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Research Article

An Equivalent Circuit Model for Lithium Battery of Electric Vehicle considering Self-Healing Characteristic

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Considering the self-healing phenomenon of lithium batteries during intermittent discharge, a self-healing characteristic-based equivalent circuit model of lithium batteries is proposed. The mathematical description of the lithium battery in the self-healing process is obtained through the analysis of the equivalent circuit model. Based on experimental platform, an experiment considering self-healing characteristic was performed. Result shows that the self-healing characteristic-based lithium battery equivalent circuit model can describe the voltage of the lithium battery accurately during the self-healing process.

1. Introduction

Energy is the foundation of the society progress and development and it is vital to develop a new energy storage that is efficient and environmentally friendly and more necessarily put it to effect [1]. Electric vehicles have received extensive attention due to their features such as cleanliness and high efficiency [2, 3]. The lithium-ion battery is one of the best choices for electric vehicle battery because of its small volume, light weight, and low self-discharge rate [4]. However, power batteries have become an important factor that influences the performance and stability of electric vehicles [5].Therefore, the research on the safety and reliability of lithium-ion batteries has become the focus of attention [6–8]. Huang et al. [9] proposed a new method to estimate the state of charge (SOC) and state of health (SOH) of a battery by using the amount of voltage change per unit time during the discharge process of battery. Based on the battery cycle-life test data, it is found that the state of health has a linear relationship with the reciprocal of the unit time voltage drop, which is a function of the state of charge. This method realizes the online estimation of SOC and SOH and the model is proved to have robustness. Zou et al. [10] proposed a combined SOC and SOH estimation method through the lifetime of a lithium-ion battery. Two Extended Kalman Filters of two time scales are used to estimate SOC in real time and update SOH offline, which provides accurate SOC and SOH estimations. Xiong et al. [11] used adaptive extended Kalman filter (AEKF) to estimate the state of charge of lithium batteries. The AEKF algorithm improves the traditional KF and solves the defect of inaccuracy on nonlinear problems. Besides, the AEKF algorithm can improve the prediction accuracy by adaptively updating the process and measurement noise covariance. However, the above researches focus on the ideal working condition and do not take the intermittent discharge of the lithium battery in the actual operation into account. In fact, self-healing phenomenon could be found during the intermittent discharge of lithium batteries [12]. In other words, the capacity of the battery will rebound when standing. There is no doubt that the self-healing phenomenon could be a benefit to prolong the useful life of lithium batteries [6]. Therefore, further research is needed under this condition.

Currently, the models of batteries can be divided into two categories: electrochemical models and equivalent circuit models [13]. Based on the electrochemical theory,

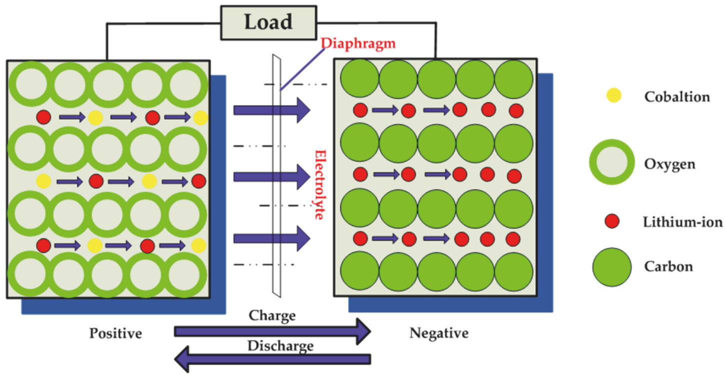

Figure 1: Lithium battery charge and discharge microscopic diagram.

the electrochemical model uses mathematical methods to describe the reaction process inside the battery. By using this model, the relationship between the cell performance and microscopic quantities can be established. However, this method is computationally complex and difficult to determine the value of parameters [14, 15]. The equivalent circuit model based on the external characteristics of the battery can avoid analyzing the internal reactions and complex parameter calculations. Comprehensively considering the accuracy and practicality of the battery model, equivalent circuit model is widely used in battery performance estimation of battery management systems [16, 17]. He et al. [18] proposed a model-based online estimation method for $LiFePO_4$ battery, which uses the Thevenin equivalent circuit model to simulate the $LiFePO_4$ battery and gives the corresponding mathematical expression equation. Feng et al. [19] proposed a new lithium battery equivalent circuit model by adding a moving average noise to the first-order resistor-capacitor circuit model. This new model simplifies the computational complexity of model parameters in a much more accurate way. Sun et al. [20] proposed a model-based dynamic multiparameter method for peak power estimation of lithium-ion batteries. This method refines the ohmic resistance of the Thevenin model for the lithium-ion battery, which improves the accuracy of the model. It is indicated that the model-based dynamic multiparameter method can be used to calculate the available power more accurately, whereas the above models cannot describe the change in self-healing phenomenon of lithium batteries. Therefore, in order to better describe the state of lithium battery in self-healing process, an equivalent circuit model of lithium battery is proposed based on self-healing characteristics.

The remainder of the paper is organized as follows. Section 2 introduces the self-healing phenomenon, which is very common in the actual use of electric vehicles. In Section 3, the equivalent circuit model based on self-healing characteristic is proposed and the analysis of the model is given. Section 4 describes the experiment platform and the experiment schedule based on LabView. In Section 5, the parameters of the model are identified and the simulation results are compared with the experiment. In addition, the error between the simulation and experiment is analyzed. In the final section, some conclusions are given.

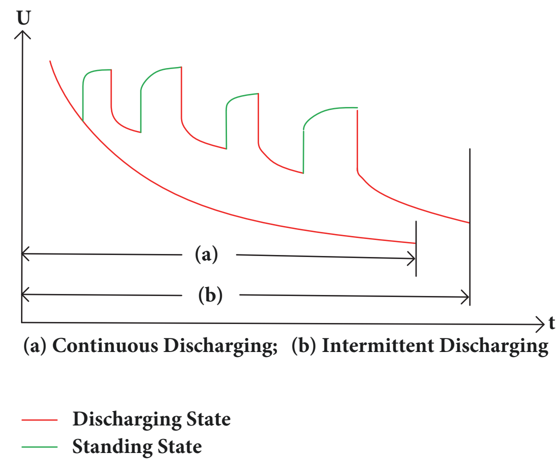

Figure 2: Comparison of lithium battery continuous discharge and intermittent discharge.

2. Self-Healing Process

In practice, three states are often used in the lithium battery. They are charging state, discharging state and standing state. As is shown in Figure 1, when the battery is charged, the positive electrode of the battery will generate lithium ions and at the same time lithium ions will pass through the electrolyte. Finally the lithium ions, generated at the positive electrode of the battery, arrive at the negative cathode of the battery and combine with graphite. And the capacity of the battery is related to the amount of lithium ions arriving at the cathode of the battery. When the battery is discharged, lithium ions in the negative electrode of the battery are separated from the graphite and returned to the positive electrode of the battery. The capacity of the battery is decreased.

In actual use, after each charge is completed, the lithium battery is repeatedly switched between discharging state and standing state, that is, intermittent discharging, as shown in Figure 2. When standing, the battery will self-heal. This

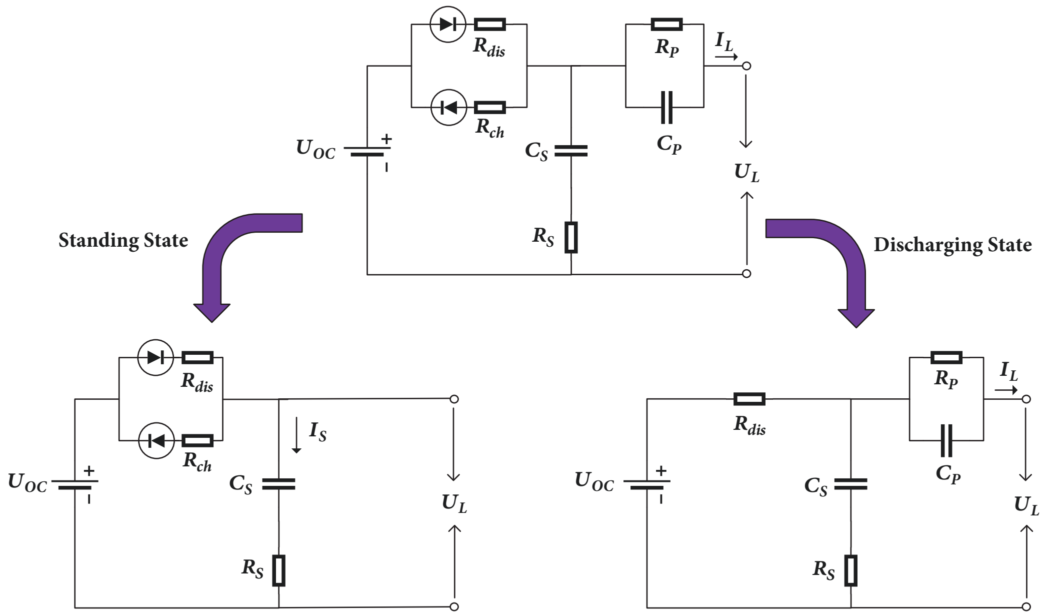

Figure 3: Lithium battery equivalent circuit model circuit diagram.

phenomenon is the reverse process of battery discharge, which is similar to the charging process of the battery, and the battery's state of charge will increase [21]. And, in the long term, this phenomenon will finally influence the state of health of lithium battery [22]. Mostly the electric vehicle is in a running and stagnant state, and the lithium battery is in a discharging and standing state so self-healing phenomenon is very common. The strength of self-healing is related to the time the battery is in standing state and it will change as the battery cycle times increase. Besides, the self-healing phenomenon will affect the remaining useful life of the battery. Therefore, it is essential to establish a battery model which could be used to describe the self-healing phenomenon of lithium-ion batteries. This paper will introduce a lithium battery equivalent circuit model based on self-healing characteristic.

3. Battery Model

3.1. Proposal of the Model. In order to better describe the voltage change of the lithium battery in the standing state, a lithium battery equivalent model based on self-healing characteristics is proposed. As shown in Figure 3, the self-healing characteristic-based model includes the open-circuit voltage U_{OC}, the internal resistance R_i of the battery, a capacitor C_S, a resistor R_S, and a RC network. The internal resistance R_i, respectively, includes a resistor R_{dis} in discharging state and a resistor R_{ch} in charging state. And I_S is the current pass through the capacitance C_S, I_L is the load current (positive for discharging state and negative for charging state), and U_L is the terminal voltage. Among them, the open-circuit voltage U_{OC} describes the voltage characteristics of the battery, and the capacitance C_S describes the capacity characteristics of the battery. The model can be divided into two parts. One part is mainly to describe the voltage of the lithium battery in discharging state and the other part is mainly to describe the voltage of self-healing phenomenon of the lithium battery in standing state.

3.2. Description of the Model. When the battery reaches a stable state, the battery voltage no longer changes. At this time, the terminal voltage is equal to the open-circuit voltage U_{OC} of the battery, which is also equal to the voltage of the capacitor C_S, as shown in

$$U_L = U_{OC} = U_{Cs} \tag{1}$$

3.2.1. Description of the Model in Discharging State. The Hybrid Pulse Power Characteristic test is conducted to describe the discharging state of the lithium battery equivalent circuit model. When the battery passes the pulse current, the voltage of the battery undergoes two stages, faster voltage conversion and slower voltage conversion. Figure 4 shows the battery voltage changes when the HPPC test is carried out.

In the faster voltage conversion, the rapid drop in voltage is mainly affected by the internal resistance R_i of the battery. The value of internal resistance R_i is related to the change in voltage, as show in (2). The slower voltage conversion in voltage is assigned to the part of the RC network including diffusion resistance R_P. And (3) describe the voltage change of the slower conversion.

$$\Delta U_{L1} = U_{OC} - U_{L-F} = U_{OC} * \frac{R_i}{R_L//R_S + R_i} \tag{2}$$

$$\begin{aligned} \Delta U_{L2} &= U_{L-F} - U_{L-S} \\ &= U_{OC} * \left(\frac{R_L//R_S}{R_L//R_S + R_i} - \frac{R_L}{R_L + R_P + R_i} \right) \end{aligned} \tag{3}$$

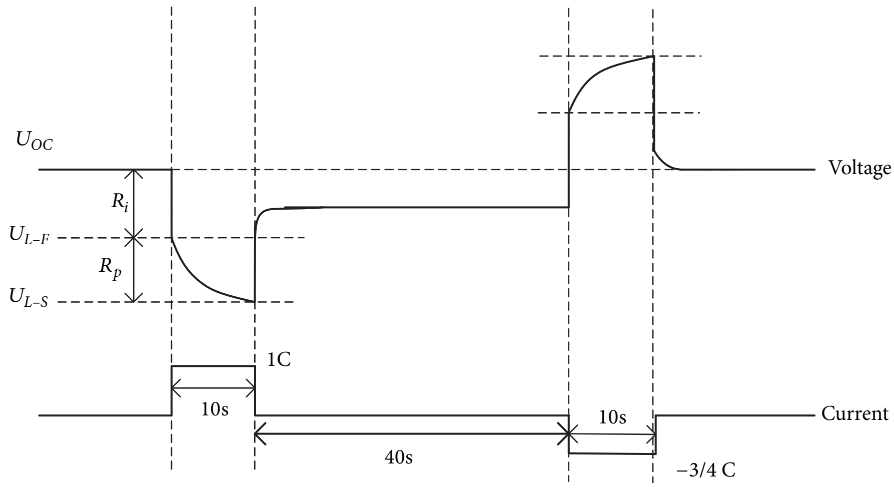

Figure 4: The lithium battery voltage and current changes in the HPPC test.

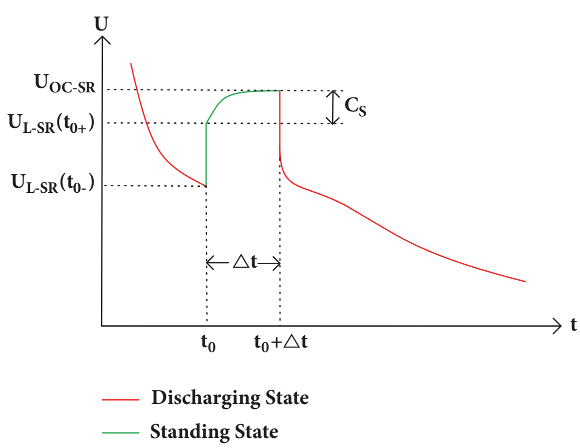

Figure 5: Self-healing test profile.

3.2.2. Description of the Model in Standing State. In order to describe the self-healing phenomenon of the battery, it is necessary to perform the self-healing test of the battery. And the self-healing test profile is shown in Figure 5. One self-healing test is performed within a single charge and discharge cycle of a lithium battery. When the charging process is completed, the lithium battery will start to discharge. At the point of t_0 when the voltage reaches the level of $U_{L\text{-}SR}$, the battery will be switched into the standing state. And the self-healing process with time interval Δt is performed. When the battery is in the standing state, no current flows through the RC network (resistance R_P and capacitance C_P), so the model can be simplified to the form in Figure 3.

At t_0(-), the lithium battery is still in the state of discharging, the voltage over the capacitor C_S can be expressed by (4); at t_0(+), the battery has been switched to the standing state, and the voltage of the capacitor C_S can be expressed by (5). Because the voltage of the capacitor cannot be abruptly changed, the voltage of capacitor C_S at time t_0(-) is equal to the voltage at time t_0(+), as shown in

$$U_{CS}\left(t_{0-}\right) = U_{L-SR}\left(t_{0-}\right) + I_L * R_P = U_{OC-SR} - U_{\mathrm{i}}\left(t_{0-}\right) \quad (4)$$

$$U_{Cs}\left(t_{0+}\right) = U_{L-SR}\left(t_{0+}\right) - U_{Rs}\left(t_{0+}\right) \quad (5)$$

$$U_{Cs}\left(t_0\right) = U_{Cs}\left(t_{0-}\right) = U_{Cs}\left(t_{0+}\right) \quad (6)$$

From (4), (5), and (6), how the voltage changes when the battery is switched from the discharging state to the standing one can be deduced.

$$\triangle U_{L-SR} = U_{Rs}\left(t_{0+}\right) + I_L * R_P \quad (7)$$

When the battery is still for an enough long period of time, the battery is in a stable state. It can be obtained by (1) that the voltage of the capacitor C_S will be equal to the open-circuit voltage of the battery $U_{OC\text{-}SR}$, while the voltage of capacitor C_S at t_0 is less than $U_{OC\text{-}SR}$. Comparing (4) and (8), it can be concluded that the lithium battery is charged by the ideal voltage source U_{OC} during the interval time Δt when the battery is in the standing state. Where the current flowing through capacitor C_S is marked as I_S, the time constant is τ and the quantity of the battery is Q_{CS}:

$$U_{Cs}\left(\Delta t \longrightarrow \infty\right) = U_{OC-SR} \quad (8)$$

$$I_S = C_S * \frac{dU_{Cs}}{dt} \quad (9)$$

$$\tau = C_S * \left(R_{\mathrm{i}} + R_S\right) \quad (10)$$

$$Q_{Cs} = U_{Cs} * C_S \quad (11)$$

When the lithium battery is switched from the discharging state to the standing state, the voltage of capacitor Cs satisfies

$$U_{Cs} = U_{OC-SR} - \left[U_{OC-SR} - \left(U_{L-SR}\left(t_{0-}\right) + I_L * R_P\right)\right] * \exp\left[-\frac{t/C_S}{\left(R_S + R_i\right)}\right] \quad (12)$$

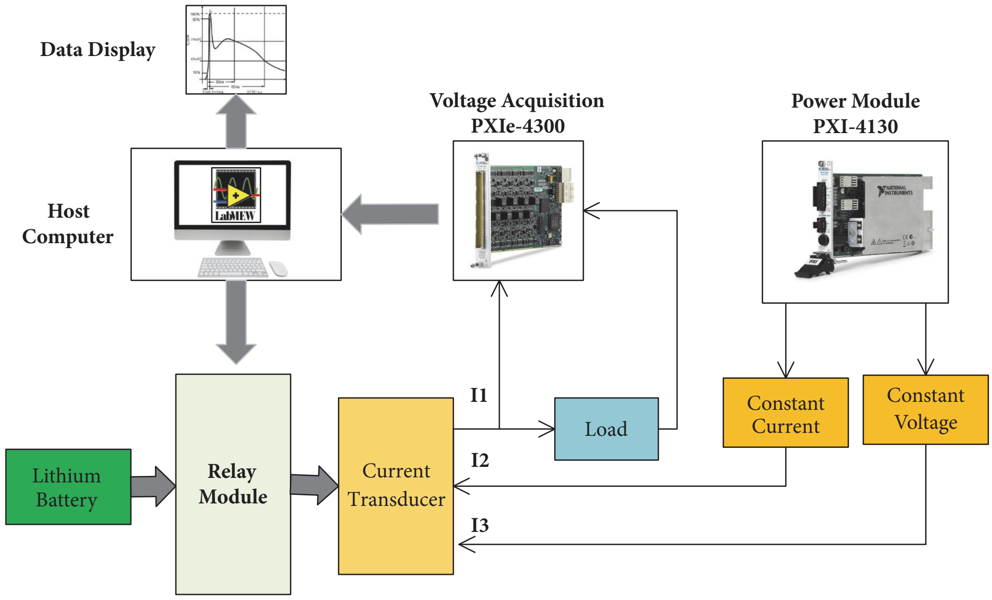

Figure 6: Lithium battery monitoring system based on *LabView*.

Meanwhile, the relationship between the terminal voltage U_{L-SR} and the voltage of capacitor U_{Cs} accords with (5). So from (5), (7), (9), and (12), the function of the terminal voltage U_{L-SR} can be derived as follows:

$$U_{L-SR} = U_{Cs} + \frac{R_S * C_S}{Cs * (R_i + R_S)} * [U_{OC-SR} - U_{L-SR}(t_{0-}) - I_L * R_P] * \exp\left(-\frac{t}{\tau}\right) \quad (13)$$

4. Experiments

4.1. Experiment Platform. In order to monitor the discharging state and the standing state of the battery, a lithium battery charge/discharge monitoring system based on *LabView2012* is established, as shown in Figure 6. The system uses *LabView 2012* as a software development platform, including upper computer, *NI* data acquisition cards, power supply modules, and relay modules. The system realizes the programming control of the discharge process of the lithium battery, simulates the transition from the discharging state to the standing state during the actual use of the lithium battery, and monitors the self-healing phenomenon of the lithium battery. The upper computer can accomplish the real-time monitoring of the lithium battery and is responsible for switching the state of the circuit. Voltage acquisition card *PXIe-4300* contains 8 analog input channels; each channel is equipped with an independent analog-to-digital converter of 16-bit resolution and can be simultaneously sampled to ensure the efficiency of data acquisition. The current sensor has a measurement range of 50 mA to 10A and is responsible for transmitting the current signal to a channel of the voltage acquisition card. The voltage, current, and other information of the battery are transmitted to the upper computer through the *PXI* bus, ensuring the accuracy and high efficiency of data transmission. *PXI-4130* is used to charge lithium batteries. It is a programmable power module that can control output constant voltage and constant current.

4.2. Experiment Schedule. In order to analyze the self-healing phenomenon during the intermittent discharge process, a set of experiments are carried out on the 18650 lithium battery and the experiment schedule is shown in Figure 7. For the purpose of obtaining the initial capacity of the lithium battery, the SCT test was performed and repeated three times. After that, the battery is discharged and the HPPC test is performed. At the same time, the test data is recorded. The key to the experiment schedule is to conduct self-healing characteristic test on the lithium battery. Among them, U^* represents the state transition voltage. When the voltage drops to U^* for the first time, the working state of the battery changes, switching from the discharging state to the standing state. The value of the state transition voltage represents the depth of discharge, which could affect the strength of the self-healing phenomenon. So, for an evident observation of the self-healing phenomenon, the state transition voltage is selected to be 3 V in this experiment. That is, when the battery voltage drops to 3 V for the first time, the battery enters the standing state and performs the self-healing test. The value of the SOC at this time can be obtained by the method of coulomb counting by the data logger of the experimental system. Experiments of three times scales are performed, respectively, 15minutes, 60 minutes, and 90 minutes. In other words, the period in the standing state is 15 min, 60 min, and 90 min. And each self-healing test is repeated three times.

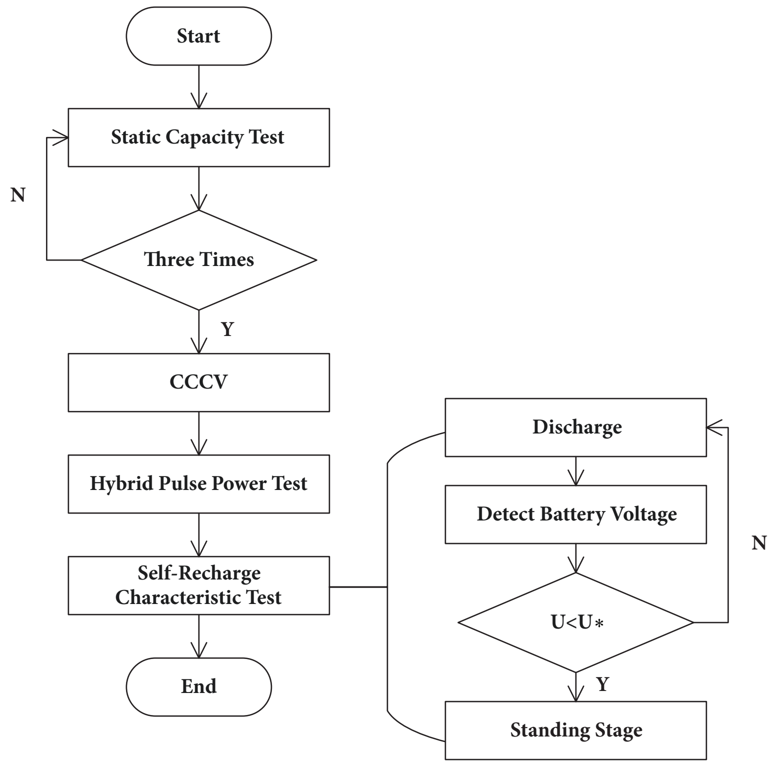

Figure 7: Experiment schedule.

Table 1: Parameter Identification Results at $U^* = 3$ V.

SOC	*Rdis*	*Rch*	*Rp*	*Cs*	*Rs*
12.23%	82.3 mΩ	81.7 mΩ	16.1 mΩ	400.851 F	0.506 Ω

5. Results and Discussion

In order to make clear the relationship between self-healing characteristics and self-healing time, this paper selects the first test data with self-healing time of 60 minutes to identify the model parameters and compares the simulated value of the battery model with measured value during the standing state. In the meantime, the parameters obtained from this experiment are applied to the other experiments with the same self-healing time and also to multiple sets of experiments with different self-healing times. The results are as follows.

5.1. Parameter Identification. Using the test data to identify the unknown parameters of the battery model is the basis for analysis and discussion of the results. MATLAB 2018 provides a variety of methods to achieve the fitting functions, one of which is Cftool. Cftool has a visual interactive interface and provides numbers of fitting functions, so this paper selects Cftool as the fitting tool. The parameter identification results are shown in Table 1.

5.2. Evaluation on the Battery Model. After the model parameters are obtained from the first experiment test data with self-healing time of 60 minutes, the simulated value of the model is compared with the measurements. Figures 8(a), 8(b), and 8(c) represent the results of the comparison between the simulations and the experiment measurements of three times, of which the self-healing time is 60 min. After the lithium battery is switched from the discharging state to the standing state, the model is able to describe the rising status of the lithium battery voltage. And when the standing time is long enough, the simulation value is still very close to the terminal voltage of the lithium battery. Repeat the experiment with a standing time of 60 min and compare the test data with the simulated values of the model. Result shows that the model can simulate the process of the other experiments with the same self-healing time, as shown in Figures 8(b) and 8(c).

Figure 9 shows the error characteristic curve between model simulation values and experiment measurements when the self-healing time is 60 min. When the battery starts to switch from the discharging state to the standing state, the battery voltage suddenly changes. In this short period, the model has a larger error. But, after a brief change in voltage, the model can better describe the status of the lithium battery. And as the battery voltage tends to be flat, the model error decreases and approaches the level of zero.

In order to prove that this model can describe the state of lithium batteries with different self-healing time, experiments with self-healing time of 15 min and 90 min are designed. And the parameters obtained from the experiment with a self-healing time of 60 min are applied to experiments with self-healing time of 15 min and 90 min. As is shown in Figures 10 and 11, the model can also describe the status of the battery.

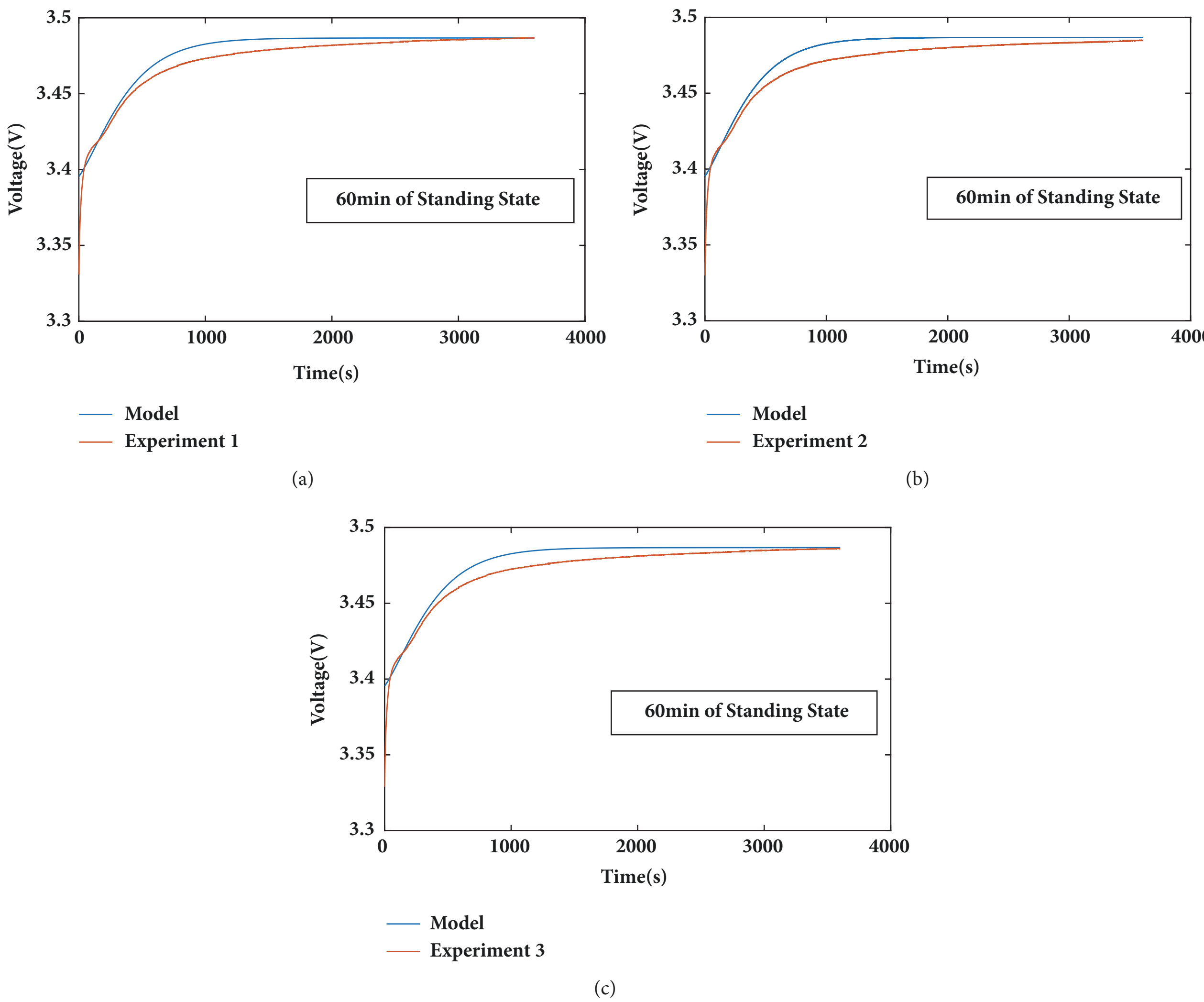

FIGURE 8: Comparison of model simulations and measurements at self-healing time of 60 minutes: (a) experiment 1, (b) experiment 2, and (c) experiment 3.

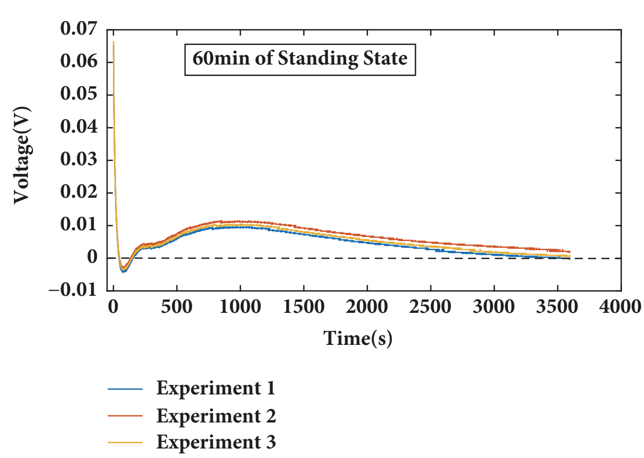

FIGURE 9: Comparison of the error between the model simulations and experiments measurements at self-healing time of 60 minutes.

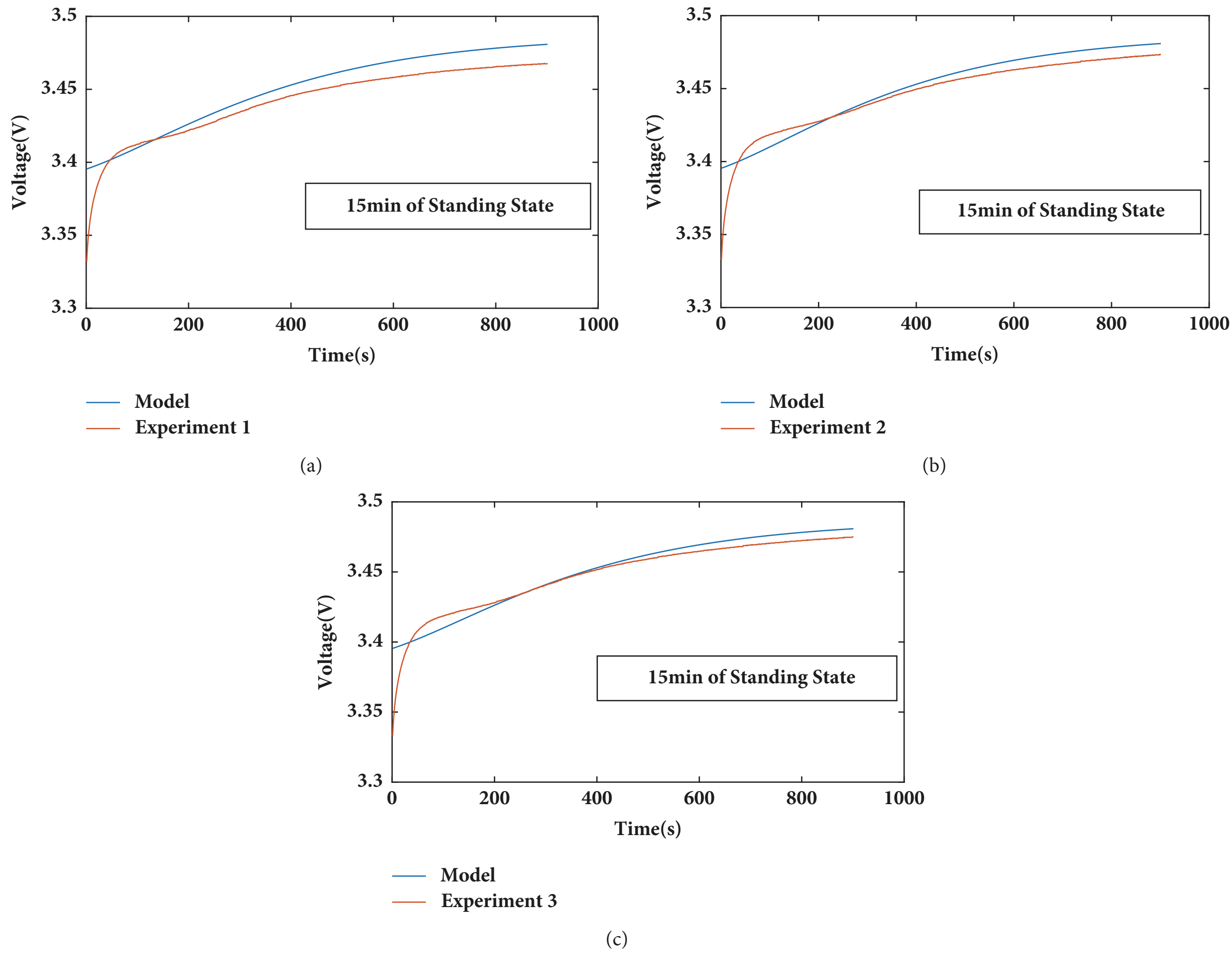

Figure 10: Comparison of model simulations and measurements at self-healing time of 15 minutes, (a) experiment 1, (b) experiment 2, and (c) experiment 3.

Figures 12 and 13 are the error curves between the model simulations and the experiment measurements when the self-healing time is 15 min and 90 min, respectively. In the state transition stage, there is a large error between the model and the measurement but the error between the model and the measurement gradually decreases along with time, and the error tends to be stable, which is similar to the result at self-healing time of 60 min.

5.3. Accuracy Analysis of the Battery Model. The accuracy of the lithium battery model will be analyzed by the maximum error (the maximum value of the voltage error), the mean error (the average value of the voltage error), and the RMSE (the root-mean-square error of the voltage). Three experiment test datasets for self-healing time of 15 min, 60 min, and 90 min are analyzed. The results are shown in Table 2.

In the three experiments with self-healing time of 60 minutes, the maximum error is less than 70 mV, the maximum error rate is also less than 2%, and the root-mean-square error is less than 8 mV. When using this model for accuracy analysis of test data with self-healing time of 15 min and 90 min, the maximum error does not exceed 70 mV. Except that the maximum error rate of the third group of experiments with self-healing time of 90 minutes is slightly more than 2%, the maximum error rate of the rest of the tests is less than 2%. And the root-mean-square error is less than 13 mV. Therefore, the model has high accuracy and efficiency.

6. Conclusion

This paper discusses the working state of lithium battery in actual cases, which aims at the self-healing phenomenon in the process of intermittent discharge and proposes an equivalent circuit model for self-healing phenomenon. The function of the model is obtained when the lithium battery is switched to the standing state from the discharging state. By using a LabView-based lithium battery test system, the self-healing characteristic-based experiment is designed, and the parameters of the model are identified through test data. Experiment results prove that the model can accurately describe the voltage change of the battery in the standing state with different self-healing time. The error between

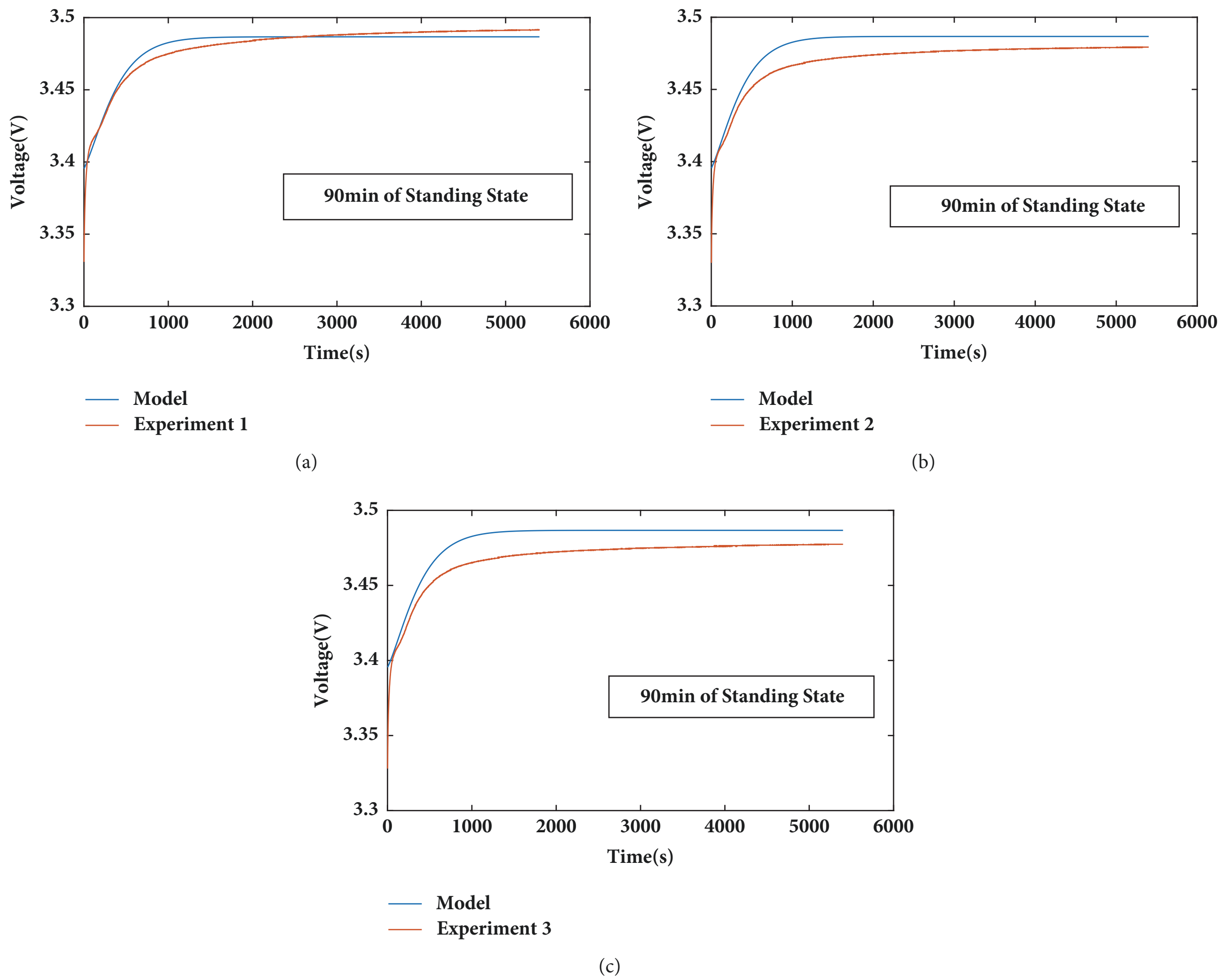

FIGURE 11: Comparison of model simulations and measurements at self-healing time of 90 minutes, (a) experiment 1, (b) experiment 2, and (c) experiment 3.

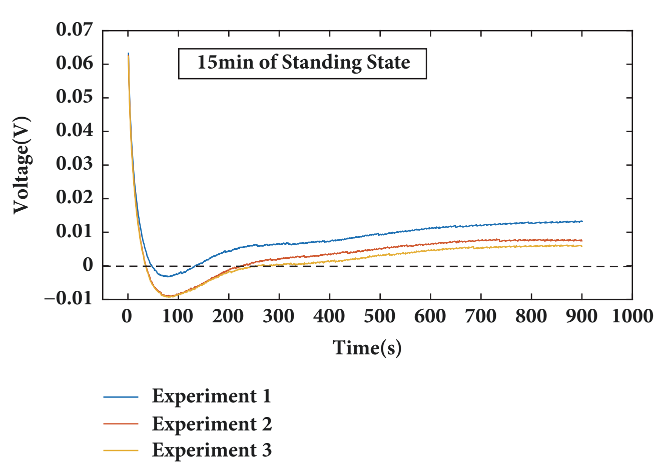

FIGURE 12: Comparison of the error between the model simulations and experiments measurements at self-healing time of 15 minutes.

Table 2: Model error analysis.

Time of Standing State	Number of Experiments	Maximum/V	Mean/V	RMSE/V	Max.Error Rate(%)
60 min	1	0.06464	0.004535	0.006093	1.94
	2	0.06556	0.006485	0.007588	1.97
	3	0.06655	0.005302	0.006689	1.99
15 min	1	0.06342	0.008516	0.010537	1.91
	2	0.06277	0.003718	0.007682	1.88
	3	0.06241	0.002196	0.006796	1.87
90 min	1	0.06466	0.000354	0.004623	1.94
	2	0.06555	0.010587	0.011145	1.97
	3	0.06746	0.012269	0.012731	2.03

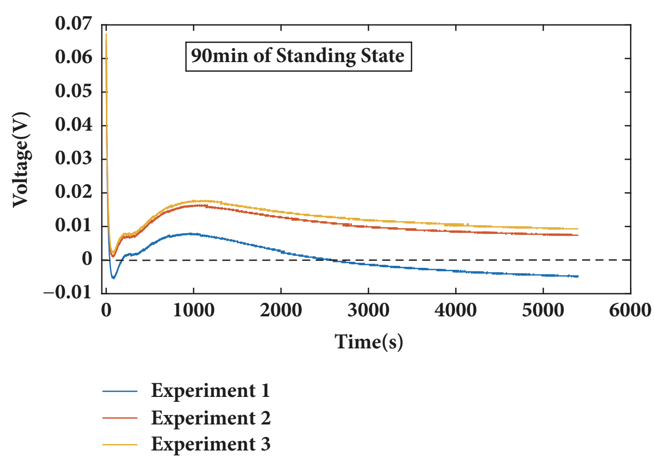

Figure 13: Comparison of the error between the model simulations and experiments measurements at self-healing time of 90 minutes.

the simulations and measurements is maintained within a stable range and the model is highly accurate. In spite of the advantages of the equivalent circuit model for self-healing characteristic, the description for the working state of lithium batteries is complicated to some degree and the identification of battery parameters needs more experiments. Future works aim at the optimization of the model and parameter identifications.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

All authors declare they have no conflicts of interest.

Acknowledgments

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References

[1] J. B. Dunn, L. Gaines, J. C. Kelly, C. James, and K. G. Gallagher, "The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction," *Energy & Environmental Science*, vol. 8, no. 1, pp. 158–168, 2015.

[2] J. Hu, H. Morais, T. Sousa, and M. Lind, "Electric vehicle fleet management in smart grids: a review of services, optimization and control aspects," *Renewable & Sustainable Energy Reviews*, vol. 56, pp. 1207–1226, 2016.

[3] D. Huang, J. Tang, and L. A. Zhao, "A fault diagnosis method of power systems based on gray system theory," *Mathematical Problems in Engineering*, vol. 2015, Article ID 971257, 11 pages, 2015.

[4] J. Jaguemont, L. Boulon, and Y. Dubé, "A comprehensive review of lithium-ion batteries used in hybrid and electric vehicles at cold temperatures," *Applied Energy*, vol. 164, pp. 99–114, 2016.

[5] A. Fotouhi, D. J. Auger, K. Propp, S. Longo, and M. Wild, "A review on electric vehicle battery modelling: from lithium-ion toward lithium-sulphur," *Renewable & Sustainable Energy Reviews*, vol. 56, pp. 1008–1021, 2016.

[6] L. Wu, X. Fu, and Y. Guan, "Review of the remaining useful life prognostics of vehicle lithium-ion batteries using data-driven methodologies," *Applied Sciences*, vol. 6, no. 6, p. 166, 2016.

[7] W. Yan, B. Zhang, W. Dou, D. Liu, and Y. Peng, "Low-cost adaptive lebesgue sampling particle filtering approach for real-time li-ion battery diagnosis and prognosis," *IEEE Transactions*

on Automation Science and Engineering, vol. 14, no. 4, pp. 1601–1611, 2017.

[8] M. E. Orchard, P. Hevia-Koch, B. Zhang, and L. Tang, "Risk measures for particle-filtering-based state-of-charge prognosis in lithium-ion batteries," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 11, pp. 5260–5269, 2013.

[9] S.-C. Huang, K.-H. Tseng, J.-W. Liang, C.-L. Chang, and M. G. Pecht, "An online SOC and SOH estimation model for lithium-ion batteries," *Energies*, vol. 10, no. 4, 2017.

[10] Y. Zou, X. Hu, H. Ma, and S. E. Li, "Combined State of Charge and State of Health estimation over lithium-ion battery cell cycle lifespan for electric vehicles," *Journal of Power Sources*, vol. 273, pp. 793–803, 2015.

[11] R. Xiong, F. Sun, X. Gong, and H. He, "Adaptive state of charge estimator for lithium-ion cells series battery pack in electric vehicles," *Journal of Power Sources*, vol. 242, pp. 699–713, 2013.

[12] A. Eddahech, O. Briat, and J.-M. Vinassa, "Lithium-ion battery performance improvement based on capacity recovery exploitation," *Electrochimica Acta*, vol. 114, pp. 750–757, 2013.

[13] X. S. Hu, S. B. Li, and H. Peng, "A comparative study of equivalent circuit models for Li-ion batteries," *Journal of Power Sources*, vol. 198, pp. 359–367, 2012.

[14] X. Lai, Y. Zheng, and T. Sun, "A comparative study of different equivalent circuit models for estimating state-of-charge of lithium-ion batteries," *Electrochimica Acta*, vol. 259, pp. 566–577, 2018.

[15] H. He, R. Xiong, and J. Fan, "Evaluation of lithium-ion battery equivalent circuit models for state of charge estimation by an experimental approach," *Energies*, vol. 4, no. 4, pp. 582–598, 2011.

[16] X. Chen, W. Shen, Z. Cao, A. Kapoor, and I. Hijazin, "Adaptive gain sliding mode observer for state of charge estimation based on combined battery equivalent circuit model in electric vehicles," in *Proceedings of the IEEE 8th Conference on Industrial Electronics and Applications (ICIEA '13)*, pp. 114–123, IEEE, June 2013.

[17] H. W. He, R. Xiong, H. Q. Guo, and S. C. Li, "Comparison study on the battery models used for the energy management of batteries in electric vehicles," *Energy Conversion and Management*, vol. 64, no. 4, pp. 113–121, 2012.

[18] H. He, R. Xiong, and H. Guo, "Online estimation of model parameters and state-of-charge of LiFePO4 batteries in electric vehicles," *Applied Energy*, vol. 89, no. 1, pp. 413–420, 2012.

[19] T. Feng, L. Yang, X. Zhao, H. Zhang, and J. Qiang, "Online identification of lithium-ion battery parameters based on an improved equivalent-circuit model and its implementation on battery state-of-power prediction," *Journal of Power Sources*, vol. 281, pp. 192–203, 2015.

[20] F. Sun, R. Xiong, H. He, W. Li, and J. E. E. Aussems, "Model-based dynamic multi-parameter method for peak power estimation of lithium-ion batteries," *Applied Energy*, vol. 96, no. 3, pp. 378–386, 2012.

[21] T. Qin, S. Zeng, J. Guo, and Z. Skaf, "A rest time-based prognostic framework for state of health estimation of lithium-ion batteries with regeneration phenomena," *Energies*, vol. 9, no. 11, p. 896, 2016.

[22] T. Qin, S. Zeng, J. Guo, and Z. Skaf, "State of health estimation of li-ion batteries with regeneration phenomena: a similar rest time-based prognostic framework," *Symmetry*, vol. 9, no. 1, p. 4, 2016.