Online SOC Estimation of Power Battery Based on Closed-loop Feedback Model

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Abstract
It is an important research area for electric vehicle battery management system to estimate battery state of charge (SOC) online real-time accurately. This paper summarizes the advantages and disadvantages of existing SOC basic estimation algorithm, introduces the Feedback Correction Factor, proposes the Closed-loop Feedback online SOC estimation algorithm which combined with the Coulomb Counting Method and Open-Circuit Voltage Method, experiments to test and verify accuracy and convergence of this algorithm. The results show that the algorithm has high accuracy, compared to true value, the maximum error is controlled within 2%; when SOC initial value is inaccurate, the algorithm converges fast, steady-state error is controlled within 2%.

Key words: Closed-loop Feedback Model, Feedback Correction Factor, Coulomb Counting, Open-Circuit Voltage.

1. INTRODUCTION
Due to the dwindling reserves of fossil fuels and the greenhouse effect gradually intensifying, all the countries around the world are actively developing low-carbon, environmentally friendly, renewable new energy strategy. In recent years, pure electric vehicles have made great development, because of usage of electricity in operation, electric vehicles can achieve zero pollution, zero emissions in running links, which causing the world's attention as an important new energy strategy. However, at present the batteries still have more than a half cost of pure electric vehicles, the batteries cost is still the main "bottleneck" in the development of electric vehicles. LiFePO4 batteries become an ideal power source for electric vehicles according to their features of long life, good safety and low cost.

Compared to traditional vehicles, pure electric vehicles are driven by lithium-ion battery packs, so it is the core issue for developing pure electric vehicles to manage battery packs rationally (Lee and Kim and Lee, 2008; Li, Lu and Ouyang, 2010 ).In the battery management system, State of Charge (SOC) estimation is the most important thing to be considered, accurate SOC estimation can not only provide intuitively real-time vehicle recharge mileage for the driver, but also provide an important basis for the vehicles energy management, State of Health(SOH) estimation, fault diagnosis.

Currently, many SOC estimation algorithms are under researched (Li and Klee, 2013;Wang and Zhang, 2015; Hu and Hu, 2014; Tong and Matthew, 2015;Waag and Fleischer, 2014; Mastali and Vazquez-Arenas, 2013), such as Coulomb Counting Method, Open-Circuit Voltage Method and considering parameter modification Coulomb Counting Method. Some advanced algorithms such as Kalman filter algorithms, neural networks, fuzzy logic and other methods have been proposed. However, the resource consumption of these methods is relatively large. Coulomb Counting Method is easy and practical, but due to the current measurement error, the accumulated error increases gradually over time, and the initial SOC value can't be given by this method (Li and Klee, 2013). The accumulated error can be reduced by using high-precision current sensor (Wang and Zhang, 2015). SOC of the batteries can be determined by the relationship between SOC and EMF(Pattipati and Balasingam, 2014 ). However, LiFePO4 batteries exist obvious voltage platform area, a slight voltage fluctuation will bring considerable SOC error. This paper presents a closed-loop feedback online SOC estimation algorithm which combine of Coulomb Counting Method and Open-Circuit Voltage Method, the Feedback Correction Factor is introduced to balance the advantages and disadvantages of the two methods. The presented algorithm can effectively solve the SOC initial value inaccurate and error accumulation problem.

2. PROBLEM STATEMENT
2.1. SOC Definition
There is no uniform standard definition for State of Charge (SOC), the currently widely accepted program
is to measure it with capacity as an indicator, generally expressed as a percentage (Lu Languang and Han Xuebing, 2013), as shown in Formula (1): \[ SOC = \frac{Q_{\text{remain}}}{Q_{\text{rated}}} \times 100\% \] (1)

Wherein, $Q_{\text{rated}}$ is the rated capacity, $Q_{\text{remain}}$ is the current remaining capacity of batteries, batteries internal capacity Q can't be measured directly, it is needed to estimate though the external parameters of the batteries, commonly used methods are Coulomb Counting Method and Open-Circuit Voltage Method.

2.2 Definition and Insignificancy of Coulomb Counting Method

The principle of Coulomb Counting Method is to monitor the batteries discharge (or charge) current in a certain period and integrate the current to get the change of capacity, as shown in Formula (2): \[ \Delta Q = \int_{t_1}^{t_2} i(t)dt \] (2)

The real-time SOC value can be calculated from Formula (1) and Formula (2), as shown in Formula (3): \[ SOC = SOC_{t_1} - \frac{1}{Q_{\text{rated}}} \int_{t_1}^{t_2} i(t)dt \] (3)

Where $SOC_{t_1}$ is the batteries SOC value at initial time $t_1$. From Formula (3) we can see that the accuracy of real-time SOC value depends on two variables: The most important one is the initial SOC value, which is $SOC_{t_1}$, the error will be passed to the real-time SOC value; the followed one is the current $i(t)$ measurement accuracy, and the error will be accumulated to the real-time SOC value.

2.3 Definition and Insignificancy of Open-Circuit Voltage Method

The principle of Open-Circuit Voltage Method is based on the power batteries EMF and SOC have a one-to-one relationship, that is, when SOC in the 0% to 100% change interval, each given SOC value there is the only one corresponding to the EMF; At the same time when the batteries are not in charge or discharge, that is, the operating current is 0, the batteries open-circuit voltage and electromotive force equal. LiFePO4 power batteries SOC-EMF curve is shown in Figure 1:

![Figure 1](image)

According to Figure 1, LiFePO4 power batteries have a significant operating voltage platform area. The batteries open-circuit voltage is 3.0V at SOC = 10% and 3.2V at SOC = 90%, and the variation of open-circuit voltage is only 0.2V in the range of SOC from 10% to 90%. When using the Open Circuit Method to measure SOC, the voltage inspection unit must have a high measurement accuracy, through the linear calculation easy to know, when open-circuit voltage measurement bring in error of 0.01V, SOC estimation will produce 4% error. In addition, due to the hysteresis effect of LiFePO4 batteries, batteries must be fully quiescent about 1 hour after a working state end, then the open circuit voltage will rebound back to the electromotive force, which electric vehicles in real-time operation can't be met.

3. CLOSED-LOOP FEEDBACK SOC ESTIMATION METHOD

The accurate estimation of batteries performance is based on batteries internal chemical reaction equation, which depends on precise physical and chemical laws, lots of assumptions and empirical parameters, so it is
only suitable for laboratory research. In the process of electric vehicles real-time on-line driving, the estimation of state parameters are mainly based on external parameters such as batteries voltage, current, temperature and other real-time measurements. According to the above sections, the Coulomb Counting Method and Open-Circuit Voltage Method have their own advantages and disadvantages. Therefore, this paper presents a Closed-loop Feedback Estimation Method which combines two methods, and designs the Feedback Correction Factor $\lambda$. Schematic is shown in Figure 2:

![Figure 2. Closed-loop Feedback Online SOC Estimation Method Schematic](image)

According to the schematic diagram, the Closed-loop Feedback SOC Estimation Method can be described by 5 functions, which are shown in the following:

\[
\Delta SOC = \int i_k \, dt
\]  

(4)

\[
SOC^*_k = SOC_{init} - \Delta SOC
\]  

(5)

\[
SOC^{OCV}_k = f\left(\sum OCV / n\right)
\]  

(6)

\[
P_k = \lambda \times SOC^{OCV}_k - (1 - \lambda) \times SOC_k
\]  

(7)

\[
SOC_k = SOC^*_k + P_k
\]  

(8)

The system runs as follows:

(a) In system step time interval, the coulomb counting thread real-time measures batteries operating current $i_k$, and integrals $i_k$ with time, obtains the cumulative change of capacity, calculates the SOC change $\Delta SOC$, figures out the algebraic sum with system initial value $SOC_{init}$, due to the $SOC_{init}$ is an estimated value, obtains the real-time estimation value $SOC^*_k$, as shown in Formula (5).

(b) After system obtains the real-time estimation value $SOC^*_k$, system enters the real-time SOC output process. The first loop feeds back $SOC^*_k$ as real-time estimated SOC value to the OCV correction thread, which is used as the basis for the next time SOC correction.

(c) OCV correction thread measures the real-time batteries open-circuit voltage $u_k$, queries off-line established OCV-SOC table. Due to LiFePO$_4$ batteries has a significant discharge voltage platform, in order to reduce the SOC estimation error caused by voltage measurement error, system uses the moving average method which averages the latest n OCV value to query OCV-SOC off-line table, as shown in Formula (6).

(d) System synthesizes $SOC^{OCV}_k$ and $SOC_k$, introduces the Feedback Correction Factor $\lambda$, as shown in Formula (7), figures out the real-time bias $P_k$, sums $P_k$ and $SOC^*_k$, obtains the real-time SOC value, as shown in Formula (8), enters the next loop.

(e) The value of Feedback Correction Factor $\lambda$ is between [0,1], $\lambda$ is used to adjust the look-up table.
and real-time $SOC_k$ weight which estimate SOC in the next moment, we can adjust the different weights according to LiFePO$_4$ batteries discharge curve at different stages.

4. EXPERIMENT VERIFICATION

In order to verify the performance of using the Closed-loop Feedback Model to real-time estimate SOC, 40Ah LiFePO$_4$ batteries which made in Luoyang, China are used for charge and discharge experiments at room temperature (25°C), experiment platform is shown in Figure 3:

![Figure 3. Experiment Platform Photos](image)

FUDS conditions in the USABC batteries test manual are used to be the batteries test conditions. FUDS is a variable power test, which simulates the charging and discharging pressure of electric vehicles in the urban road environment. The manual defines the batteries power density as 79W/Kg, considering the recent increase in manufacturing process of LiFePO$_4$ batteries, and referencing batteries factory instructions, the experiment batteries power density is taken to 200W/Kg, batteries maximum power discharge current is taken to 100A. A single FUDS condition is 1372 seconds, this experiment uses 8 FUDS conditions, as shown in Figure 4:

![Figure 4. Single FUDS Variable Power Curve](image)

4.1 Closed-loop Feedback Algorithm Accuracy

Full charge the test batteries, run FUDS conditions at room temperature, after 8 loops, the batteries discharge is completed, SOC and error curves are shown in Figure 5:

![Figure 5. Full Discharge SOC and Error Curves](image)
According to Figure 5. Closed-loop Feedback Algorithm for SOC estimation accuracy is high, the error in the whole process has been controlled within 2%. It can be seen from the fig5, at the beginning and end of the discharge process, the error is small; in the discharge voltage platform area, the error is larger. This reason is that feedback loop of the Closed-loop Feedback Algorithm depends on batteries open-circuit voltage as a measure. At the beginning and the end of the discharge process, the SOC-EMF curve changes violently and the system has high precision. In the discharge voltage platform area, voltage is relatively stable, so the system estimation error is relatively large.

4.2 Convergence of Inaccurate Initial SOC Value

An unavoidable problem in online SOC estimation of electric vehicles is the need of an initial SOC value at the start of the system, which is often inaccurate during actual operation. For example, after electric vehicles long-term placement to restart, because of batteries self-discharge effect, if system uses the last SOC value, there will be a certain error to the true value. In order to verify the convergence of Closed-loop Feedback Algorithm to the inaccurate SOC value, the true SOC value of the batteries to be tested is set to 0.8, the initial SOC of algorithm is set respectively to 0.6 and 0.9, after FUDS conditions operated, the system convergence curve and error curve are shown in Figure 6 and Figure 7:

[Graphs showing convergence and error curves for different initial SOC values]

Figure 6. Inaccurate Initial SOC System Convergence Curve

Figure 7. Inaccurate Initial SOC System Error Curve

It can be seen that when the initial SOC value is not accurate, the Closed-loop Feedback Algorithm converges quickly within 100 seconds and reaches steady state within 300 seconds, the steady-state error is less than 2%.

5. CONCLUSION

This paper discourses the definition of SOC and discusses the advantages and disadvantages of 2 basic SOC estimation methods. On the basis of the two methods, a closed-loop feedback on-line SOC estimation method is proposed. Feedback Correction Factor $\lambda$ is introduced to adjust the proportion of current integration and open-circuit voltage in the new algorithm. Experiment results show that the proposed algorithm can estimate SOC online real-time accurately, and the SOC value will converge quickly to the true value when the initial SOC value is not accurate.
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