Parameters Sensitivity Analysis of Lithium Batteries Composite Equivalent Model for SOC Estimation

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Abstract. For the lithium battery electrochemical composite equivalent model, the sensitivity of model parameters to the battery state of charge (SOC) estimation is analysed in order to determine the influence of model parameters on SOC estimation and provide optimization basis for SOC estimation algorithm based on battery model. Firstly, the sensitivity analysis method of model parameters is defined, and the sensitivity of model parameters to SOC estimation of lithium ion batteries is quantitatively analysed based on MATLAB software. Then, based on MATLAB /Simulink, the extended Kalman filter algorithm is used to simulate the SOC estimation under variable model parameters and analyse the influence of parameter changes on the SOC value. The experimental results show the correctness and validity of the quantitative analysis results of parameter sensitivity, and provide the corresponding basis for the research of SOC estimation algorithm of lithium-ion battery variable parameter model.

1. Introduction
The battery state of charge (SOC) represents the residual capacity of the battery [1]. SOC estimation is a key part of the battery management system. By accurately estimating the SOC value of the battery, the battery can be maintained within a reasonable application range to prevent various damage or safety accidents caused by overcharging or overdischarging. Lithium-ion battery SOC estimation methods include ampere measurement method, open circuit voltage method, neural network method and model-based kalman filter [2-3]. The kalman filtering method based on the battery model is widely used to estimate the SOC value of lithium-ion battery. The theory and practice verify the effectiveness and accuracy of the proposed method in SOC estimation [4-7]. The lithium-ion battery model is a complex nonlinear model with multiple parameters, and the battery model parameters are affected by temperature and usage time. When using the model-based algorithm for SOC estimation, changes in model parameters will have a greater impact on SOC estimation accuracy [9-10]. In order to reduce the influence of model parameter changes on SOC estimation, scholars can modify the model parameters online and modify the model according to the change of model parameters in real time, that is, the SOC estimation is performed by changing the model parameters, thus improving the accuracy of SOC estimation [11-16]. However, due to the large number of parameters in the lithium-ion battery composite model, if all the parameters in the model are identified online and corrected in real time, the problems of complex calculation, slow SOC estimation, and lag are faced. So the paper studies the sensitivity of each parameter in the model to the SOC estimate, and analyse the degree of influence of each parameter change on the SOC estimate. When the SOC estimation is performed by using the variable model parameter method, the parameter with low sensitivity and low influence on the SOC estimation
value can be set as a fixed value, and only other key parameters can be identified online. The research results provide the basis for online identification parameter selection for the lithium-ion battery variable model parameter SOC estimation algorithm. On the basis of improving the accuracy of SOC estimation value, the number of online identification parameters of lithium ion battery can be reduced, and the complexity of SOC estimation can be reduced.

2. Material and Methods

2.1. SOC estimation based on Kalman filter algorithm

2.1.1. Electrochemical composite model of lithium ion battery

Electrochemical model is based on the electrochemical reaction mechanism between the electrode, diaphragm and electrolyte to describe the relevant characteristics of the battery, including the process of ion concentration change in the electrolyte during operation of the battery, the electrode reaction process, etc\[6\][14]. In practical applications, the electrochemical reaction in the battery is complicated, and it can be simplified to be equivalent to the electrochemical equivalent model such as sherpherd model, unnwehr universal model and ernst model. Equation 1 is sherpherd model, Equation 2 is unnwehr universal model, and Equation 3 is ernst model.

\[
y_k = E_0 - R_i - K_i / x_k \\
y_k = E_0 - R_i - K_i x_k \\
y_k = E_0 - R_i - K_1 \ln(x_k) + K_4 \ln(1 - x_k)
\]

Among them, \(y_k\) represents the battery terminal voltage, \(i_k\) represents the instantaneous terminal current of the battery at time \(k\), \(x_k\) represents the battery SOC value at time \(k\), \(E_0\) represents the battery open circuit voltage, \(R\) represents the battery internal resistance, and \(K_i\) represents the battery polarization internal resistance. In order to combine the advantages of the three models, an electrochemical composite model was established. The expression of the composite model is shown in Equation 4:\[1\][5][7]:

\[
y_k = K_0 - R_i - K_i / x_k - K_2 x_k + K_3 \ln(x_k) + K_4 \ln(1 - x_k)
\]

2.1.2. Application of Kalman Filtering Algorithm in SOC Estimation

The state equation of the battery is obtained based on the composite model in equation (4) and the amperometric method\[15\], as shown in equation (5).

\[
x_{k+1} = x_k - (\eta \Delta t) / C_n
\]

Obtain an observation equation for a lithium ion battery based on equation (4).

In equation (5), \(C_n\) represents the rated capacity of the battery, \(\eta\) represents the coulombic efficiency, and \(\Delta t\) is the sampling time. Based on equations (4) and (5), the Kalman filter algorithm can be used to estimate the SOC of lithium-ion batteries. The detailed estimation steps and results can be referred to [5] and [6].

2.2. Model parameter sensitivity analysis

2.2.1. Sensitivity definition

In the observation equation described in formula (4), \(y_k\) and \(i_k\) can be measured by sensors, and other parameters \(K_0 \sim K_4\) and \(R\) need to be identified by corresponding parameters. In order to study the influence of parameters \(K_0 \sim K_4\) and \(R\) on the SOC estimation value, the local sensitivity analysis method was used to analyze the sensitivity of the parameters in the composite model\[17\][18].
equation (4) as a general mathematical model: 

\[ x = f(y, k_0, k_1, \ldots, k_i), \]

among them, \( k_i \) is the model parameter in equation (4). \( S \) is defined as the sensitivity of model parameter \( k_i \) to \( x \)

\[ s_i = \frac{\partial f(y, k_0, k_1, \ldots, k_i)}{\partial k_i} \]

When calculating \( s \), \( y \) is set to a fixed input value, and other parameter values other than \( k_i \) are also set to a fixed value. Since the magnitude of each \( k_i \) in the model parameters is relatively large, in order to uniformly analyze and compare the sensitivity of the model parameters to \( x \), it is necessary to standardize the sensitivity, as shown in equation (7).

\[ s^* = \frac{\partial f(y, k_0, k_1, \ldots, k_i)}{\partial k_i} \frac{k_i}{f(y, k_0, k_1, \ldots, k_i)} \]

### 2.2.2. Parameter sensitivity analysis

The parameter sensitivity analysis of the lithium ion battery composite model was carried out by using the sensitivity calculation formula of the formula (7), and the model initialization parameters are shown in Table 1. In order to avoid solving the complex \( x \) function of equation (4), the numerical analysis method is used to calculate the parameter sensitivity analysis. The steps are shown in Figure 1.

| Initial parameter                        | Numerical value |
|------------------------------------------|-----------------|
| Terminal voltage \( y(V) \)              | 3.0             |
| Charge and discharge current \( i_k(A) \)| 25              |
| Model matching coefficient \( K_0 \)     | 3.7             |
| Model matching coefficient \( K_1 \)     | 0.0003          |
| Model matching coefficient \( K_2 \)     | -0.01           |
| Model matching coefficient \( K_3 \)     | 0.3             |
| Model matching coefficient \( K_4 \)     | -0.003          |
| Internal resistance \( R (\Omega) \)     | 0.01            |
3. Results

3.1. Parameter $K_0$ sensitivity analysis
According to the solution step shown in Figure 1, the parameter sensitivity is solved based on Matlab, and the parameter $K_0$ is set to vary between 0 and 4, and the maximum relative change rate of the parameter is 100%. The trend of the sensitivity $s$ of the SOC value to the parameter $K_0$ is shown in Figure 2. It can be seen from Figure 2 that $s$ varies with the value of $K_0$, and the maximum sensitivity exceeds 7, indicating that the parameter $K_0$ has a relatively large influence on the estimation of the SOC value.

3.2. Parameter $K_1$ sensitivity analysis
The setting parameter $K_1$ changes between 0 and -0.12, and the maximum relative change rate of the parameter exceeds 100%. According to the solution step shown in Figure 1, the parameter sensitivity is solved based on Matlab, and the change trend of the sensitivity $s$ of the SOC value to the parameter $K_1$ is shown in Figure 3. It can be seen from Figure 3 that the absolute value of $s$ maximum sensitivity does not exceed 0.25, indicating that parameter $K_1$ has little effect on the SOC value.

3.3. Parameter $K_2$ sensitivity analysis
Set the parameter $K_2$ to change between 0 and -0.2, and the maximum relative change of the parameter exceeds 100%. According to the solution step shown in Figure 1, the parameter sensitivity is solved based on Matlab. The trend of the change in the sensitivity $s$ of the SOC value to the parameter $K_2$ is as shown in Figure 4. It can be seen from the figure that the maximum sensitivity of $s$ does not exceed 0.3, indicating that the parameter $K_1$ has little effect on the SOC value.

3.4. Parameter $K_3$ sensitivity analysis
The parameter $K_3$ varies between -0.7 and 0.3, and the maximum relative change rate of the parameter exceeds 100%. The trend of the change in the sensitivity $s$ of the SOC value to the parameter $K_3$ is as shown in Figure 5. It can be seen from the figure that the value of $s$ varies between 0 and 1.8, indicating that parameter $K_3$ has a certain influence on the SOC value.
3.5. Parameter $K_4$ sensitivity analysis

The parameter $K_4$ varies between -0.23 and 0, and the maximum relative change rate of the parameter exceeds 100%. The change trend of the sensitivity $s$ of the SOC value to the parameter $K_4$ is as shown in Figure 6. It can be seen from the figure that the maximum sensitivity does not exceed 0.3, indicating that the parameter $K_4$ has little effect on the SOC value.

3.6. Parameter $R$ sensitivity analysis

The parameter $R$ varies from 0 to 0.015, and the maximum relative change rate of the parameter is 100%. The trend of the sensitivity $s$ of the SOC value to the parameter $R$ is as shown in Figure 7. It can be seen from the figure that the maximum sensitivity of $s$ is close to 3, indicating that the parameter $R$ has a relatively large influence on the SOC value.

3.7. Parameter sensitivity analysis summary

The sensitivity analysis results of the above SOC estimation values for $K_0$ to $K_4$ and $R$ parameters are uniformly described by a histogram, as shown in Figure 8. It can be seen from the figure that the change of each model parameter has a certain influence on the SOC estimation value, wherein the parameters $K_0$, $K_1$, and $R$ have large influences, and other parameters have little influence.

4. Conclusions

Based on Matlab, the sensitivity of each parameter in the electrochemical composite model of lithium-ion battery to the SOC estimation value was quantitatively analyzed. The relative change rate of the model parameters is not less than 100%, and the parameter variation range completely exceeds the normal value range of the battery model parameters in practical applications. The analysis results show that $K_0$, $K_1$, and $R$ have great influence on SOC estimation, while parameters $K_2$, $K_3$, and $K_4$ have little influence on SOC estimation. The research results of the thesis can provide a basis for the study of the SOC estimation algorithm for the variation of the model parameters of lithium-ion batteries, and also have reference value for the online correction of other model parameters of lithium-ion batteries and the optimization of SOC algorithm.
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