Research on Battery SOC Estimation Algorithm for Energy Storage Power Station

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Abstract. This paper takes the high-power lithium battery as the research object. The battery capacity is 40Ah. The state of charge (SOC) of lithium cannot be measured directly. We establish an equivalent circuit model of the battery and use Matlab/Simulink to simulate the equivalent circuit model of the battery. The simulation results and analysis show that the designed control strategy can accurately estimate the SOC of the battery and provide a theoretical basis for the designed algorithm in the practical application of energy storage power stations.

1 Introduction

With the gradual development of clean energy power generation technology and energy storage technology. Energy storage power plants have become a key method to ensure the safe operation of the power grid. In 2010, the State Council issued a decision about accelerating the cultivation and development of strategic emerging industries and decided to strengthen the integration and storage of new energy. The 12th Five Year Plan of national energy science and technology clearly proposed the development of large capacity and rapid energy storage devices. In October 11, 2017, the National Energy Administration released the first guiding policy for China energy storage industry which pointed out the problems in current stage of energy storage technology and industrial development and put forward energy storage technology and industry development goals and main tasks in the next ten years in China.

The policy clearly states that the development of the energy storage industry will be promoted in two phases in the next 10 years. The first phase (2017-2020) will realize the transition of energy storage from research and development to commercial application. The second phase (2020-2025) will achieve large scale commercial application. The application of grid energy storage grows rapidly in 2018 which brings China's energy storage market into the year of "GW/GWH". In 2018 the scale of energy storage projects in China was 1018.5mw/2912.3mwh which was 2.6 times of the total scale in 2017. According to this calculation, the market will reach 50 to 60 GW in the end of the 14th five year plan. In 2050 the market will reach 200GW and the market scale will exceed 300 billion dollars.

As the only energy source of energy storage station, the performance of battery determines the performance of energy storage station directly. There is of great significance to get the remaining power of the battery and grasp the performance of the battery in real time to the output of the energy storage power station. The remaining power of the battery is the most important parameter that directly reflects the performance information of the
battery. The remaining power of the battery is also called the state of charge (SOC). The state of charge of the battery is the ratio between the available energy and the total energy of the battery which reflects the amount of the remaining power of the battery. SOC is defined as the ratio between the remaining power of the battery to the rated capacity under the same conditions at a certain discharge rate [1] as is shown in (1):

$$SOC = SOC_0 - 1/Q_a \int_0^t \eta Idt$$ (1)

The SOC cannot be directly measured. However, SOC has a relationship with the factors of voltage, current and temperature of the battery that makes SOC can be estimated by these measured parameters. The accurate estimation of SOC can ensure that the battery will not be overused. For example, if the estimated value of SOC is lower than real SOC, the user can only use part of the battery power while discharging the battery. The same error will occur to overcharge while charging the battery which will reduce battery life. When the SOC estimated value is higher than the actual SOC, the battery will be under charged and the total available energy will be reduced.

The accuracy of SOC estimation algorithm also affects the performance of energy storage power station. This is because SOC estimation is applied to the power regulation of energy storage system. The power dispatching center issues AGC regulation instruction to the power plant when the grid frequency changes. The energy storage system makes corresponding to charge or discharge. If the SOC estimation of battery is not correct, it will cause over charge or over discharge of battery which will seriously affect the battery life of energy storage system. The accurate estimation of SOC and control of SOC reasonably have a great influence on the battery protection and performance of the energy storage station.

Matlab/Simulink is used to model the battery and estimate the SOC of the battery in this paper. The battery model is established and simulated in Matlab. The control strategy of SOC estimation is designed in Matlab which provides theoretical basis for the actual operation of the energy storage power station.

2 Establishment of lithium-ion battery model

The Lithium-ion battery is a high-performance battery in which Li+ is repeatedly detached and embedded between the positive and negative electrodes. It consists of negative electrode, positive electrode, electrolyte and diaphragm. The chemical expression of Li-ion battery is:

$$LiMO_y \leftrightarrow Li_{1-x}MO_y + xLi^+ + xe^-$$ (2)

$$LiC \leftrightarrow Li_{1-x}C + xLi^+ + xe^-$$ (3)

The battery shows part of the characteristics of the resistance and capacitance under the current stimulation. Johsonl [2-3] used resistance, capacitance and other electronic components to simulate the battery. The parameters of resistance and capacitor were identified by experiments to simulate the dynamic and static characteristics of battery. Mark E. Orazim [4] proved that the dynamic and static characteristics of the battery can be represented by the equivalent circuit in Fig. 1. \(V_0\) is the open circuit voltage of the battery, \(R_i\) is the equivalent internal resistance of the battery that includes the positive and negative electrode materials of the battery. \(R_1C_1\) and \(R_2C_2\) are used to simulate the dynamic
characteristics of the battery which includes the migration and diffusion of electrons between the positive electrode, electrolyte and negative electrode.

\[ S\dot{OC} = -\frac{\eta}{Q_N} I \]
\[ \dot{V}_1 = -\frac{1}{R_1C_1}V_1 + \frac{1}{C_1}I \]
\[ \dot{V}_2 = -\frac{1}{R_2C_2}V_2 + \frac{1}{C_2}I \]
\[ V_0 = IR_1 + V_1 + V_2 + V \]

The relationship between open circuit voltage (OCV) and SOC is nonlinear [5], we can get the relationship between open circuit voltage and SOC in (5).

\[ V_0 = f(SOC) \quad \text{(5)} \]

We can get (6) by transforming the above equation from (4).

\[ \begin{bmatrix}
S\dot{OC} \\
\dot{V}_1 \\
\dot{V}_2
\end{bmatrix} =
\begin{bmatrix}
0 & 0 & 0 \\
0 & -\frac{1}{R_1C_1} & 0 \\
0 & 0 & -\frac{1}{R_2C_2}
\end{bmatrix}
\begin{bmatrix}
SOC \\
V_1 \\
V_2
\end{bmatrix} +
\begin{bmatrix}
-\frac{\eta}{Q_N} \\
\frac{1}{C_1} \\
\frac{1}{C_2}
\end{bmatrix}I \quad \text{(6)}
\]

\[ V = f(SOC) - IR_1 - V_1 - V_2 \]

3 Parameter identification of battery model

In order to calculate each parameter in the equivalent circuit model of Fig. 1, this paper uses the limited memory least square method to identify the battery model parameters. The principle of identifying the parameters is as in (7):
\[ V(k) - V(k) = i(k) \left( \frac{R_1}{R_1C_1 + 1} + \frac{R_2}{R_2C_2 + 1} + R_i \right) \]

\[ M(k)^T = [V(k-1) - V_{oc}(k-1) \ V(k-2) - V_{oc}(k-2) \ I(k) \ I(k-1) \ I(k-2)] \]

\[ \theta = [k_1 \ k_2 \ k_3 \ k_4 \ k_5] \]

\[ y(k) = M(k)^T \theta \]

\[ \omega(k) = [y(k-2) \ y(k-1) \ I(k) \ I(k-1) \ I(k-2)] \]

(7)

We also need to use the relationship between OCV and SOC to determine M(k) and y(k). We can get the identification results by the limited memory least square method [6] in table 1.

**Table 1. Parameter identification results.**

| parameter | Ri   | R1   | R2   | C1    | C2    |
|-----------|------|------|------|-------|-------|
| value     | 0.0056 | 0.00059 | 0.0020 | 549180 | 17956 |

The relationship between the OCV and the SOC can be obtained by quickly charging and discharging the battery [7]. The steps of the experiment are as follows:

1. Discharge the selected battery cell at room temperature until it reaches the 3V cut-off voltage, and leave it for 12 hours accurately to prepare for the next step.
2. Charge the battery with a constant current of 1C. Stop charging for 5 minutes when the SOC increase 10%. Then repeat the above process until the battery is full charging.
3. Allow the battery to stand at full power for 12 hours.
4. Discharge the battery with a constant current of 1C. Stop discharging for 5 minutes when the SOC decrease 10%. Repeat the above process until the voltage reaches the cut-off voltage. Then record data of the whole process, as shown in table 2.

**Table 2. Voltage of Each static stage in experiment.**

| SOC | Minimum voltage | Maximum voltage | SOC | Minimum voltage | Maximum voltage |
|-----|-----------------|-----------------|-----|-----------------|-----------------|
| 0%  | 3.50            | 9.27            | 60% | 3.7912          | 3.7543          |
| 10% | 3.5766          | 3.5125          | 70% | 3.8609          | 3.8192          |
| 20% | 3.6412          | 3.5351          | 80% | 3.9334          | 3.8894          |
| 30% | 3.6701          | 3.6207          | 90% | 4.0126          | 3.9736          |
| 40% | 3.6984          | 3.6499          | 100%| 4.1044          | 4.0514          |
| 50% | 3.7293          | 3.6941          |     |                 |                 |

We use the minimum value points of SOC charge static stage and maximum value points of SOC discharge static stage to fit with curves respectively and find the average value of two curves. The relationship curve between OCV and SOC of the battery can be obtained as shown in Fig. 2.
We use the discharge motor to test the battery to verify the battery model. Then we compare the output voltage curve of battery with the simulate voltage of the model as is shown in Fig. 3. It can be seen that the model error in the charging and discharging stage is \( \pm 0.03 \text{V} \).

4 Estimation algorithm for SOC

This paper uses a state observer based on the model to estimate the SOC of the battery. In order to simplify the design of the observer, the traditional observer algorithm simplifies the characteristics of the battery such as linearizing the relationship between the OCV of the lithium-ion battery and the SOC [8]. It is not applicable to lithium-ion batteries with a non-linear relationship between OCV and SOC. There is another problem that makes some unrealistic hypothesis while designing the observer. For example the current change rate is assumed to be 0 in [9-10]. However the current changes drastically in the actual operation of the energy storage power station. The assumption that the rate of change is zero is invalid. The observer designed in this paper improves the above two problems. It will increase the complexity of the observer and the estimation accuracy will increase accordingly. Fig. 4 is the basic structure diagram of the observer.
We can discretize (6) and get (8).

\[
\begin{bmatrix}
SOC(k+1) \\
V_1(k+1) \\
V_2(k+1)
\end{bmatrix} =
\begin{bmatrix}
0 & 0 & 0 \\
0 & -\frac{1}{R_1C_1} & 0 \\
0 & 0 & -\frac{1}{R_2C_2}
\end{bmatrix}
\begin{bmatrix}
SOC(k) \\
V_1(k) \\
V_2(k)
\end{bmatrix} +
\begin{bmatrix}
\frac{Q_N}{1/C_1} \\
1/C_1 \\
1/C_2
\end{bmatrix} I(k)
\]

(8)

The above equation is non-linear. We design an observer for the above non-linear equation. The first condition is that the system must be observable. We can use the following method to judge the observability of a non-linear system as in [11]. The sufficient condition for the observability of the system is that the observability matrix is full rank for a nonlinear system as shown in (8). The observability matrix of a nonlinear system is defined as shown in (9).

\[
O = \frac{do(x)}{dx} = \frac{d}{dx}
\begin{bmatrix}
h(x) \\
L_f h(x) \\
L_f^2 h(x)
\end{bmatrix}
\]

(9)

\(L_f\) is the Lyapunov function which is defined as (10).

\[
L_f h(x) = \frac{dh(x)}{dx} f(x,u)
\]

\[
L_f^2 h(x) = \frac{dL_f^2 h(x)}{dx} f(x,u)
\]

(10)

We can get (11) from (8).

\[
\begin{align*}
h(x) &= f(SOC) - V_1 - V_2 \\
L_f h(x) &= \frac{1}{R_1C_1} V_1 + \frac{1}{R_2C_2} V_2 \\
L_f^2 h(x) &= -\frac{1}{R_1^2C_1^2} V_1 - \frac{1}{R_2^2C_2^2} V_2
\end{align*}
\]

(11)

We can get the observability matrix of the battery state equation from (9) and (11).

\[
O =
\begin{bmatrix}
f′(SOC) & 0 & 0 \\
0 & \frac{1}{R_1C_1} & \frac{1}{R_2C_2} \\
0 & -\frac{1}{R_1^2C_1^2} & -\frac{1}{R_2^2C_2^2}
\end{bmatrix}
\]

(12)

We know it is non-linear between OCV and SOC. So we can conclude that in (13).

\[
f′(SOC) \neq 0 \quad \frac{1}{R_1C_1} \neq 0 \quad \frac{1}{R_2C_2} \neq 0
\]

(13)

The system is observable and the state quantity can be observed through the state observer. The observer we applied in this paper is the Walcott-Zak nonlinear observer [12].
This observer is based on simple Romberg feedback and introduces a feedback amount that changes with the error. The sliding mode observer can be written in (14).

\[
\dot{x} = A_x \tilde{x} - H(y - \hat{y}) + B_u u + M(e, \rho)
\]

\[
M(e, \rho) = \begin{cases} 
  g(e, \rho) e \neq 0 \\
  0, e = 0 
\end{cases}
\]

The error \( e \) is between the observer’s output and the actual output. The non-linear part makes the error converge to 0. The design of the observer includes the parameter matrix \( H \) and the function \( g(x) \) to stabilize the observer. We use the equivalent control principle combined with the Lyapunov stability principle to design the observer parameters. According to the Walcott-Zak observer, the structure of the sliding mode observer is designed as shown in (15).

\[
\begin{aligned}
\dot{x}_1 &= (1 - \frac{1}{R_1 C_1})x_1 + \frac{1}{C_1} u - h_1 (y - \hat{y}) \\
\dot{x}_2 &= (1 - \frac{1}{R_2 C_2})x_2 + \frac{1}{C_2} u - h_2 (y - \hat{y}) \\
\dot{x}_3 &= \dot{x}_3 - \frac{\eta}{Q_N} u - h_3 (y - \hat{y})
\end{aligned}
\]

We can get the error between the actual output and the state observer output in equation (16).

\[
e_y = y - \hat{y} = f(x_1) - f(\hat{x}_3) - x_1 - \dot{x}_2 = f'(\xi) \dot{x}_3 - x_1 - \dot{x}_2
\]

We use (15) to minus (8) and get (17).

\[
\begin{aligned}
\dot{x}_1 &= (1 - \frac{1}{R_1 C_1})x_1 + h_1 e_y \\
\dot{x}_2 &= (1 - \frac{1}{R_2 C_2})x_2 + \frac{1}{C_2} u - h_2 e_y \\
\dot{x}_3 &= \dot{x}_3 + h_3 e_y
\end{aligned}
\]

We choose the Lyapunov function and get the sufficient conditions for the observer to be stable in (18).

\[
V = \frac{1}{2} \dot{x}_1^2 + \frac{1}{2} \dot{x}_2^2 + \frac{1}{2} \dot{x}_3^2
\]

\[
\dot{V} = \ddot{x}_1 \dot{x}_1 + \ddot{x}_2 \dot{x}_2 + \ddot{x}_3 \dot{x}_3
\]

We can get (19) through (16) to (18).

\[
\dot{V} = (1 - h_1 - \frac{1}{R_1 C_1}) \ddot{x}_1^2 + (1 - h_2 - \frac{1}{R_2 C_2}) \ddot{x}_2^2 + (1 + f'(\xi)) h_3 \ddot{x}_3^2
\]

\[-(h_1 + h_2) \dddot{x}_1 \ddot{x}_1 + (f'(\xi) h_1 - h_3) \dddot{x}_2 \ddot{x}_2 + (f'(\xi) h_2 - h_3) \dddot{x}_3 \ddot{x}_3
\]

The sufficient condition for stable system is that the matrix \( H \) is negatively definite.
\begin{equation}
H = \begin{bmatrix}
1 - h_1 - \frac{1}{R_1 C_1} & -\frac{h_1 + h_2}{2} & \frac{f'(\xi)h_1 - h_3}{2} \\
-\frac{h_1 + h_2}{2} & 1 - h_2 - \frac{1}{R_2 C_2} & \frac{f'(\xi)h_2 - h_3}{2} \\
\frac{f'(\xi)h_1 - h_3}{2} & \frac{f'(\xi)h_2 - h_3}{2} & 1 + f'(\xi)
\end{bmatrix}
\end{equation}

According to the above formula, the sufficient conditions for the convergence of the observer can be obtained in (21) to (23).

\begin{equation}
m_1 = \frac{1}{R_1 C_1}, m_2 = \frac{1}{R_2 C_2}
\end{equation}

\begin{equation}
\begin{cases}
1 - h_1 < m_1 \\
2m_1 + h_1 - 2 - 2\sqrt{(m_1 + m_2 - 2)(h_1 + m_1 - 1)} < h_2 \\
h_2 < 2m_1 + h_1 - 2 + 2\sqrt{(m_1 + m_2 - 2)(h_1 + m_1 - 1)} \\
1 + f'(\xi) \frac{m_1 + m_2 - 2}{m_1 + m_2 - 2} (Ah_2 + Bh_1 - 2AB - g(h_1, h_2)) < h_3 \\
h_3 < \frac{1 + f'(\xi)}{m_1 + m_2 - 2} (Ah_2 + Bh_1 - 2AB + g(h_1, h_2))
\end{cases}
\end{equation}

\begin{equation}
g(K_1, K_2) = \sqrt{(4AB - C^2)(A - K_1)(B - K_2)} \\
A = K_1 + m_1 - 1 \\
B = K_2 + m_2 - 1 \\
C = K_1 + K_2
\end{equation}

Then use the parameters in Table 1 to solve (22) and get the gain matrix of the observer. The parameters of the gain matrix are selected in (24)

\begin{equation}
h_1 = -0.73, h_2 = 0.29, h_3 = 0.05
\end{equation}

The single battery capacity of the energy storage system is 40Ah. 16 batteries form a battery-group, 17 battery-groups form a battery-cluster and 8 battery-clusters form a control unit. We assume that the initial value of SOC is 90%. We use (24) as the observer gain and build the observer we propose in Fig. 4. Then we simulate the observer in Matlab. We use 1C discharge rate to discharge the system for 20 seconds and stand for 80 seconds. We can get the simulate results in Fig. 5.

![Figure 5. Results for simulink.](image-url)
According to the simulation results in Fig. 5, the initial value of SOC is 90%. The red line is the theoretical value of SOC and the blue line is the estimated value of SOC. It can be seen that the error of the estimated SOC value at the initial stage of the algorithm estimation is large. This is caused by the initial value of the designed observer. As the simulation time increases, the estimated SOC value gradually increases and get close to the theoretical value which shows the good tracking performance of the observer algorithm.

5 Conclusions

In this paper, we take the lithium-ion battery in the energy storage power station as the research object and identify the parameters of the equivalent circuit model. The identified parameters of the battery model can simulate the dynamic and static characteristics of the battery. The state observer is designed to estimate the SOC of the battery and build algorithm model in Simulink. Then we compare the estimated SOC with theoretical SOC value which verifies the accuracy of the estimation algorithm. It provides a theoretical basis for the algorithm in the energy storage power station.

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