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Research Article

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Modeling and simulation of second-order EKF-based SOC estimation for lithium-ion batteries

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Abstract: The state-of-charge (SOC) estimation of batteries is crucial in applications such as electric vehicles and energy storage systems, and the key to achieving this goal lies in the establishment of an equivalent circuit model that can accurately reflect the dynamic behavior of batteries. In view of the characteristics of lithium iron phosphate batteries, this paper will discuss in depth how to build a reasonable equivalent circuit model. Lithium iron phosphate batteries have been widely used in various energy management systems due to their high safety, long life and stable electrochemical performance. However, due to its complex electrochemical processes and nonlinear characteristics, it is challenging to build a model that can accurately reflect its performance. An accurate battery model can not only effectively simulate the dynamic behavior of the battery under actual operating conditions, but also provide a more reliable basis for the SOC estimation algorithm, thus significantly improving the estimation accuracy. This is of great significance for optimizing the battery management system, extending the service life of the battery, and improving the overall system performance.

Keywords: electric vehicle power battery pack, second order EKF, SOC estimation, battery modeling

0. Preface

Today, the demand for clean energy is growing stronger and stronger in all countries. The demand for clean energy is becoming stronger and stronger in all countries, China also strongly supports new energy industries industry, such as electric vehicles [1]. We also strongly support new energy industries, such as electric vehicles, in terms of policy and funding. Moreover, electric energy can be stored and transmitted, which is an ideal clean energy [2]. Therefore, in order to reduce carbon emissions and environmental pollution. Therefore, in order to reduce carbon emission and environmental pollution, it is imperative to implement electric vehicles. Electric vehicles are indispensable, and electric vehicles [3]. Batteries are indispensable. Batteries are inseparable from Charging and discharging process is indispensable, Therefore, it is of great importance to model the battery with relative accuracy [4-7].

1. Equivalent Circuit Models Commonly Used for Batteries

The equivalent circuit model of a battery is used to simulate the operating state of a battery by connecting different circuit components in series and parallel to simulate the external characteristics of the actual battery operation. The equivalent circuit model is applicable to many types of batteries and the parameter model is easy to recognize [8].

1.1. Rint equivalent circuit model

The Rint equivalent circuit model is the most basic circuit model, which connects an ideal voltage source in series with a resistor as shown in Figure 1.1. This model has a simple structure but cannot reflect the changes inside the battery under operating conditions, so it is not suitable for modeling batteries [9].

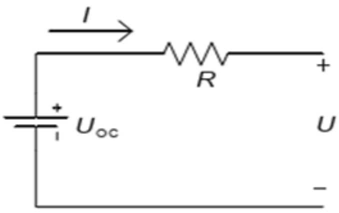


Figure 1.1: Rint equivalent circuit model structure

1.2. Thevenin model

The main structure of the first-order Thevenin model is to add an RC loop structure diagram as shown in Fig. 1.2 on the basis of the Rint model, which can reflect the dynamic response of the battery. However, a single RC loop is not enough to fully reflect the dynamic performance of the battery, and the equivalent circuit model still does not take into account the hysteresis voltage phenomenon of the battery[10].

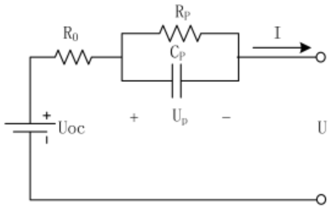


Figure 1.2: First order Thevenin equivalent circuit model structure

1.3. PNGV model

The PNGV model is based on the first-order Thevenin model with the addition of capacitance to describe the change in open-circuit voltage due to the change in load current over time, the model has a high degree of accuracy and dynamic performance but still does not take into account the hysteresis voltage of the battery. The structure is shown in Figure 1.3[11].

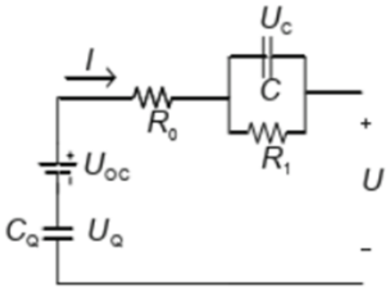


Figure 1.3 *PNGV equivalent circuit model structure*

1.4. Circuit model with hysteresis characteristics

The circuit model with hysteresis voltage takes into account the hysteresis characteristics of the battery on the basis of the resistive-capacitive equivalent circuit, and its circuit structure is shown in Fig. 1.4. Vh is the hysteresis voltage of the battery, C0 is the capacitance that reacts to the change of the open-circuit voltage with the cumulative capacity of the battery Uoc is the open-circuit voltage, R0 is the Ohm's internal resistance, Rf is the polarization internal resistance, Cd is the double-dielectric-layer equivalent capacitance, and ZW is the Weber's impedance [12].

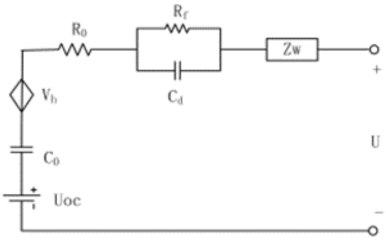


Figure 1.4: Circuit structure with hysteresis circuit modeling

2. Battery Equivalent Modeling

The link between the remaining power SOC of the battery and the battery itself is taken into account in the modeling process to facilitate the simulation and analysis of the circuit. The overall circuit structure of the battery model is shown in Figure 2.1. It consists of SOC calculation model, equivalent voltage source model and equivalent impedance model, respectively. The SOC calculation adopts the ampere-time integration method, the hysteresis voltage of the battery is added in the equivalent voltage source model, and the second-order RC equivalent impedance model is adopted in the equivalent impedance model.

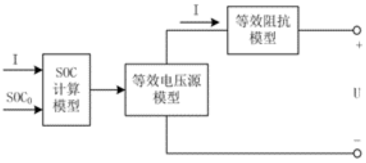


Figure 2.1: Overall circuit structure of the battery model

2.1. SOC calculation model

The SOC calculation model is shown in Fig. 2.2, where Cn represents the rated capacity of the battery; the current control current source in the figure represents the value of the current flowing through the capacity of the battery as the value of the current flowing through the battery, all of which is the current I, with I<0 for charging and I>0 for discharging; and the SOC represents the battery's residual charge, and therefore the value of the SOC is in the range of 0-1.

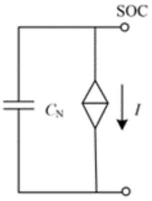


Figure 2.1: SOC calculation model

Knowing the initial charge SOC0 of the battery, the remaining charge SOC of the battery can be obtained according to the ampere-time method Calculated as follows

$$SOC(t) = SOC_0 \cdot \frac{\int I(t) \cdot dt}{C_n}$$

2.2. Equivalent voltage source model

The equivalent voltage source model of the battery is shown in Fig. 2.2, EMF is the equilibrium potential of the battery, EMF is controlled by the SOC of the battery and is a function of the remaining battery charge SOC; Vh is the hysteresis voltage of the battery, which is also a function of the SOC and is affected by the historical current of the battery, therefore, an inductor Lh is added to this equivalent circuit model to represent the hysteresis voltage affected by the historical current.

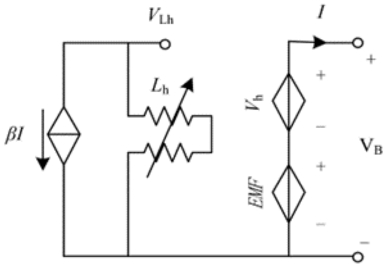


Figure 2.2: Equivalent voltage model

2.3. Equivalent impedance modeling

Theoretically, the higher the order of the RC network, the more the description of the external characteristics of the battery is in line with the actual operating conditions of the external characteristics of the battery is in line with the actual operating conditions of the battery, but, at the same time, the more complex the parameter identification is, which is not suitable for the SOC algorithm estimation of the battery, so it is crucial to reasonably choose the order of the RC network. In this paper, the order of the equivalent RC network is determined by utilizing RC networks of different orders to fit the steady state changes of the battery.

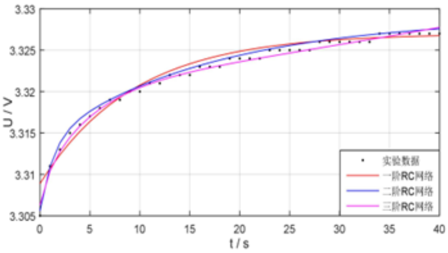
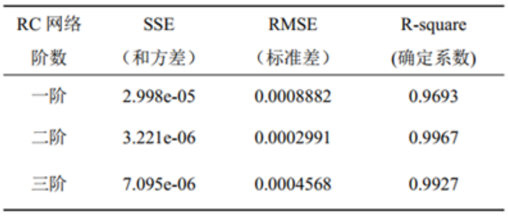


Figure 2.3: Fitted voltage curves for RC networks of different orders

Fig. 2.3 represents the voltage variation curves of the battery at rest fitted by RC networks of different orders, and the Goodness of fit results of the fitted curves are shown in Table 2.1. The goodness of fit of the curve is mainly reflected by three indicators: SSE (sum variance), RMSE (standard deviation) and R-square (coefficient of determination), in which the coefficient of determination is used to characterize the advantages and disadvantages of the curve-fitting effect, and generally takes a value in the range of 0~1, with a value closer to 1 indicating that the data fitting results are better. And the variance represents the good or bad effect of data prediction, the more SSE tends to 0, indicating that the data prediction results are better.

Table 2.1: Comparison of goodness-of-fit results for RC networks of different orders



RC 网络 阶数	SSE （和方差）	RMSE （标准差）	R-square (确定系数)
一阶	2.998e-05	0.0008882	0.9693
二阶	3.221e-06	0.0002991	0.9967
三阶	7.095e-06	0.0004568	0.9927

Combined with the comparison of the fitting goodness results in Fig. 2.3 and Table 2.1, it can be seen that the fitting errors of the second-order RC network and the third-order RC network are not much different, and the first-order fitting results are worse compared to the second-order and the third-order ones. Since the second-order RC network is simpler and more convenient than the third-order model for parameter identification and algorithm estimation in the later stage, and it can better describe the external characteristics of the battery compared with the first-order model, the equivalent impedance model of the second-order, RC network is established as shown in Fig. 2.4.

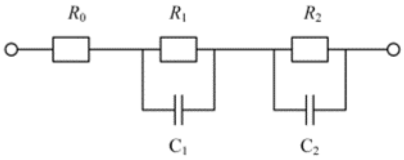


Figure 2.4: Equivalent impedance model

2.4. Equivalent circuit model of a battery

The circuit model of the first three sections is combined to obtain the final equivalent circuit model as shown in Fig. 2.5, which not only describes the relationship between the hysteresis voltage Vh and open-circuit voltage EMF of the battery and the SOC of the battery, but also allows the SOC of the battery to be estimated directly by means of the integration of the ampere-time.

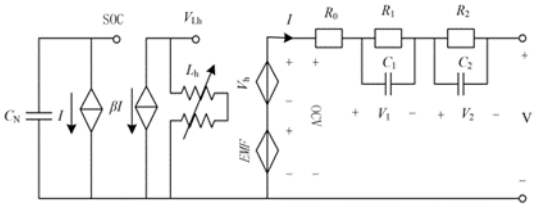


Figure 2.5 *Equivalent circuit model of a battery*

Since the circuit components in the battery model are all commonly used simple components of the circuit, it is simple to implement in MATLAB/simulink. Through Kirchhoff's law, the mathematical equations are established for the battery model, and it is convenient to simulate and analyze the battery model with experimental validation according to the mathematical equations. According to the KCL law of the circuit, the mathematical relationship equation about the current is obtained as follows:

$$\begin{cases} I = \dfrac{V_2}{R_2} + C_2 \dfrac{dV_2}{dt} \\ I = \dfrac{V_2}{R_2} + C_2 \dfrac{dV_2}{dt} \end{cases}$$

The mathematical expression about the voltage is obtained from the KVL of the circuit as shown in equation 2.3 (2.3)

The current expression in Eq. (2.2) is transformed to produce a mathematical expression suitable for circuit simulation, which can be easily implemented in the simulation model using addition, subtraction and integration operations:

$$\begin{cases} V_1 = \int \dfrac{I - \dfrac{1}{R_1}}{C_1} dt \\ V_2 = \int \dfrac{V_2}{C_2} dt \end{cases}$$

3. Battery Equivalent Modeling

3.1. Model Simulation

In order to verify the correctness of the established model and the results of the identified parameters, it is necessary to compare and analyze the measured voltage values with the simulated voltage values. According to the circuit analysis in Chapter 2, the simulation model of the battery is built in the software as shown in Figure 3.1.

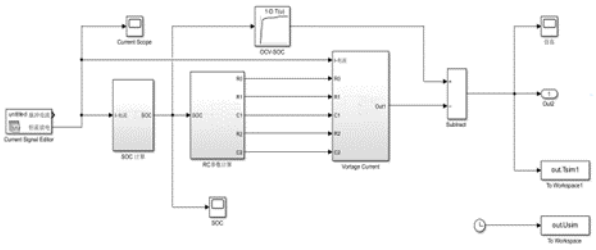


Figure 3.1: Simulation model of the battery

The simulation model of the battery consists of four main parts:

(1) The current signal module is mainly used to generate the actual current signal for simulation, and the constant current signal and pulse signal are mainly used for verification in this paper.

(2) The residual power calculation module is mainly used to obtain the SOC value by the ampere-time method, and the simulation model is shown in Figure 3.2.

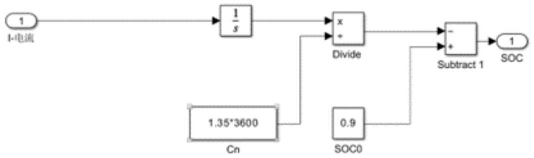


Figure 3.2: SOC calculation module

(3) The RC parameter calculation module mainly finds the RC parameter values corresponding to each SOC by using the lookup module in the toolbox, and the simulation model is shown in Figure 3.3.

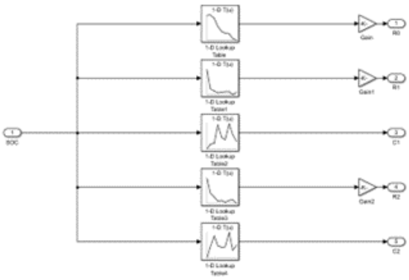


Figure 3.3: RC calculation module

(4) The voltage calculation module is mainly used to obtain the relationship between the battery terminal voltage and the RC network voltage through equations (2.2) and (2.4).

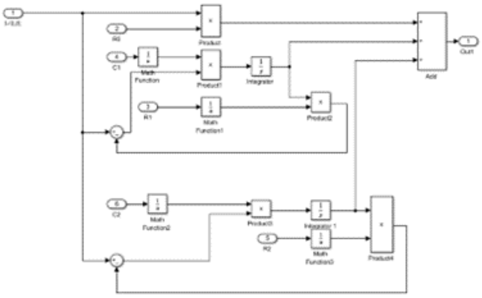


Figure 3.4: End Voltage Calculation Module

3.2. Simulation verification analysis

(1) Constant current discharge verification analysis Constant current discharge is mainly verified by using 1C discharge multiplier, and the simulation result curve under this condition is shown in Fig. 3.5 as the simulation curve of measured voltage and simulation voltage.

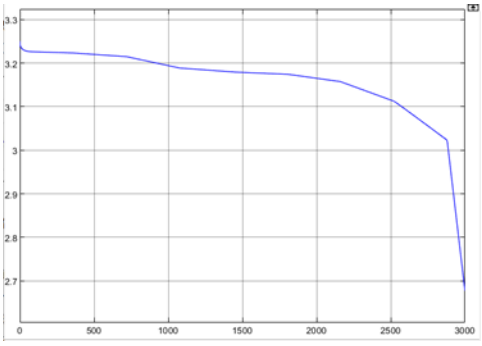


Figure 3.5: Constant current discharge voltage simulation curve

(2) Pulse discharge verification analysis

Pulse discharge verification is mainly to intercept the experimental data in a cycle for verification, set the initial SOC = 0.9, the current signal module set the current as 1.35A pulse current, through the discharge of 10s, static 40s for the model simulation and verification, to obtain the simulation results of the pulse discharge of the map shown in Figure 3.6.

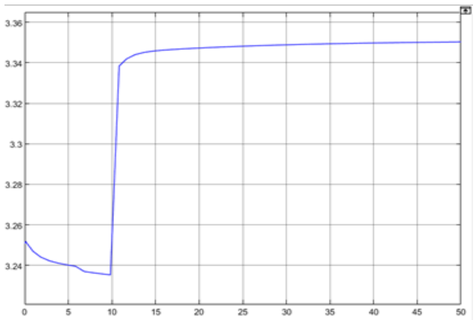


Figure 3.6: Pulsed Discharge Voltage Simulation Curve

During the pulse discharge process, the battery model voltage error fluctuates within the range of 0.015V, and gradually increases with the discharge time; at the moment of the end of the pulse discharge, the dynamic response characteristics of the battery lead to the instantaneous model error reaches 0.02V; in the process of the pulse discharge static process, due to the battery's rebound voltage characteristics, the simulated value of the model gradually converges to the actual voltage value, and the error finally converges to about 0V.During the resting process of pulse discharge, the rebound voltage characteristic of the battery makes the simulated value of the model gradually converge to the actual voltage value, and the error finally converges to about 0V

4. Summary

In this paper, we compare and analyze the advantages and disadvantages of the commonly used equivalent circuit models, on the one hand, we consider the hysteresis voltage phenomenon of the battery, on the other hand, we fit the rebound voltage characteristic of the battery by different orders of RC circuit, and we establish the second-order RC circuit model with hysteresis voltage characteristic after considering the simplicity of the model and the approximation degree of the battery characteristics, which can accurately simulate the dynamic and static operating characteristics of the battery.

References

[1]. Sulzer V, Mohtat P, Aitio A, et al. The challenge and opportunity of battery lifetime prediction from field data[J]. Joule, 2021, 5(8): 1934-1955.

[2]. Zhang Y, Zhao M. Cloud-based in-situ battery life prediction and classification using machine learning[J]. Energy Storage Materials, 2023, 57: 346-359.

[3]. Geslin A, Van Vlijmen B, Cui X, et al. Selecting the appropriate features in battery lifetime predictions[J]. Joule, 2023, 7(9): 1956-1965.

[4]. 蒋杭廷,张倩倩,张松通,等.化学电源内阻测量及状态监测策略分析研究[J/OL].储能科学与技术,1-23[2024-07-29].https://doi.org/10.19799/j.cnki.2095-4239.2024.0282

[5]. 王志福,杨忠义,罗崴,等.基于数据驱动的锂离子动力电池剩余使用寿命预测方法综述[J].科学技术与工程,2023,23(15):6279-6289.

[6]. Dang W, Liao S, Yang B, et al. An encoder-decoder fusion battery life prediction method based on Gaussian process regression and improvement[J]. Journal of Energy Storage, 2023, 59: 106469.

[7]. 周继香,闫泽远,李淼林.基于进化算法与数据驱动的锂离子电池寿命预测[J].电源技术,2024,48(04):679-684.

[8]. 金晶,王京,周奕辰,等.电力数据驱动的电池剩余寿命预测研究[J/OL].工程设计学报,1-8[2024-07-29].http://kns.cnki.net/kcms/detail/33.1288.TH.20240408.0850.002.html.

[9]. 李炳金,韩晓霞,张文杰,等.锂离子电池剩余使用寿命预测方法综述[J].储能科学与技术,2024,13(04):1266-1276.DOI:10.19799/j.cnki.2095-4239.2024.0098.

[10]. Wang X, Ye P, Liu S, et al. Research Progress of Battery Life Prediction Methods Based on Physical Model[J]. Energies, 2023, 16(9): 3858.

[11]. Shao J, Li J, Yuan W, et al. A novel method of discharge capacity prediction based on simplified electrochemical model-aging mechanism for lithium-ion batteries[J]. Journal of Energy Storage, 2023, 61:106788.

[12]. Sadabadi K K, Jin X, Rizzoni G. Prediction of remaining useful life for a composite electrode lithium ion battery cell using an electrochemical model to estimate the state of health[J]. Journal of Power Sources, 2021, 481: 228861.