Progressive intelligence estimation of SOC based on multiple models

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Abstract. In order to accurately estimate stage of charge(SOC) of the electric car lithium-ion battery, the paper used a variety of equivalent circuit model and built space state equation, through real-time online with forgetting factor recursive least squares identification battery model parameters, dynamic real-time update battery model state equation, the experimental condition to make use of the Matlab simulation, based on the battery circuit model of joint (FFRLS - EKF) algorithm, and joined the battery stage of health(SOH),The average error of the obtained SOC estimate is less than 1.8% and the maximum error is less than 3%. Finally, the accuracy of FFRLS-EKF-SOC is verified, and the error accumulation problem is solved.

1. Introduction
With the increase of environmental pollution and the shortage of non-renewable energy, the development of renewable and efficient clean energy has become a hot spot today. Among them, the characteristics of electric vehicles with high efficiency and energy saving are favored by people. The power battery is the energy carrier that drives the electric vehicle forward, which determines the working performance of the whole vehicle.

At present, the more commonly used methods of charge estimation are: the one is the SOC that is directly estimated based on the electrochemical reaction inside the battery, and the other is an indirect estimation based on the external characteristic parameter to establish an equivalent model[1]. Considering that the electrochemical reaction inside the battery is complicated, it is more common to use the indirect method to detect the external characteristic parameters of the battery. The indirect method for estimating battery SOC mainly includes: discharge experiment method, open circuit voltage method, ampere-hour integral method, neural network method, fuzzy logic method, Kalman filter method, data-driven method, etc.[2][3]. For the characteristics of lithium-ion battery nonlinearity, this paper uses FFRLS-EKF-SOC is used to estimate and study the SOC of lithium-ion batteries.

2. Equivalent circuit model and parameter identification

2.1. Two battery equivalent circuit models
The equivalent circuit can clearly reflect the characteristics of the physical properties of the battery. At present, the commonly used equivalent circuit models are Rint type, Thevenin type, PNGV type, GNL type, and second-order RC equivalent circuit model [4]. This paper uses a second-order RC and a simplified GNL circuit model. Figure 1 shows an equivalent second-order RC circuit. UL is the terminal
voltage of the external circuit of the battery, and voltage source \( E \) is the open circuit voltage \([5]\). The losses during the operation of the lithium-ion battery mainly include the concentration polarization (combined by \( R_1 \) and \( C_1 \)) and the electrochemical polarization (combined with \( R_2 \) and \( C_2 \)) and ohmic loss \((R_i)\). Each module is connected in series to form a lithium ion second-order RC equivalent model.

![Second-order RC equivalent circuit model](image1)

**Figure 1.** Second-order RC equivalent circuit model

For the second-order RC equivalent circuit shown in Figure 1, according to Kirchhoff’s voltage law and current law, the following equation can be obtained:

\[
U_L = E - R_i \cdot I - \left[ U_{1o} e^{-t/\tau} + I \cdot R_1 \left( 1 - e^{-t/\tau} \right) \right] - \left[ U_{2o} e^{-t/\tau} + I \cdot R_2 \left( 1 - e^{-t/\tau} \right) \right] 
\]

(1)

Among them, \( U_{1o} \) is the polarization initial voltage of the model, \( I \) is constant current, time constant \( \tau = R \cdot C \).

The GNL equivalent model has many parameters and complex structure. The identification algorithm based on GNL equivalent circuit model and Taylor’s expansion into high-order operation in SOC estimation are more complicated, which is not conducive to engineering implementation. To this end, we simplifies the self-discharge factor on the basis of GNL. The simplified GNL model is shown in Figure 2.

![Simplified GNL equivalent circuit model](image2)

**Figure 2.** Simplified GNL equivalent circuit model

For the simplified GNL equivalent circuit model shown in FIG. 2, the state equation in the frequency domain can be obtained from the circuit relationship as shown in the following formula (2).

\[
U_h = \left( \frac{R_1}{R_i C_1 s + 1} + \frac{R_2}{R_i C_2 s + 1} + \frac{1}{C_s} + R_i \right) I + U
\]

(2)
2.2. Battery fitting parameters

In this paper, the dynamic process parameters of a lithium battery under typical operating conditions are obtained under the ADVISOR platform. In the ADVISOR simulation platform, the UDDS simulation study was carried out using the gm_ev1_in model and the ESS_L17_temp model lithium-ion battery. According to Kirchhoff's current law, the current \( \Sigma I = 0 \) is passed, and it is allowed to stand for 30 minutes. The voltage at the current end, that is, the open circuit voltage (OCV), is measured. The simulation was started with an SOC of 10% interval, and 10 sets of road terminal voltage data were measured. The data was fitted using the polyfit tool of Matlab software, and the OVC-SOC relationship fitting curve as shown in Fig. 3 was made. The OCV-SOC curve expression at this time is,

\[
OCV = 1283705SOC^6 + 3275159SOC^5 + 1511743SOC^4 + 2471572SOC^3 + 2760513SOC^2 + 1287585SOC + 239019
\]  

(3)

![Figure 3. OCV-SOC relationship graph](image)

2.3. Identification of equivalent circuit model parameters

The battery model parameter identification methods are mainly online and offline. In this paper, the online parameter identification with the forgetting factor recursive least squares method is used to solve the data accumulation and saturation phenomenon of the least squares parameter identification, and the OVC-SOC relationship fitting curve as shown in Fig. 3 was made. The OCV-SOC curve expression at this time is,

\[
\theta (k) = \hat{\theta} (k - 1) + K (k) \left( y (k) - \varphi ^T (k) \theta (k - 1) \right)
\]

(4)

\[
K (k) = \frac{P (k - 1) \varphi (k)}{\lambda + \varphi ^T (k) P (k - 1) \varphi (k)}
\]

(5)

\[
P (k) = \frac{1}{\lambda} \left[ I - K (k) \varphi ^T (k) \right] P (k - 1)
\]

(6)

In the above formula, the original parameter estimation value is expressed in the above formula. The observation value \( y (k) \) for this time is the actual value of the system. The above equation represents the original parameter estimation value. The observation value \( y (k) \) for this time is the actual observation
of the system. The value of the forgetting factor is (0.95, 1), and I is the corresponding observation matrix.

The parameter identification of the second-order RC circuit model, the simplified second-order RC equivalent circuit state equation according to the model diagram shown in Figure 2 is,

\[
E = \left( \frac{R_1}{R_1 C_1 s + 1} + \frac{R_2}{R_2 C_2 s + 1} + \frac{1}{C_0 s} + R_i \right) I + V
\]  

(7)

The parameter values obtained by discretization are,

\[
R_1 = \frac{\tau_1 c + \tau_2 R_i - d}{\tau_1 - \tau_2}
\]

(8)

\[
R_2 = c - R_i - R_1
\]

(9)

\[
C_1 = \frac{\tau_1}{R_1}, \quad C_2 = \frac{\tau_2}{R_2}, \quad R_i = -\frac{k_5}{k_2}
\]

(10)

The simplified GNL simplified circuit model parameter identification, according to the model diagram shown in Figure 2, to simplify the GNL equivalent circuit state equation as shown below.

\[
E = \left( \frac{R_1}{R_1 C_1 s + 1} + \frac{R_2}{R_2 C_2 s + 1} + \frac{1}{C_0 s} + R_i \right) I + U_L
\]

(11)

The simplification result is discretized, and the parameter value is obtained by using the FFRLS algorithm for parameter identification processing,

\[
R_1 = \frac{d - (c - R_i) \tau_1}{\tau_2 - \tau_1}
\]

(12)

It can be seen from the discrete parameter derivation that the parameter identification results of the two models are basically the same, but the simplified GNL model is relatively large for the third-order equation, and the RC equivalent model is relatively simple. Therefore, the second-order RC circuit is used for parameter identification.

3. Algorithm simulation based on circuit model

3.1. Improved EKF based on circuit model

According to the instantaneous value of the defined SOC, it can be obtained by integration,

\[
S_{soc,k+1} = S_{soc,k} + \eta \int_{i_k} \frac{dt}{Q_{rate}}
\]

In the middle, \( S_{soc} \) is initial value, \( \eta \) is discharge efficiency, \( Q_{rate} \) is rated capacity, \( S_{soc,k+1} = S_{soc,k} - \frac{\eta \Delta t}{Q_{rate}} i_k \). In the formula, \( S_{soc,k+1} \) is the SOC value of the (k+1)th sampling point. \( i_k \) is the sampled current value of the kth point.

In summary, for the second-order RC equivalent circuit shown in Figure 1, the equation of state is,
The state space vector of the EKF, the state transition matrix and the control matrix are:

\[
X_k = \begin{bmatrix}
SOC(k + 1) \\
U_1(k + 1) \\
U_2(k + 1)
\end{bmatrix}, \quad A_k = \begin{bmatrix}
1 & 0 & 0 \\
0 & e^{-\frac{\Delta t}{R_{SOH} C_0}} & 0 \\
0 & 0 & e^{-\frac{\Delta t}{R_{SOH} C_0}}
\end{bmatrix}, \quad B_k = \begin{bmatrix}
\frac{-\eta \Delta t}{Q_{rate}} \\
R_1 \left(1 - e^{-\frac{\Delta t}{R_{SOH} C_0}}\right) \\
R_2 \left(1 - e^{-\frac{\Delta t}{R_{SOH} C_0}}\right)
\end{bmatrix}, \quad D = \begin{bmatrix}
R_0 + R_{SOH} \left(1 - SOH_{C_0}\right)
\end{bmatrix}
\]

Where \(R_0\) is the internal resistance of the battery at the factory, \(R_{SOH}\) is the ohmic internal resistance at the current time, \(SOH\) is defined as the health status of the battery, indicating the health of the battery, and the \(SOH\) is defined according to the battery capacity attenuation,

\[
SOH = \frac{C - C_{END}}{C_0 - C_{END}} \times 100\%
\]

Where \(C_0\) is the capacity of the initial battery, \(C\) is the capacity of the battery at the current time, and \(C_{END}\) is the capacity at the end of the battery life. The EKF algorithm is a multi-cycle process. The specific process is shown in Figure 4.

**Figure 4. EKF algorithm recursive flow chart**
3.2. FFRLS-EKF-SOC based on battery circuit model
The EKF algorithm relies on the accuracy of the model, while the lithium battery operates in a non-linear mode of operation, causing internal parameters to change as well. Therefore, we need to update the internal parameters of the battery online, and use the joint algorithm to estimate the SOC of the power battery online. The forgetting factor recursive least squares parameter identification is used, the updated parameters are applied to the EKF algorithm, the current SOC value is estimated, and the OCV is obtained according to the OCV-SOC relationship curve. The specific process is as shown in Fig. 5.

![Figure 5. SOC estimation strategy based on FFRLS-EKF joint algorithm](image)

In Matlab, the data under UDDS conditions are used for simulation, and a comparison chart and SOC error comparison chart between An-SOC, FFRLS-EKF-SOC and REL-SOC are obtained, as shown in Figure 6 below.

![Figure 6. SOC estimated value and error curve under UDDS operating conditions](image)

It can be seen from Fig. 6 that the initial stage integration method and FFRLS-EKF-SOC have higher estimation accuracy, but with the accumulation of time, the cumulative error of the ampere-time integration method is gradually increased, using FFRLS-EKF The algorithm can effectively solve the cumulative error, and the measured SOC value is closer to the actual result. The average error of the FFRLS-EKF algorithm is within 1.8%, and the maximum error range is less than 3%.

4. Conclusion
In this paper, based on the nonlinear working mode of lithium battery, internal chemical loss, electrochemical loss, ohmic internal resistance and other characteristics, a second-order RC equivalent circuit model and a simplified GNL model are established. The two models are respectively parameter distinguish by least squares method. In this paper, the second-order RC is chosen as the equivalent model,
and the SOC of the lithium battery is estimated by FFLLS-EKF-SOC. The introduction of SOH in the SOC estimation more realistically reflects the true state of the battery and improves the estimation accuracy of the battery SOC.

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