The measurement and analysis for Open Circuit Voltage of Lithium-ion Battery

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Abstract: In this paper, charging and discharging characteristic of Lithium-ion Battery is studied. The relationship between open circuit voltage and model parameters is analyzed based on RC equivalent circuit model. Charging and discharging characteristic of a brand of Lithium-ion battery was tested. By fitting the terminal voltage data, the OCV-SOC curve was compared with the actual OCV-SOC curve. The analysis results show that the deviation between the fitting curve and the actual curve is within the effective range.

1. INTRODUCTION
In the application of lithium-ion batteries, the most concerned problem is the State of Charge (SOC) of Lithium-ion battery. The common way to estimate SOC is the combination of the integration method and the open-circuit voltage method. However, the measurement process of open-circuit voltage method takes a lot of time, which will be limited in practical application. In this paper, the factors related to open circuit voltage are analyzed by combining the equivalent circuit model of lithium-ion battery and the charging and discharging characteristics of lithium-ion battery, and the measurement method of open circuit voltage is given. Finally, the experimental data are processed and analyzed. The fitting curve is compared with the actual OCV-SOC curve by fitting the terminal voltage data during the charging and discharging process of lithium-ion battery, and the accuracy of the fitting curve is verified.

2. RC EQUIVALENT CIRCUIT MODEL
The equivalent circuit model uses traditional circuit elements such as resistor, capacitor and constant voltage source to form a circuit network to describe the external characteristics of lithium-ion battery. The model uses voltage source to represent the thermodynamic equilibrium potential of lithium-ion battery, and RC network to describe the dynamic characteristics of lithium-ion battery. Equivalent circuit model has better applicability to the working state of lithium-ion battery, and can deduce the state equation of the model, which is convenient for analysis and application.

Fig. 1 shows a typical n-Order RC network:
Fig. 1 Circuit structure of n-RC model

$U_{oc}$ represents the Open-Circuit Voltage (OCV) of the lithium-ion battery. $R_i$ represents the contact resistance of parts. RC network represents polarization characteristics of lithium-ion battery. The n-RC model is discretized and the transfer function of the model is obtained.\(^3\)

$$G(s) = \frac{U(s) - U_{oc}(s)}{\tilde{u}(s)}$$

$$E(s) = U_i(s) - U_{oc}(s)$$

$$E(s) = -\tilde{u}(s)\left(\frac{R_1}{1 + R_i C_1 s} + \frac{R_2}{1 + R_i C_2 s} + \cdots + \frac{R_c}{1 + R_i C_s s}\right)$$

Mapping the equation based on s plane to z plane:

$$G(z^{-1}) = \frac{c_m z^{-1} + \cdots + c_2 z^{-2} + z^{-m}}{1 - c_1 z^{-1} - \cdots - c_m z^{-m}}$$

$c_m$ are model correlation coefficients. The OCV is coupled with SOC, working temperature $T$ and aging state $A_{age}$. To simplify the calculation, the following assumptions are made.

Assumption 1: The influence of the battery’s consumption or absorption of electricity within the unit sampling interval on its SOC is approximately zero.

Assumption 2: The temperature of the lithium-ion battery remains unchanged within the unit sampling interval.

Assumption 3: Aging status of lithium-ion battery in unit sampling interval remains unchanged.

Based on the above assumptions, there are the following formulas in the discrete domain:

$$\Delta U_{oc, k} = U_{oc, k} - U_{oc, k-1}$$

Equivalent circuit model can help us understand the structure of lithium-ion battery and the relationship between open circuit voltage and circuit parameters.

3. CHARGING AND DISCHARGING CHARACTERISTICS OF LITHIUM-ION BATTERIES

In this paper, a 3.65A·H NMC lithium-ion battery is used. The lower cut-off voltage of the battery is 3V and the upper cut-off voltage is 4.2V.

Lithium-ion batteries use constant current to constant voltage charging mode. Charging starts at a constant current stage, and the battery voltage is low. In this process, the charging current is stable. As the charging continues, the battery voltage gradually rises to 4.2V. At this time, the charger should immediately switch to constant voltage charging. The fluctuation of charging voltage should be controlled within 1%, and the charging current gradually decreases. When the current drops to a certain range, it enters the trickle charging stage. In trickle phase, the charger continues to charge the lithium-ion battery at a constant rate, so that the battery is in full condition.
Lithium-ion battery is discharged in constant current mode. The lithium-ion battery is discharged at a constant current. The cut-off voltage of it is 3V at the lower end. The discharge current is 0.8C in this paper. When lithium-ion battery is discharged, the first is that the discharge current should not be too large. Excessive current will cause internal heating, which may cause permanent damage. Secondly, if the battery voltage can't be lower than the discharge termination voltage, it will produce over-discharge phenomenon, which will also cause permanent damage to lithium-ion battery.[4]

The following are the current and voltage waveforms during charging and discharging:

![Fig. 2 Current and Voltage Curves](image)

4. TEST METHOD OF OPEN-CIRCUIT VOLTAGE

The purpose of open circuit voltage measurement is to measure the open circuit voltage of lithium-ion battery and to establish the relationship between OCV and SOC of lithium-ion battery. Each battery system has its own OCV curve. Under certain temperature, SOC has a fixed relationship with OCV. At the same time, OCV will also be affected by battery aging, so OCV can be used as a basis for the diagnosis of SOH in lithium battery.[5]

The open circuit voltage measurement needs to test the charging and discharging processes separately.

The open circuit voltage measurement methods for lithium-ion battery under charging state are as follows:[6]

A. Lithium-ion battery is discharged to the lower cut-off voltage at constant current for 5 hours. The end voltage is measured as the open-circuit voltage at SOC=0%.

B. The battery is charged by constant current and constant voltage charging mode. The cut-off condition is that the maximum available capacity of charging capacity is 5%, or the charging current drops to the cut-off current, and the terminal voltage is measured after standing for 5 hours.

C. Repeat the process B until the lithium-ion battery is fully charged.

The open-circuit voltage measurement methods for lithium-ion batteries under discharge state are as follows:

D. The lithium-ion battery is charged with constant current and then constant voltage for 5 hours, and its terminal voltage was measured. The value was regarded as the open circuit voltage when SOC = 100%.

E. The lithium-ion battery is discharged with constant current. The cut-off condition is that the maximum available discharge capacity reaches 5% or the battery voltage is reduced to the lower cut-off voltage. The measured terminal voltage value is measured after 5 hours

F. Repeat the process E until the Lithium-ion battery reaches the lower cut-off voltage.

The open circuit voltage curves measured during charging and discharging are as follows:

The dotted line represents the charging process and the solid line represents the discharging process.
5. CURVE FITTING OF TERMINAL VOLTAGE DURING CHARGING AND DISCHARGING

In the process of measuring the open circuit voltage of lithium-ion battery, it is found that each time the open circuit voltage value is measured, the battery needs to be stationary for a period of time before the end voltage value can be taken as the open circuit voltage value. Static battery is designed to distribute electrolytes evenly in order to obtain a stable terminal voltage. In the actual operation of lithium-ion battery, due to the polarization characteristics of battery, the measured terminal voltage can't be used as open circuit voltage when the lithium-ion battery is not stationary. The polarization characteristics of battery can be reflected by the RC link in the equivalent model of battery.

The terminal voltage data measured during charging and discharging are fitted with the mean value. The process is as follows:\textsuperscript{7}\textsuperscript{8}

\[ y = \sum_{i=0}^{n} a_i x^i = a_n x^n + a_{n-1} x^{n-1} + \cdots + a_1 x + a_0 \]  

(6)
\( a_i \) represents the required coefficients.

Using the matrices represent the above polynomials.

\[
Y = X_0A
\]  

(7)

The expression of \( A \) is obtained by polynomial calculation.

\[
A = (X_0^TX_0)^{-1}X_0^TY
\]  

(8)

The curve obtained by fitting calculation is shown in the figure, and the equation of fitting curve is as follows:

\[
Y = -8.719282791242637e^{-17}x^8 - 2.638130563683569e^{-14}x^7 + 1.978521072619686e^{-11}x^6 - 3.857065515772513e^{07}x^5 + 3.681395273298247e^{09}x^4 + 1.947345668605119e^{06}x^3 + 5.86046469492734e^{04}x^2 - 0.096806444656671x + 2.971024094124971
\]  

(9)

The results of each order in the fitting calculation are as follows:

In order to verify the relationship between the measured terminal voltage and the actual open-circuit voltage, the fitting curve of the terminal voltage is compared with the actual open-circuit voltage curve. The results are as follows:
Fig. 8 Difference between Fitting Curve and Actual Curve

The dotted line represents the fitting curve of terminal voltage and the solid line represents the actual open circuit voltage curve.

6. CONCLUSION

By comparing the fitting curve with the actual open circuit voltage curve, it is found that the fitting curve has a high coincidence with the actual open circuit voltage curve and basically keeps the same.

The actual open circuit voltage curve describes the relationship between the open circuit voltage and the State of Charge (SOC) of lithium-ion battery, namely OCV-SOC curve. Through experimental analysis, it is verified that the terminal voltage curve obtained by fitting the measured value of the battery working is basically consistent with the actual OCV-SOC curve. Therefore, the terminal voltage at work can be linked with SOC, which provides a basis for estimating SOC using the terminal voltage value.

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