polarization. $U_D$ and $U_T$ are voltage of the parallel components. In addition, the open circuit voltage (OCV) is represented by $U_{oc}$ which has a direct correspondence with SOC, i.e., SOC can be accurately determined by OCV in equilibrium state. $U_{mean}$ is terminal voltage of the "mean cell" (the mean terminal voltage of all series connected cells). And $I$ is current of the battery pack, positive for discharge and negative for charge.

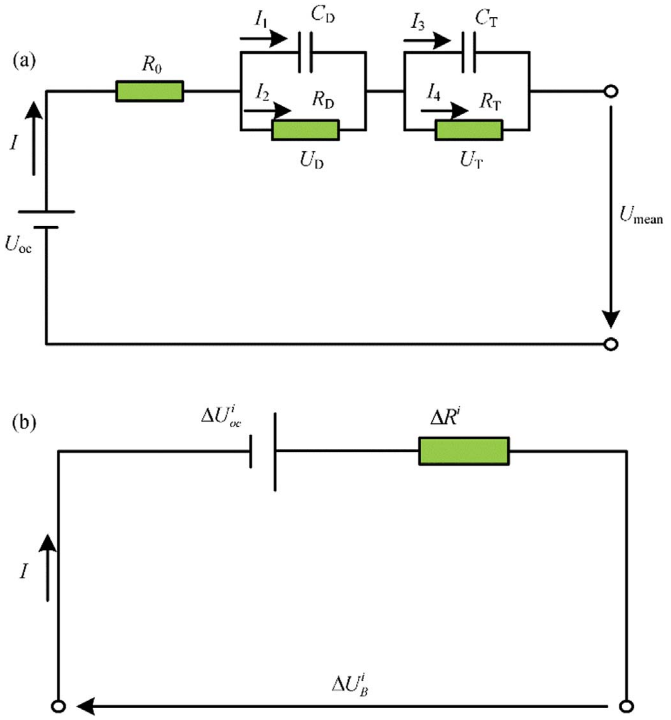

**Fig. 1.** ECM for MDM. (a) Second-order RC model for CMM; (b) Hypothetical Rint-model for CDM.

The SOC is defined as the ratio between the remained capacity in a battery and the total capacity that can be stored [14,15]. And the most commonly used ampere-hour integral equation is as follows:

$$SOC = SOC_{initial} - \frac{\int \eta I dt}{C_n} \tag{1}$$

where $\eta$ is the coulomb efficiency, for Li-ion batteries, $\eta \approx 1$. $C_n$ is the nominal capacity and $SOC_{initial}$ is the initial mean SOC of the battery pack.

Using a rectangular approximation for integration and a small enough sampling period $\Delta t$, the mean SOC discrete-time approximate recurrence can be obtained as follows:

$$SOC_{mean,k} = SOC_{mean,k-1} - \left(\frac{\eta \Delta t}{C_n}\right) I_{k-1} \tag{2}$$

This is the basis for including SOC at $k$ as the first state variables in the state vector of the CMM, with SOC as the state and $I_k$ as the input.

In addition, voltages, currents and internal states, which describe the characters of the CMM shown in Fig. 1a are in the following form:

$$I_1 + I_2 = I_3 + I_4 = I \tag{3}$$

$$\frac{\int I_1 dt}{C_D} = I_2 R_D = U_D \tag{4}$$

$$\frac{\int I_3 dt}{C_T} = I_4 R_T = U_T \tag{5}$$