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# SOC Estimation of $LiFePO_4$ Battery Based on Improved Ah Integral Method

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***Abstract***

*State of charge (SOC) is the most important status parameters of energy storage system, which is able to predict the available mileage of electric vehicle. In fact, the accuracy of SOC estimation plays a vital role in the usability and security of the battery. To fully consider the practical demands, a novel method to predict SOC of* $LiFePO_4$ *battery is presented in this paper, which defines he correct coefficient separately under two working conditions of charging and discharging. Based on effective factors such as coulombic efficiency, charge and discharge current, and temperature, an Ah integral SOC estimation method with two kinds of efficiency correct coefficients is established by performing massive experimental study. Experiments prove that the estimated error of SOC is less than 5%. Compared with the original Ah method, the improved Ah methods are more advantageous in the accuracy and reliability.*

***Keywords***: *LiFePO4 battery, state of charge (SOC), the ampere-hour (Ah) method*

## 1. Introduction

The LiFePO4 battery applies widely in electric instruments, vehicles and medical equipment. The advantages of high average output voltage, low self-discharge rate, no memory effect and long service life bring it wide and prospective applications in the field of power supplying[1,2].Strong supporthave been given by government on the funds, manpower, policy, etc. [3]. As one of the key technologies of the battery management system (BMS), the prediction of SOC can prevent overcharge and overdischarge so as to monitorthe value ofSOC and to balance the energy according to characteristic difference among the cells in the battery pack to ensure the consistency of battery power. In this way, it may keep the battery a longer service life of use [4-6]. Among the existingestimation methods, the Ampere-hour (Ah) method is the most common one. The basic definition of SOC is shown in Equation (1):

$$SOC(t) = SOC_0 - \frac{1}{C_{nom}}\int_0^{\tau} I d\tau \quad (1)$$

Herein, SOC(t) stands for the charging state at time t, and SOC0 stands for the initial SOC. Also, *I*is the current and Cnom is the nominal capacity of the battery. In this way, the discharge capacity is calculated by the product of discharge current and discharge time, and the current SOCis defined as the difference of the initial SOC and the discharge capacity. As the method estimates SOCthrough the integral of the load current and is of great stability and facility, it has become the most widely used validation means in the field of electric vehicle design. However, some effective factors such as coulombic efficiency, current rate and temperature are sure to add difficultiesto SOC estimation. Nowadays, the related research in improving the accuracy of LiFePO4 battery SOC estimation have being a research focus, and usually parameters of charge and discharge process are the same, which ignores the objectively differences between charge and discharge process. Furthermore, current methods merely establish the parameter without taking enough effective factors into account, and as a result, it limits their further applications. A novel model to predict SOC of $LiFePO_4$ battery is presented in this paper, which defines the correct coefficients under two working conditions of

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charging and discharging separately. The proposed method is based on the effective factors of charge and discharge current, coulombic efficiency and temperature. Finally, an improved Ah method is established by performing a large number of experiments to make up the accuracy defect of the single correct coefficient model.

## 2. Improved Ah Method

The original Ah method shows as:

$$\mathrm{Q} = \int I d\tau \tag{2}$$

Apparently, the estimated errors will accumulateover timewithout the error correction of the influences ofeffective factors. For this reason, the original Ah methodhas been improved with efficiency coefficients to increase the accuracy of SOC estimation in the research [7-9].

When the battery chargesat the current rate of *I*,

$$SOC(t) = SOC_0 - \frac{\int_0^\tau \eta_i I d\tau}{C_{nom}} \tag{3}$$

Where, $\eta_i = C_0/C_i$is the charge efficiency at current temperature, and is defined as the ratio of the discharge quantity and the charge quantityof the current rate of *I*.

By contrast, when the battery discharges at the current rate of *I*,

$$SOC(t) = SOC(0) \cdot \eta_0 - \frac{\int_0^\tau I d\tau}{C_{nom}} \tag{4}$$

Where,$\eta_0 = C_0/C_{nom}$is the discharge efficiency at current temperature, and also is defined as the ratio of the discharge quantityof discharge rate *I* and the charge quantityof the rated current.

## 3. Method Experimental Analysis

### 3.1. Experiment Apparatus

The system of SOC estimation comprises three parts: the hardware testing platform, the software system on upper computer and SCM (Single-Chip Microcomputer) controlling program. The frame diagram is shown in Figure 1.

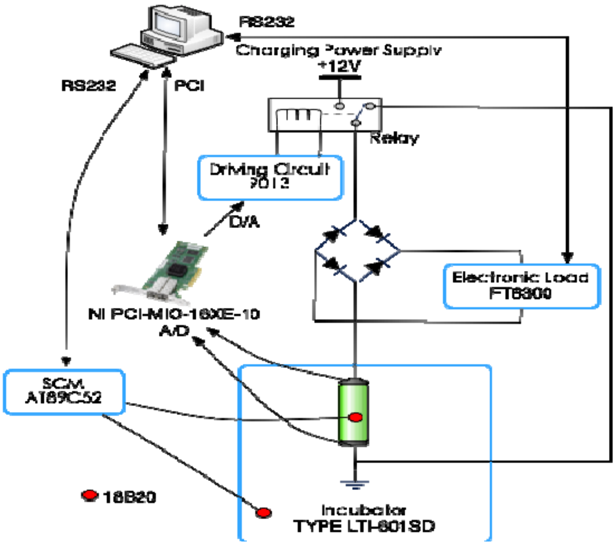

Figure 1. The Frame Diagram of Battery Testing System

The hardware system includes DAQ card, SCM controlling system, Hall sensor, electronic load, computer and incubator. The rectifier bridge is used to switchthe charge and discharge procedure automatically. The electronic load controls the constant current size during the course of charge and discharge. The incubator, ranging from -10□ to 40℃, provides different temperature conditions, and DAQ device takes charge of the acquisitions of voltage and current. The capacity of the LiFePO4 battery tested in the experiments is 1AH and the nominal voltage is 3.2V. As one kind of high power battery, the selected battery is primarily used on occasion that high-rate discharge is required, as in electromobile and Hybrid Electric Vehicle (HEV). Additionally, the featureof small capacity aids to shorten the charging and discharging cycle so as to expedite the experiment and research process.

### 3.2. Experimental Data Acquisition and Analysis

The experiments were conducted at different temperatures of 40℃, 25□, 10℃, 0℃, -10℃ and different charge-discharge rate of 1/3C, 2/3C, 1C, 1.5C, 2C, 3C, 4C, equates to 0.33A, 0.67A, 1A, 1.5A, 2A, 3A, 4A respectively. Table 1 shows the charge efficiencies at different temperatures and charge-discharge currents.Charge efficiency data is equal to the battery release power (Standard conditions: 20 □& 1C ) divided by the charge into the battery power.

Table 1. Charge Efficiency at Different Temperatures and Currents

| | | Charge Current (A) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 0.33 | 0.67 | 1 | 1.5 | 2 | 3 | 4 |
| Temperature (℃) | 40 | 100.34% | 100.16% | 100.03% | 99.91% | 99.83% | 99.77% | 99.71% |
| | 25 | 100.48% | 100.21% | 100.02% | 99.90% | 99.75% | 99.41% | 99.29% |
| | 10 | 101.49% | 102.28% | 100.57% | 98.42% | 96.73% | 95.33% | 96.72% |
| | 0 | 102.52% | 102.25% | 101.56% | 99.31% | 94.53% | 95.93% | 93.11% |
| | -10 | 103.34% | 102.89% | 101.76% | 97.07% | 95.61% | -- | -- |

The capacity of the battery decreases rapidlyat low temperatures. Otherwise, the charged electricity is about 0.027AHat the current of 3A and the temperature of -10□, while it reduces to 0.0079AH when the battery charges at the current of 4A and the same temperature. Since the charge efficiencies of these two data are meaningless, they are removed from the list. Correspondingly, Table 2 shows the discharge efficiencies at different temperatures and discharge currents.Charge efficiency data is equal to the battery release power divided by the charge (Standard conditions: 20 □& 1C ) into the battery power.

Table 2. Discharge Efficiency at Different Temperatures and Currents

| | | Discharge Current (A) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 0.33 | 0.67 | 1 | 1.5 | 2 | 3 | 4 |
| Temperature (℃) | 40 | 108.8% | 108.34% | 107.54% | 106.62% | 105.85% | 103.88% | 102.17% |
| | 25 | 99.74% | 100.51% | 99.47% | 99.20% | 98.74% | 97.69% | 97.46% |
| | 10 | 99.00% | 87.45% | 85.62% | 84.03% | 82.97% | 81.92% | 83.39% |
| | 0 | 97.87% | 81.03% | 76.24% | 73.11% | 71.33% | 70.61% | 73.81% |
| | -10 | 78.63% | 55.94% | 51.14% | 48.58% | 47.24% | 46.57% | 46.70% |

As shown in Table 1 and Table 2, parts of the data are greater than 100%, because the charged electricity cannot fully release (100%) in actual use due to the existence of internal resistance and line loss. For assuring that the actual discharge capacityis not less than the rated capacity, the battery-makers would increase the available capacityin manufacture. The experimental results show thatthe full charge capacity gradually decreased with the current increased.

To create the relationship among charge and discharge efficiency, temperature and current, thepolynomial fitting is applied to the results. Figure 2 shows the curve fitting of the charge and discharge efficiencies.

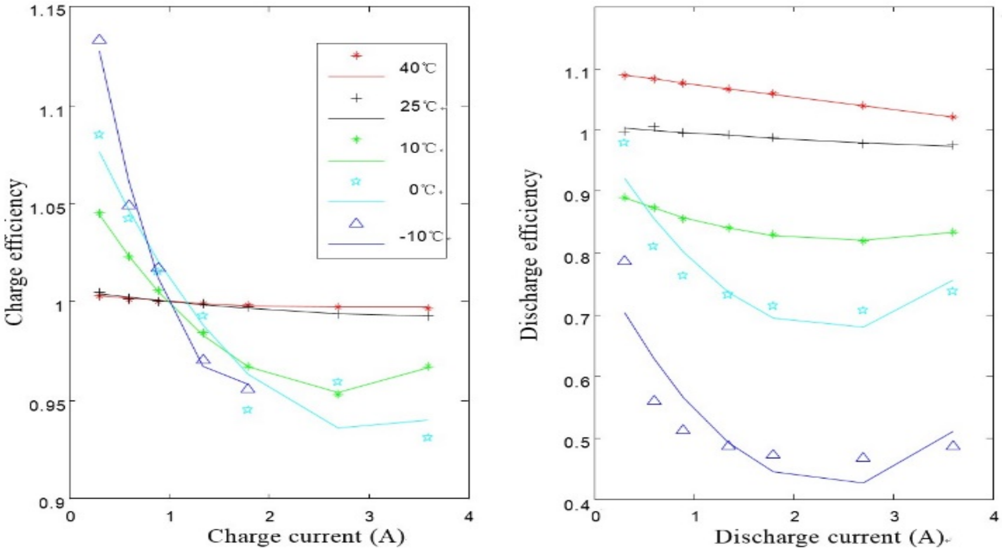

Figure 2. The Efficiencies Curve of the Charge and Discharge

The coefficients of charging efficiency are fitted as Equation (5) under the charge condition of I<0.

$$\eta_i = P(0)I^2 + P(1)I + P(2) \tag{5}$$

The coefficients P(0), P(1) and P(2) are calculated respectively, and listed in Table 3.

Table 3. Coefficients of Charging Efficiency

| Temperature (℃) | P(0) | P(1) | P(2) |
|---|---|---|---|
| 40 | 0.0008 | -0.0048 | 1.0044 |
| 25 | 0.0008 | -0.0065 | 1.0061 |
| 10 | 0.0148 | -0.0823 | 1.0677 |
| 0 | 0.0189 | -0.1153 | 1.1094 |
| -10 | 0.0883 | -0.2984 | 1.2090 |

The polynomial fitting is applied to acquire the charge efficiency at any temperature and current conditions. As a result, P-temperature curve fitting formula is shown in Equation (6) and then the corresponding regressing equation is obtained as Equation (7).

$$\begin{cases} P(0) = 0.0425 - 0.0014T \\ P(1) = -0.1682 + 0.0053T \\ P(2) = 1.1297 - 0.0039T \end{cases} \tag{6}$$

$$\eta_i = (0.0425 - 0.0014T)I^2 + (-0.1682 + 0.0053T)I + (1.1297 - 0.0039T) \tag{7}$$

While under the discharge condition(I >0), the coefficients of discharging efficiency are fitted as (8).

$$\eta_0 = Q(0)I^2 + Q(1)I + Q(2) \tag{8}$$

Table 4. Coefficients of Discharging Efficiency

| Temperature(℃) | $Q(0)$ | $Q(1)$ | $Q(2)$ |
|---|---|---|---|
| 40 | 0.0002 | -0.0210 | 1.0948 |
| 25 | 0.0006 | -0.0113 | 1.0054 |
| 10 | 0.0135 | -0.0696 | 0.9099 |
| 0 | 0.0306 | -0.1492 | 0.8807 |
| -10 | 0.0257 | -0.1277 | 0.6164 |

In the same way, the coefficients *Q(0)*, *Q(1)* and *Q(2)* are also calculated respectively, and listed in Table 4.

Similarly, the polynomial fitting is also applied to analyse the coefficients Q(0), Q(1) and Q(2). In addition, the robust-fit function in the toolbox of Matlab has been used to eliminate the gross error points which may deteriorate the regressing precision. And then Q-temperature curve fitting formula is calculated and shown as Equation (9). The regressing equation is then obtained by Equation (10).

$$\begin{cases} Q(0) = 0.0189 - 0.0005T \\ Q(1) = -0.1113 + 0.0028T \\ Q(2) = 0.7952 + 0.0083T \end{cases} \tag{9}$$

$$\eta_0 = (0.0189 - 0.0005T)I^2 + (-0.1113 + 0.0028T)I + (0.7952 + 0.0083T) \tag{10}$$

Finally, the improved Ah integral SOC estimation equation is proposed in Equation (11).

$$SOC(t) = SOC(0) \cdot \eta_0 - \frac{\int_0^\tau \eta_i I d\tau}{C_{nom}} \tag{11}$$

Where,

$$\begin{cases} \eta_0 = 1 \\ \eta_i = (0.0425 - 0.0014T)I^2 + (-0.1682 + 0.0053T)I + (1.1297 - 0.0039T) \end{cases} \tag{12}$$

if it is under the charge condition ($I$<0). Otherwise,

$$\begin{cases} \eta_0 = (0.0189 - 0.0005T)I^2 + (-0.1113 + 0.0028T)I + (0.7952 + 0.0083T) \\ \eta_i = 1 \end{cases} \tag{13}$$

if it is under the discharge condition ($I$>0).

### 3.3. Experimental Verification

To validate the accuracy of the improved Ah integral SOC estimation method, this paper proposed the experimental verification with 1AH $LiFePO_4$ battery, followed by the result analysis and comparison of original Ah method were performed. In view of the two procedures of charging and discharging, verification experiment was divided into two parts [10, 11].

Verification experiment 1, according to the charge procedure ($I$<0), includes the following steps. First, empty the battery, and charge itrespectively in 0.5A, 1.5A, 3A at 22℃, 12℃, -2℃ for a preset time. Second, estimate SOC with the improved Ah integral method. Finally, keep discharging the battery until the terminal voltage reaches the cutoff voltage, and then record the discharge quantities. Table 5 shows the estimates and errors of the improved Ah method under the charge condition as well as the comparison with original Ah method. “Real SOC” was calculated by later constant current discharge experiments.

By contrast, according to the charge procedure (I>0), verificationexperiment 2 includes the following steps. First, fully charge the battery, and then discharge itrespectively in 0.5A, 1.5A, 3A at 22℃, 12℃, -2℃ for a preset time. Second, estimate SOC with the improved Ah integral method. Finally,keep dischargingthe battery until theterminal voltage reached the cutoff voltage and thenrecord thedischarge quantities. Table 6 shows the estimates and errors of the improved Ah method under the discharge condition as well as the comparison with original Ah method.

Table 5. Comparison of Estimates and Errors under the Charge Condition

| | Charge Current(A) | Charge Time(s) | Discharged Quantity(%) | Estimates of the original method (%) | Errors of the original method (%) | Estimates of the improved method (%) | Errors of the improved method (%) |
|---|---|---|---|---|---|---|---|
| 22℃ | 0.5 | 1433 | 20.19 | 19.90 | -0.29 | 20.32 | 0.13 |
| | 1.5 | 905 | 37.52 | 37.71 | 0.19 | 37.30 | -0.22 |
| | 3 | 340 | 28.98 | 28.33 | -0.65 | 28.57 | -0.41 |
| 12℃ | 0.5 | 1597 | 22.70 | 22.18 | -0.52 | 23.00 | 0.30 |
| | 1.5 | 1214 | 50.02 | 50.58 | 0.56 | 49.77 | -0.25 |
| | 3 | 443 | 35.46 | 36.92 | 1.46 | 36.93 | 1.47 |
| -2℃ | 0.5 | 1018 | 14.59 | 14.14 | -0.45 | 14.98 | 0.39 |
| | 1.5 | 783 | 29.87 | 32.63 | 2.76 | 31.69 | 1.82 |
| | 3 | 245 | 15.36 | 20.42 | 5.06 | 20.60 | 5.24 |

Table 6. Comparison of Estimates and Errors under the Discharge Condition

| | Discharge Current(A) | Discharge Time(s) | Discharged Quantity (%) | Estimates of theoriginal method (%) | Errors of the originalmethod (%) | Estimates of the improved method (%) | Errors of the improved method (%) |
|---|---|---|---|---|---|---|---|
| 22℃ | 0.5 | 896 | 81.76 | 87.56 | 5.80 | 83.05 | -1.29 |
| | 1.5 | 749 | 63.83 | 68.79 | 4.96 | 60.89 | 2.94 |
| | 3 | 263 | 70.02 | 78.08 | 8.06 | 68.06 | 1.96 |
| 12℃ | 0.5 | 1176 | 67.98 | 83.67 | 15.69 | 69.58 | 1.60 |
| | 1.5 | 702 | 53.80 | 70.75 | 16.95 | 51.48 | -2.32 |
| | 3 | 369 | 44.88 | 69.25 | 24.37 | 47.03 | 2.15 |
| -2℃ | 0.5 | 995 | 59.65 | 86.18 | 26.13 | 58.69 | -0.96 |
| | 1.5 | 833 | 28.21 | 65.29 | 37.08 | 30.09 | -1.88 |
| | 3 | 372 | 27.16 | 69.00 | 41.84 | 29.70 | -2.54 |

According to the experimental results, the improved Ah integral SOC estimation method is highly precise and practically valid. Apparently, the performance of the improved estimation method is more prominent in the case of lower temperature and higher current.

## 4. Conclusion

In order to predict SOC of LiFePO4 battery precisely and to prevent overcharge and overdischarge effectively, an improved Ah integral SOC estimation method is presented in this paper, which defines the correction parameters under two working conditions of charging and discharging. Taking the practical application taken into consideration, the efficiency correct coefficient of SOC estimation is established for different working conditions. According to the verification experiments, the improved Ah integral method introduced in the paper is capable to reduce the influences caused by effective factors such as coulombic efficiency, charge and discharge current and temperature. The experimental results demonstrate that this novel method is more accurate and reliable.

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