

A New State of Charge Estimation for Lithium-ion Battery Based on Sliding-Mode Observer and Battery Status

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Abstract: Lithium-ion (Li-ion) battery has been widely used in electric vehicles and renewable-energy. It is urged to provide more accurate State of Charge (SOC) in these applications. This paper proposes a new method for SOC estimation. In this method, a new equivalent circuit battery model with one RC block is designed considering self-discharge. Compared with the conventional methods, some improvements have been achieved. Firstly, a Sliding Mode Observer (SMO) is adopted to estimate the SOC. Secondly, the new method divides the SOC estimation into two stages which include charging stage and discharging stage according to the battery status. The series resistance and parallel resistance of RC block in the battery model are taken into account to estimate the SOC in discharging of battery. It enhances the SOC estimation accuracy especially for large discharge current. Finally, a simulation is conducted to verify the performance of the method.

Key Words: Lithium-ion Batteries, SOC Estimation, Sliding Mode Observer, Battery Status

1 Introduction

With the rapid development of electric vehicles (EVs) and renewable-energy generators, there is growing interest in the energy storage device [1]. The lithium-ion battery has emerged as the most prominent energy storage device. Compared with nickel-cadmium (NiCd) and nickel-metal-hydride (NiMH) battery, it has the merits of high energy, power densities. And it does not suffer from the memory effect.

The practices on commercial Li-ion battery products show the importance of battery management system (BMS). A high performance of BMS can improve the Li-ion battery operating efficiency and prolong the lifetime of battery. However, optimal energy utilization is one of the most challenges in the BMS. As the indication of battery energy, SOC plays an important role in BMS. The accuracy of SOC can influence the battery when starting the charging, and when stopping the discharging especially in the situation of large power such as Evs [2]. In other words, the high degree of accuracy can protect the battery from overcharged or overdischarged. A bad SOC estimation might significantly damage the battery and ultimately result in reduced battery life. So the Li-ion battery applied in the engineering intensifies the need of precise SOC estimation algorithm.

To get the SOC of Li-ion battery accurately, there are abundant studies about SOC estimation in recent years. Many of them use the battery equivalent circuit models combining open-loop methods or close-loop methods to estimate the SOC. Among the open-loop methods, the coulomb counting method is the most commonly used, which presents high accuracy of SOC with precise current measurement [3]. In general, the result of coulomb counting method can meet requirements in the engineering. However, there are two problems to reduce the property of the algorithm. One is that it is hard to get the initial SOC. To get the initial SOC, it needs to rest the battery for several hours,

which is impossible when the battery is on the runtime. The other is that there is accumulated error when integrating the measured current with time. It needs to be corrected by periodic recalibration. What's more, the coulomb counting method does not account for self discharge and battery inner resistance. It also reduces the SOC estimation accuracy especially for the large current flowing in and out battery.

Except for coulomb counting method, some other close-loop methods are developed. Plett proposed Kalman filtering method to estimate the battery SOC [4]. It optimally estimates the battery SOC from the noise in the environment. However, this method requires complex mathematical calculation and memory resources. What's more, imperfect modeling and the restriction of Gaussian distribution of the external noises may degrade its performance. And it can lead to failure in real applications [5]. SMO is another method to estimate the battery SOC. It can eliminate the model error when the system reaches to predefined sliding surface [6]. Although overcoming the drawbacks in coulomb counting method, but it does not consider the battery inner resistance and self discharge, which reduces the overall SOC accuracy. Except for methods, Fuzzy logic methodology uses the fuzzy theory to estimate SOC. It needs more prior knowledge when getting battery impedance model, which is trivial and inconvenient. Neural network method can estimate the SOC but require complex computation [7]. There are other electro-chemistry methods to get the SOC [8]. They can provide guide for manufacturing process of Li-ion battery but may not be suitable in the situation whose controller is microcontroller.

In general, many SOC estimating methods do not consider battery status (including charging, discharging and rest) and parasitic parameters. In this paper, a new SOC estimation based on SMO method and battery status is proposed. The proposed method uses equivalent circuit model with one RC block to model the battery. It requires little computation and memory resources and can be applied to real application with lower hardware configuration. The method divides the SOC estimation into two stages, ie, charging and discharging. When the battery is discharging,

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it considers battery inner resistance [9]. These two stages use SMO to estimate the SOC. The proposed method can improve the SOC estimation accuracy particularly in the situation of large battery current.

The rest of the paper is organized as follows: In section 2, a equivalent circuit model is proposed to describe the battery behavior; In section 3 and 4, the SMO for SOC estimation considering the battery status is designed. In section 5, a MATLAB/Simulink simulation is conducted to show the performance of the proposed SOC estimation method. Finally, the conclusions are drawn in section 6.

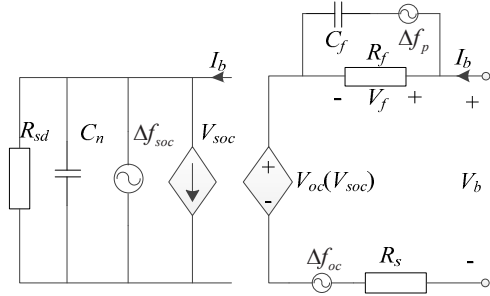


Fig. 1. Equivalent circuit model of the Li-ion battery

2 Battery Model

The Equivalent circuit model of the Li-ion battery used in this paper is shown in Fig.1. The model can mimic the precise dynamic behavior of the lithium-ion battery. In this model, the open circuit voltage (OCV) is represented by a controlled voltage source, $V_{oc}(V_{soc})$. It is a function of battery's SOC, which is denoted by V_{soc} . Furthermore, an instantaneous terminal voltage variation due to the battery current I_b is given by inserting a series resistance denoted by R_s . R_s is also called ohmic resistance. It can expend the energy and reduce SOC when the battery is discharging. Nevertheless, the RC block (C_f, R_f) shows the dynamics response of battery voltage when a step load current is applied. The whole charge capacitor R_{sd} is denoted by C_n ($C_n=3600C_Q$, C_Q is norm capacity (A*h)) and the self-discharge energy loss due to long time storage. Although the Li-ion has low self-discharge, It still influence the accuracy of SOC especially for large current I_b . Since there are modeling errors, uncertainties and time-varying elements in the model, Δf_p , Δf_{oc} and Δf_{soc} stand for these errors and uncertainties. The model is simple and the model errors can be compensated by the robust SMO.

The dynamics of voltage across RC block can be described as

$$\dot{V}_f = -\frac{1}{R_f C_f} V_f + \frac{I_b}{C_f} + \Delta f_p \quad (1)$$

The battery terminal voltage V_b can be expressed as

$$V_b = V_{oc}(V_{soc}) + I_b R_s + V_f + \Delta f_{oc} \quad (2)$$

I_b can be expressed as

$$I_b = \frac{V_b - V_{oc} - V_f}{R_s} \quad (3)$$

There are two assumptions: one is that the derivative of the terminal voltage with respect to the current is negligible since a fast sampling (hundreds of microsecond) of in real applications time is obtained; the other is that the OCV($V_{oc}(V_{soc})$) is piecewise linear in V_{soc} , So

$$V_{oc} = k * V_{soc} \quad (4)$$

The voltage across the C_n is V_{soc} , ie, SOC. Its dynamic is given by

$$\dot{V}_{soc} = -\frac{V_{soc}}{R_{sd} C_n} + \frac{I_b}{C_n} + \Delta f_{soc} \quad (5)$$

Substituting (3) into (5) yields

$$\dot{V}_{soc} = -\frac{V_{soc}}{R_{sd} C_n} - \frac{V_f}{R_s C_n} - \frac{V_{oc}}{R_s C_n} + \frac{V_b}{R_s C_n} + \Delta f_{soc} \quad (6)$$

From the two assumptions and (4), the derivative of the V_b can be expressed as

$$\begin{aligned} \dot{V}_b &= V_{oc}(\dot{V}_{soc}) + \frac{d}{dt}(I_b R_s) + \dot{V}_f + \Delta f_{oc} \\ &= -\frac{V_b}{R_f C_f} + \frac{V_{oc}(V_{soc})}{R_f C_f} + \frac{I_b}{C_f} + \frac{I_b}{C_n} + \frac{I_b R_s}{R_f C_f} - \frac{V_{soc}}{R_{sd} C_n} + \Delta f_{oc} \end{aligned} \quad (7)$$

Since the value of $R_{sd} C_n$ is large enough, V_{soc} ranges from 0 to 1, $\frac{V_{soc}}{R_{sd} C_n}$ can be zero. It is noteworthy that the SOC estimation should consider this item when the battery does not work. Finally, the system's state space was described by the following equations

$$\begin{aligned} \dot{x} &= Ax + BI_b + \Delta f \\ y &= Cx \end{aligned} \quad (8)$$

Where

$$\begin{aligned} n_1 &= \frac{1}{C_f}, n_2 = \frac{1}{C_f} + \frac{1}{C_n} + \frac{R_s}{R_f C_f} \\ m_1 &= \frac{1}{R_f C_f}, m_2 = \frac{1}{R_s C_n}, m_3 = \frac{1}{R_{sd} C_n} \end{aligned} \quad , x = \begin{bmatrix} V_b \\ V_{soc} \\ V_f \end{bmatrix}$$

$$A = \begin{bmatrix} -m_1 & m_1 k & 0 \\ m_2 & -m_3 - m_2 k & -m_2 \\ 0 & 0 & -m_1 \end{bmatrix}, B = \begin{bmatrix} n_2 \\ 0 \\ n_1 \end{bmatrix}$$

$$C = [1 \ 0 \ 0], \Delta f = \begin{bmatrix} \Delta f_{oc} \\ \Delta f_{soc} \\ \Delta f_p \end{bmatrix}$$

3 The design of SMO

To estimate the SOC of Li-ion battery using SMO, observability of the observer is discussed firstly. The observability matrix of the system is as follows

$$obsv = \begin{bmatrix} C \\ CA \\ CA^2 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ -m_1 & m_1 k & 0 \\ a & b & c \end{bmatrix} \quad (9)$$

Where

$$\begin{aligned} a &= m_1^2 + m_1 m_2 k, c = -m_1 m_2 k \\ b &= -m_1 k - m_1 m_3 k - m_1 m_2 k^2 \end{aligned}$$

According to the row echelon matrix of (10), one can obtain rank (obsv) = 3. So the state variables V_b, V_{soc}, V_f can be observed.

Secondly, the SMO $\hat{V}_b, \hat{V}_f, \hat{V}_{soc}$ is designed by using the theory of SMO control. The SMO function for \hat{V}_b can be built as

$$\dot{\hat{V}}_b = -m_1 \hat{V}_b + m_1 k \hat{V}_{soc} + n_2 I_b + L_b \text{sgn}(V_b - \hat{V}_b) \quad (10)$$

Where \hat{V}_{soc} is the estimation of V_{soc} .

Designing the sliding-mode surface $s_b = e_b = V_b - \hat{V}_b$, the derivative of s_b can be given as

$$\dot{s}_b = -m_1 e_b + m_1 k e_{soc} + \Delta f_{oc} - L_b \text{sgn}(s_b) \quad (11)$$

Where $e_{soc} = V_{soc} - \hat{V}_{soc}$, so one can obtain

$$s_b \dot{s}_b = -m_1 e_b^2 + m_1 k e_{soc} e_b + \Delta f_{oc} e_b - L_b \text{sgn}(s_b) e_b \quad (12)$$

To ensure the convergence of SMO \hat{V}_b , let $s_b \dot{s}_b < 0$,

$$|m_1 k e_{soc} e_b| + |\Delta f_{oc} e_b| - L_b \text{sgn}(s_b) e_b < 0 \quad (13)$$

one can get

$$L_b > |\Delta f_{oc} + m_1 k e_{soc}| \quad (14)$$

Where $||$ is the absolute value function. Selecting the value of L_b satisfying the condition (15), the SMO surface s_b can be reached. Applying the equivalent control method of SMO to (13), the \dot{e}_b and e_b could be zero and the model uncertainties Δf_{oc} can be compensated after some finite time.

Then, one can obtain

$$e_{soc} = \left\{ \frac{L_b}{m_1 k} \text{sgn}(e_b) \right\} \quad (15)$$

After that, the estimation function \hat{V}_{soc} for V_{soc} can be given by

$$\dot{\hat{V}}_{soc} = -(m_3 + m_2 k) \hat{V}_{soc} - m_2 \hat{V}_f + m_2 \hat{V}_b + L_{soc} \text{sgn}(e_{soc}) \quad (16)$$

Designing the sliding-mode surface $s_{soc} = e_{soc}$, one can obtain

$$s_{soc} \dot{s}_{soc} = -(m_3 + m_2 k) e_{soc}^2 - m_2 e_f e_{soc} + m_2 e_b e_{soc} + \Delta f_{soc} e_{soc} - L_{soc} \text{sgn}(e_{soc}) e_{soc} \quad (17)$$

Where $e_f = V_f - \hat{V}_f$, It is assumed that $s_{soc} \dot{s}_{soc} < 0$, because the estimator for V_b has been reached to the sliding-mode surface, $e_b = 0$, one can obtain

$$|\Delta f_{soc} e_{soc}| - L_{soc} \text{sgn}(e_{soc}) e_{soc} - m_2 e_f e_{soc} < 0 \quad (18)$$

Selecting L_{soc} satisfying the condition (19), the sliding-mode surface s_{soc} can be reached. According to the equivalent control method of SMO, one can obtain

$$e_f = \frac{-L_{soc}}{m_2} \text{sgn}(e_{soc}) \quad (19)$$

The observer function for V_f is given as

$$\dot{\hat{V}}_f = -m_1 \hat{V}_f + n_1 I_b + L_f \text{sgn}(e_f) \quad (20)$$

Designing the sliding-mode surface $s_f = e_f$, the derivative of s_f can be given as \dot{s}_f

$$\dot{s}_f = -m_1 s_f + \Delta f_p - L_f \text{sgn}(e_f) \quad (21)$$

The $s_f \dot{s}_f$ can be obtained

$$s_f \dot{s}_f = -m_1 s_f^2 + \Delta f_p s_f - L_f \text{sgn}(e_f) e_f \quad (22)$$

By selecting the L_f to satisfy $s_f \dot{s}_f < 0$, the observer function \hat{V}_f can reach to sliding-mode surface.

In order to eliminate chattering of \hat{V}_b , the saturation function $\text{sat}(e)$ is adopted to replace the sgn function.

$$\text{sat}(e) = \frac{e^{6.28e} - e^{-6.28e}}{e^{6.28e} + e^{-6.28e}} \quad (23)$$

To sum up, the structure of observer equations for state variables V_b , V_{soc} , V_f is shown Fig. 2.

4 SOC estimation considering the battery status

Since the battery is a highly nonlinear device, SMO is well suited for solving the nonlinear problem. It needs fairly accurate battery model to eliminate the model uncertainties and requires little time for implementing and this solves the problems of coulomb counting method. The SOC can be

estimated by the SMO designed in section 3. However, it worths noting that the SOC estimation is different between battery charging and discharging.

The new SOC estimation method in this paper makes some improvements to the common SOC algorithm. Firstly, the new SOC estimation method takes into account the effect of self-discharge resistor when charging and discharging the battery. It's still necessary for the Li-ion battery with low self-discharge. Secondly, the new SOC estimation method calculates the energy consumption of R_s and R_f on the basis of SMO when the battery is discharging.

So the proposed SOC estimation in this paper is divided into two parts. When the battery is charging, the SOC estimation uses the SMO

$$\text{soc} = \hat{V}_{soc} \quad (24)$$

When the battery is discharging, the SOC estimation can be given as

$$\text{soc} = \hat{V}_{soc} - \frac{\int_{t_0}^{t_1} (I^2 R_s + \frac{\hat{V}_f^2}{R_f}) d\tau}{\int_{t_0}^{t_1} V_b I_b d\tau} \quad (25)$$

Where t_0 is starting time, t_1 is the end time.

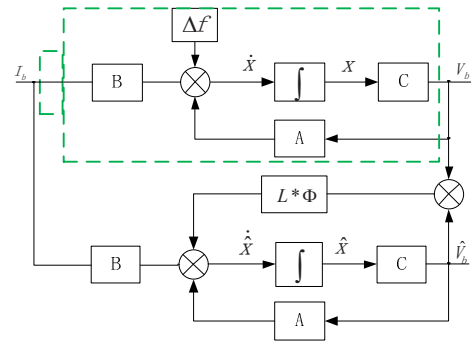


Fig.2. The structure of sliding-mode observer

Where

$$L = [L_b \quad L_{soc} \quad L_f], \Phi = \begin{bmatrix} \text{sat}(V_b - \hat{V}_b) \\ \text{sat}\left(\frac{L_b}{m_1 k} \text{sat}(V_b - \hat{V}_b)\right) \\ \text{sat}\left\{\frac{-L_{soc}}{m_2} \text{sat}\left(\frac{L_b}{m_1 k} \text{sat}(V_b - \hat{V}_b)\right)\right\} \end{bmatrix}$$

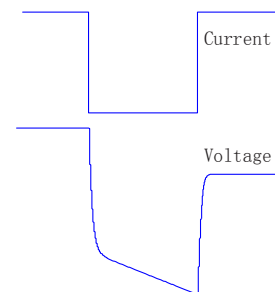


Fig.3. The experiment of battery discharge

The discharge experiments are conducted to get the parameters of the battery model in Fig.1. The experiment process is shown in Fig.3. Firstly, charging the battery up to 100% and leave the battery for two hours. Secondly,

discharging the battery for ten minutes at 1C (6A) rate current and then leaving it unused for one hour. The SOC of the battery declines by 10%. Repeating the second steps six times until the SOC of the battery reaches zero. By these steps, the parameters of battery model can be recognized. The relationship between SOC and OCV can also be obtained.

5 Simulation

To verify the performance of the proposed SOC estimation in this paper, a digital simulation for 6000mAh Li-ion battery based on MATLAB/Simulink R2013A is conducted.

Table 1: The parameters of Li-ion model

Model parameters	Value
R_f	0.01 Ω
C_f	200F
C_n	21600 As
R_s	0.003 Ω
R_{sd}	1000 Ω

Table 2: The gain of SMO

SMO gain	Value
L_b	0.12
L_f	0.01
L_{soc}	0.02

The model parameters of the Li-on battery for simulation are given in Table 1. To simplify the relationship between SOC and OCV, the gain of OCV vs SOC is $k=1.4$. Since the voltage of battery ranges from 2.8 to 4.2, ie:

$$OCV = 1.4 * SOC + 2.8 \quad (26)$$

To simulate the noises in the real applications, the pseudorandom noise is added to the Li-ion battery (6000mAh). The frequency of the pseudorandom noise is 100Hz. The maximum value is 0.1V and the minimum value is -0.05V. The value of discharge current is 6A. The battery discharges for 4 seconds and stop discharging for 1 second. Repeat this process till the voltage of battery drops to 2.75V. The part of the discharging current is shown in Fig.4. The initial value of battery voltage is 4.2V and the SOC is 1.

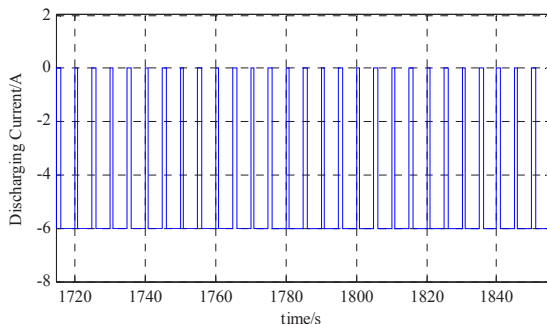


Fig.4 The part of the discharging current in simulation.

The simulation result of \hat{v}_b is shown in Fig.5. And the error between estimated value and real value is shown in Fig. 6. As we can see from Fig.5 and Fig.6, the accuracy of \hat{v}_b estimation using *sat* function can be higher than *sgn* function.

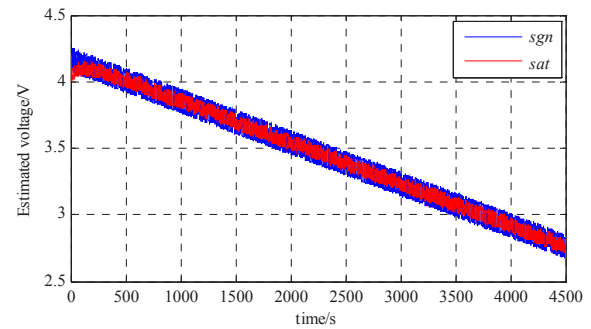


Fig.5. The estimated voltage of battery using *sat* and *sgn*

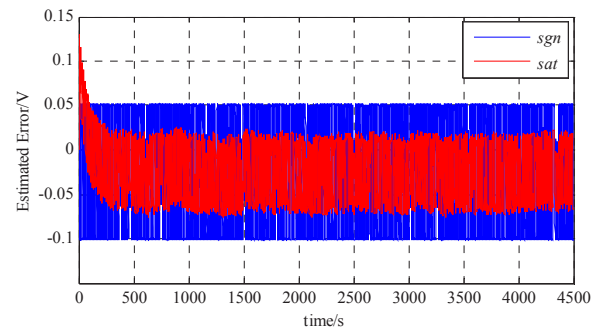


Fig.6. The estimated error of battery voltage using *sat* and *sgn*

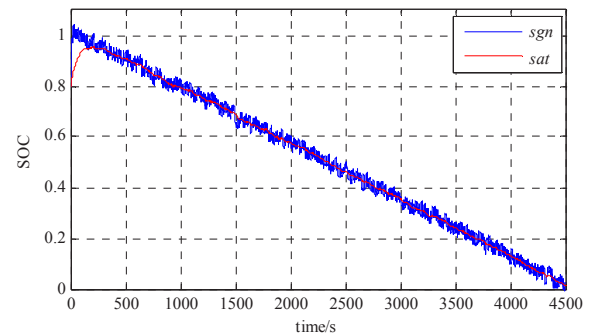


Fig.7. The estimated SOC of battery using *sat* and *sgn*

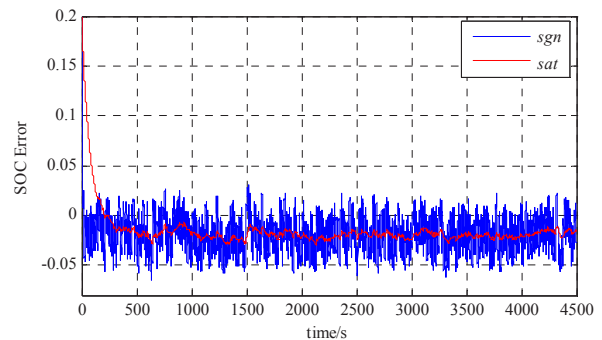


Fig.8. The estimated error of SOC using *sat* and *sgn*

The estimated SOC \hat{v}_{soc} is shown in Fig.7. And the error between estimated value and real value is shown in Fig.8. The initial value of estimated \hat{v}_{soc} is 0.8 and the error with real value is 0.2. Sees from the Fig.7, the estimated value can track the real value using the proposed method. As you can see from the Fig.8, the max error between estimated SOC and real SOC using *sat* function is 3%. It is lower than using *sgn* function. It should be noted that the convergence speed using *sat* function is slower than *sgn* function.

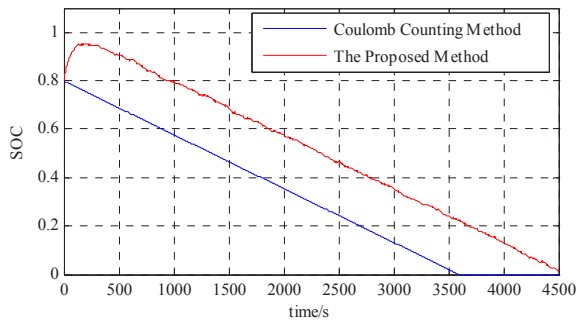


Fig.9. The estimate SOC using two methods

The comparison between the coulomb count method and the proposed method is shown in Fig.9. As you can see that there is no demand of initial value compared with coulomb count method. The estimated SOC can track the real value quickly using the proposed method.

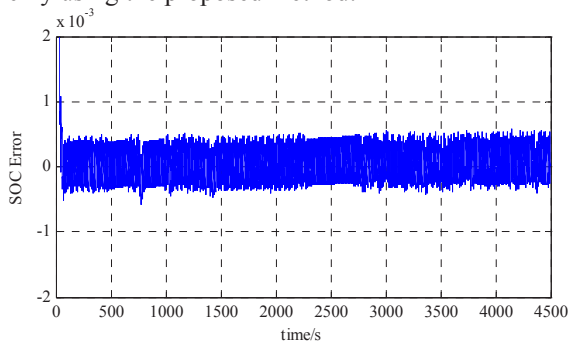


Fig.10. The estimated SOC without pseudorandom noise

The SOC estimated error using sgn function without adding pseudorandom noise to V_b is shown in Fig.10. There is high accuracy. However, the estimated error can be increased when there is a model error. The max error of SOC estimation is 3% from the Fig.8 by using the sat function.

6 Conclusion

This paper proposes a new SOC estimation method for Li-ion battery. A new equivalent circuit battery model considering self-discharge is adopted in this method. Besides, the use of SMO can compensate the model errors and solves the problems of coulomb counting method. In addition, the SOC estimation method in this paper considers the influence of inner resistance of battery according to the battery status. The saturation function is designed to reduce the chattering phenomena. Finally, the simulation results show that it's better than the traditional method. In a word, the proposed SOC estimation method is valuable in engineering practice since a lower hardware configuration and software design.

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