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Study on Cycle-Life Prediction Model of Lithium-Ion Battery for Electric Vehicles

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This paper proposes a novel method for rapid determination of battery cycle life. Based on the relationship between the battery capacity, Arrhenius formula, temperature accelerated stress and charge-discharge current accelerated stress, a fitting formula is obtained to predict the battery capacity fading rate and battery charge-discharge cycle numbers. It is shown in the lithium-ion cell tests that the proposed formula can accurately reflect the tendency of battery capacity fading, and the estimation error is less than 5%.

Keywords: Lithium-ion battery；Cycle- life；Prediction model； Battery capacity fading.

1. INTRODUCTION

Whether electric vehicles can be mass produced largely depends on the development of power batteries [1,2]. So far, battery performance and test specifications have become the research focuses, however studies on battery reliable lifetime prediction are still rare. Therefore, it is of great significance to establish a battery cycle life model for battery reliable lifetime prediction and further improvement of battery performance.

The relationship of cell resistance changing with temperature, State of Charge (SOC) and ΔSOC was obtained by Wright et al. [3] and Bloom et al. [4] after an accelerated lifetime test of lithium-ion battery. This test was performed at several temperatures with 60% and 80% SOC, after which an empirical model was established to predict the battery lifetime when battery power drops to 50%. Wang et al. [5] concluded that the battery cycle-life is related to the charge-discharge rate, temperature and the depth of discharge, and a semi-empirical life model was proposed to predict the battery cycle-life. Ramadass et al. [6] proposed a semi-empirical model to predict the cycle-life of battery capacity fading according to first principles model, considering the decrease of SOC, the decrease of discharge voltage with the increase of the internal resistance of Solid Electrolyte Interface (SEI) film, as well as the battery large-rate discharge capacity fading with lower electrode diffusion coefficient. Ning et al. [7] conducted a quantitative analysis of the impact of the charge cut-off voltage and discharge depth on the battery cycle life, and then proposed a general life cycle model to compensate for the abovementioned shortcoming. A battery lifetime judge model was established by Li and Su [8] to determine the health status of the battery according to the basic principles of reliable testing theory and accelerated life testing. Dong et al. [9] utilized the Support Vector Regression-Particle Filter to predict the battery remaining useful life value and update the remaining useful life probability distribution to the end-of-life cycle. Han et al. [10] performed battery cycle life tests with different temperatures (5 ℃ and 45 ℃), and then employed on-line estimation and periodical calibration to estimate the battery capacity loss on-board.

However all the above mentioned methods overlook the difference between the charge current and discharge current, instead, they all treat the charge current and discharge current as a unified variable. In fact, charge current and discharge current affect the change of battery resistance and change of temperature discriminatively, namely they exert different influences on battery capacity attenuation [11]. Therefore, based on the revised Arrhenius equation, a new semi-empirical battery lifetime determining method is developed to predict the lithium-ion battery capacity fading. The proposed method regards the charge and discharge currents as two independent variables and considers the influences of ambient temperature and domestic charge-discharge system. It is proven in the tests that the proposed method can predict the battery capacity fading rate with satisfactory accuracy.

2. BATTERY TEST

In this section, a real vehicle test is first introduced to provide insights into the current magnitude distribution under actual vehicle running condition. Based on the current distribution information from the vehicle test, battery charging and discharging tests are then conducted to find out what key factors affect the battery capacity fading rate.

2.1 Charge-discharge current distribution

A real vehicle test was conducted with an ambient temperature of 25 ℃ to obtain the battery charge-discharge current range under the actual vehicle running condition. Some of testing data are plotted in Fig. 1. The incidences of different current magnitudes occurring in the test are shown in Fig. 2.

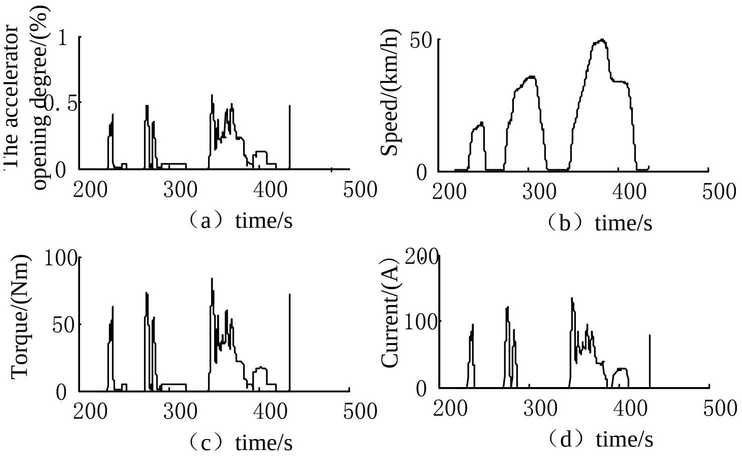

Figure 1. Testing results under actual working condition.

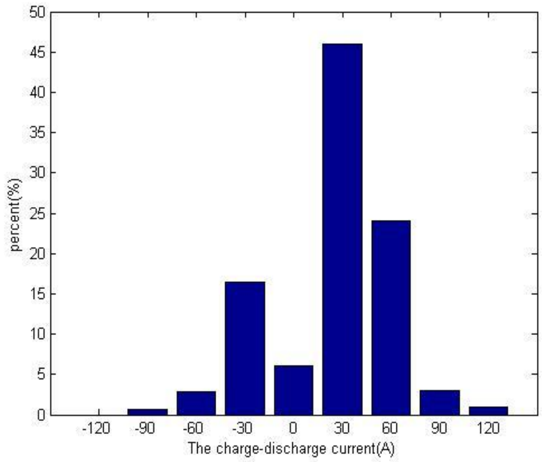

Figure 2. Incidences of different current magnitudes under actual working condition.

The charge-discharge current of lithium-ion battery is concentrated in the vicinity of 30 A and 60 A in the actual working condition. The incidence of the discharge current (positive value) of 30 A is as high as 46%, and the incidence of the charge current (negative value) of 30 A reaches 16.5%. The incidence of the charge current of 60 A is 2.8%, while that of the discharge current of 60 A is 24%.

2.2 Test object and instrument

The test object is a 6 Ah soft package lithium-ion battery cell whose positive electrode is $LiCoO_2$, negative electrode is graphite and negative electrode tab is Ni-Cu. This battery cell is manufactured by China Aviation Lithium Battery Co., Ltd, and a photo of this cell is shown in Fig. 3. The complete battery system (equipped on the above experimental electric vehicle) consists of 90 battery cells, with each cell’s rated voltage being 3.6 V. The total voltage of this battery system is 324

V. The test instrument, BTS15005C4 battery tester (shown in Fig. 3), is from Ningbo Bate Technology Co., Ltd. The parameters of the instrument are shown in Table 1.

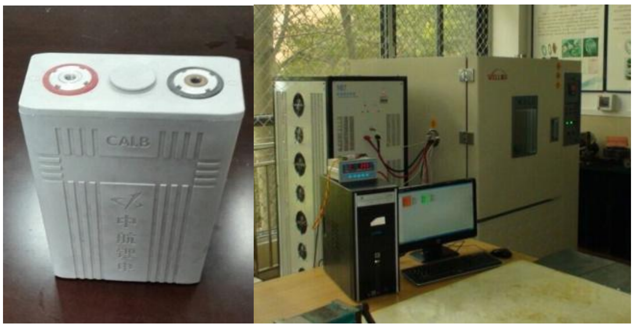

Figure 3. Test battery cell and test instrument

Table 1. Parameters of the BTS15005C4 battery tester

Parameters	Values
Charge voltage	0-5 V
Discharge voltage	0.8-5 V
Charge current	0.3-80 A
Discharge current	0.3-150 A
Voltage acquisition precision	±(0.1%FS+0.1%RD）
Current acquisition precision	±(0.1%FS+0.1%RD）
Minimum record frequency	0.5 s

2.3 Test process

The effects of temperature and charge-discharge current on the battery cycle-life were taken into account in this test. As the lithium-ion batteries for electric vehicles usually work in the ambient temperature range from 20 ℃ to 40 ℃, and it is obvious that battery lifetime fading is faster when the battery is exposed to higher temperature. So the ambient temperature of the experiment was set to 30 ℃ and 40 ℃ respectively to accelerate the test. The battery charge currents were selected as 5 C (30 A) and 10 C (60 A), while the battery discharge currents were 5 C (30 A) and 10 C (60 A), according to the charge-discharge current incidence diagram (Fig. 2) obtained from the above real vehicle test. Then, a test was conducted to verify the influence of temperature and charge-discharge current on the lithium-ion battery capacity fading rate, and the test stopped when the battery capacity dropped to 80% of its rated capacity. The specific experimental procedures were set as follows [12]:

Charging procedure:

1. Keep the battery in room temperature for 1 h to ensure that the battery internal temperature is consistent with the ambient temperature.
2. Discharge the battery in the Constant Current (CC) stage of 1/3 C until the voltage drops from the calibration value to 3.0 V. Then stand by the battery for 30 min.
3. Charge the battery until the charging time reaches 0.2 h with a 5 C constant charging current, or the charging time reaches 0.1 h with a 10 C constant charging current, or the voltage reaches 4.2 V. Then stand by the battery for 30 min.
4. Discharge the battery in the CC stage of 1 C until the voltage drops to 3.0 V. Then, stand by the battery for 30 min.
5. Repeat the third and forth steps for 10 times, then stand by the battery for one day and measure the battery capacity with charge and discharge currents of 1/3 C. The test should be terminated when the battery capacity drops to 80% of its rated capacity.

Discharging procedure:

1. Keep the battery in room temperature for 1 h to ensure that the battery internal temperature is consistent with the ambient temperature.
2. Discharge the battery in the CC stage of 1/3 C until the voltage drops from the calibration value to 3.0 V. Then stand by the battery for 30 min.
3. Charge the battery in the CC stage of 1 C for 1 h, then stand by the battery for 30 min.
4. Discharge the battery with a constant current of 5 C and 10 C respectively until the voltage reaches 2.5 V. Then stand by the battery for 30 min.
5. Repeat the third and forth steps for 10 times, then stand by the battery for one day and measure the battery capacity with charge and discharge currents of 1/3 C. The test should be terminated when the battery capacity drops to 80% of its rated capacity.

2.4 Test result analysis

As seen from the battery charge-discharge cycle life test data in Fig. 4, the lithium-ion battery capacity fading rate has a non-linear relationship with the number of cycles. It is observed from Fig. 4 (a) and 4 (c) that the temperature is an important factor affecting the battery capacity fading rate (the higher the ambient temperature is, the greater the fading rate will be). From Fig. 4 (d) and 4 (f) , we see that the discharge current is another important factor which influences the battery capacity fading rate (the greater the current is, the faster the battery capacity fades). It is also shown in Fig. 4 (c) and 4 (d) that the influence of the charge current is much higher than that of the discharge current. We know from the battery charge-discharge principle that the battery charging process is an exothermic reaction and the discharging process is an endothermic reaction. A great amount of heat is released from the inside of battery when charging, and the battery internal temperature rises quickly due to ineffective heat dissipation caused by the restricted space of the battery shell. This phenomenon results in serious battery cathode active material pulverization and fast battery lifetime fading.

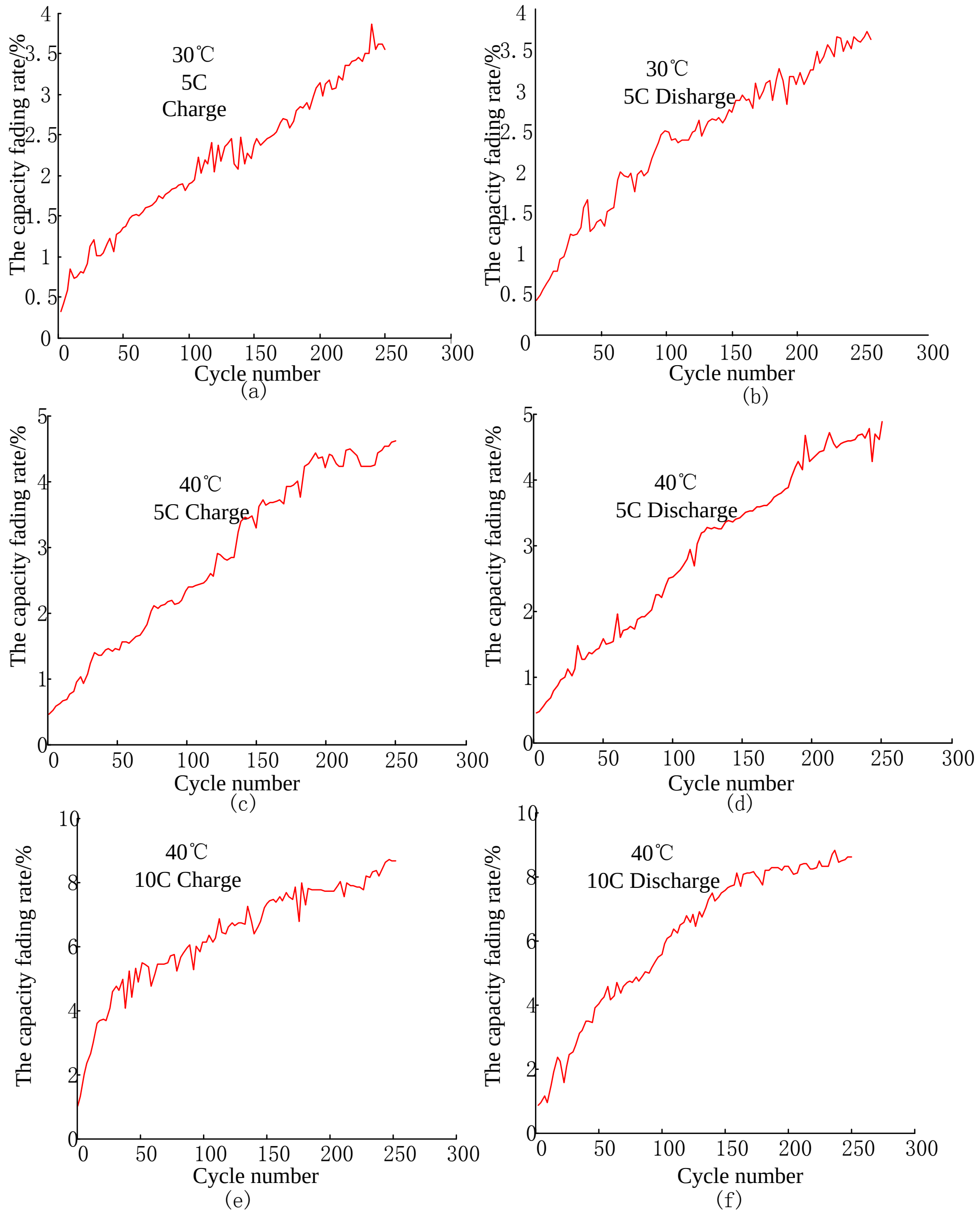

Figure 4. Partial results of the battery cycle-life test.

3. BATTERY LIFE MODEL

3.1 Battery life model

As can be seen from Fig. 4, the battery capacity fading rate C_r and the cycle numbers N are related by the following function [10]:

$$C_r = mN^n \qquad (1)$$

where m and n are two coefficients. The values of m and n can be determined by means of curve fitting using limited testing data, as shown in Table 2 (‘+’ for charge, ‘-’ for discharge).

Table 2. Curve fitting values of coefficients *m* and *n*.

Parameters	*T*=293 K *I*=+5 C	*T*=303 K *I*=+5 C	*T*=313 K *I*=+5 C	*T*=313 K *I*=-10 C	*T*=313 K *I*=+1 C	*T*=313 K *I*=+10 C
m	0.3334	0.292	0.2716	0.2548	0.2834	4.604
n	0.6045	0.5249	0.7627	0.6298	0.5592	0.3745

The values of *m* and *n* at different temperatures and charge-discharge currents are not the same, as shown in Table 2. Thus *m* and *n* can be seen as functions of the temperature，discharge current and charge current. As a result, one can rewrite equation (1) as follows:

$$C_r = m(I_{\text{charge}}, I_{discharge}, T) N^{n(I_{\text{charge}}, I_{\text{discharge}}, T)} \qquad (2)$$

where **Error! Reference source not found.** $m(I_{\text{charge}}, I_{\text{discharge}}, T)$ and **Error! Reference source not found.** $n(I_{\text{charge}}, I_{\text{discharge}}, T)$ are two functions of the temperature discharge current and charge current, **Error! Reference source not found.** I_{charge} denotes the charge current, **Error! Reference source not found.** $I_{\text{discharge}}$ denotes the discharge current, *T* represents the average operating temperature, and *N* stands for the cycle numbers of battery.

Assuming that the battery pack is in an ideal constant ambient temperature, and that the charge-discharge current is not dependent on the ambient temperature, the battery capacity fading coefficients *m* and *n* can be expressed by the following equations:

$$m(I_{\text{charge}}, I_{\text{discharge}}, T) = \lambda_1 f_1(I_{\text{charge}}) f_2(I_{\text{discharge}}) f_3(T) \qquad (3)$$

$$n(I_{\text{charge}}, I_{\text{discharge}}, T) = \lambda_2 f'_1(I_{\text{charge}}) f'_2(I_{\text{discharge}}) f'_3(T) \qquad (4)$$

where **Error! Reference source not found.** $f_1(I_{\text{charge}})$ and **Error! Reference source not found.** $f'_1(I_{\text{charge}})$ are two functions of the battery charge current, **Error! Reference source not found.** $f_2(I_{\text{discharge}})$ and **Error! Reference source not found.** $f'_2(I_{\text{discharge}})$ are two functions of the battery discharge current, and **Error! Reference source not found.** $f_3(T)$ and **Error! Reference source not found.** $f'_3(T)$ are two functions of the temperature. The values of λ_1 and λ_2 are dependent on the battery materials and processing technology.

Then, substituting equations (3) and (4) in equation (2) leads to the final expression for the battery capacity fading rate, as follows:

$$C_r = \lambda_1 f_1(I_{\text{charge}}) f_2(I_{\text{discharge}}) f_3(T) N^{\lambda_2 f'_1(I_{\text{charge}}) f'_2(I_{\text{dischage}}) f'_3(T)} \qquad (5)$$

3.2 Determination of the current and temperature functions

The electric stress (such as voltage, current, and power) has the following power function relationship with certain features of the product life according to the reflection theory model [13]:

$$\xi = Av^C \qquad (6)$$

where ξ is a certain feature of the product life, A is a constant, v is the electric stress, and C is a constant depending on activation energy.

According to equation (6), the following assumptions can be made:

$$f_1(I_{\text{charge}}) = A_{\text{charge}} I_{\text{charge}}^{C_1} \quad (7)$$

$$f_2(I_{\text{discharge}}) = A_{\text{discharge}} I_{\text{discharge}}^{C_2} \quad (8)$$

$$f_1^{'}(I_{\text{charge}}) = A_{\text{charge}}^{'} I_{\text{charge}}^{C_1^{'}} \quad (9)$$

$$f_2^{'}(I_{\text{discharge}}) = A_{\text{discharge}}^{'} I_{\text{discharge}}^{C_2^{'}} \quad (10)$$

where **Error! Reference source not found.** A_{charge}, $A_{\text{discharge}}$, $A_{\text{charge}}^{'}$, $A_{\text{discharge}}^{'}$, C_1, C_2, $C_1^{'}$, $C_2^{'}$ are constants. Based on the experimental data and equations (3), (4), (7), (8), (9) and (10), when the ambient temperature is constantly 313 K and there is only a constant discharge current, we have that $f_1(I_{\text{charge}})$ is equal to **Error! Reference source not found.** A_{charge}, $f_1^{'}(I_{\text{charge}})$ is equal to **Error! Reference source not found.** $A_{\text{discharge}}^{'}$, and $f_3(T)$ and $f_3^{'}(T)$ are constants. Then, the values of **Error! Reference source not found.** $A_{\text{discharge}}$, $A_{\text{discharge}}^{'}$, C_2, $C_2^{'}$ can be obtained. On the other hand, when the ambient temperature is constantly 313 K and there is only a constant charge current, we have that $f_2(I_{\text{discharge}})$ is equal to A_{charge} **Error! Reference source not found.**, $f_2^{'}(I_{\text{discharge}})$ is equal to $A_{\text{charge}}^{'}$ **Error! Reference source not found.**, and $f_3(T)$ and $f_3^{'}(T)$ are constants. As a result, the values of $A_{\text{discharge}}$ **Error! Reference source not found.**, $A_{\text{discharge}}^{'}$ **Error! Reference source not found.**, $C_1, C_1^{'}$ can be obtained. The above values are shown in Table 3 and Table 4.

Table 3. Curve fitting parameters for coefficient *m*.

Function	$f_1(I_{\text{charge}})$		$f_2(I_{\text{discharge}})$		$f_3(T)$	
Parameter	A_{charge}	C_1	$A_{\text{discharge}}$	C_2	ε	Λ
Value	0.1939	0.3428	0.2558	0.1905	942.7677	-4.3516

Table 4. Curve fitting parameters for coefficient *n*.

Function	$f'_1(I_{\text{charge}})$		$f'_2(I_{\text{discharge}})$		$f'_3(T)$	
Parameter	A'_{charge}	C'_1	$A'_{\text{discharge}}$	C'_2	ε'	Λ'
value	0.6258	0.1595	0.5655	0.0257	-1059.5988	0.5655

Similarly, based on the Arrhenius model, the relationship between the ambient temperature and certain features of the product life takes the following form [4, 8, 10, 14]:

$$X = A e^{-\frac{\Delta E}{KT}} \qquad (11)$$

where X represents another certain feature of the product life, A is the frequency factor, ΔE is the activation energy, K denotes the Boltzmann constant (0.8617×10^{-4} eV/K), T is the absolute temperature with the unit of K.

Letting $\varepsilon=\Delta E/K$, one can rewrite equation (11) in the following form:

$$X = A e^{-\frac{\varepsilon}{T}} \qquad (12)$$

Based on equation (12), the following assumptions can be made:

$$f_3(T) = A e^{-\frac{\varepsilon}{T}} \qquad (13)$$

$$f_3^{'}(T) = A^{'} e^{-\frac{\varepsilon^{'}}{T}} \qquad (14)$$

where ε, $\varepsilon^{'}$, A and $A^{'}$ are all constants. The values of ε , $\varepsilon^{'}$, A and $A^{'}$ can be obtained by setting temperature as the variable, when the charge-discharge current is constant. These values are shown in Table 3 and Table 4.

Substitution of the parameter values in Tables 3 and 4 in equations (3) and (4) leads to the following expressions of m and n:

$$m = \lambda_1 * 0.00063915 I_{\mathrm{charge}}^{0.3428} I_{\mathrm{discharge}}^{0.1905} e^{\frac{942.7677}{T}} \qquad (15)$$

$$n = \lambda_2 * 6.8335 I_{\mathrm{charge}}^{0.1095} I_{\mathrm{discharge}}^{0.0257} e^{-\frac{1059.5988}{T}} \qquad (16)$$

Modifying the formulas according to the experimental data, the final battery capacity fading rate expression is achieved:

$$C_r = 0.0165658 I_{\mathrm{charge}}^{0.3428} I_{\mathrm{discharge}}^{0.1905} * e^{\frac{942.7677}{T}} N^{14.2335 I_{\mathrm{charge}}^{0.1595} I_{\mathrm{discharge}}^{0.0257} * e^{-\frac{1059.5988}{T}}} \qquad (17)$$

Li and Su [8] treat the current and temperature as the variables to build the lifetime model shown as follows:

$$\mathrm{C_r} = (26794.698 * \exp(0.734/\mathrm{T}) - 0.155/\mathrm{I} - 26179.913) * \mathrm{n}_e^{(785.46*\exp(-0.844/\mathrm{T}+0.122*I-782.972)} \qquad (18)$$

4. EXPERIMENTAL VERIFICATION

Two experiments were carried out in this study to verify the efficacy and accuracy of the proposed battery capacity fading model and compare with the lifetime fading model established by Li[6]. The experimental details are explained in sections 4.1 and 4.2.

4.1 Experimental verification with constant charge-discharge current

The temperature of lithium-ion battery on an Electric Vehicle (EV) is usually between 30 ℃ and 40 ℃ when the vehicle is in practical operation. So the test temperature was set to 30 ℃ and 40 ℃ respectively to simulate the actual condition. The charge-discharge experimental verification procedure of the lithium-ion battery model is the same as the test method in section 2.3. Note that due to battery aging, the battery capacity presents a certain degree of fading. Thus, after every 10 charge-discharge cycles, the battery capacity was tested and the test value was then employed as the standard value for the next step of experiment. Also, the charge time was adjusted to prevent battery over-charge or over-discharge.

Based on the abovementioned test program, the characteristics of the battery capacity fading rate under different working conditions are measured. The experimental results and the calculated values using the model equation are compared and plotted in Fig. 5.

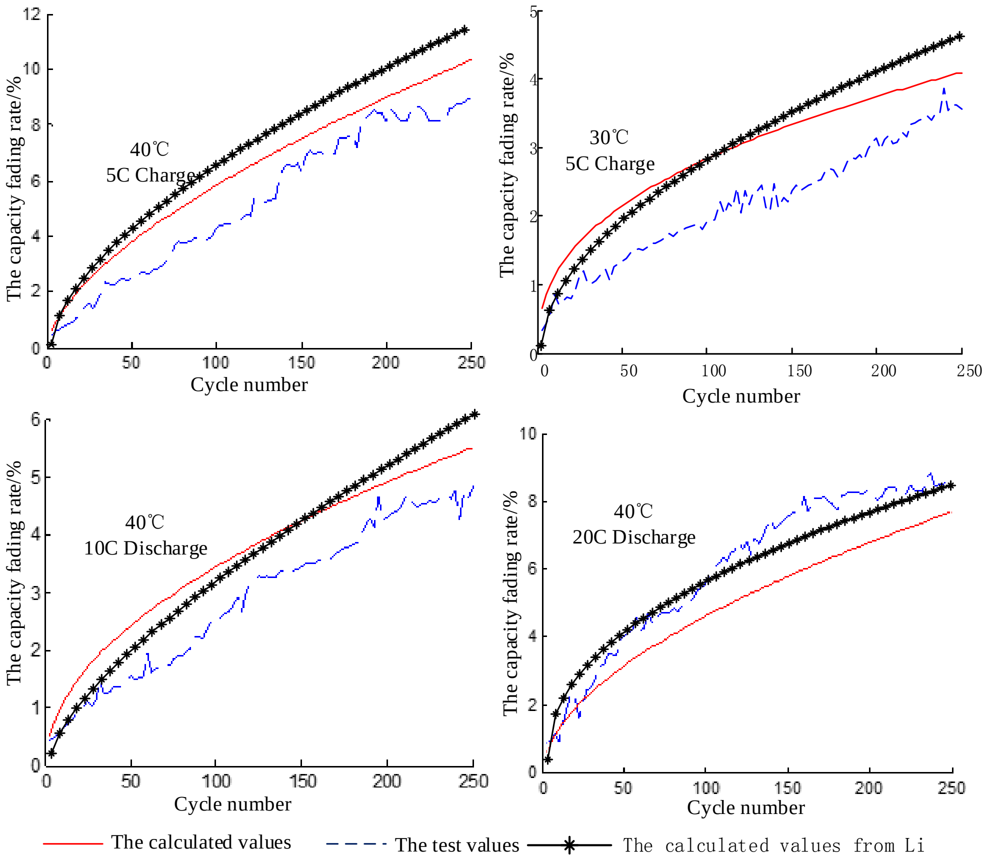

Figure 5. Comparisons of the calculated and test results.

The comparisons of the test results, the calculated values and the calculated values from Li reveal that the proposed model can predict the tendency of battery capacity fading with satisfactory accuracy and the estimation error is less than 2%, and it can follow the tendency better than the calculated values from Li with the increasing of cycle numbers.

4.2 Experimental verification under different working conditions

The charge-discharge current data can be acquired by means of online real-time measurement using a Controller Area Network (CAN) card when the lithium-ion battery on an EV works under rapid acceleration condition or regenerative braking condition. The acquired data were processed and simplified, and an experimental circular curve of battery charge-discharge was obtained, as shown in Fig. 6.

In the actual driving condition, the battery has a charge-discharge current of $I = I_i$ **Error! Reference source not found.** (i =1, 2, 3…), and the corresponding time is $t = t_i$ (i =1, 2, 3…) when the battery finishes a driving cycle. Besides, the battery has a single current of $I = I_j$ **Error! Reference source not found.**(j =1, 2, 3…), and the corresponding time is $t = t_j$ **Error! Reference source not found.**(j =1, 2, 3…) in one charge-discharge loop. Namely the number of charge-discharge cycles should increment once when the battery charge time reaches t_j **Error! Reference source not found.** with the charge current of I_j **Error! Reference source not found.**. The battery current in an actual operating condition can be converted to the corresponding charge-discharge numbers N_i according to the above principle:

$$N_i = {t_i}/{t_j} \qquad (18)$$

where t_i is the real action time of current I_i in an actual operation, t_j **Error! Reference source not found.** is the real action time of current I_j in a charge-discharge cycle.

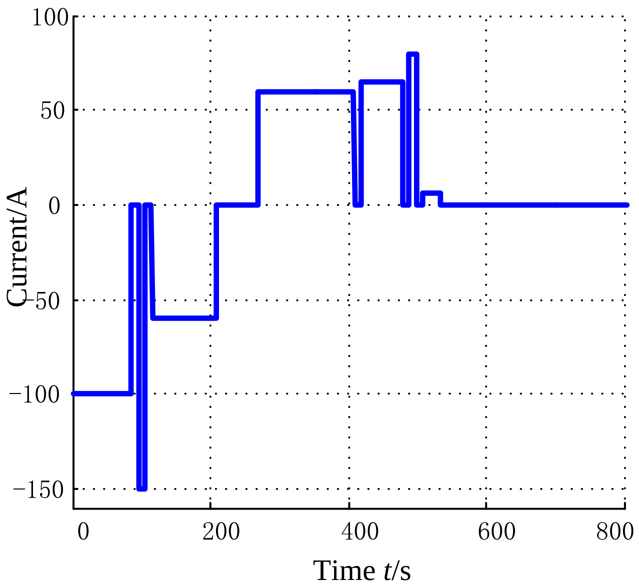

Figure 6. Charge-discharge current of a circular experiment.

Substituting the transformed N_i, temperature and charge-discharge current in equation (17) leads to the expression of the battery capacity fading rate C_{ri}. Then, a summation of the battery capacity fading rates is obtained:

$$C_r = \sum_{i=1}^{n} C_{ri} \qquad (19)$$

where C_r **Error! Reference source not found.** is the battery capacity fading rate, i is the charging times of the battery charge-discharge current I_i, C_{ri} **Error! Reference source not found.** is the battery capacity fading rate of the i th**Error! Reference source not found.** battery charge-discharge cycle.

Charging the battery with a current of 1/3C provides the actual battery capacity, when the number of battery charge-discharge cycles is 10. Thus, both the measured battery capacity fading rate and the predicted value resulted from the above equations can be obtained. The comparison between the actual and predicted values is shown in Fig. 7.

The comparisons of the test results, the calculated values and the calculated values from Li reveal that the proposed model can predict the tendency of battery capacity fading with satisfactory accuracy and the estimation error is less than 5%, and it can follow the tendency better than the calculated values from Li with the increasing of cycle numbers.

The existing errors between the calculated and actual values are due to the following reasons:

1) Firstly, the fitting values of m and n present some extent of errors because of insufficient experimental data.

2) Secondly, the battery working environment is quite complex. Apart from the ambient temperature and battery charge-discharge current, there are other affecting factors such as the battery charge-discharge depth, environmental humidity and vibrations. These factors influence the battery capacity nonlinearly, as a result, the model presents certain errors.

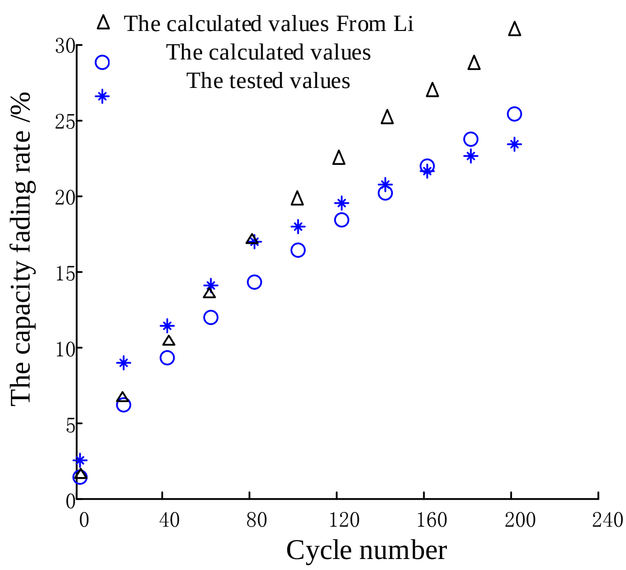

Figure 7. Predicted values and actual values of the capacity fading rate

5. CONCLUSION

This study employs the exponential fitting method to calculate the parameters of the battery capacity fading equation according to the experimental data. The parameters were modified based on the principle of the revised Arrhenius model, and then the expressions of various parameters were obtained with the charge current and discharge current being two independent variables. Moreover, the actual experimental data were compared with the calculated values produced by the proposed model. The comparison results verify that this prediction model is effective and it can predict the tendency and rate of battery capacity fading accurately. The estimation error of battery capacity is less than 5%. This model lays a theoretical foundation for future production and use of lithium-ion batteries.

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