The study of equivalent circuit model of battery based on parameters identification multi-dimensional look-up table method

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Abstract. Establishing reasonable and accurate battery model is important to battery energy storage system as well as parameter estimation for battery management system, such as SOC, SOH. In this paper, aiming at the equivalent circuit model, to improve its accuracy, the impact of the age, temperature, SOC, load current, self-discharge and other factors are considered, the experimental data is obtained under different conditions of reasonable experimental settings, using multiple linear regression method to get the model structure parameter off-line. Using the results establish an equivalent circuit model based on multi-dimensional look-up table, the model structure parameters can be interpolated lookup data based on conditions to suit the battery. Finally, design simulation examples verify the correctness and non-structural parameters of the model SOC, SOH implementation strategies.

1. Introduction

The establishment of the battery model is the basis of improving the battery reaction performance, battery application system simulation, battery SOC and SOH parameter estimation, and optimizing the battery management system. Due to the complexity of the working conditions of power batteries, the modeling and management of power batteries, parameter identification and other aspects need to be further studied. According to the principle of battery modeling and the characterization of external characteristics, the battery model can be divided into physical and chemical equation model, equivalent circuit model, thermal model and fitting model [1]. Equivalent circuit model refers to the selection of appropriate circuit elements to describe the internal activation loss, polarization loss and ohmic loss of the battery based on the internal reaction principle of the battery, so as to achieve the purpose of characterizing the external characteristics of the battery. Compared with other battery models, the equivalent circuit model is straightforward and does not involve complex electrochemical parameters inside the battery. The mathematical equation of the model can be written, which is convenient for analysis and application, and suitable for co-simulation with load and charge and discharge circuits [2], so it has been widely used.

The establishment of equivalent circuit model mainly includes two contents, one is to choose the topology structure, the other is to determine the model structure parameters. Topological structures include Rint model [3], RC model [3], Thevenin model [4], PNGV model [5], GNL model [6], etc.
The values of structural parameters are obtained by various identification methods. Parameter identification can be divided into online and offline processing methods. Online identification is to identify and modify the parameters in real time according to the current operating data of the battery. Off-line identification is to pre-set the working conditions and obtain the operating data through repeated experiments, so as to obtain the model parameters. The parameters obtained by on-line identification generally change with the working condition, and parameters of off-line identification can be represented as fixed values or variable values related to working conditions. The working conditions of power batteries are complex and have serious time-varying nonlinearity. Parameter identification requires high data accuracy and sampling rate, so off-line identification is commonly used. In reference [7], the quasi-synthetic function of the identification results was calculated online. In reference [8], the identification results were made into a data table, which was searched online to obtain appropriate parameters. Literature [9] considered the influence of temperature and SOC. Literature [10] considered the influence of SOC and current on the parameters of the battery model. Literature [11] divides SOC estimation methods into open circuit voltage method, ampere hour integral method, advanced estimation method and compound method. Literature [12] analyzed four equivalent circuit model parameters, based on the battery test system for HPPC testing of the battery, using the least squares method for model parameter identification. Literature [13] studied the distribution characteristics of battery voltage inconsistency under equilibrium conditions by using SOC-based equilibrium strategy. Literature [14] describes the specific application of each model in battery research, and analyzes their respective advantages and limitations. In literature [15], the influence of temperature and hysteresis voltage on the equivalent model of lithium battery is discussed. The equivalent circuit model of integrated lithium battery based on temperature is designed.

In conclusion, based on the equivalent circuit model, the off-line identification method is proposed to obtain the structure parameters in order to make the structure parameters conform to the actual situation. In order to ensure the completeness and accuracy of the data sources needed for identification, the modeling process needs to take into account factors such as temperature, charge-discharge current, SOC, cycle life and so on, and the effect of self-discharge on battery capacity is also to be considered. First, an effective experimental process and experimental data expression method are designed. Secondly, multiple linear regression algorithm is designed to identify the model parameters, obtaining a wide range of applicable battery model and expressing it in the form of data sheet and algorithm. Then designing the model and the implementation strategy of SOC and SOH, and finally carrying out the simulation.

2. Experimental process and data expression

In view of the factors affecting battery parameters, the rules of the interaction between these factors are obtained through experiments, then designing the experiment and the appropriate storage mode of the experiment. The battery cycle life test is the longest and basic testing process. The process is carried out at a certain temperature and a certain standard of charging and discharging, and recording the charging and discharging energy until reaching the set termination conditions. High sampling rate and high current and voltage precision data of battery are the basic data for structure parameter identification of equivalent circuit model, for example, hybrid pulse power characterization(HPPC) testing procedure. In this paper, by improving the original HPPC cycle experiment, and different current is tested each time. In order to shorten the experimental period, the transient testing process and the life steady-state testing process can be crossed. In order not to affect the life test results, the discharging and charging time of each time should be consistent to ensure the SOC value is relatively constant. Taking the battery life test as the main line, the transient tests at different temperatures, SOC and charge-discharge currents are carried out at some discrete points of the cycle times, and recording the relevant data. Self-discharging test can be carried out independently.

(1) Supposing the battery cycle life is N times, when the battery reaches the termination condition, it is necessary to obtain the full charging and full discharging energy of each cycle [7] and store it in the array during the cycle life test for N times in total.
\[ \begin{align*}
W1C[n] \\
W1D[n]
\end{align*} \quad n \in [1, N] \] (1)

\[ \begin{align*}
W1C(n) &= \int_{t_1}^{t_2} U_b(\tau) * i_b(\tau) d\tau (i_b > 0) \\
W1D(n) &= -\int_{t_1}^{t_2} U_b(\tau) * i_b(\tau) d\tau (i_b < 0)
\end{align*} \] (2)

\( U_b(\tau) \) represents the terminal voltage of the battery. \( i_b(\tau) \) represents the battery load current, it is stipulated that the current is positive when the battery is charging and the current is negative when the battery is discharging. \( t_1 \) and \( t_2 \) respectively represent the starting and ending time of the charging process. \( U_b(t_1), U_b(t_2) \) respectively represents the starting voltage and ending voltage of the charging process. \( i_b(t_1), i_b(t_2) \) respectively represents the starting current and ending current of the charging process.

The accumulative total charging and discharging electric energy \( W2C, W2D \) of the battery in the whole life.

\[ \begin{align*}
W2C &= \sum_{n=1}^{N} W1C(n) \\
W2D &= \sum_{n=1}^{N} W1D(n)
\end{align*} \] (3)

(2) The equivalent cycle times can be defined to calculate the battery life. From the time the battery is put into use to the current time, the total electric energy charged and discharged by the battery is respectively denoted as \( W3C, W3D \).

\[ \begin{align*}
W3C(t) &= \int_{0}^{t} U_b(\tau) * i_b(\tau) d\tau (i_b > 0) \\
W3D(t) &= -\int_{0}^{t} U_b(\tau) * i_b(\tau) d\tau (i_b < 0)
\end{align*} \] (4)

Then the value of the equivalent cycle times \( n_e \) can be calculated according to Equation (5).

\[ n_e = \frac{W3C}{W2C} * N \text{ or } n_e = \frac{W3D}{W2D} * N \] (5)

Generally, \( n_e \) is greater than \( N \) when battery usage reaches the termination condition.

The health status of the battery can be obtained from Equation (6).

\[ \text{SOH} = 1 - \frac{n_e}{N} \] (6)

(3) In the steady-state life test process, a group of transient tests is carried out every \( A \) time, assuming that \( K \) times are carried out.

\[ K = \lceil N/A \rceil \] (7)

In order to facilitate the subsequent interpolation operation, the number of cycles corresponding to the \( K \)th transient test group was recorded.

\[ L[k] = (k-1)A, \quad k \in [1, K] \] (8)

(4) In each transient test group, \( D \) temperatures were selected for testing respectively. The value range of temperature is \([T_{\text{min}}, T_{\text{max}}]\), and the temperature interval is:

\[ \Delta T = \frac{T_{\text{max}} - T_{\text{min}}}{D-1} \] (9)

So:

\[ T[d] = T_{\text{max}} + \Delta T * (d-1), \quad d \in [1, D] \] (10)
3. Analysis of parameter identification mechanism of battery model

For the identification of the structural parameters of the equivalent circuit model, a certain circuit model can be selected to identify the structural parameters of the battery model according to a certain method, so as to obtain the parameters of the battery model under different working conditions and establish a practical model.

In this paper, multiple linear regression method is used for parameter identification, Thevenin model is taken as an example to illustrate the parameter identification process of the battery model, and its model structure is shown in Figure 1.

![Figure 1. The topology of the Thevenin model.](image)

In the Figure 1, $U_{OC}$ represents the open circuit voltage of the model, $R_O$ represents the internal resistance, $R_P$ represents the polarization resistance, $C_P$ represents polarization capacitance, $I_b$ represents the working current of a battery, $U_b$ represents terminal voltage, it is stipulated that the load current sign is positive when the battery is discharged and negative when the battery is charged. The output equation of the battery can be obtained.

$$U_b = U_{OC} - R_O I_b - R_P I_P$$

Finally, multiple linear regression analysis is performed. The error sum of squares is minimized according to the requirements, then the parameters $R_O$ and $R_P$ in Thevenin model can be obtained.

4. The implementation strategy of the equivalent circuit model established

The battery model uses the algorithm to control the controlled voltage source to realize the change of battery terminal voltage, and load changes are simulated with a controlled current source. BMS can calculate SOC and SOH by collecting terminal voltage, load current and temperature of the battery. The simulation circuit structure is shown in Figure 2.

![Figure 2. The circuit diagram of simulation.](image)

According to the structure parameters of the battery model obtained above, given the initial relevant data of the battery, the battery under different working conditions can be simulated. Under the condition of knowing the working current and temperature, the changing process of the terminal voltage, charged state and healthy state of the battery can be obtained. Because of the aging of the battery and the temperature have a great influence on the remaining electric energy, so the simulation process should also reflect this change. As the battery temperature and life change, the SOC should be modified in time to ensure that the current SOC value can reflect the real state of the battery under the current working condition.
5. The simulation analysis

5.1. Verification of parameter identification by multiple linear regression method

First, the equivalent circuit model is used to improve HPPC experiment and obtain the transient data of the battery. The selection of operating conditions is shown in Table 1.

| Equivalent cycle number | The temperature | SOC | Current |
|--------------------------|----------------|-----|---------|
| 200 times                | 20°C           | 0.5 | 20A     |

Battery parameters used in this test are shown in Table 2.

| Discharge @23°C | Max.Cont current 60A | Peak @60sec 100A | Cut-off voltage 2.50V |
|-----------------|----------------------|-----------------|---------------------|
| Charge @23°C    | Max.Cont current 20A |                  | Cut-off voltage 3.85V |

First, discharge the battery at 20A for 10s under this condition, then let it rest for 20s, then charge it at 20A for 10s, then let it rest for 20s. The load current can be realized by controlled current source. The value of terminal voltage and load current were collected with the sampling period $T_s=0.01s$. The structural parameters of the battery model were identified by multiple linear regression method. According to this data, the structural parameters of the battery charged and discharged at 20A can be identified respectively. According to the identification results, the change of the battery terminal voltage obtained by simulation and the comparison with the experimental data are shown in the Figure 3.

The results show that the error of terminal voltage is less than 3%, which proves that the structural parameters of the battery model obtained by multiple linear regression identification method are accurate and reliable.
5.2. Co-simulation verification of battery model and BMS

Using the battery model, verifying the BMS SOC estimation method can accurately estimate the SOC of the battery, and the battery model and BMS parameters are initialized separately as shown in Table 3.

|                | SOC initial value | Equivalent cycle number | Equivalent cycle number used | W(Wh) |
|----------------|-------------------|-------------------------|-------------------------------|-------|
| Battery model  | 0.5               | 2000                    | 200                           | 96    |
| BMS            | 0.7               | 2000                    | 200                           | 96    |

Working condition setting and simulation results are shown in Figure 4.

It can be seen from the results that the discharging condition of the battery is 200 s with a current of \( I=20A \) at \( T=20^\circ C \). Then change the temperature to 0°C, keep the current unchanged and continue to discharge to 400s. Then change the temperature to 10°C. The battery is at no load when \( t=600s \). When \( t=700s \), charging the battery to 850s with 20A current.

It can be seen from the estimation result of the SOC by the battery management system and the actual SOC comparison of the battery model. When \( t=200s \), the actual capacity of the battery increases due to the temperature rise of the battery, and the SOC of the battery increases. When \( t=400s \), the temperature drops again, so the value of SOC has a sudden drop. Although the initial SOC initial value of the BMS is different from the actual battery value, the battery is empty. After the BMS is in a static state, the BMS accurately corrects the SOC value and keeps it consistent with the battery model.

It can be seen from the curve of SOH that as the battery is discharged, the health of the battery is decreasing. Since the SOH of the battery is calculated according to the discharge of the battery, the health of the battery does not change when the battery is unloaded or charged.
6. Discussion
Proposed method in this paper is relatively complex. The data used in this paper hasn’t covered the whole test process, so the validity of results needs further verification.

7. Conclusions
In this paper, the equivalent circuit model of power battery is identified through experiments, and the equivalent circuit model based on multi-dimensional table lookup method is established. The parameters of the battery model were obtained by multi-dimensional table lookup method according to the operating parameters. Relevant simulation examples are designed to get the following conclusions.

(1) The identification results of model parameters by multiple linear regression method are accurate and reliable.

(2) The multi-dimensional table lookup method can be used to simulate the battery model accurately.

(3) The model can fully consider the influence of temperature, charge and discharge current, SOC and cycle life on the model parameters. Considering the influence of temperature and cycle life on battery capacity, the SOC was modified and estimated.

(4) Combined with the battery management system, the state of the battery is divided into running state and static state. The accurate estimation of SOC can be realized by calculating and modifying the SOC of the battery in different states with different methods.

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References
[1] Ji yingxu, Wang mingwang, Sun wei, et al. 2016 Power technology 40(03) 740-742
[2] Johns on V H 2002 Journal of Power Sources 110(8) 321-329
[3] Salameh ZM, CasaccaM A and LynchW A 1992 IEEE Transactions on Energy Conversions 7(1) 93-97
[4] United States Idaho National Engineering&Environmental Laboratory 2001 PNGV Battery TestManual Revision 3 http://avt.inl.gov/energy_storage_lib.shtml
[5] Lin Chengtao, Qiu bin and Chen quanshi 2006 Automotive engineering 28(3) 229–234
[6] O Erdinc, B Vural and M Uzunoglu 2009 Clean Electrical Power Page 383-386
[7] Lin Chengtao, Qiu bin and Chen quanshi 2006 Automotive engineering 28(1) 38-42+47
[8] Zhang bin, Guo liantui, Li hongyi, et al. 2009 Power technology 33(5) 417-421
[9] Suleiman Abu-Sharkh and Dennis Doerffel 2004 Journal of Power Sources (130) 266-274
[10] Ji yingxu, Du haijiang and Sun hang 2014 Electric measurement and instrument 51(4) 18-22
[11] Ma Liping and Xia Baojia 2003 Power technology 27(5) 245-249
[12] Xu Jianing, Yan Lei, Xu Bingliang, et al. 2017 Electrical Measurement & Instrumentation 54(2) 1-6
[13] Yan Xin, Zhang Xiaohu, Chen Yongzhen, et al. 2018 New Technology of Electrical Engineering and Energy 37(9) 24-32
[14] Yang Jie, Wang Ting, Du Chunyu, et al. 2019 Review of lithium ion battery model research Energy Storage Science and Technology DOI: 10.12028/j.issn.2095-4239.2018.0143
[15] Li Xiaopeng, Yuan Xueqing, Li Bo, et al. 2019 Electrical Measurement & Instrumentation 56(3) 35-41