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Peak power calculation based on least square method

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Abstract

The peak power of battery has important significance for the optimization of electric vehicle power matching and BMS control strategy. In this paper, the peak power of the battery is predicted based on the impedance. By measuring the impedance under different charge and discharge currents, an impedance-current model is established to get the peak power. Furthermore, based on the first-order Thevenin model and the least square method, the relationship between SOP and polarization resistance and ohmic resistance is obtained.

Keywords: battery, internal resistance,SOP

1. Introduction

By estimating SOP(state of power), the current working state of the battery pack can be evaluated to avoid over-charging and over-discharge of the battery and prolong the service life of battery. There are many methods to estimate the battery power, such as composite pulse method, U-I model method, etc., however, factors such as SOC or temperature are usually not considered, which makes it difficult to be used in practical systems. In this paper, a simple method for estimating the peak power state of a battery is proposed, and the parameters of the battery model are identified by using the least square method through the first-order Thevenin model. The results show that the peak power estimated by the new method coincides with the peak power estimated by the multi-stage pulse experiment method, and the accuracy is higher, which is more suitable for engineering practice.

2. Peak power estimation method

The peak power of the battery is derived from the Rint model.

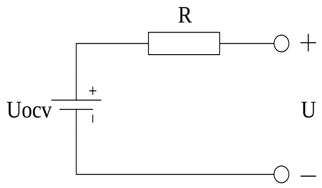


Fig.1 Rint model

Battery terminal voltage U meets:

$$U = U_{OCV} - I \times R \tag{1}$$

The impedance of R under different current is obtained by experiment, and the relationship between impedance R and current I can be established:

$$R = f(I) \tag{2}$$

Let Imax denote the current when the battery is discharged to the upper and lower limit voltages by constant current discharge for 10 seconds.

$$I_{max} = \frac{U_{OCV} - U}{R} \tag{3}$$

Imax is obtained by Simultaneous equations (2) and (3), then the peak power can be calculated:

$$P = I_{max} * U \tag{4}$$

3. experimental design

Charge and discharge experiments on a 60Ah LiFePO4 lithium ion battery at 25℃. Pulse currents of 1.0C, 1.5C, 2C, 2.5C, 3C, 3.5C and 4.0C were used to charge and discharge the battery for 10 seconds. After each discharge, the battery was charged to keep the SOC consistent. The full SOC data were obtained by repeated the experiment.

4. Analysis of experimental results

4.1 Battery impedance-pulse current models

It was found that the battery impedance decreases as the charge-discharge current increases. Taking 25℃ and 0.3 SOC as an example, the relationship between battery impedance and charge discharge pulse current is shown in Fig.2, Fig.3.

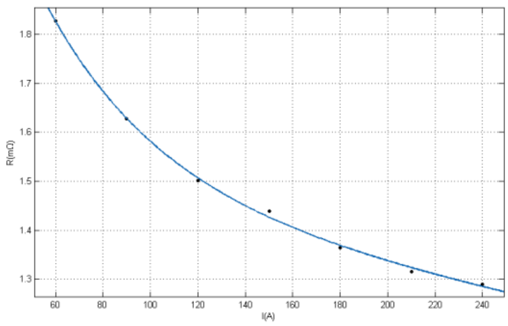


Fig.2 Battery impedance at different pulse charge currents at 25 ℃, 0.3SOC

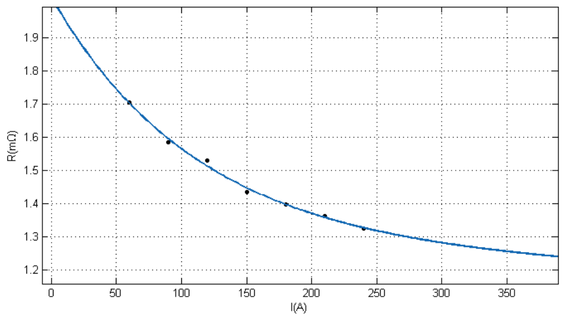


Fig.3 Battery impedance at different pulse discharge currents at 25 ℃, 0.3SOC

The following equation is adopted for the fitting:

$$R = ae^{bx} + ce^{dx} \tag{5}$$

Where, a, b, c and d are parameters, R is the battery impedance, and x is the impulse current. The specific data is shown in table 1.

Table 1 Parameters in R-I fitting according to equation (5)

SOC：0.3	a	b	c	d	R^2	RMSE
Pulse discharge	0.7378	-0.009088	1.285	-0.0001357	0.9938	0.01507
Pulse charge	1.233	-0.02109	1.553	-0.0008156	0.9987	0.009832

R2 is close to 1, and the RMSE is 0.01507 close to 0, which indicates that the fitting effect is good and the precision is high.

Bring the open circuit voltage and discharge cutoff voltage of the battery at 25 °C and 0.3 SOC into Eq.3 ,I_{max} can be calculated by Eq. 2,3 and 5.

$$I_{max}^{dis} = 398.52\text{A} \quad I_{max}^{cha} = 240.77\text{A}$$

Then Pmax can then be calculated using Eq.4

$$P_{max}^{dis} = 1115.85\text{W} \quad P_{max}^{cha} = 866.41\text{W}$$

According to the experimental data of all SOC states, the battery impedance (Fig.4, Fig.5) and the maximum charging and discharging power (Fig.6) under different SOC states can be further obtained by the same method.

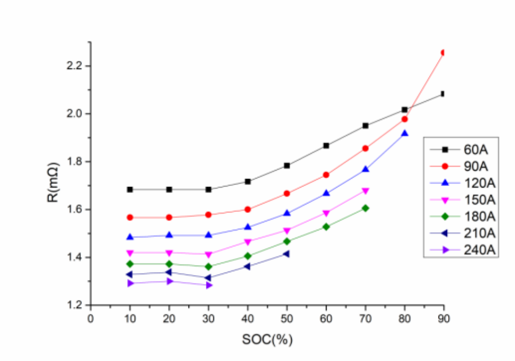


Fig.4 R-SOC relationship at 25 ℃ charge

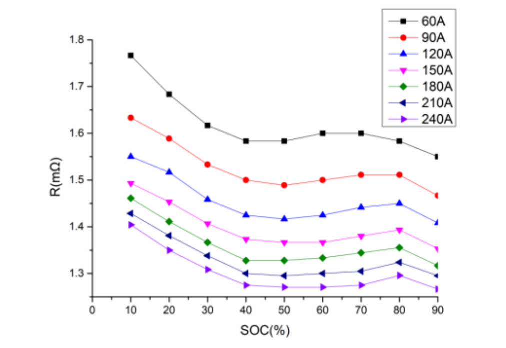


Fig.5 R-SOC diagram at 25 ℃ discharge

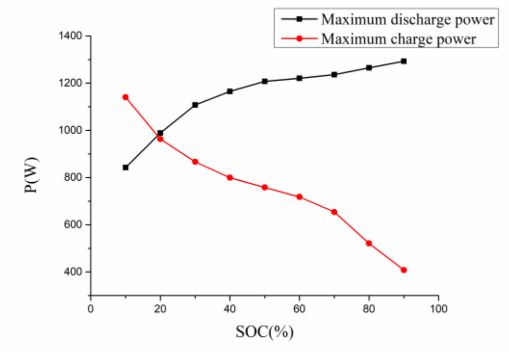


Fig.6 Battery maximum charge and discharge power at 25 ℃

It can be seen that the battery impedance basically increases exponentially with SOC in charging state. Within the range of 10%~30% SOC, the battery impedance does not change much. However, the impedance of the battery increased exponentially after 40% SOC.As the SOC of the battery increases, the pulse current from charging to the cut-off voltage of the battery gradually decreases.

Under 10%~80% SOC, it can be seen that the battery impedance decreases as the battery charging pulse current increases in the same SOC state, However, at 90% SOC, the battery impedance increases with the increase of the battery pulse current, indicating that the influence of SOC is greater than the impact of the pulse current on the battery impedance at high SOC.

4.2 Multistage pulse power estimation

The multistage pulse experiment method uses an exponential function to estimate the trend of the relationship between voltage and current at the end of pulse discharge. Comparing with the peak power obtained by the above method, the results are shown in table 2.

Table 2 Comparison of two estimation methods at 0.3 SOC,25℃

SOC：0.3	U-I model	R-I model	relative error（%）
Maximum discharge power（W）	1141	1115.85	2.20
Maximum charge power（W）	869.36	866.41	0.339

The maximum charge and discharge power obtained by the new method is almost the same as that obtained by the traditional multi-stage pulse method, and the relative error is less than 3%, which proves the feasibility of the new method.

In order to verify the accuracy of the algorithm, compare it with the true value of the power. Taking the current 240A of 10s charged to the cut-off voltage 3.6V as the true maximum charge current, the true value of the maximum charging power is 864W.Comparing the maximum charging power of the two models in Table 3, the relative errors are 0.62% and 0.28% respectively, which indicating that the new method has higher accuracy.

5. The relationship between SOP and battery internal resistance

Thevenin model is used to study the relationship between SOP and battery internal resistance.

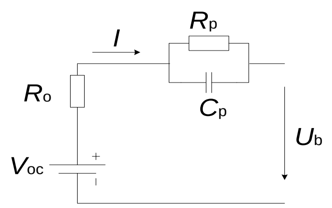


Fig.7 Thevenin equivalent model

As shown in Fig.7, Ub is the terminal voltage of the battery, Voc is the open circuit voltage (OCV), Ro is the ohmic internal resistance, Rp is the polarization internal resistance, CP is the polarization voltage of the battery, I is the current of the battery.

According to the model of Fig.7 and Kirchhoff's law, the time domain relations can be obtained:

$$V_{oc} = U_b + U_o + U_p \quad (6)$$

$$U_o = IR_o \quad (7)$$

$$\dot{U}_p = -U_p / C_p R_p + I / C_p \quad (8)$$

I is the input of the battery model system, U is the output of the battery model system, U = - Ub + Voc. According to Laplace transformation and bilinear transformation, the difference equation of the system can be obtained as follow:

$$U(k) = -a_1 U(k-1) + b_0 I(k) + b_1 I(k-1) \quad (9)$$

According to the difference equation (9), the least square method is used to identify the parameters of the system. The parameters are identified with 10s pulse current and voltage data and 1s sampling time in MATLAB.

5.1 The relationship between ohmic resistance, polarization resistance and current

Taking the 25 ℃ and 50% SOC pulse discharge state as an example, the variation of the parameters of the system with current is identified by the least squares method as shown in fig.8.

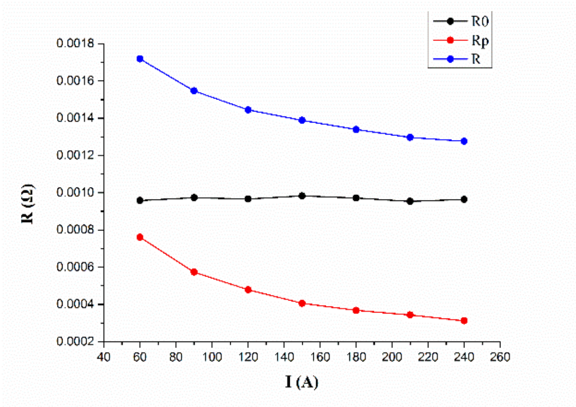
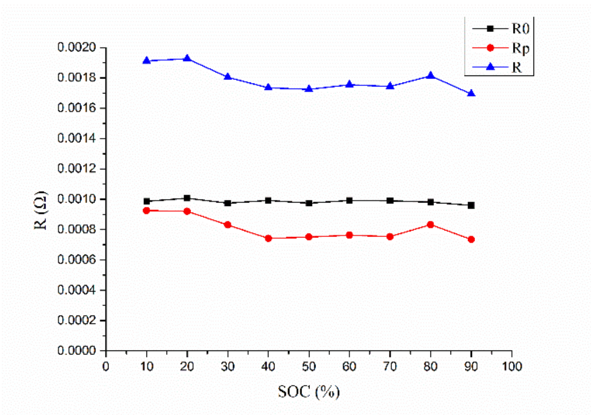


Fig.8 R-I relationship at 25 ℃ ,50% SOC discharge

The red line in the figure above indicates the polarization resistance of the battery, the black one is ohmic resistance, and the blue one is the total internal resistance of the battery. It can be seen from the figure that the ohmic internal resistance of the battery changes little with the current, while the polarization internal resistance decreases with the increase of the battery current, and the decreasing trend gradually slows down, basically decreasing in an exponential form.It can be seen that the current affects the total impedance of the battery by affecting the polarization internal resistance of the battery.

5.2 The relationship between ohmic resistance, polarization resistance and SOC

Taking the 25 ℃ and 1C pulse current as an example, the variation of the parameters of the system with the SOC is identified by the least squares method as shown in fig.9 and fig.10.



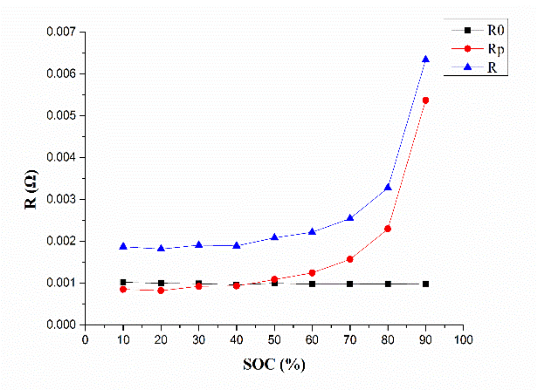


Fig.9 R-SOC relationship at 25 ℃, 1C pulse discharge Fig.10 R-SOC relationship at 25 ℃, 1C pulse charge

It can be seen from the figure that the ohmic internal resistance of the battery changes little with the SOC regardless of the state of charge or the state of discharge. The relationship between polarization resistance and SOC can be divided into two types: In the state of discharge, the polarization resistance generally decreases; In the charging state, the polarization internal resistance increases with the increase of SOC, and tends to accelerate in the high SOC range.

5.3 The relationship between ohmic resistance, polarization resistance and temperature

Taking the 50% SOC and 1C pulse current as an example, the variation of the parameters of the system with the SOC is identified by the least squares method as shown in fig.11 and fig.12.

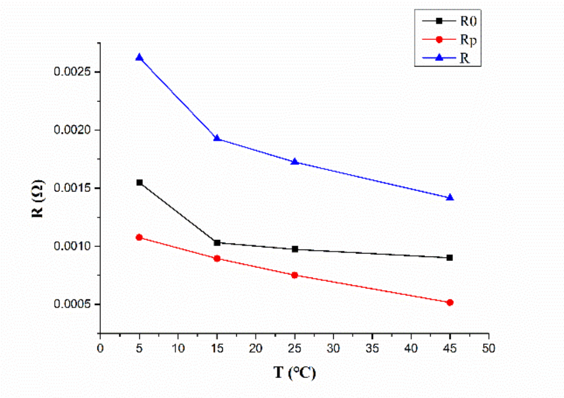


Fig.9 R-T relationship at 50% SOC, 1C pulse discharge

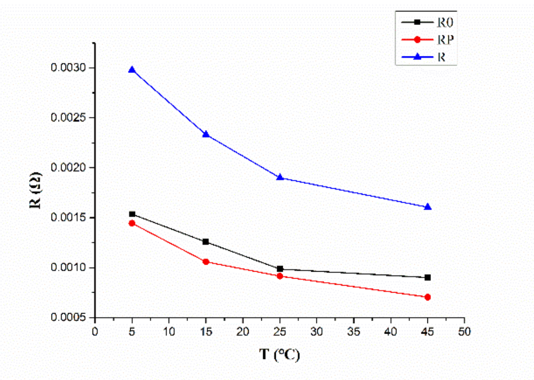


Fig.10 R-T relationship at 50% SOC, 1C pulse charge

It can be seen from the figure that the total internal resistance of the battery decreases with increasing temperature regardless of the state of charge or discharge. At low temperature, the total internal resistance is large because of ohmic internal resistance, and then the decrease of total internal resistance with temperature is mainly the decrease of polarization internal resistance. Generally, the ohmic resistance decreases exponentially with temperature, while the polarization resistance decreases linearly with temperature.

5.4 Function expression derivation

The following table can be obtained by synthesizing the conclusions of section 5.1-5.3:

Table 2 Variation of polarization resistance and ohmic resistance

	Ohmic resistance（R0）	Polarization resistance（Rp）
I	Almost unchanged	Decreased exponentially with increasing I
T	Decreased exponentially with increasing I	Decreased Linearly with increasing T
SOC	unchanged	Increased exponentially with increasing SOC in charging state

As can be seen from the above table, R0 does not change much with current. It can be considered that R0 is independent of current. Therefore, R0=f (T,SOC) can be set, and the data of R0 at 1C pulse current and each temperature point is fitted to obtain the following relationship:

$$R_0 = a \cdot e^{\left(\frac{b}{T}\right)} + c \cdot SOC \tag{10}$$

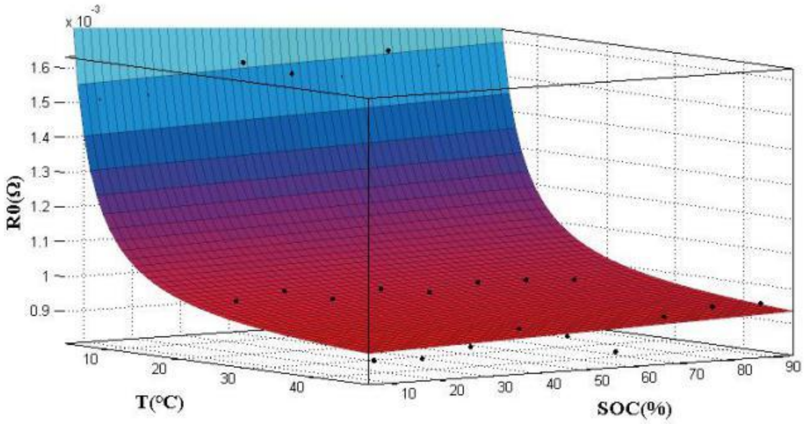


Fig.11 R_0-T,SOC relationship at 1C pulse discharge

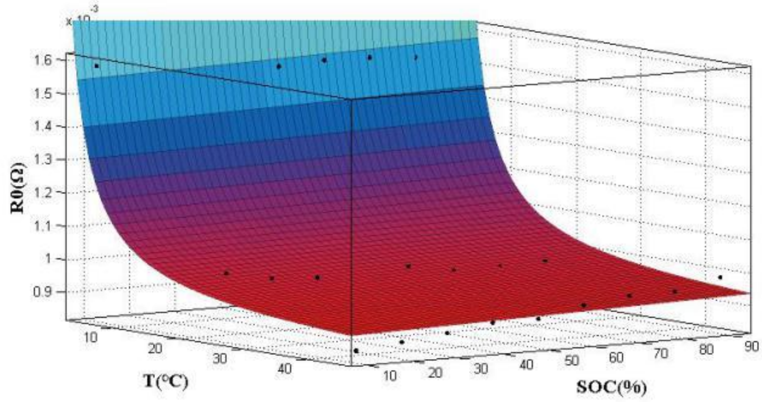


Fig.12 R_0-T,SOC relationship at 1C pulse charge

In order to explore the relationship between Rp and I, T, SOC, the relationship between Rp and two of them needs to be obtained first, that is Rp=f (I, SOC). Then add the influence factors of temperature and get Rp=f (I, T, SOC).

According to the Rp decreases with the increase of I, the data of Rp at different I and SOC at 15℃ are fitted to get the following relationship:

$$R_p = a\frac{\ln(I)}{I} + b \bullet SOC^3 + c \bullet SOC^2 + d \bullet SOC + f \tag{11}$$

Table 3 Parameter identification results

T:15˚C	a	b	c	d	f	R2
Pulse discharge	0.01054	1.843e-10	2.005e-8	-4.867e-6	0.0003451	0.9406
Pulse charge	0.01827	1.093e-8	-1.125e-6	3.702e-5	-0.0005352	0.9339

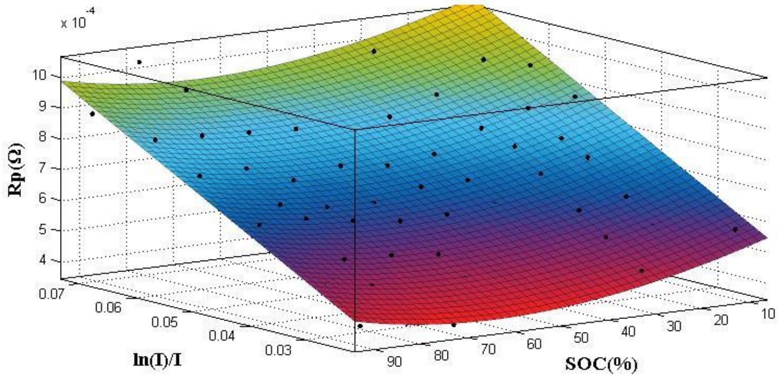


Fig.13 Rp-I,SOC relationship at 15 ℃ pulse discharge

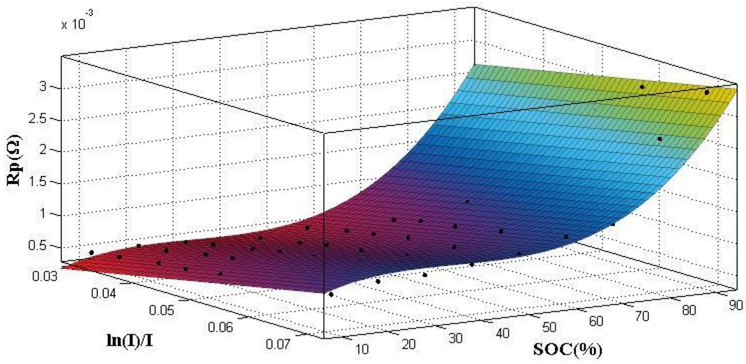


Fig.14 Rp-I,SOC relationship at 15 ℃ pulse charge

It can be seen from fig.8 that the polarization internal resistance Rp has a linear relationship with temperature, which can be assumed as follows:

$$Rp(T) = Rp(25℃) + k*(T-25) \tag{12}$$

Combined with Rp=f (I, SOC), it can be concluded that:

$$R_p(I, SOC, T) = a\frac{\ln(I)}{I} + b \bullet SOC^3 + c \bullet SOC^2 + d \bullet SOC + k \bullet (T-25) + f \tag{13}$$

5.5 Peak power calculation

The following results can be derived from equation (6), (7) and (8)

$$Up = I \bullet R_p \bullet (1-\exp(-\frac{t}{R_p \bullet C_p})) \tag{14}$$

$$I \bullet R_0 + I \bullet R_p \bullet (1-\exp(-\frac{t}{R_p \bullet C_p})) = V_{oc} - U_b \tag{15}$$

Where t is the total duration of the data,V_{oc} is the open circuit voltage, U_b is the terminal voltage. They are all known parameters. By substituting equations (11) and (13) into (15), the maximum charge and discharge current I_{max} at different temperatures and SOC can be obtained, and the peak power can be calculated from P= I_{max}*U.

6. Conclusion

In this paper, the experimental results show that the peak power estimated by impedance and current model is equivalent to the peak power estimated by the multistage pulse experiment method, and the accuracy is higher. Based on the first-order Thevenin model and the parameters identified by the least square method, the maximum charge and discharge current of the battery under different states can be obtained by establishing the relationship between R and I, T, SOC.Then the peak power is obtained.It is also concluded that the current affects the total impedance of the battery mainly by affecting the polarization internal resistance of the battery.

In the future, the method can be applied to the battery management system through programming to realize its application in real life and optimize the battery performance.

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