SOC Estimation Method of Lithium Ion Battery for Contact Wire and Battery Hybrid Electric Railway Vehicle

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Recent years have seen some railway vehicles equipped with secondary batteries on board to improve their energy saving performance. Such vehicles need accurate and stable SOC (state of charge) estimation, which is important for managing battery energy. This paper reports on a SOC estimation method for on board lithium ion batteries developed for the contact-wire and battery hybrid electric railway vehicle. This method enables stable SOC estimation and automatic tuning of parameters, such as battery capacity and battery inner resistance. These characteristics of the estimation method were evaluated by way of running tests on the JR-Shikoku Yosan railway line.

Keywords: lithium ion battery, state of charge (SOC), battery capacity, hybrid electric vehicle

1. Introduction

Over recent years, many technologies have been developed to improve the energy saving performance and maintainability of railway vehicles, with the use of the large-capacity secondary batteries [1]. The LH02 electric railway vehicle or “Hi-tram” (Fig. 1), developed by the authors in 2007 is an example of this type of technology [2]. It has a 600 V-120 Ah lithium ion battery on board. This means that the vehicle runs in battery mode where there is no contact wire. Moreover, it contributes to improving the availability of the regenerative brake, and reduces energy consumption for running. Care must be taken when operating in battery-mode to avoid depletion of the battery. Consequently, it is crucial to have accurate and stable estimation of the battery SOC (state of charge). SOC data can be employed to various ends: estimation of the remaining running distance on a non-electrified line, calculation of the charge time required at a quick-charge station, and reduction of the motor torque when SOC appears to be low, etc.

Some of the areas for improving conventional SOC estimation methods include overcoming the following drawbacks: 1) difficulty in obtaining model parameters, 2) sharp, rapid fluctuation in estimated SOC values, especially on in-cab displays. A SOC estimation method was therefore devised to address these issues, enable calculations which were accurate and stable calculation enough for practical use, and make it easier to obtain model parameters [3]. The new method was then applied to an LH02 on-board
battery system shown in Fig. 2. Two series of running tests to examine the performance of this new SOC estimation method were then performed. The first tests were carried out on the Sapporo-city municipal tramway, between Nov. 2007 – Mar. 2008. The second tests were performed on the JR-Shikoku Yosan railway line, in Nov. 2009. During the latter series the LH02 reached a maximum speed of 80 km/h running only on the on board battery.

This paper describes the developed SOC estimation method and reports on results from the performance verification running tests with JR-Shikoku.

2. Configuration of the battery system

The traction circuit of type-LH02 is shown in Fig. 3. Two power sources, the contact wire and the battery, are connected in parallel via chopper 1 (COV1) and chopper 2 (COV2). This is a hybrid system configuration. During hybrid operation, the power to and from the contact wire is preferentially utilized. When the required power is higher than the limit value provided through the trolley system, etc., the shortfall in power is compensated by the battery. The voltage of the battery is maintained within the set range thanks to adjustment-charge function, which uses power from the contact wire.

The specifications of the battery system are given in Table 1. The rated voltage of the cell is 3.6 V, and its rated capacity is 30 Ah. The system consists of 4 banks in parallel; one bank comprises 21 modules in series; and one module consists of 8 cells in series. In case of malfunction or an accident, the molded case circuit breaker (MCCB in Fig. 3) automatically cuts off only the malfunctioning bank, so that the remained banks can continue to operate. A high-voltage alarm or low-voltage alarm is given when the voltage of any one cell among the total 672 cells fouls the 2.5 V – 4.3 V range for a specified duration. Including a margin, SOC is defined as follows: 0% corresponds to the state with an average OCV (open circuit voltage) of 2.9 V, and 100% to that of 4.1 V, considering the practical operating range. This definition is based on the OCV curve shown in Fig. 4(a). OCV indicates the terminal voltage measured only after several hours without charging and discharging, and is almost constant. The battery capacity Q[Ah] stands for the discharge amount while SOC varies from 100% to 0%. Q is described as FCC (full charge capacity) in some cases; and is not the rated value measured just after manufacturing, but rather the present estimated value. The theoretical value of SOC between 0% and 100% is then defined by (1) so the variation changes linearly to the discharge amount D[Ah].

\[
SOC = \frac{Q - D}{Q} \times 100\% 
\]  

Table 1 Specifications of the battery system boarded on the type-LH02

<table>
<thead>
<tr>
<th>Positive-electrode active material</th>
<th>Lithium manganese oxide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated capacity</td>
<td>30 Ah / cell</td>
</tr>
<tr>
<td>Rated cell voltage</td>
<td>3.6 V / cell</td>
</tr>
<tr>
<td>Mass</td>
<td>Approx. 2.0 kg / cell</td>
</tr>
<tr>
<td>High voltage protection</td>
<td>4.3 V / cell (Maximum)</td>
</tr>
<tr>
<td>Low voltage protection</td>
<td>2.5 V / cell (Minimum)</td>
</tr>
<tr>
<td>High temperature protection</td>
<td>65 °C (Maximum)</td>
</tr>
<tr>
<td>Definition of SOC 100%</td>
<td>4.1 V (Average cell voltage)</td>
</tr>
<tr>
<td>Definition of SOC 0%</td>
<td>2.9 V (Average cell voltage)</td>
</tr>
<tr>
<td>Configuration of the battery system</td>
<td>Whole system = 4 banks in parallel</td>
</tr>
<tr>
<td></td>
<td>1 bank = 21 modules in series</td>
</tr>
<tr>
<td></td>
<td>1 module = 8 cells in series</td>
</tr>
<tr>
<td>Ratings of the whole system</td>
<td>604.8 V – 120 Ah</td>
</tr>
<tr>
<td>Maximum current of the whole system</td>
<td>1000 A (For quick charge)</td>
</tr>
</tbody>
</table>

Measurement or estimation of Q and D while the bat-
tery system is on board will cause errors. So it has a difficulty to obtain the theoretical value of SOC.

3. Fundamental methods for SOC estimation

There are two fundamental methods used for SOC estimation. In this paper, one is called the voltage reference method and the other is the coulomb counting method. The SOC obtained by the former method is described as \( S_1 \); and by the latter as \( S_2 \).

3.1 Voltage reference method

This method employs \( E \), measured or estimated OCV, then converts \( E \) to the SOC \( S_1 \), as shown in Fig. 4(a). The conversion is executed by using a specific function or a reference table of the battery. The function of the battery system is given by (2), and it provides accurate approximation of the measured characteristics.

\[
S_1 = a_0 E + a_1 E^2 + a_2 E + a_3 (= f(E)) \tag{2}
\]

where \( a_0 - a_3 \) indicate specific coefficients of the battery system.

This method was marked with positive ("+)") and negative points ("-"") as follows:

-: No accumulation of errors because no integration operation is executed.
-: Variation of battery capacity, \( Q \), due to degradation, has no influence on calculated SOC.
-: OCV \( E \) contains errors due to estimation, especially when the battery current varies.
-: When \( f(E) \) becomes different from the actual system, it leads to errors in SOC.

OCV is not measured during and just after the period of charge or discharge. Following on estimation of OCV requires assumed battery models. The commonly used model consists of voltage source, resistance, and series connected RC-parallel elements. The greater the number of elements connected in series, the higher the accuracy of the OCV estimate becomes, as described in references [4] and [5].

However, it is not practical to apply complicated models with so many parameters to railway vehicle equipment since it would be difficult to measure and tune all the model parameters. On-board model parameters should be obtained after the system is mounted in order to consider the resistance of interconnection lines inter alia, and should be adjusted periodically to keep in line with battery degradation.

With a view to resolving these issues, a simple battery model was employed, as shown in Fig. 5. Although the accuracy of OCV estimation is slightly lower, this error is compensated when the method is combined with the calculation shown in the next section 3.2, and the overall method is easier to apply.

3.2 Coulomb counting method

This method is based on the time integration of the discharge or charge current, as shown in Fig. 4(b). The following equations (3) and (4) explain this method:

\[
\Delta D_2 = \frac{1}{3600} \int_{t_1}^{t_2} Q \, dt \tag{3}
\]

\[
\Delta S_2 = -\frac{\Delta D_2}{Q} \times 100 \tag{4}
\]

where \( t \) is absolute time, and \( T \) is the calculation period. The variation in discharge amount is expressed as \( \Delta D_2 \), and that of SOC is expressed as \( \Delta S_2 \). This method is almost the same as the SOC definition in equation (1). However, this method only scores one advantage point (mark "+"), for three negative points (mark "-"), as follows:

+:SOC variation is continuous.
-: The measurement error of the battery current is accumulated through the integration operation.
-: Initial value of \( S_2 \), \( S_2(0) \), has to be obtained by some other method.
-: The measurement error of the battery current is accumulated through the integration operation.

Because of the disadvantage points, this method cannot be employed in isolation.

4. Developed SOC-estimation method

The developed SOC-estimation method is explained in this chapter. The disadvantages of the two fundamental methods described in Chap. 3, can be compensated by combining them.

4.1 Outline of the developed method

Combining the voltage reference and coulomb counting methods is already a well-known theory. However, few practical examples of them being associated appear to exist.

As such a new simple combination method was developed which withstands fluctuation of model parameters, and is designed to operate with the door-opening signal. Figure 6 shows the whole block diagram of the developed method.
method. The input signals are: the battery terminal voltage, \( V \), the battery current, \( I \), the average battery temperature, \( T_b \), and the door-opening signal. The estimated SOC is displayed on a cabin screen and recorded along with the other parameters, the OCV, the battery capacity, the inner resistance, etc.

### 4.2 Estimation of OCV

Assuming a simple battery model, in Fig. 5, the equation of \( V_{rr} \) is given as follows.

\[
V_{rr} = \frac{1}{C_r} \int \left(-I - \frac{V_{rr}}{R_r}\right) dt
\]

Practically, the integral equation (5) is converted to the approximated difference equation based on the trapezoidal integration rule.

The voltage \( V_{rd} \) is given as

\[
V_{rd} = -R_d I
\]

Thus, the estimated OCV, \( E \), is described in the following equation:

\[
E = V - V_{rd} - V_{rr}
\]

### 4.4 Automatic tuning of the battery parameters

The estimated battery capacity is also corrected soon after the door opens. The battery capacity, \( Q \), is corrected as shown in Fig.8, assuming that the dominant reason for any difference between \( S_1 \) and \( S_2 \) is an estimation error of the battery capacity, \( Q \). When the absolute value of change of \( S_1 \) from the previous correction to the next is less than the absolute value of change of \( S_2 \), the estimated \( Q \) should be decreased, and vice versa. As this correction is repeated, \( Q \) seems to converge towards the true value of the battery capacity. As the difference between \( S_1 \) and \( S_2 \) can occur for other reasons, namely a measuring error of the battery current, etc, so should the estimated value of \( Q \) be examined experimentally.

The initial value of the inner resistance of the battery is determined by a function of the battery temperature, \( T_b \). Then, it is corrected after the quick change in battery...
current. Since one calculating period, 1 sec, is short, the change of the terminal voltage, $V'$, is almost equal to that of $V_d$, which leads to the next equation:

$$R_d = \frac{V - V'}{I - I'}$$

where $V$ and $I$ are the present sample data, and $V'$ and $I'$ are the previous sample data. Every time the new $R_d$ is calculated by (8), the retained value of $R_d'$ is corrected appropriately. Corrections of $Q$ and $R_d$ deemed to be too small are excluded to avoid excessively frequent correction, when they are in the dead zone.

### 4.5 Obtaining the model parameters of the battery

The equivalent-circuit parameters, shown in Fig.5 were obtained by analyzing the transient waveforms shown in Fig.9. These waveforms were measured in the preparation period before the running test. The 101 A-charge stopped at 0 sec., and the average battery temperature was 23 °C. According to the approximated curve of $V$ from 0 sec. to 100 sec., the parameters were calculated as follows: $R_d = 62.0$ mΩ, $R_r = 30.1$ mΩ, $C_r = 1190$ F. It was assumed that the ratio of $R_d$ to $R_r$ was fixed at 30/62 and the value of $C_r$ was constant regardless of the battery temperature. After the correction of $R_d$, the value of $R_r$ was calculated as $R_r$ multiplied by 30/62.

### 5. Experimental result of the running test

This chapter describes the SOC-estimation performance through the running tests. The following indices were used for evaluation:

1. Linearity of the SOC versus discharge amount $D$, 
2. Smallness of the SOC fluctuations generated by the correction.

To be precise, SOC estimation performance should be evaluated by comparison of the theoretical and estimated values. However it is difficult to obtain the theoretical value for the reasons mentioned in Chap.2. This explains the recourse to index 1). The purpose of index 2) was to avoid steep fluctuation in SOC so that it could be used as the appropriate drive assist information.

#### 5.1 General conditions of the running test

Running tests were carried out in Nov. 2009, between Tadotsu and Sakaide stations (11.4km) on the JR-Shikoku Yosan railway line. Tests were performed 4 times to measure the running distance achieved with on board battery energy alone.

Figure 10 shows one of the results of the running distance tests. Up to the lapsed 5500 sec. into the running test, running energy was supplied only by the battery. After that the battery was charged by the power from the contact wire, and the running energy was sourced both from the contact wire and the battery, which is also known as hybrid-mode running. As a result of charging, the SOC recovered to almost its initial value. The deep discharge and charge were carried out in the total measuring period.

At the lapse of 5500 sec. period in the running test, while power was being supplied from the battery, the low battery voltage alarm was triggered in the 3rd and the 4th bank; these banks were automatically cut off, when the battery SOC reached 6.8%. The motor torque reduction control entered into operation as the number of operational banks fell to the remaining 1st and 2nd bank batteries. In fact, it is preferable for the low battery voltage alarm to go off after SOC reaches 0%. Consequently, the countermeasure for this issue was to change the definition of SOC, to increase the value of OCV defined at 0%-SOC.

#### 5.2 Linearity of the calculated SOC

The estimation performance of the parameters is shown in Fig.11. The SOC waveform, estimated during the battery-mode period, has good linearity compared to an approximated line for this period, where the difference between the approximated line and the estimated waveform is less than 1.5%. During the hybrid-mode period however, the difference between the approximated line and the estimated waveform increases to 6.6%. There is a probability that the error between the theoretical value and the estimated value is almost the same as 6.6%. The large difference occurs only while the battery is mainly charged. This
indicates that the risk of causing the battery to empty is not so high, although this is an issue which should be improved. A probable cause is the difference with the function \( f(E) \) between the discharge period and the charge period, as the function \( f(E) \) is obtained through the discharge test only. It is possible to employ another function during the charge period.

After the lapse of 9000 sec. in the running tests, SOC increases from 80% to 90%, and the charge current decreases because of the constant-voltage charge control. In this period, the above mentioned difference of SOC falls back towards its initial value.

The waveform of the estimated OCV, \( E \), is presented in Fig.12. The OCV, \( E \), shows small fluctuation due to the change in terminal voltage, \( V \), when the battery current changes steeply. This issue is probably caused by the simple battery model employed for the OCV estimation. In practice however, the probability of OCV and \( S \) being referred to just after the steep change in the battery current, is low. Since the door-opening signal, used for the trigger of SOC correction, is generated after the vehicle decelerates and stops, the battery current gradually reduces with no steep change for the several seconds before the door open

5.3 Other estimated parameters

The battery temperature, which was the average of all 672 battery cells, increased from 15 °C to 25 °C, at the beginning and at the end of the measurement period respectively. The estimated inner resistance, \( R + R_n \), decreased, as shown in Fig.11, tendency which corresponds to the battery temperature change. Small step changes are also obtained, due to the characteristics provided by the correcting operation in (8).

The estimated value of \( Q \) fluctuated between 113 and 122 Ah. The calculated actual capacity by the gradient of the approximate line during the discharge period was obtained as 112Ah. The estimated value of \( Q \) was almost equal to the calculated actual one, and demonstrated a good match.
signal. Consequently the estimation error of OCV seldom causes a sudden step deviation of the estimated SOC.

5.4 Consideration for SOC jumping

The extended waveforms presented in Fig.13 include the displayed SOC, $S_r$. At the lapse of 5640 sec. of the running test, $\Delta SOC$, the absolute value of the SOC fluctuation, is approx. 2%. A similar SOC fluctuation occurred just after the mode change: from the battery-mode running to hybrid-mode running. The reason for the latter appears to be that the function $\forall(E)$ differs between before and after the mode change.

Figure 14 shows the histogram of the fluctuation step of SOC, $\Delta SOC$. The total number of SOC corrections was 35, the average value of $\Delta SOC$ was 0.59%, and the its maximum value was 2.08%. There seems to be no problem with approx. 0.5% $\Delta SOC$. Though the 2% fluctuation is a rare case, a more accurate calculation method would be desirable.

Fig. 14 The histogram of the fluctuation step of SOC

6. Conclusions

For vehicles mainly driven by battery, the remaining amount of battery energy should be displayed in the cabins with some meter, similar to the fuel gauge of the automobiles. SOC (state of charge) is one of the important indices to indicate the remaining energy of batteries. In this paper, the developed SOC estimation method is described, which is used for the hybrid railway vehicle, type LH02 named ”Hi-tram”, equipped with 600 V-120 Ah lithium ion battery system. Through the running tests of Hi-tram on the JR-Shikoku Yosan railway line, the SOC estimation results were examined as follows:

a) SOC Fluctuations: the average 0.59%, the maximum 2.08%.
b) Linearity of the estimated SOC waveform: its deviation from the approximate line is within 1.5% during the battery-mode period, and 6.6% during the hybrid-mode period.

Those SOC estimation results indicated the enough performance for practical use. Moreover the other parameters as the inner resistance and the capacity of the battery were also properly estimated through the running test.

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