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Research on SOC Estimation Algorithm for Lithium Battery Based on EKF Algorithm and Ampere-hour Integration Method

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Abstract—**Accurate estimation of state of charge (SOC) in power battery is the key point of electric vehicle management system. In this paper, the problem of accurate estimate of the SOC for lithium battery is considered. The composite model of the battery is established, and the parameters of the model are identified by the recursive least square algorithm. The extended Kalman filtering algorithm (EKF) and current time integral method are combined to estimate the battery SOC, the working voltage and the battery SOC are considered as observation variables and state variables. The model is built in Matlab/Simulink, and the simulation of the current on the battery is carried out by simulating the FUDS working conditions. Simulation results show that the proposed algorithm can accurately estimate the SOC in the dynamic process of the lithium battery, and the error can be kept in the range of** $\pm 2\%$ **.**

Keywords—lithium battery; Stage of Charge (SOC); Extended Kalman Filter (EKF); composite model

I. INTRODUCTION

With the aggravation of environmental pollution, more and more attention has been paid to the development of electric vehicles, which has become a hot issue in the field of research. The key problem that restricts the development of electric vehicles is the effective management of power battery pack, and the accurate estimation of State of Charge (SOC) is the difficult and key problem of battery management system. Therefore, the SOC estimation algorithm of lithium battery is studied in this paper.

At present, the main methods of SOC estimation for lithium ion batteries are: the open circuit voltage method, ampere-hour integral method, neural network method, Kalman filtering method and so on. Generally, the open circuit voltage method requires the battery to be stationary for a long time, so the battery SOC cannot be estimated in the dynamic condition[1]; The most commonly used method in engineering is ampere-hour integration method, but this method requires accurate initial value of SOC, and easy to appear on the cumulative error in the integration process[2]; The neural network method can be applied to any battery with high estimation accuracy, but need a large number of training samples[3]; Online estimation of Kalman filtering algorithm can achieve SOC of lithium battery, and no need to consider the initial value problem for the lithium ion battery is a nonlinear system, the traditional Kalman filter is generally used for linear systems, usually using the Extended Kalman filter (EKF) algorithm to realize the lithium ion battery SOC estimation, the EKF method has a strong effect on correction the initial value of SOC, especially suitable for electric vehicle batteries with large current variation[4, 5].

The identification accuracy of the battery SOC is also related to the selection of the battery model. The most commonly used battery model is the equivalent circuit model to describe the dynamic characteristics of the battery. In literature[6], the equivalent models of Rint, Thevenin, PNGV and GNL are analyzed, and their advantages and disadvantages are pointed out. They cannot describe the transient response of the battery, or the accuracy is low, or the model is too complex, so it is not easy for the online identification of the electric vehicle. Literatures[7,8] have studied the empirical model of the battery, this scheme has the advantages of small computational complexity, simple model structure and high identification accuracy, so it is suitable for on-line identification of electric vehicles.

For ampere-hour integral method in the process of estimate the battery SOC requires precise initial SOC and cumulative error in the process of running not amend current shortcomings, the EKF algorithm with ampere-hour integral method to estimate the battery SOC, battery model based on the experience of model compound. Battery charging and discharging capacity calculation using ampere-hour integral method, and use it as a state equation and observation equation using the open circuit voltage V as a function of the battery SOC to establish, in combination with EKF algorithm to estimate the battery SOC. EKF algorithm for SOC initial value has a strong correction ability, every time the SOC estimate values that can take advantage of the last to modify the identification of previous values, to overcome the problems by using ampere-hour integral method separately, and easy to project implementation.

II. SELECTION OF BATTERY MODEL AND IDENTIFICATION OF PARAMETERS

In this paper, a composite model of three empirical battery models is used to estimate the battery SOC. The composite model takes SOC as the state variable of the system, the charge discharge current and the ambient temperature as input, the battery operating voltage as output, their workload is not big, the calculation is simple and easy to be implemented in engineering. The three models are as follows:

Shepherd model:

$$y_k = E_0 - Ri_k - K_i / x_k \tag{1}$$

Unnewehr universal model:

$$y_k = E_0 - Ri_k - K_i x_k \tag{2}$$

Nernst model:

$$y_k = E_0 - Ri_k + K_2 \ln(x_k) + K_3 \ln(1 - x_k) \tag{3}$$

In the formula: y_k is the working voltage of the battery, x_k is the SOC value of the battery, R is battery resistance, R will change with the state of charge and discharge, E0 is the electromotive force when the battery SOC is 100%, K_1, K_2, K_3 are model matching coefficients, the algorithm of composite model is better than any of the above mathematical models, the equation of state is expressed as follows:

State equation:

$$x_{k+1} = x_k - \left(\frac{\eta \Delta t}{Q_n}\right) \mathrm{i}_k \tag{4}$$

Output equation:

$$y_k = k_0 - Ri_k - \frac{K_1}{x_k} - K_2 x_k + K_3 \ln(x_k) + K_4 \ln(1 - x_k) + v(k) \tag{5}$$

In the formula v(k) is the observation noise, the unknown quantity $R, K_0, K_1, K_2, K_3, K_4$ can be obtained by recursion least square algorithm (RLS). The basic idea of recursive least squares algorithm is: This estimate = the last estimate + correction quantity, This algorithm does not need to store historical data, reduces the burden of CPU, and can realize the online identification of parameters.

If let $\theta=(K_0,R_d,R_c,K_1,K_2,K_3,K_4)T$, then it can be considered as the parametric vector of the model, the recursive least square formula can be summed up as follows:

$$P_K = \left[I - \frac{P_{K-1}\phi_{K-1}\phi^T{}_{K-1}}{1 + \phi^T{}_{K-1} P_{K-1} \phi_{K-1}} \right] P_{K-1} \tag{6}$$

$$\hat{\theta}_K = \hat{\theta}_{K-1} + P_K \phi_{K-1} \left[y_K - \phi^T{}_{K-1} \hat{\theta}_{K-1} \right] \tag{7}$$

The RLS can also be described as:

$$\hat{\theta}_K = \hat{\theta}_{K-1} + L_K \left[y_K - \phi^T{}_{K-1} \hat{\theta}_{K-1} \right] \tag{8}$$

$$P_K = \left[I - L_K \phi^T{}_{K-1} \right] P_{K-1} \tag{9}$$

$$L_K = \frac{P_{K-1}\phi_{K-1}}{1 + \phi^T{}_{K-1} P_{K-1} \phi_{K-1}} \tag{10}$$

In the formula L_k is the gain vector, Pk is a symmetric non-augmented matrix, $\hat{y}_k = y_k - \phi^T{}_{k-1}\hat{\theta}_{K-1}$,t is predicated on the output of the historical data based on the k-1 moment. In this paper, a small initial value is given for θ_0, P_0.

The recursive least squares algorithm is programmed and simulated in Matlab, the analog current curve is shown in figure 1, the parameter identification curve and error curve are shown in figure 2, 3.

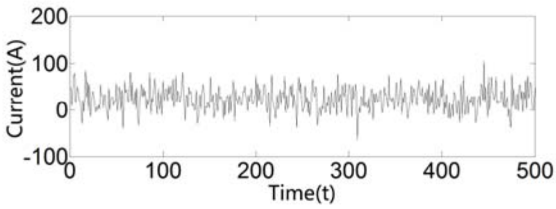

FIGURE I. SIMULATED CURRENT CURVE

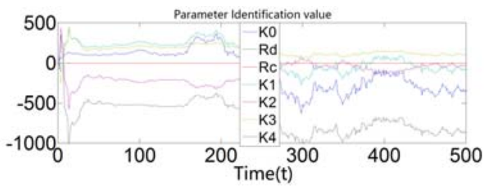

FIGURE II. PARAMETER IDENTIFICATION CURVE

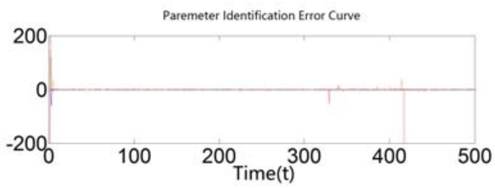

FIGURE III. PARAMETER IDENTIFICATION ERROR CURVE

It can be seen from the diagram that the error of parameter identification converges to zero at last. Table 1 is the parameter identification value.

TABLE I. PARAMETER IDENTIFICATION VALUE

K_0	R_d	R_c	K_1	K_2	K_3	K_4
-181.38	-0.25	-0.23	31.30	-97.50	137.95	-748.67

III. RESEARCH ON BATTERY SOC ESTIMATION ALGORITHM

This article combines EKF algorithm and Ampere-hour integral method to estimate the battery SOC, battery model choose composite model, and the equation of state of the battery is established according to Ampere-hour integral method and composite model, the cumulative error of the current in the initial value of SOC and Ampere-hour integral method is corrected by EKF algorithm, and the accurate estimation of the battery SOC is realized.

The battery SOC has a great relationship with charge discharge current and ambient temperature, the maximum capacity of the battery varies with the charging current and ambient temperature，so a correction is required to calculate the amount of battery charged or emitted by Ampere-hour integral method. The effect of charge discharge current on SOC was studied by using charge discharge efficiency SOC model, using multiple constant current discharges to calculate the charge discharge ratio coefficient. At room temperature of 25 degrees Celsius, the experimental data are obtained by discharging the full charged single cell at different rates, as shown in table 2.The effect of temperature on the battery SOC can be achieved at the same discharge ratio, separating the fully charged single cell at different temperatures and the data is shown in table 3.

TABLE II. EFFICIENCY RATING UNDER DIFFERENT CHARGING AND DISCHARGING CURRENTS

Current value	*Efficiency* η_i
-80	0.95
-40	0.965
-20	0.97
0	1
20	0.98
40	0.93
80	0.92

TABLE III. EFFICIENCY RATING UNDER DIFFERENT CHARGING AND DISCHARGING CURRENTS

Current value	*Efficiency* η_T
-20	0.9
-10	0.955
0	0.98
25	1
40	1.005
60	0.94
-20	0.9

The above experimental data is modified by using the look up module of Ampere-hour integral method in Ampere-hour integral method, $\eta=\eta_i\eta_T$.

In this paper, I adopt the battery compound model and establish the state space expression of the extended kalman filtering algorithm (EKF).

State equation:

$$x_{k+1} = x_k - \left(\frac{\eta_i \eta_T \Delta t}{Q_n}\right) \mathrm{i}_k \tag{11}$$

Observation equation:

$$\begin{aligned} y_k = K_0 - Ri_k - \frac{K_1}{x_k} - K_2 x_k + \\ K_3 \ln(x_k) + K_4 \ln(1 - x_k) + v(k) \end{aligned} \tag{12}$$

The extended kalman filtering has a strong ability to modify the algorithm, it can solve the initial value problem and current accumulation problem of Ampere-hour integral method, the state equation listed by Ampere-hour integral method reduces the computation of the system and is beneficial to the project realization.

The implementation process of EKF algorithm is as follows:

Step 1: Initial state quantity X (0),Y(0),Covariance matrixP_0.

Step 2: State prediction

$$X(k+1) = X(k) - \left(\frac{\eta \Delta t}{Q_n}\right) i_k \tag{13}$$

Step 3: Observation and prediction

$$\begin{aligned} Y(k) = K_0 - Ri_k - \frac{K_1}{x_k} - K_2 x_k + \\ K_3 \ln(x_k) + K_4 \ln(1 - x_k) \end{aligned} \tag{14}$$

Step 4: First order linear state equation, solve the state transition matrix

$$A_k = \frac{\partial f(\mathrm{x}_k, \mathrm{u}_k)}{\partial x_k} = 1 \tag{15}$$

Step 5: First order linear observation equation, solve the observation matrix

$$\begin{aligned} C_K = \frac{\partial y_k}{\partial x_k} = k_1 / (x_k)^2 - K_2 + \\ K_3 / x_k - K_4 / (1 - x_k) \end{aligned} \tag{16}$$

Step 6: Solve the covariance matrix P_k

$$P_k = A_k P_{K-1} A^T{}_k + Q_w \quad (17)$$

Step 7: Solve the EKF filter gain L_k

$$L_k = \frac{P_k C^T{}_k}{C_k P_k C^T{}_k + R_v} \quad (18)$$

Step 8: Solve the status updates

$$X(\mathrm{k}) = \mathrm{x}_k + L_k(\mathrm{Y}_k - \mathrm{y}_k) \quad (19)$$

Step 9: Covariance update

$$P(\mathrm{k}) = (\mathrm{I} - \mathrm{L}_k \mathrm{C}_k)\mathrm{P}_k \quad (20)$$

Covariance matrix, process noise and observation noise are closely related to the type of battery and data acquisition system. Data sampling period is usually decided by charge discharge efficiency and the conditions of battery operating. The above is a calculation cycle of improving EKF algorithm.

IV. EXPERIMENTAL RESULTS AND SIMULATION ANALYSIS

In this paper, a simulation model is built in Matlab/Simulink. FUDS (Federal Urban Driving Schedule) is obtained from the battery charge discharge current data by USABC when the hybrid electric car ran. The schedule is 1,372 seconds, and the experiment only intercepted the first 500 seconds. The simulation model is built in Simulink and the schedule current curve is shown in figure 4.

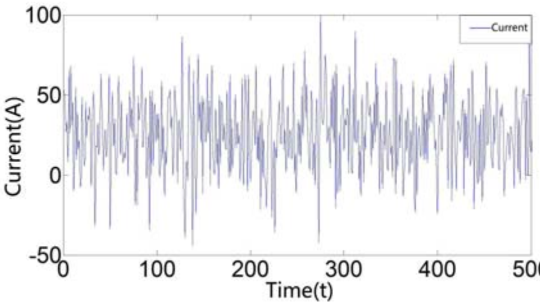

FIGURE IV. CURRENT CURVE OF FUDS

Battery SOC with a capacity of 45Ah was estimated in the case of FUDS. Running simulation model and respectively Ampere-hour integral method and improved EKF algorithm are used to estimate battery SOC. the estimates curve of battery SOC and error curve are shown in figure 5, 6.

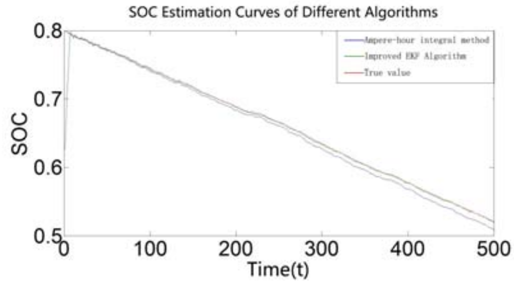

FIGURE V. ESTIMATES CURVE OF BATTERY SOC

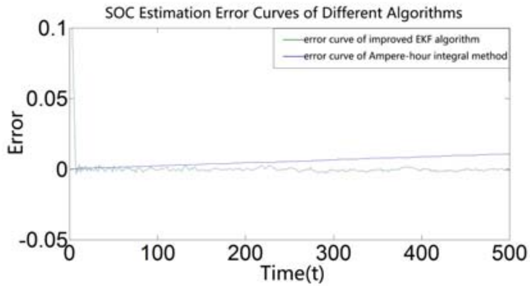

FIGURE VI. ERROR CURVE OF BATTERY SOC

It can be seen from the figure above, The initial value of Ampere-hour integral method must be accurate and the cumulative current error is getting bigger and bigger without correction. It Cause the estimation error of battery SOC to become bigger and bigger. When improving EKF algorithm is used to estimate battery SOC, it is unnecessary to consider initial value. The estimation of battery SOC converges rapidly to the true SOC. As time goes on, this algorithm can also estimate the SOC value of battery very well and the error remains within the range plus minus two percent.

V. CONCLUSION

This paper studied the estimation algorithm of Electric car lithium battery pack SOC. Aiming at the disadvantage of Ampere-hour integral method, an improved EKF filtering algorithm is proposed to estimate the battery SOC. This method combines EKF algorithm with Ampere-hour integral method. The battery state equation is established under the battery recombination model. The model parameters is identified by recursiving least squares algorithm, in this paper, and the battery voltage V and the battery SOC are used as models of Observation variable and State variables, and simulation is carried out under FUDS. The simulation results show that the improved EKF algorithm can accurately estimate the battery SOC and correct the initial value error of the battery SOC well. The improved EKF algorithm has a strong inhibitory effect on noise and can estimate the battery SOC accurately. The error remains within the range plus minus two percent.

REFERENCES

[1] Lang Fu, Mingxing Du,Bin Liu, Kexin Wei.The SOC estimation of lithium ion battery based on open-circuit voltage method and kalman filter method [J]. Journal of tianjin university of technology, 2015, 31(6): 9-13.

[2] Zhe Li, Languang Lu, Minggao Ouyang. Comparison method of battery SOC estimation to improve the accuracy of Ampere-hour integral method[J]. Journal of Tsinghua university (JCR Science Edition), 2010, 50(8), 1293-1296.

[3] Chao Deng,Pengfei Shi.Prediction of residual capacity of MH/Ni battery based on neural network[J]. Journal of Harbin Institute of Technology, 2003, 35 (11): 1405-1408.

[4] Baojie Liu,Yan Wang, Tianming Yin. Electric vehicle battery management system [J]. Electric automation, 2010, 32(1): 60-62.

[5] Yong Sun, Zilin MA, Gongyou Tang, Zheng Chen, Nong Zhang. Estimation method of state-of-charge for lithium-ion battery used in hybrid electric vehicles based on variable structure extended kalman filter[J]. Chinese Journal of Mechanical Engineering, 2016, 29(4): 717-726.

[6] Yujian Jia, Da Xie,Yujie Gu.Classification and characteristics of equivalent circuit model of electric car battery [J]. Power and energy, 2011, 32(6): 516-521.

[7] Jun Bi,Yanqiong Kang, Sai Shao.The Nernst model parameter identification of pure electric vehicle power lithium battery[J]. Automotive engineering, 2015, 37(6): 725-730.

[8] Morre, Stephen, Merhdad Eshani. An empirically based electro source horizon lead acid battery model[J]. SAE transactions, 1996(105): 421.

[9] Hu Zhang, Zhengxi Li, Chaonan Tong. Off line identification of induction motor parameters based on recursive least square algorithm[J]. Chinese Journal of Electrical Engineering, 2011, 31(18): 79-86.