Applied Energy 177 (2016) 384–392

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Determination of the battery pack capacity considering the estimation error using a Capacity–Quantity diagram

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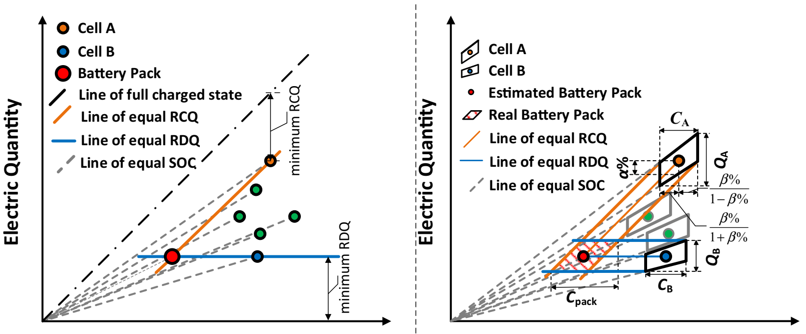
HIGHLIGHTS

- Quantitative analysis on estimation errors of pack capacity estimation is proposed.
- The C–Q diagram is utilized to analyze the estimation error of pack capacity.
- An equation calculating error of pack capacity estimation is proposed.
- The analysis can help choose a proper accuracy of SOC estimation for BMS.
- The analysis can help choose a proper accuracy of SOH estimation for BMS.

GRAPHICAL ABSTRACT



The Capacity-Quantity diagram used to define the states of battery pack

Using the Capacity-Quantity diagram to determine the pack capacity considering estimation errors

ARTICLE INFO

Article history:
Received 28 February 2016
Received in revised form 9 May 2016
Accepted 21 May 2016

Keywords:
Battery pack capacity
Capacity–Quantity diagram
Estimation error
State-of-charge
State-of-health

ABSTRACT

Accurate estimation of the capacity of a battery pack is essential for the battery management system (BMS) in electric vehicles. The SOCs and capacities of individual cells are the prerequisites for accurately estimating the capacity of a battery pack. This paper proposes quantitative analysis on how the estimation errors of individual cells' SOCs and capacities influence the estimation error of the battery pack capacity using an approach named Capacity–Quantity diagram (C–Q diagram). The analysis concludes that the estimation error of cell SOC has more influence on the estimation error of pack capacity than the estimation error of cell capacity does. The theoretical analysis is further validated by an experiment using six NCM batteries connected in series with different initial SOC variations. The results help to guide the determination of specifications, e.g., the estimation error of the SOC and that of the capacity, during the design process of a BMS.

1. Introduction

Lithium-ion batteries have been widely used as the power source of electric vehicles (EVs) in recent years [1,2]. Generally,

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http://dx.doi.org/10.1016/j.apenergy.2016.05.137
0306-2619/

the battery system for EVs is composed of numerous single cells, because the voltage and capacity of a single battery are insufficient [3]. Consequently, the battery management system (BMS) in EVs requires accurate estimation of the battery pack capacity, to monitor the capacity fade and avoid abusive conditions such as overcharge and over-discharge [4–6].

Variations of individual cells within the pack always exist due to inconsistencies during manufacturing and inhomogeneity of the working conditions [7]. Two typical approaches for estimating the SOC and capacity of the battery pack are available considering cell variations [8,9]. The first approach utilizes the "Mean+Difference Model" [8,10–12]. This kind of approach introduces a "Mean Model" to represent the mean state, which takes advantage of similar states among single cells and guarantees the accuracy. To capture cell variations, a model named the "Difference Model" was appended to the "Mean Model" [8]. Plett [8] firstly introduced the concept of the "Mean+Difference Model" in 2009 and fulfilled an estimation of the cell SOCs within a battery pack using the bar-delta filter. Dai et al. [10] developed a method to estimate the cell SOC using EKF (Extended Kalman Filtering). Zheng et al. [11] developed the "Mean+Difference Model" to estimate the cell SOCs and resistances of a battery pack. Sun and Xiong [12] screened the cell parameters as the mean model parameters and estimated the cell SOCs of a battery pack. However, the "Mean+Difference Model" approach cannot estimate the pack capacity and is only used for estimating the SOCs and resistances of individual cells.

The second approach converts the pack state estimation problem into a 2-cell estimation problem. To be specific, the first fully charged cell and the first completely discharged cell are the worst cells that are used to determine the state of the battery pack [9,13,14]. However, approaches on the identification of the two worst cells remains unknown. In other words, the full estimation, i.e. estimation of the states for all of the cells in the battery pack, must be performed to select the two worst cells. However, full estimation, which requires huge amount of computing resources, is hardly available to be applied in BMS [15–19].

In conclusion, the battery pack capacity estimation is based on the estimation of the cell SOCs and capacities of the battery pack. The errors, which exist in the estimation of individual cells' SOCs and capacities, influence the accuracy of the state estimation for the battery pack.

This paper provides an original investigation on the determination of the battery pack capacity considering the estimation error using a Capacity–Quantity diagram. Previous works have been proposed to estimate the battery pack capacity, and the SOCs and capacities of individual cells, separately. However, there is still no literature that has discussed the relationship between the estimation of the battery pack capacity and the estimation of the cell SOCs and capacities. Therefore, how the estimation errors in the SOCs and capacities of individual cells affect the accuracy of the battery pack capacity estimation requires further investigation. An approach named the "Capacity–Quantity diagram" (C–Q diagram) was used to determine the battery pack capacity [8,9]. However, the C–Q diagram has not been utilized to analyze the estimation error of the battery pack capacity yet. Hence, this paper provides quantitative analysis on how the estimation errors of the cell SOCs and capacities influence the estimation error of the battery pack capacity. The error analysis is conducted with the help of the C–Q diagram [8,9]. The analysis can provide guidance to choose proper accuracy of the estimation algorithms for cell SOC and capacities during BMS design, and broaden the horizon of the BMS technology.

The paper is organized as follows. In Section 2, the definition of pack capacity is introduced, and the relationship between the capacity of the battery pack and the SOCs and capacities of individual cells are analyzed. The C–Q diagram is briefly introduced and used to describe the relationship between the state of individual cells and the state of battery pack. In Section 3, quantitative analysis on the capacity estimation error of the battery pack are conducted based on the C–Q diagram. In Section 4, experiments using six NCM batteries connected in series with different initial SOC variations are performed to validate the theoretical analysis.

2. The C–Q diagram

2.1. The capacity of the battery pack

A battery pack connected in series reaches the end of charge (EOC) once the maximum cell voltage reaches the charge cut-off voltage. Similarly, the battery pack reaches the end of discharge (EOD) when the minimum cell voltage decreases to the discharge cut-off voltage, as shown in Fig. 1. The capacity of the battery pack is defined as the electric quantity released from EOC to EOD.

Considering that the coulombic efficiency is approximately 100% for lithium ion batteries, the capacity of a battery pack can be calculated by Eq. (1).

$$C_{\text{pack}} = \min_{1\leqslant i\leqslant n}\{RCQ_i\} + \min_{1\leqslant i\leqslant n}\{RDQ_i\} \tag{1}$$

where C_{pack} is the capacity of the battery pack, n is the number of series-connected cells in the pack, and RCQ_i is the remaining charging electric quantity of the ith cell, while RDQ_i represents the remaining discharging electric quantity of the ith cell, as shown in Fig. 1. The capacity of a battery pack is determined by the two worst cells, the cell (Cell A) with the minimum remaining charging electric quantity (RCQ) determines the EOC, whereas the cell (Cell B) with the minimum remaining discharging electric quantity (RDQ) determines the EOD.

Furthermore, Eq. (1) can be rewritten as

$$C_{\text{pack}} = \min_{1\leqslant i\leqslant n}\{SOC_i \times C_i\} + \min_{1\leqslant i\leqslant n}\{(1 - SOC_i) \times C_i\} \tag{2}$$

where SOC_i and C_i are the SOC (state of charge) and capacity of the ith cell, respectively.

2.2. The C–Q diagram

A Capacity–Quantity diagram as in [20] is a graphic illustration of Eq. (2), and can be utilized to determine the capacity of the battery pack (C_{pack}). As shown in Fig. 2, the x axis of the C–Q diagram denotes the cell capacity, whereas the y axis is the electric quantity. The orange dot in Fig. 2 denotes the C–Q state of Cell A, whereas the green dot denotes that of Cell B. C_{pack} is the x-value of the red dot, which is the intersection of the orange line and the blue line. The green dots represent the state of other cells in the battery pack. Moreover, the equal SOC line can be presented using the gray dotted line in Fig. 2 [21].

The scheme of the capacity estimation of the battery pack in a BMS is depicted in Fig. 3. Correlated algorithms estimate the SOCs and capacities of each of the cells of the battery pack with inputs of the voltage (V) and current (I) measure from the battery pack using sensors. The two worst cells can be selected to estimate the C_{pack} according to the C–Q diagram. The voltage and current have measurement errors, and the algorithms have estimation errors. Hence the SOCs and capacities of the two worst cells are not accurate. The C_{pack} determined by the C–Q diagram considers the effects of the SOC and capacity estimation accuracies.