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A State-of-Charge and Capacity Estimation Algorithm for Lithium-ion Battery Pack Utilizing Filtered Terminal Voltage

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Abstract

In electric vehicle (EV) and hybrid electric vehicle (HEV) application, accurate information of state-of-charge (SOC) and capacity of each cell are required for elaborate SOC/capacity estimation algorithm of the battery pack. However, the measurement of the states of all cells using sophisticated algorithms increases the computation time beyond practicality, because the computation time required for the SOC/capacity estimation of the battery pack is directly affected by the number of unit cells. In this work, a simple SOC and capacity estimation algorithm for Li-ion battery pack is newly proposed by using filtered terminal voltage. The SOC estimation algorithm using filtered terminal voltage extracts an estimated current information from the terminal voltage of the battery pack through equivalent-circuit model (ECM)-based filters without sensing the current. Consequently, it drastically reduces computational steps for the SOC estimation algorithm. With the fact that all the current flowing through the series-connected cells in pack are identical, the estimated current value of each cell should be identical. As a result, it can be known that this algorithm enables us to obtain the relative proportion of SOC/capacity information of each cells and battery pack with minimal complexity increase. To validate the performance of the proposed approach, a scaled-down HEV profile is used for a pack consists of twelve 18650 series-connected Li-ion batteries (12S1P). The experimental results verify the performance of the proposed battery pack SOC estimation algorithm.

Keywords: battery pack, filtered terminal voltage, lithium-ion batteries, state estimation, state-of-charge (SOC)

1 Introduction

In order to achieve the state-of-charge (SOC) and capacity estimation of a series-cell configured battery pack, information on average value of cell voltages and pack current is widely used. It assumes that electrochemical characteristics of all cells are approximately identical. That is, when there exist discrimination among cells because of aging and cell's different electrochemical characteristics, the variation of average cell voltages may not represent each cell's SOC/capacity. Moreover, total capacity in the pack is surely limited by the specific cell that has the lowest capacity. Thus, it may be erroneous to use an average value of cell voltages as a critical indicator for expression of pack's characteristics.

Nowadays, numerous works have been studied in order to achieve correct SOC/capacity estimation of battery pack using each cell's voltage and capacity information [1]. However, these works have an inevitable drawback of increased computation time required for SOC/capacity estimation due to constructing sophisticated algorithms that can measure all cell's states. In addition, the SOC/capacity performance of the battery pack is determined by a specified unit cell that has the lowest remaining capacity and lowest chargeable capacity.

This work present a new method that uses information on filtered terminal voltage for SOC/capacity estimation without using cell current information [2]. This drastically reduces the computation time and robustness against difference among cell's parameter. The cell current can be estimated using the filtered terminal voltage. Thus, without current information, it is definitely possible to compensate cell's difference for SOC/ capacity estimation although each characteristic of cells is originally different. Through this work, an improved methodology for efficient SOC/ capacity estimation is elaborately investigated. Experimental results for SOC/capacity estimation of cells and a series-cell configured battery pack are shown for verification of this work.

2 Proposed estimation method

This work presented the estimation methodology using only terminal voltage without current data [2]. This work applied the same coefficients for current estimation of each cell. From characteristic of a series-cell configured battery pack, it can be simply assumed that its estimated values should be approximately identical. Unfortunately, because of difference in electrochemical characteristics, these coefficients should be compensated. Thus, in this work, the PI controller additionally considered in order to update coefficients for minimizing the difference among estimated currents.

2.1 Current sensor-less estimation using filtered terminal voltage

Figure 1 displayed the simple RC battery model used in the current sensor-less estimation method. This model considers the discharging capacity C_n of Eq. (1) the OCV–SOC relation of Fig. 1 as an important role to determine the parameter C. If the smoothing factor α of Eq. (2) is calculated from the sampling time T_s and RC parameter (resistance and capacitance), information on estimated current can be obtained from Eq. (3). Furthermore, from this equation, it is possible to estimate the SOC of each cell based on estimated current via Ampere-counting, as expressed in Eq. (4).

$$C = C_n \frac{\text{dSOC}}{\text{dOCV}} \tag{1}$$

$$\alpha = \frac{T_s}{T_s + RC} \tag{2}$$

$$I[k] = (1-\alpha)\cdot\left(I[k-1] + \frac{(V_t[k]-V_t[k-1])}{R} \right) \tag{3}$$

$$\text{SOC}[k] = \text{SOC}[k-1] + \frac{I[k]}{C_n} T_s \tag{4}$$

Because of current offset error, Ampere counting has a possibility of divergence. However, these estimated currents are calibrated from the terminal voltages for reducing the current offset error. Moreover, the SOC estimation error can be determined by the maximum amount of current and insensitivity to any changes of the parameter. Therefore, a technique for a relative comparison among cells should be properly required.

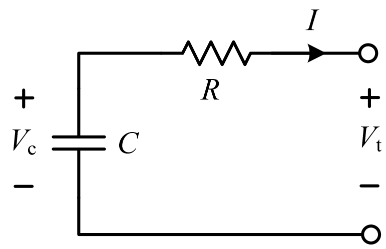

Figure 1: Simple RC battery model

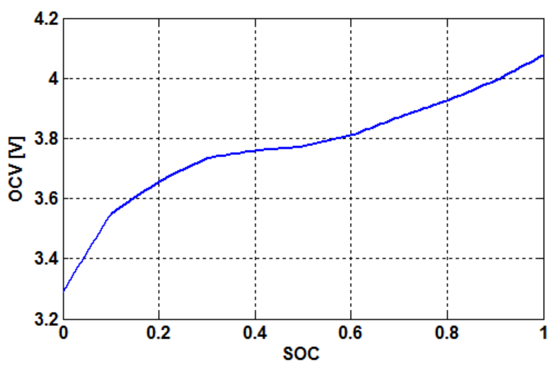

Figure 2: Battery OCV–SOC curve

2.2 Estimated current equalizer

By and large, if the true values of R and C (Fig. 1) are identical, it is easily known that the values of estimated currents are similar. Unfortunately, because of inevitable electrochemical differences among cells in the pack, the currents are actually differently estimated.

For equalization of these values, this work uses simple PI controllers for compensating the differences of parameters R and C among cells. The parameters R and RC time constant respectively determine the magnitude and the waveform of the estimated current. In order to achieve this goal, the ratio R and C of i-th cell, $G_{R,i}$, $G_{C,i}$ in Eqs. (5) and (6) are defined as the coefficient for obtaining a new R and C values.

$$R_{\text{new},i} = R_i \cdot G_{\text{R},i} \quad (5)$$

$$C_{\text{new},i} = C_i \cdot G_{\text{C},i} \quad (6)$$

2.3 SOC/Capacity of battery pack

Figure 3 shows the entire block diagram for SOC and capacity estimation. In this figure, there are N cells in a series-cell configured battery pack. The current information on a specific cell is defined as a reference current. The SOC and capacity of the pack can be easily obtained from information on cell's SOC and capacity based on the capacity ratio previously described in Section 2.2. The value of capacity of the pack C_{pack} is expressed as

$$C_{\text{pack}} = \min(SOC_i \cdot C_i) + \min((1 - SOC_j) \cdot C_j) \quad (7)$$

where SOC_i and C_i are the SOC and capacity of i-th cell in the series cell-configured battery pack, respectively.

$$\text{SOC}_{\text{pack}} = \frac{\min(\text{SOC}_i \cdot C_i)}{C_{\text{pack}}} \quad (8)$$

As expressed in Eq. (7), the value of C_{pack} is critically determined by the specified cell that has the lowest remaining capacity and lowest chargeable capacity. From this relation, the SOC of the battery pack can be calculated as Eq. (8) regardless of the absolute value of the capacity.

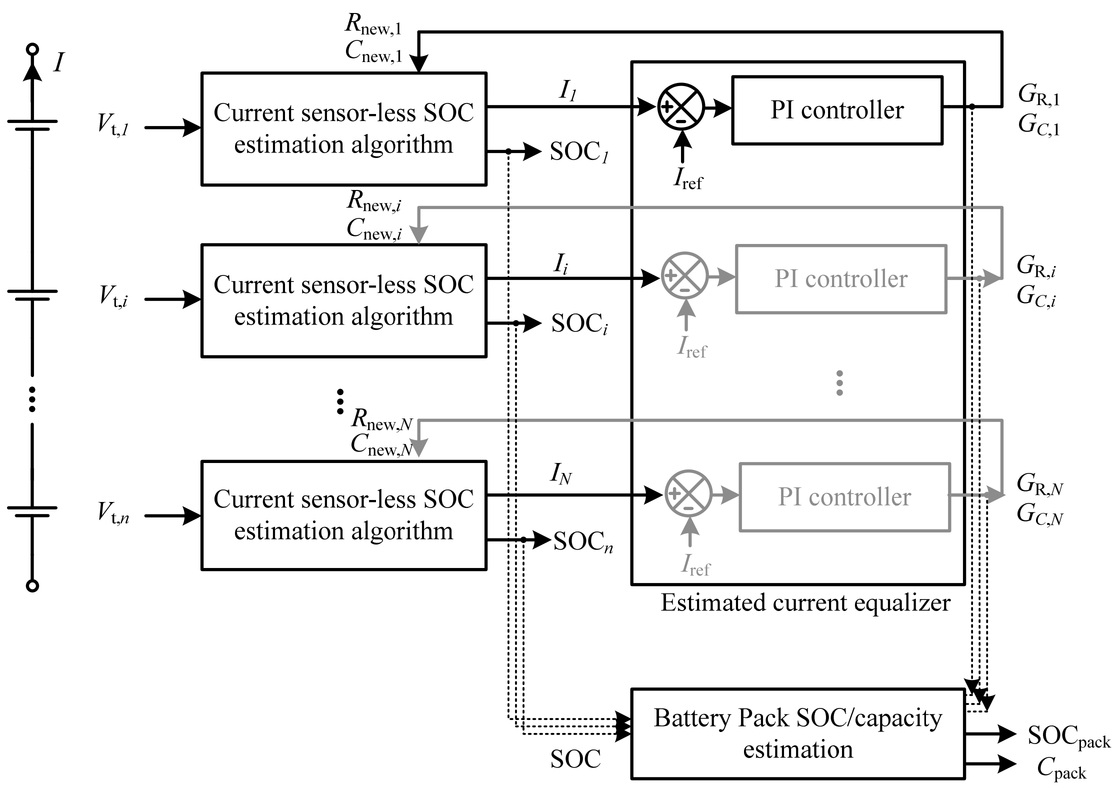

Figure 3: Block diagram of the proposed battery pack SOC/capacity estimation algorithm

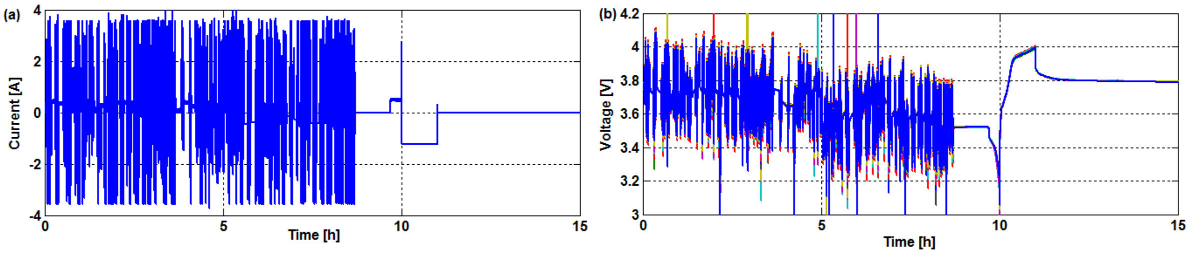

Figure 4: Sensed current and voltages data from BMS: (a) Battery pack current (b) Battery cell voltages

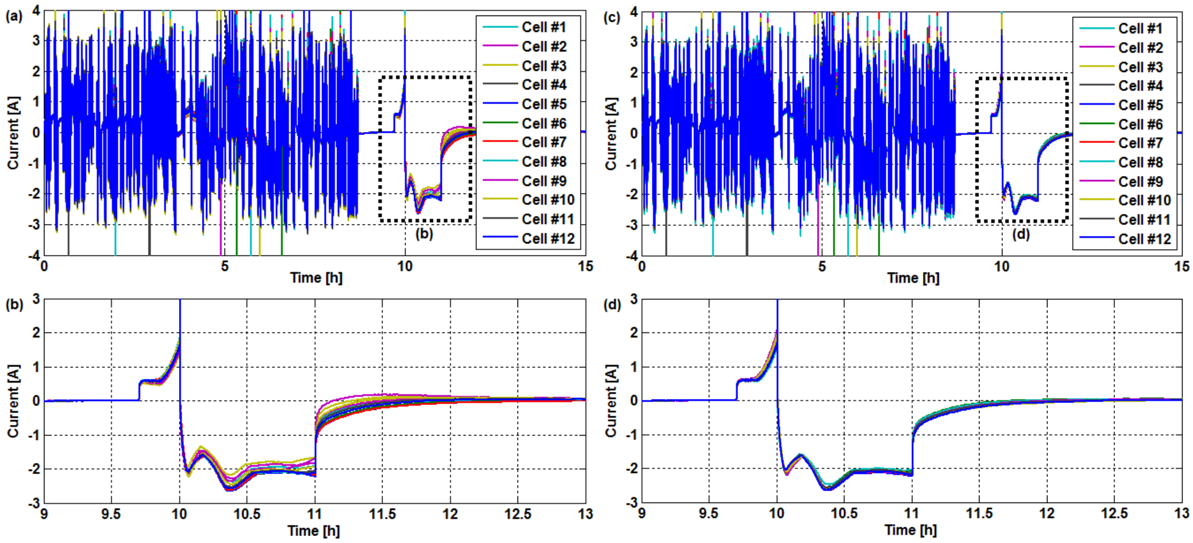

Figure 5: Experimental result: (a) Estimated current of each cell before using estimated current equalizer, (b) Expanded waveform of (a), (c) Estimated current of each cell after using estimated current equalizer, (d) Expanded waveform of (b)

3 Verification

In this section, a single pack of twelve series-connected batteries (12S1P), which are Samsung SDI 2.6Ah 18650 Li-ion batteries, is used to verify the effectiveness of the proposed method. Figure 4 shows the scale-down HEV current profile and its measured voltages for the conducted experiments.

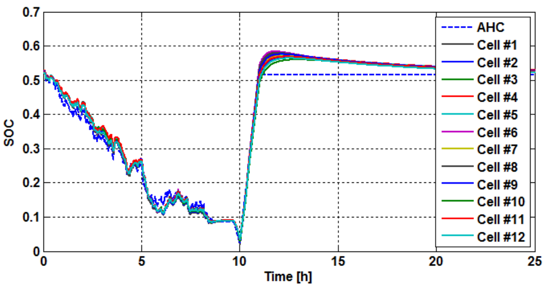

Figure 6: SOC of each cell and calculated SOC from Ampere counting

When the scaled-down HEV current profile is applied, an experimental result of the estimated currents is shown in Fig. 5(a). Because of an inevitable initial error in parameter value of R and C_n, the estimated currents of each cell may be different. In order to check the estimated current in detail, the enlarged shape of Fig. 5(a) is displayed in Fig. 5(b) in terms of constant current charge or discharge sequence. By this experimental result, cell #8 can be well defined as the reference cell, namely $I_8=I_{ref}$. After block equalization of the estimated current, they are finally converged, as shown in Figs. 5(c) and (d). The estimated SOC information of each cell is simultaneously shown in Fig. 6. In this work, Ampere-counting adopting average value of cell's discharge capacity is selected as the indicator for demonstration of this proposed algorithm. Then, cell #1 has the lowest remaining capacity and chargeable capacity. For this reason, it is possible to estimate the SOC/capacity of the battery pack using SOC/capacity information of cell #1 in Fig. 6.

4 Conclusions

In summary, the proposed approach enables us to describe the difference among the cells and the status of the battery pack by the proportionality factor with related to each cell. This algorithm is far less computational complexity and robustness over difference among cell's parameter.

Acknowledgments

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