Temperature characteristics of SOC estimation for traction battery system

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Abstract: In order to determine the effect of temperature on the SOC estimation accuracy of the battery system, the electrical performance of the battery system was studied by charge/discharge and environmental testing equipment. When SOC is equal to or greater than 80%, the result shows larger error between the actual SOC of battery system and the recorded SOC of BMS system, which are 3.81% and 4.43% at -10 ℃ and 0 ℃ respectively, and the error is 2.41% at 25 ℃. The error between the actual SOC of battery system and the recorded SOC of BMS system tend to decrease firstly and then increase as the temperature increased, and the error is 0.31% at 25 ℃. In conclusion, temperature has a significant impact on the SOC estimation of battery system, the actual SOC of battery system shows a trend of rapid increase and followed by a rise slowly, while the recorded SOC of BMS system shows a trend of continuous increase, resulting in the error between the actual SOC and the recorded SOC. Besides, the minimum error of SOC estimation appears at 25 ℃.

1. Introduction

As the most important part of power battery system, battery management system (BMS) has many functions [1], such as monitoring and estimating state of charge (SOC), state of health(SOH) and state of life(SOL) for power battery system. SOC shows remaining capacity of battery system, and prevents it from over-charge and over-discharge [2]. The accuracy [3] of SOC estimation provides reasonable evidences for maintain and usage of battery system [4]. Therefore, it is significant to test and analyze the accuracy of SOC estimation.

Currently, SOC estimation of cell and module are simulated and tested at room temperature by many researchers. But their conclusions based on single construction lacks of necessary verification. Algorithm might be not considered for different temperature conditions. What’s more, the complicated battery system which is used for high energy application is not researched deeply. Those battery systems are usually composed of thermal management [1], balance device [5], high voltage delay, and so on. Different types of battery system cannot be described in the general model because of various chemical systems. Several key parameters of battery system have directly influence on capacity and power, such as cell resistance, module parallel and series types. So an accurate estimation model is necessary for battery system to present SOC.

In this paper, an electrical test system is built for battery system composed of environmental chamber, charge and discharge device. By using test system, SOC estimation accuracy characteristics of battery system are analyzed in different temperature and SOC conditions. A series experiment will
be carried out for battery system to identify the reason why error changes between recorded SOC and real SOC. Where, recorded SOC is uploaded from battery management system, using estimation algorithm. The real SOC is shown in charge and discharge system, which is the actual energy transferring between battery system and experiment devices.

2. Experiment procedure

2.1. Experiment scheme
The model of charge and discharge test device is EVT300-0800-3×80KW IGBT. Testing voltage can be adjusted from 0 to 800 volts. And testing current can be adjusted from 0 to 300 amperes in each channel. Environment chamber is designed for explosion-proof, with the model of HRT710Q-51. The internal volume of chamber is 1$\text{m}^3$ where internal length, width and height are all 1 meter. Chamber that simulates battery environment condition has adjustable temperature, ranging from -70 $\text{C}$ to 150 $\text{C}$. The model of chiller used for cooling and warming battery system is AHLF30-45A, and its adjustable temperature is ranging from -30 $\text{C}$ to 90 $\text{C}$. The model of low voltage DC power source used for BMS is IT6512, which is programable ranging from 0 to 80 volts. The maximum current of DC source is 120 amperes. All the equipment used in experiment are connected through communication interface in synchronism.

The schematic diagram of test arrangement and main test equipment are shown in figure 1 and figure 2, respectively.

![Figure 1. The schematic diagram of test arrangement.](image-url)
2.2. Experiment condition and step

Experiment condition and steps are as follows: firstly, battery system is connected as normal operation mode. Then a power source is linked into battery management system for operating. Secondly, temperature conditions and SOC needed to be adjusted for different SOC estimation accuracy experiment. The temperature of chamber should be set at 45 °C, 25 °C, 0 °C and -10 °C, respectively. The SOC should be set at ≥80% and ≤30%, respectively. When the temperature has been hold at a condition, test step needed to be detailed as following two conditions:

1) When SOC of battery system is greater than or equals 80%:
   a) Charge battery system at 1C to 100% SOC;
   b) Rest for 1h;
   c) Discharge at ((Q_0)/A) for 10min;
   d) Rest for 10min;
   e) Test battery system according to Tab. 1 for 10 cycles;
   f) Rest for 10min;
   g) Charge at ((Q_0)/3)A for 20min;
   h) Charge at ((Q_0)/6)A for 10min;
   i) Rest for 10min;
   j) Record SOC uploaded from BMS;
   k) Charge battery system at 1C to 100% SOC, and record charging capacity Q_1;
   l) Calculate real SOC by ((Q_0-Q_1)/Q_0) ×100%.

2) When SOC of battery system is less than or equals 30%:
   a) Charge battery system at 1C to 100% SOC;
   b) Rest for 1h;

Figure 2. The main test equipment
c) Discharge at \((lQ_0)A\) for 40min;
d) Rest for 20min;
e) Test battery system according to Tab. 1 for 10 cycles;
f) Rest for 10min;
g) Record SOC uploaded from BMS;
h) Discharge battery system at 1C to 0% SOC, and record discharging capacity \(Q_1\);
i) Calculate real SOC by \((Q_1/Q_0) \times 100\%\).

Where, \(Q_0\) stands for the mean value of usable capacity among three times test. And the test error must be less than 2%. The cycle of charge and discharge mode is shown in table 1. The current profile of charge/discharge process is shown in figure 3.

**Table 1.** The time increment of charge and discharge process

| Duration time/s | Cumulative time/s | Current rate/C |
|-----------------|-------------------|----------------|
| 23              | 23                | -1             |
| 8               | 31                | -1/3           |
| 23              | 54                | 1/3            |
| 26              | 80                | -0.01          |

**Figure 3.** The current profile of charge/discharge process

3. Experiment result

After finishing all the above steps, testing data can be recorded and shown in table 2.

**Table 2.** The SOC estimation accuracy at different temperature

| T/℃ | SOC/% | \(Q_0/Ah\) | BMS SOC/% | \(Q_1/Ah\) | Real SOC/% | Error/% |
|------|-------|-------------|-----------|-------------|------------|---------|
| 45   | ≥80%  | 140.909     | 96%       | 10.309      | 92.68%     | 3.32%   |
|      | ≤30%  |             | 34%       | 44.216      | 31.38%     | 2.62%   |
| 25   | ≥80%  | 136.997     | 94%       | 11.518      | 91.59%     | 2.41%   |
|      | ≤30%  |             | 30%       | 40.670      | 29.69%     | 0.31%   |
| 0    | ≥80%  | 131.229     | 87%       | 119.988     | 91.43%     | -4.43%  |
|      | ≤30%  |             | 19%       | 39.436      | 30.05%     | -11.05% |
| -10  | ≥80%  | 128.609     | 75%       | 101.356     | 78.81%     | -3.81%  |
|      | ≤30%  |             | 16%       | 41.14819    | 31.99%     | -15.99% |
3.1. Estimation accuracy of SOC ≥ 80%
Following experiment step (1), the data of SOC estimation accuracy can be recorded at different temperature, shown in table 2. Then figure 4(a) is made for analyzing that the differences between real SOC and recorded SOC, which is uploaded by BMS at different temperature, when SOC of battery system is greater than or equals 80%. The error between real SOC and recorded SOC is shown in figure 4(b). The result shows that: SOC recorded by BMS increases continuously when test temperature rises. Meanwhile, real SOC increases firstly and turns stable later. At the range of -10 °C to 0 °C, the value of recorded SOC is less than the real. But the real SOC turns greater than the recorded when test temperature set from 45 °C to 25 °C. Then, the error between recorded and real SOC decays firstly and increases later, ranging from 0 °C to 45 °C. At the 25 °C, the minimum error is found as 2.41%. The error showed at lower temperature is greater than that at high temperature.

(a) Recorded SOC and real SOC.

(b) Error

Figure 4. The result of test process at different temperature (SOC ≥ 80%)
3.2. *Estimation accuracy of SOC ≤ 30%*

Following experiment step (2), the data of SOC estimation accuracy can be recorded at different temperature, shown in table 2. Then figure 5(a) is made for analyzing that the differences between real SOC and recorded SOC, which is uploaded by BMS at different temperature, when SOC of battery system is less than or equals 30%. The error between real SOC and recorded SOC is shown in figure 5(b). The result shows that: SOC recorded by BMS increases continuously when test temperature rises. Meanwhile, real SOC changes stably when test temperature is set from -10 °C to 45 °C. Ranging from -10 °C to 0 °C, recorded SOC differences from real value, especially at the temperature of -10 °C. The earlier with 31.99% is twice as much as later with 16%. So the maximum error shows as 15.99% between recorded and real SOC. Expect for higher and lower temperature, they have not much distance at the temperature of 25 °C, with the minimum error value of 0.31%.

As shown in figure 5(b), low temperature reduces accuracy of estimation algorithm, resulting in biasing recorded SOC from real SOC. This mechanism protect battery system will not be damaged by rapid change of temperature, especially at low temperature. At the high temperature, recorded SOC presents a little higher than real SOC in figure 5(a). The trend of changing could found in further experiment with more temperature points.

![Figure 5(a): Recorded SOC and real SOC.](a)
4. Discussions

As shown in figure 4(a) and figure 5(a), recorded SOC grows up continuously with the rise of temperature. In actual application, real SOC of battery system is not related positively with temperature. Although available capacity increases with the rising of temperature, changing rate of internal resistance shows different. At lower temperature, internal resistance of battery becomes larger and larger with increasing rate when temperature turns down. But at higher temperature, internal resistance increases slowly with rise of temperature [6]. The error of estimation accuracy is caused by many reasons above.

As shown in figure 4(a) and figure 5(a), the value of real SOC changes slowly ranging from 0 °C to 25 °C, even if SOC of battery system is set as ≥80% or ≤30%. This phenomenon is so different from recorded SOC by BMS that an obvious error is caused. As a result, the estimation accuracy begins worse and worse. At the temperature of -10 °C, both recorded SOC and real SOC are lower than initial value which is set as SOC ≥80%. The values of recorded and real SOC are 75% and 78.81%, respectively.

As shown in figure 4(b) and figure 5(b), tendency of error can be calculated and drawn. The minimum error is found at the temperature of 25 °C, when SOC of battery system is set as ≥80% or ≤30%. At the same time, the error is 2.41% and 0.31%, respectively.

What is more, temperature has an effect on positive and negative material, electrolyte, structure and so on [7]. As shown in figure 6(a), 6(b) and 6(c), actual capacity of battery system is rising with higher temperature. Available capacity of battery increases 12.4 Ah at 45 °C comparing with -10 °C, and rising rate of capacity is stable mostly in the whole temperature range. It is caused mainly by higher chemical response rate and improved usage rate of active material, to promote capacity of battery system. On the contrast, lower temperature reduces dispersal rate of Li⁺, but increases internal resistance so that actual capacity is decayed [8]. Those characteristics can be analyzed in further research.
(a) Absolute capacity.

(b) Rise of absolute capacity.
5. Conclusions
The experiment research of SOC estimation accuracy was carried out at different temperature for battery system, using charge and discharge device and environment chamber. The main conclusions are as follows:

(1) When SOC is greater or equals 80%, the error of SOC between real value and estimated decreases firstly, and then the error increases at high temperature range, according to the rise of temperature. The minimum of estimation error is 2.41% at room temperature for battery system. Battery system presents a lower SOC at lower temperature than higher temperature, because high internal resistance appears.

(2) When SOC is less or equals 30%, the error of SOC between real value and estimated decreases firstly, and then the error increases at high temperature range, according to the rise of temperature. This tendency of error shows the same with conclusion (1). And the best condition of estimation is found at room temperature, with the error of 0.31%.

(3) As for battery system, the real SOC value is not affected by temperature obviously, ranging from 0 °C to 25 °C. On the contract, estimation value upload by BMS turns positive relationship with the rise of temperature. As a result, the estimation accuracy of SOC becomes worse and worse. That means algorithm of estimation might be designed for protection purpose when electrical devices are under low temperature condition.

(4) The temperature of 25 °C is the best condition for testing to get the minimum estimation error. Lower temperature expands estimation error and reduces available capacity of battery system, because chemical response rate of battery is mainly limited. Limitation causes greater internal resistance of battery, which is the main reason of lower capacity. Meanwhile, designer of estimation algorithm does not take it into account so that recorded SOC differs from real SOC. At the room temperature, the lower SOC is, the smaller estimation error turns.

Including this paper, current research of SOC estimation accuracy are mainly based on simulation and experiment for a specific structure of battery system. But different types of chemical battery will turn various characteristics in study when accuracy of algorithm increases. These are the further research for power battery system.
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