A Simple 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 by use of sophisticated algorithms increase the computation time of the entire algorithm beyond practicality, because the computation time required for SOC/capacity estimation of the battery pack is directly affected by the number of unit cells and the time required for SOC/capacity estimation of a specified unit cell. Therefore, 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 a terminal voltage of the battery pack through equivalent-circuit model (ECM)-based filters without using current information. Consequently, it can be expected to obtain a simple SOC estimation algorithm with a fewer computational steps, but it is impossible to obtain capacity information or update coefficient of a single cell due to the absence of additional current information. With the information 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 properly used 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 of state-of-chARGE (SOC) and capacity estimation of the series-cell configured battery pack, information on average value of cell voltages and pack current is widely used. This work considered that electrochemical characteristics of all cells are approximately identical. That is, when there is cell inconsistency because of
cell’s aging and different electrochemical characteristics, the variation of average cell voltages is smaller than that of each cell. Besides, a total of energy in the pack is surely limited by the specific cell that has the lowest energy, namely capacity. As current status, it may be difficult 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 has an inevitable drawback of increased computation time required for SOC/capacity estimation due to constructing sophisticated algorithms that can measure all cell’s states. Increased computation time required is directly affected by unit cell’s number and the time required for SOC/capacity estimation of a specified unit cell. 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. Therefore, an improved work that has some advantages such as simplicity and ability of cell’s characteristic discrimination to design the SOC/capacity estimation should be newly proposed. Unfortunately, so far, little definitive answer has been given to this question.

This work gives insight to design a new method that uses information on filtered terminal voltage for SOC/capacity estimation [2]. Above all, there is no necessity for using current information for estimation. This algorithm has the abilities such as less computation time and robustness against difference among cell’s parameter. Specifically, for estimation of a series-cell configured battery pack, this work considered an assumption that each value of cell’s current previously estimated from algorithm is same within the battery pack. 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 of cells and a series-cell configured battery pack are shown for verification of this work.

2 Proposed estimation method

In this paper, the estimation algorithm used filtered terminal voltage without the use of current information [2]. By applying this algorithm with the same coefficient to each cell, estimated current of each cell is obtained and its value should be similar because of the same current flows to the series-connected batteries. However, these estimated current have slight differences due to the differences in cell characteristics. The PI controller in the proposed algorithm attempt to update coefficient of each cell for reducing the differences between the estimated currents.

2.1 Current sensor-less estimation using filtered terminal voltage

Current sensor-less SOC estimation algorithm that use a simple RC battery model is shown in Fig. 1. In this battery model, OCV–SOC relationship in Fig. 2 and battery capacity, $C_n$, play an important role to determine the model parameter $C$ in Eq. (1). If the smoothing factor $\alpha$ in Eq. (2) is calculated from sampling time $T_s$ and RC parameter described above, the estimated current of each cell is obtained as Eq. (3). Furthermore, the SOC of each cell is estimated from the Ampere counting of the estimated current in Eq. (4).

$$C = C_n \frac{dSOC}{dOCV} \quad \text{(1)}$$
$$\alpha = \frac{T_s}{T_s + RC} \quad \text{(2)}$$

Figure 1: Simple RC battery model

Figure 2: Battery OCV–SOC curve
\[ I[k] = (1 - \alpha) \cdot \left( I[k-1] + \frac{(V_i[k]-V_i[k-1])}{R} \right) \] (3)

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

Ampere counting method is a possibility of divergence due to current offset error, but these estimated current already calibrated from the terminal voltage for eliminating the current offset error. In addition, SOC error is determined by the maximum amount of current and insensitive to small changes of the parameter; thus, it can be seen as suitable for a relative comparison of each cell.

### 2.2 Estimated current equalizer

In general, the estimated current values could be identical if we can use the actual \( R \) and \( C \) parameters, which reflect the characteristics of each cell. However, due to the difference \( R \) and \( C \) values of battery cells in a pack, the estimated currents have different values.

For equalizing these values, in this paper, simple PI controllers are used for compensating the difference of \( R \) and \( C \). The \( R \) parameter determines the magnitude of the estimated current and \( \alpha \) parameter affects the form of an estimated current waveform. 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.

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

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

### 2.3 SOC/Capacity of battery pack

Fig. 3 shows a structural view of the entire algorithm. The series-connected battery pack consists of \( N \) cells and the estimated current of specific cell is defined as a reference current.

The SOC/capacity of battery pack is obtained through the SOC/capacity of cells with capacity ratio in Section 2.2. The battery pack capacity \( C_{\text{pack}} \) is expressed as

\[ C_{\text{pack}} = \min(SOC_i \cdot C_i) + \min((1 - SOC_i) \cdot C_i) \] (7)

where \( SOC_i \) and \( C_i \) are the SOC and capacity of \( i \)-th cell in the series-connected battery pack.

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**Figure 3**: Block diagram of the proposed battery pack SOC/capacity estimation algorithm
The battery pack capacity in Eq. (7) is determined by the magnitude of the lowest remaining capacity and lowest chargeable capacity. In this relation, the battery pack SOC in Eq. (8) can be calculated regardless of the absolute value of the capacity.

\[
\text{SOC}_{\text{pack}} = \frac{\min(SOC_i, C_i)}{C_{\text{pack}}} \tag{8}
\]

The battery pack capacity in Eq. (7) is determined by the magnitude of the lowest remaining capacity and lowest chargeable capacity. In this relation, the battery pack SOC in Eq. (8) can be calculated regardless of the absolute value of the capacity.

### 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. Fig. 4 shows the scale-down HEV current profile and its measured voltages for the conducted experiments.

Fig. 5(a) is the experimental result of the estimated currents when current profile is applied. Due to the initial error in \( R \) and \( C_n \), the estimated current of each cell is different. Fig. 5(b) is the expanded waveform of Fig. 5(a) for analyzing the detail shape of the estimated current waveform when constant current charge and discharge profile are applied. In this experiment, cell #8 is decided as the reference cell; thus, \( I_8 \) becomes the \( I_{\text{ref}} \). After estimated current equalizer block is operated, the result of the estimated current are converged as shown in Figs. 5(c) and (d).

At that time, estimated SOC of each cell is shown in Fig. 6. SOC calculated by the Ampere counting

![Figure 4: Sensed current and voltage data from BMS: (a) Battery pack current (b) Battery cell voltages](image)

![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)](image)

![Figure 6: SOC of each cell and calculated SOC from Ampere counting](image)
with average value of cell’s capacity is used to demonstrate the performance of the algorithm. In here, cell #1 is the lowest remaining capacity cell and lowest chargeable capacity cell. For this reason, the SOC/capacity of the battery pack is obtained through the SOC/capacity of cell #1 in Fig. 6.

4 Conclusions
In summary, the present study indicate that the proportionality factor of each cell describe the difference between the cell and the status of the battery pack. This proposed algorithm shows less computational complexity and robustness against difference among cell’s parameter. Further studies will be required to improve the performance of the PI controller that affects to reduce the difference between actual and estimated proportionality factor and be to provide more data for this result.

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