Hybrid Estimation Algorithm for Lithium-ion Battery based on PI Observer

Denggao Huang*, Yuehui Wang, Jing Zhao**,Xu Wang**, Zhongwen Zhu**, Tong Wang**, Yilu Zhou**, Peng Jin **, Cheng Li ****

** China Automotive Technology and Research Center Co. Ltd. Tianjin, China (Tel: +86-022-84379777-8294; e-mail: huangdenggao@catarc.ac.cn).*
*** China Automotive Technology and Research Center Co. Ltd. Tianjin, China (Tel: +86-022-84379777-8294; e-mail: wangyuehui@catarc.ac.cn).*

Abstract: In view of poor adaptive ability and accuracy when estimating SOC with a single algorithm, a hybrid estimation algorithm with PI observer and Coulomb counting method is proposed in this paper. The algorithm firstly uses the RLS (Recursive Least Squares) method to identify parameters of the battery. Secondly, the open circuit voltage is calculated by the PI observer. Based on the difference between the calculated value and the estimated value, a PI dynamic adjustment is performed. Thus the integration coefficient of the Coulomb integration is optimized in real time. The research shows that, the method can dynamically correct the cumulative deviation of the Coulomb method.

Keywords: Parameter identification, PI observer, Coulomb counting method, SOC dynamic correction

1. INTRODUCTION

Lithium-ion batteries are widely used in the fields of electric vehicles and aerospace. They need to be monitored by a battery management system (BMS) in use. SOC (State of Charge) is one of the important state variables for lithium-ion batteries (Liu et al., 2015). Accurate SOC estimation is helpful to prolong the life span of battery (Mao et al., 2014) through preventing overcharge and over-discharge.

Estimation methods of SOC include OCV (open circuit voltage) method, Coulomb counting method, internal resistance method, KF (Kalman filter) method and NN (neural network) method (Wu, 2017). When the Coulomb counting method and the open-circuit voltage method are separately implemented, the estimated results are proven inaccurate due to algorithm deficiencies (Li et al., 2019). The accuracy of the neural network method is relatively high (Lin et al., 2014), but its application is limited by a large amount of calculation in each case. In recent years, more researchers focus on hybrid algorithm, which overcomes the shortcomings of the single estimation methods and improves the SOC estimation accuracy (Bao and Yu, 2013). A combination of the open circuit voltage method and the Coulomb counting method can correct the accumulated error of integration process (Mao, 2014), but can't eliminate the dynamic error caused by the current noise. A combination of open circuit voltage method and Kalman filter method solves the problem of large initial error caused by the deviation of initial value, and improves the overall estimation accuracy. (Mao, 2014) proposed a complex hybrid algorithm based on EKF, Coulomb counting and OCV method. The results show that the complex hybrid algorithm has good performance in dynamic discharging process and can meet the accuracy requirements at different environment temperature. The maximum SOC estimation error is less than 2.18%. Sun put forward a hybrid algorithm of open circuit voltage method and Coulomb counting method, in which a PI (proportional integral) regulator was used to correct the deviation of the Coulomb counting method. The estimation error is within 1% (Sun, 2017).

Different from the researches above, this paper proposes a hybrid algorithm of PI observer and Coulomb counting method for battery SOC estimation. Firstly, the second-order RC equivalent circuit model is built for the lithium-ion battery, and the battery parameters are identified online according to recursive least squares method. The open circuit voltage is calculated by the PI observer. Then, based on the deviation of the open circuit voltage between the calculated value and the estimated value, a dynamic adjustment is performed, and the coefficients of the Coulomb counting method are updated in real time. Finally, the algorithm is verified by the NEDC working condition. The results show that this algorithm can effectively correct the accumulated error and dynamic error caused by the initial SOC error and current signal noise.

2. LITHIUM-ION BATTERY MODEL

There are many types of equivalent circuit models of battery, including the Rint model, PNGV model, Thevenin model, etc. (Zhang et al., 2014) Considering the accuracy and complexity of the model, this paper selects the second-order RC model to build the battery model. Fig.1 shows the second-order equivalent circuit model of the battery. U_L is the open circuit voltage, i is the current in the battery, R_0 is the internal ohmic resistance, R_1 and C_1 are the electrochemical polarization resistance and capacitance of the battery, R_2 and C_2 are the concentration polarization resistance and capacitance respectively. Based on Kirchhoff's law and the dynamic characteristics of the second-order equivalent circuit, Formula (1) can be obtained.

m=1, 2. U_1 , U_2 are terminal voltages of R_1 and R_2 respectively. The characters of open circuit voltage with SOC are one of the most important parameters in battery. The relationship between battery SOC and open circuit voltage was identified by experiment. Collected data are sorted and the relationship is approximated by a serial of linear sections. The linearization formula of battery SOC and OCV is shown in (2). The figure of battery SOC and OCV is shown in Fig. 2.

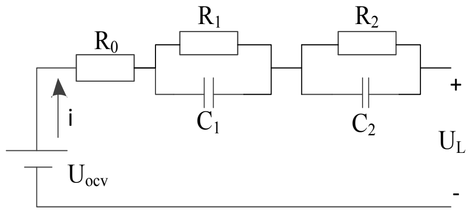


Fig.1. Second order RC equivalent circuit model of batter

$$\begin{cases} i = \frac{U_m}{R_m} + C_m \frac{\mathrm{d}U_m}{\mathrm{d}t} \\ U_{\mathrm{L}} = U_{\mathrm{ocv}} - U_1 - U_2 - iR_0 \end{cases} \quad (1)$$

$$U_{\mathrm{ocv}} = f(SOC) = A + B\cdot SOC \quad (2)$$

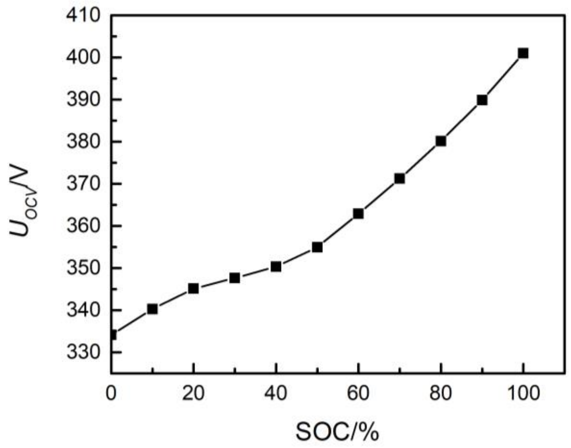


Fig.2. Linear curve of SOC and *Uocv*

In order to identify the battery parameters with RLS method, the formula of battery model is discretized according to the least square principle. The Laplace transform of Formula (1) delivers (3).

$$V_{\mathrm{L}} = U_{\mathrm{OCV}} - I_L(s)(R_0 + \frac{R_1}{1+R_1C_1} + \frac{R_2}{1+R_2C_2}) \quad (3)$$

Make $\tau_1 = R_1C_1$, $\tau_2 = R_2C_2$, and define (4) at the same time.

$$\begin{cases} a = \tau_1\tau_2, \\ b = \tau_1 + \tau_2, \\ c = R_1 + R_2 + R_0, \\ d = R_1\tau_2 + R_2\tau_1 + R_0 b \end{cases} \quad (4)$$

Update (3) with (4), the difference equation of battery equivalent model is obtained.

$$\begin{aligned} V_{ocv}(k) - V_l(k) = k_1[V_{ocv}(k-1) - V_l(k-1)] + \\ k_2[V_{ocv}(k-2) - V_l(k-2)] + k_3I(k) + \\ k_4I(k-1) + k_5I(k-2) \end{aligned} \quad (5)$$

Where k_1, k_2, k_3, k_4, k_5 represent constant coefficients.

Make $U(k-1) = V(k-1) - V_b(k-1)$.

$$\Phi^T = [-U(k-1) \;\; -U(k-2) \;\; I(k) \;\; I(k-1) \;\; I(k-2)] \quad (6)$$

$$\theta = [k_1 \;\; k_2 \;\; k_3 \;\; k_4 \;\; k_5]^T \quad (7)$$

Formula (5) can be transformed into (8) with (6) and (7). Formula (8) can be dealt with RLS method. The formula of RLS is shown in (9).

$$U_k = \Phi^T\theta \quad (8)$$

$$\begin{cases} K = P_{k-1}\Phi_k^T[\Phi_kP_{k-1}\Phi_k^T + 1]^{-1} \\ \theta_k = \theta_{k-1} + K[y_k - \Phi_k\theta_{k-1}] \\ P_k = [I - K\Phi_k]P_{k-1} \end{cases} \quad (9)$$

y_k - the output variable of the system, which is the actual battery voltage, K - the algorithm gain, P - the covariance matrix of state estimation. When the constant coefficients θ is estimated by RLS method, the battery parameters of R_0, R_1, C_1, R_2 and C_2 can be calculated according to (4).

For the validation of the battery equivalent model and the proposed hybrid algorithm, a battery experiment was conducted. The tested battery pack is shown in Fig.1, a ternary lithium battery pack with parameters listed in Table 1. It is used for hybrid electric vehicle, and the battery SOC is a very import parameter for vehicle energy optimization strategy. The test equipment is a battery charging and discharging system with control step less than 10 ms. The specification of the test equipment is shown in Table 2.

For performance comparison, the battery pack was tested under NEDC. The thermal cabin temperature was set at 25℃°. The battery discharging profiles are shown in Fig.3. Fig.4(a) is the current profile, and Fig.4(b) is the voltage profile.

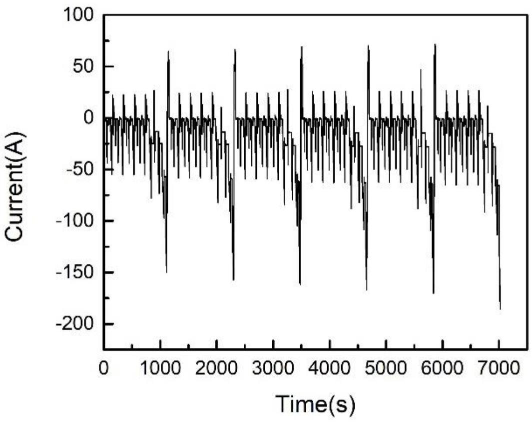
Fig.1. Experimental battery pack

Table 1 Battery pack specification

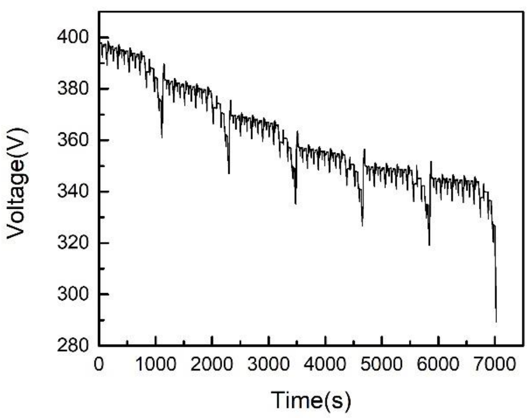
Items	Parameters
Capacity	13 kWh
Nominal voltage	350 V
Voltage range	267 ~ 403 V
Current range	-300 A~300 A
Battery type	Ternary lithium battery

Table 2 Test equipment specification

Items	Brand	Parameter
Battery test cabinet	Digatron	Voltage: 0.1%FS Current：0.1%FS
Thermal chamber	YNK/R	Less than ±2℃



(a) Current curve of battery under NEDC condition



(b) Voltage curve of battery under NEDC condition

Fig.4. Testing profile of battery under NEDC condition

3. SOC HYBRID ESTIMATION ALGORITHM BASED ON PI OBSERVER

3.1 SOC estimation principles

SOC estimation method based on PI observer is shown in Fig.5. Firstly, the initial SOC is read from memory cell of battery management system or set by manuals, which can be used for algorithm initialization of Coulomb Counting method and PI Observer. Secondly, based on the actual measuring data of current and voltage, the parameters of the battery equivalent model can be estimated by the RLS algorithm. Thirdly, the open circuit voltage of the battery can be calculated by (2), which $SOC\text{-}U_{ocv}$ is the piecewise linear relationship. The open circuit voltage $U_{OCV,PI}$ and $U_{OCV,AH}$ can be seperately calculated by the PI observer and the Coulomb method. Fourthly, the deviation of $U_{OCV,PI}$ and $U_{OCV,AH}$ is calculated, and a proportional integral controller is conducted to control the integration calculation coefficient of the Coulomb counting method. Finally, the current SOC is obtained from the Coulomb counting method.

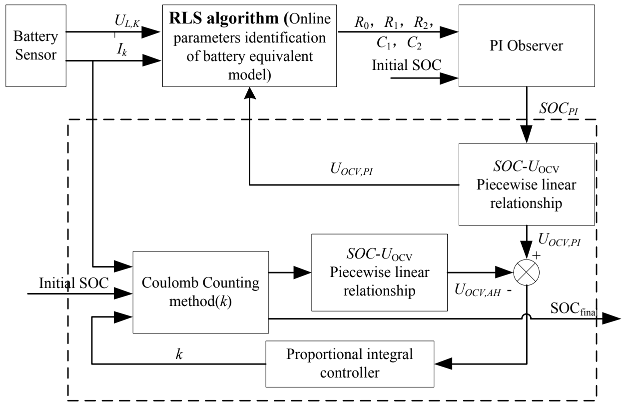


Fig.5. Hybrid SOC estimation algorithm of lithium battery based on PI observer

In the actual battery management system (BMS), the initial SOC can be referenced from (10). If the battery has been standing for less than 2 hours, the initial SOC reloads from the recorded value of BMS. Otherwise, the initial SOC will be estimated by the open circuit voltage method as the latest collection values of battery voltage. The relationship between open circuit voltage and SOC can be calculated by (2). The threshold value of 2 hours in this research is determined by the characters of the battery. Other battery pack may be different and can be found in the Hysteresis characteristic curve of voltage.

$$SOC = \begin{cases} SOC_{ocv,EEprom} & offtime < 2hours \\ SOC_{ocv,0} & offtime \geq 2hours \end{cases} \quad (10)$$

3.2 $U_{ocv,PI}$ Acquisition based on PI observer

Because of the voltage characteristics of batteries, the terminal voltage is different from open circuit voltage in the dynamic discharging process.Only after a long time standing of the battery, the terminal voltage can be approximated to the open circuit voltage. In order to calculate battery open circuit voltage in dynamic discharging process, model based algorithm are usually proposed. In this research, a PI observer is selected as part of the hybrid estimation algorithm. Derived from (1), the battery state equation was obtained, shown in (11).

$$\begin{cases} x_{k+1} = Ax_k + Bu_k \\ y_k \ \ = Cx_k + Du_k \end{cases} \quad (11)$$

x - state variable, A,B,C,D - tstate matrices, u - the input of state equation, y - the output of state equation, Q - the rated capacity of the battery, a - the measuring noise of battery voltage. The feature of PI observer is the closed-loop feedback, which eliminates the deviation between estimated value and actual acquired value (Zhao, 2016). Battery terminal voltage is a significant variable for battery SOC estimation. Considering the battery state equation, the battery voltage deviation is shown in (13). Furthermore, the battery state equation of PI observer can be translated to (14). Since the observability matrix of the system is full rank, the state equation is observable (Wang et al., 2016).

$$\begin{cases} x = \left(SOC \ \ U_{p1} \ \ U_{p2}\right)^T \\ u = i \\ A = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1/R_1C_1 & 0 \\ 0 & 0 & -1/R_2C_2 \end{bmatrix} \\ B = \begin{bmatrix} 1/Q \\ 1/C_1 \\ 1/C_2 \end{bmatrix} \\ C = \begin{bmatrix} a & 1 & 1 \end{bmatrix} \\ D = R_0 \\ y = U_L - a \end{cases} \tag{12}$$

$$e_y = U_{L,k} - y_k \tag{13}$$

$$\begin{cases} x_{k+1} = Ax_k + Bu_k + Le_y \\ y_k = Cx_k + Du_k \end{cases} \tag{14}$$

L is adjust parameter of the PI observer and the feedback regulation gain matrix, K_p is proportional gain, K_i is integral gain, e_y is the difference between the measured terminal voltage and the estimated terminal voltage.

$$L = \begin{bmatrix} l_1 & l_2 & l_3 \end{bmatrix}^T, \ l_i = K_{pi}e_y + K_{i1}\int e_y dt, \ i = 1,2,3 \tag{15}$$

Through the above analysis, the diagram of PI observer is shown in Fig.6. Battery SOC_{PI} can be calculated by (13), (14) and (15). When SOC_{PI} is estimated, the open circuit voltage $U_{OCV,PI}$ can be calculated by (2), because $SOC\text{-}U_{ocv}$ is the piecewise linear relationship.

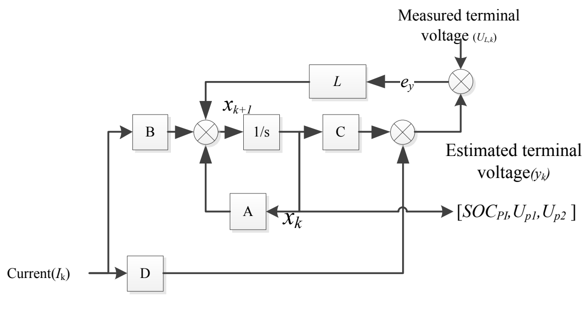


Fig.6. diagram of PI observation and estimation

3.3 A Proportional integrator of SOC

In order to continuously update battery SOC, a typical coulomb counting method is selected, shown in (16) and (17). Where, k_{PI} is the proportional gain, SOC_{AH} is the estimated SOC, Δt is the Discrete step size of the Coulomb counting method, k is the step number. When SOC_{AH} is estimated, the open circuit voltage $U_{OCV,AH}$ can be calculated by (2). δ_y is the difference between the OCV calculated based on the PI observer and the Coulomb counting, shown in (18). When there is a big difference between those two methods, the proportional integral factor will adapt the proportional gain of the Coulomb counting method. Through this adaptation process, the estimated SOC by the Coulomb counting method can be smoothly updated, and updated as the final output SOC of hybrid estimation algorithm, shown in (19). By this way, SOC jump in the final output of SOC can be avoided.

$$SOC_{AH}(k+1) = SOC_{AH}(k) - k_{PI}\frac{i\Delta t}{Q} \tag{16}$$

$$k_{PI} = K_p\delta_y + K_i\int \delta_y dt \tag{17}$$

$$\delta_y = U_{ocv,PI} - U_{ocv,Ah} \tag{18}$$

$$SOC_{final} = SOC_{AH} \tag{19}$$

Summarizing the above theoretical analysis, the proposed hybrid estimation algorithm was realized in Matlab/Simulink, shown in Fig.(7). In figure, *Exp_dataSet* is the experimental dataset for algorithm analysis, collected from experimental pack and test bench. *RLS_Estimation* is the recursive least square of the battery equivalent model. *PI_Observer* is the battery SOC estimation based on PI observer method. The dash box is the proportional integrator of SOC. The following sections will illustrate the simulation results and analysis.

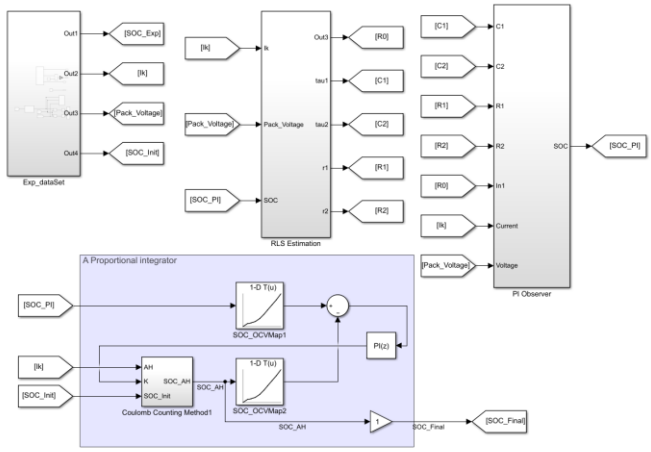


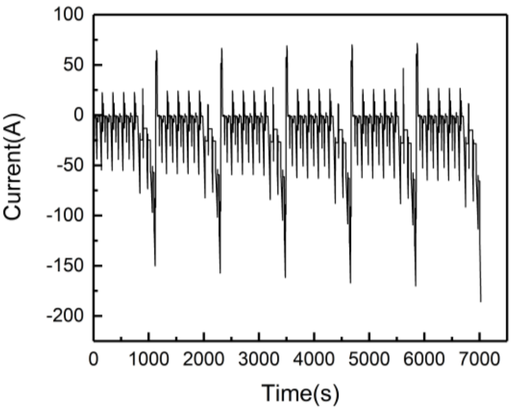
Fig.7. Simulink model and input dataset

4. SIMULATION RESULTS AND ANALYSIS

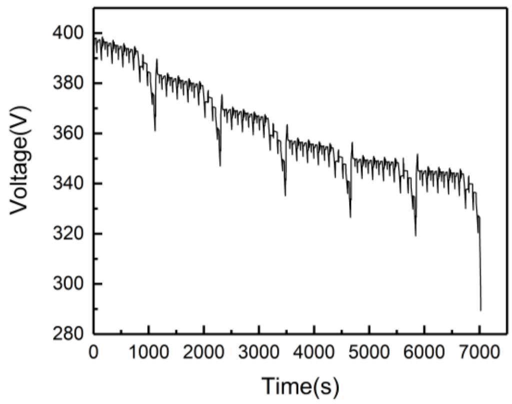
4.1 VALIDATION OF PI OBSERVER

The battery profiles of current and voltage were collected, shown in Fig.8. The battery was tested under NEDC (New European Driving Cycle), and battery SOC started from 100% to 0%. The maximum discharging current is -190A, and the maximum charging current 53A. The battery voltage decreased from 403V to 267V.

For the algorithm of PI observer, the estimated terminal voltage should approximatethe measured terminal voltage of the battery. At the same time, it's a good way to validate the algorithm of RLS and PI observer. The comparison between the estimated terminal voltage of PI observer and the measured terminal voltage of a battery is shown in Fig.9(a). The voltage deviation is shown in Fig.9(b). In Fig.9, the voltage deviation is large in the initial stage, and gradually reduces in the remaining stage. The reason is that the algorithm of RLS and PI observer is unstable in the initial stage and caused by the initial inaccurate values. The initial values include initial SOC, θ , and others. Finally, the deviation fluctuates within an interval 3V~-4V.

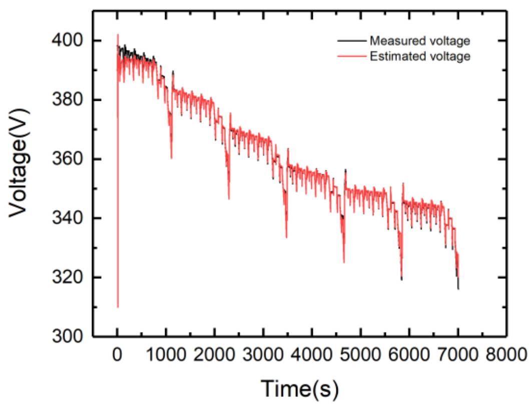


(a) Battery current profile

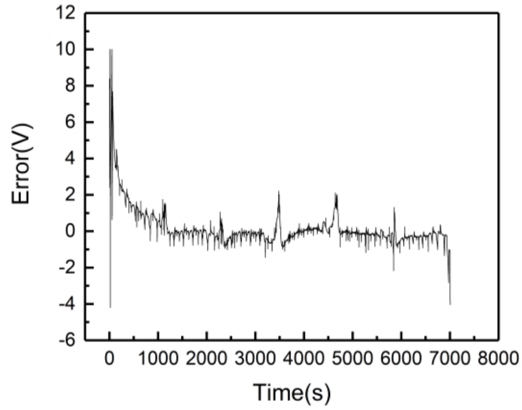


(b) Battery voltage profile

Fig.8. Battery profiles of current and voltage under NEDC



(a) Comparison between the estimated terminal voltage of PI observer and the measured terminal voltage



(b) Voltage deviation between the estimated terminal voltage of PI observer and the measured terminal voltage

Fig.9. Comparison under NEDC condition

4.2 VALIDATION OF HYBRID ALGORITHM

In order to validate the performance of the proposed hybrid estimation algorithm, other estimation methods were simulated as reference. A single Coulomb-counting method, and a hybrid algorithm of OCV correction and Coulomb counting method was built based on the references (Hannan et al., 2017; Zhang et al., 2013). The initial SOC of the above algorithms were set at 80%, and the experimental data start from SOC 100% to 0%. The estimated SOC profiles of the above algorithms were shown in Fig.10.

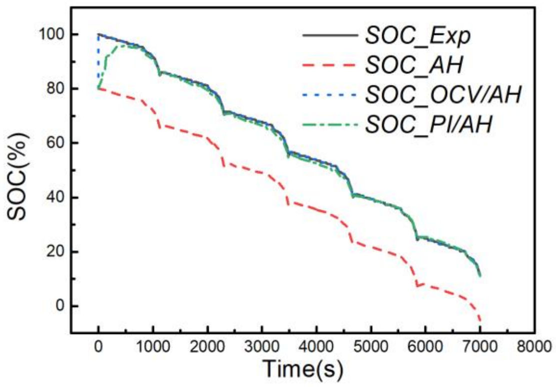


Fig.10. Comparative simulation analysis of SOC

When the initial SOC error happens, the single Coulomb counting method cannot eliminate the error. The hybrid algorithm of OCV correction and Coulomb counting method can directly correct the SOC error, when the battery has stood more than 2 hours. In practical application, the accuracy of current sensor is affected by the zero drift and resulted in acquisition error, which reducesthe accuracy of the hybrid algorithm of OCV correction and Coulomb counting method. The proposed hybrid estimation algorithm of PI observer and Coulomb counting method can slowly eliminate the static error, and can also dynamically modify the error of the integral process based on battery current.

When there is noise of packing current sensor in dynamic discharging process, the SOC estimation algorithm should correct the accumulated error caused by the Coulomb counting method, so that the SOC value is closer to the actual value. In Fig.11 and Fig.12, fixed deviations of 2A and -3.5A are injected into current data respectively. The estimated SOC values of the algorithms above were illustrated. Comparing with other two algorithms, the proposed hybrid estimation algorithm has better performance, and the maximum SOC error is 4%.

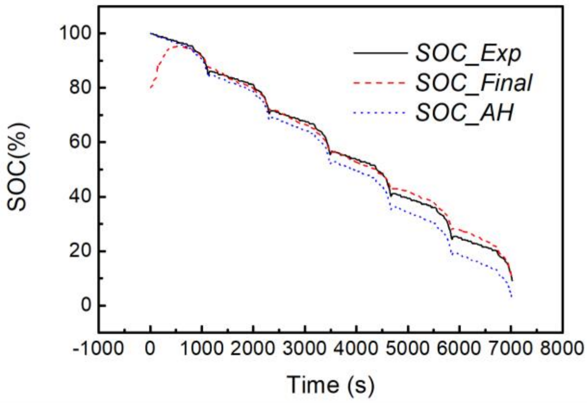


Fig.11. SOC estimation of current fixed 2A deviation

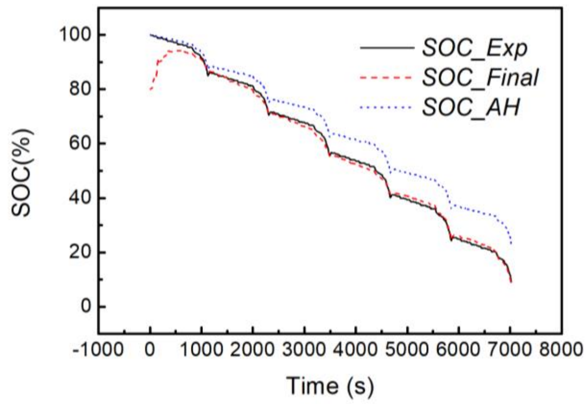


Fig.12. SOC estimation of current fixed -3.5A deviation

5. CONCLUSIONS

A hybrid estimation algorithm of PI observer and Coulomb counting method is proposed. Firstly, a second-order RC equivalent circuit model is built for the lithium-ion battery, and the recursive least squares method is applied to identify the model parameters based on battery experimental data. Secondly, the architecture of the proposed hybrid estimation algorithm is illustrated. An obvious advantage is that the estimated SOC can be smoothly updated, and SOC jump is avoided. Finally, the simulation of the proposed hybrid algorithm was carried out, and compared with the single coulomb counting method and the hybrid algorithm of OCV collection and coulomb counting method. The results show that the proposed algorithm can effectively correct the accumulated error and dynamic error caused by the initial SOC error and current signal noise.

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REFERENCES

Bao Hui, Yu Yang. (2013). Error correction of SOC estimation of battery based on ampere hour integral method. Computer simulation,30 (11): 148-151.

Liu Yanli, Yan Zhihao, Cheng Ze, et al. (2015). SOC estimation of battery based on second-order Stirling interpolation filter. Journal of electronic measurement and instrumentation , 29 (1): 55-60.

Li Jun, Wei Weiyang, Gong Sihui, Liu Feifei. (2019). SOC estimation method of electric vehicle power battery. Automotive practical technology, (14): 12-16.

Lin Chengtao, Wang Junping. (2004). Principle and application of SOC estimation method for electric vehicles, 34 (5): 66-378.

Sun Haohao, pan Tinglong, Wu Dinghui. (2017). SOC weighted online estimation based on adaptive battery model. Journal of system simulation,29 (08): 1677-1684.

M.A.Hannan, M.S.H.Lipu, A.Hussain, A.Mohamedb. (2017), A review of lithium-ion battery state of charge estimation and management system in electric vehicle applications: Challenges and recommendation, Renewable & Sustainable Energy Reviews, Vol. 78834-854.

Mao Huafu, Wan Guochun, Wang Lei, et al. (2014). SOC estimation of battery based on Kalman filter correction algorithm . Power technology, 38 (2): 298-302.

Wang Yaonan, Meng Bimin. (2016). SOC estimation of battery based on extended PSO and discrete PI observer. Journal of electronic measurement and instrumentation , 30 (01): 11-19.

Wu Chunfang. (2017). Summary of SOC estimation of power battery. Power technology, 41 (12): 1795-1798.

Zhang Yanhui, Song Wenji, Lin Shili, Lv Jie. (2013). A critical review on state of charge of batteries, Journal of Renewable & Sustainable Energy, Vol. 5 No. 2, pp. R93-R110.

Zhang Yuxuan. (2014). On line parameter identification and SOC estimation of electric vehicle power battery model. Jilin University.

Zhang Li, Liu Shuai, Liu Zhengyu, Chang Cheng. (2016). Study on adaptive parameter identification and SOC estimation of lithium ion batteries. Journal of electronic measurement and instrumentation, 30 (01): 45-51.

Zhao Ting. (2016). SOC online estimation of power lithium ion batteries. Beijing Jiaotong University.