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Improvement and Simulation Test of PNGV Equivalent Circuit Model

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Abstract. This paper mainly optimizes the existing PNGV battery model and measures the related parameters. At the same time, the corresponding simulation tests are carried out for different situations, which proves the feasibility of the optimization model, which is helpful for related research.

INTRODUCTION

PNGV is a representative model of the nonlinear low-order model [1], which was formally proposed in 2001 and then became a classic model to study the equivalent circuit model in power batteries. In order to study the characteristics of battery more accurately, this paper has improved the battery. The battery used in this paper is lithium iron phosphate battery, the battery model is ANR26650mlA, and the research and development company is American A23 Company. Through literature review [2], the working voltage of the battery is 3.2V, the highest instantaneous current at discharge is 60A, the battery charging point cut-off voltage is 3.6V, the discharge cut-off point is 2.0V, and the capacity is 2200mAh.

TRADITIONAL EQUIVALENT CIRCUIT MODEL OF PNGV AND ITS IMPROVING

The traditional PNGV, as Figure 1 shown, not only considers the influence of the running state of the battery on the battery, but also takes into account a series of factors such as the external operating environment of the battery. The running state of the battery can be accurately described, and the transient running response state can be accurately described, which can be used as the model of automobile power battery.

![Figure 1. The traditional PNGV model.](image)
We performed HPPC pulse test on the battery and obtained the corresponding voltage waveform. It can be seen from the Figure 2 that the linear drop of voltage from A to B is caused by the ohm internal resistance of the battery. The voltage change from B to C is caused by RC link. However, it is obvious that the voltage change rate of BC segment has two distinct segments, so at least two RC segments can well simulate the voltage change of BC segment. Therefore, we add a RC link based on the PNGV model. Two RC links to reflect the two poles in the impedance spectrum can more accurately simulate the variation trend of voltage in HPPC test. The improved PNGV model is shown in Figure 3.

\[
U_L = U_{ocv} - U_{p1} - U_{p2} - I_L R_0
\]
PARAMETER IDENTIFICATION AND SIMULATION OF IMPROVED PNGV MODEL

Parameter Identification of Improved PNGV Model

The improved equivalent circuit model of PNGV is different from the original model. This model contains second-order RC links, and the mathematical model is relatively complex, which is "black box modeling"[3]. Based on different SOC situations, we use the Parameter Estimation kit embedded in Simulink to obtain the test data. Then we use the fourth order polynomial to fit the discrete data as shown in formula (2). It is similar to the fitting result of fifth order polynomial, and the calculation quantity is also reduced a lot. The fitting results are shown in Table 1.

\[ f(x) = a_4x^4 + a_3x^3 + a_2x^2 + a_1x + a_0 \]  \hspace{1cm} (2)

In the equation, the independent variable \( x \) is the value of SOC, and \( f(x) \) is the Curve to be fitted. The Curve Fitting kit (Curve Fitting) provided by matlab is used for parameter Fitting.

<table>
<thead>
<tr>
<th>( R_{p1}/\Omega )</th>
<th>( C_{p1}/F )</th>
<th>( R_{p2}/\Omega )</th>
<th>( C_{p2}/F )</th>
<th>( R_0/\Omega )</th>
</tr>
</thead>
<tbody>
<tr>
<td>a_1 0.006671</td>
<td>1657</td>
<td>0.00167</td>
<td>1019</td>
<td>0.01951</td>
</tr>
<tr>
<td>a_2 0.001502</td>
<td>465.1</td>
<td>0.00240</td>
<td>337.8</td>
<td>-0.00863</td>
</tr>
<tr>
<td>a_3 -0.000091</td>
<td>-42.67</td>
<td>-0.00011</td>
<td>-52.23</td>
<td>0.02345</td>
</tr>
<tr>
<td>a_4 -0.001309</td>
<td>-97.23</td>
<td>-0.00909</td>
<td>-101.2</td>
<td>-0.03701</td>
</tr>
<tr>
<td>a_5 0.000692</td>
<td>-19.12</td>
<td>0.00019</td>
<td>-21.83</td>
<td>0.02044</td>
</tr>
</tbody>
</table>

Simulation of Improved PNGV Model

According to section 3.3, we select the appropriate SOC value. Then we use the original components in the component library in Simulink to directly build corresponding circuits for verification. According to different working conditions, we have carried out corresponding simulation test[38].

**HPPC Pulse Test Verification**

The improved model was tested by HPPC impulse current, and the battery was charged and discharged with 5C constant current. In order to ensure enough time for the battery to return to the steady state after discharge, the charging pulse was applied after the discharge was completed. We respectively used two sizes of current for charge-discharge testing.

First, the model was tested under the condition of 1.25A charge-discharge current and 4s charge-discharge time. In Simulink, four step signals are given at the battery end to achieve the acquisition of impulse current as Figure 4 shown, and we set the simulation time to 400 seconds.
FIGURE 4. Impulse current curve under 1.25A

FIGURE 5. Impulse current curve under 5A
After the simulation, we observed the waveform of the oscilloscope. It can be seen from Figure 6 that the voltage waveform of the battery simulation terminal is basically the same as the pulse waveform given. As the values of the resistance and capacitance used in the simulation model are all constant, there is a certain error, but the error is small within the allowable error range. It can be seen from Figure 6 that when charging and discharging, the SOC value of the battery is linearly related to time, which conforms to the law of constant current charging and discharging. Therefore, under this condition, the improved PNGV equivalent circuit model can well reflect the battery characteristics.

Then, we change the charge-discharge current and time. The test was conducted under the condition that the charge-discharge current was 5A and the charge-discharge time was 1 second. The step signal given is shown in Figure 5, and we set the simulation time to 200 seconds.
It can be seen from Figure 8 that the battery simulation terminal voltage waveform under the condition of 5A constant current is similar to that under the condition of 1.25A constant current. It can be seen from Figure 9 that the SOC value of the battery conforms to the law of constant current charge and discharge. Therefore, under this condition, the improved PNGV equivalent circuit model can well reflect the battery characteristics within the error allowable range.

To sum up, for HPPC impulse response, the improved PNGV equivalent circuit model can well reflect the battery characteristics within the error allowable range.
Other Charge-Discharge Forms

For the battery model, HPPC pulse test is only a more appropriate method to reflect the battery characteristics. However, in the process of using the battery, it is more about constant current and constant voltage charging, etc. In this section, the simulation response of the battery model in these cases is mainly studied.

3.2.2.1 Constant Current Pulse Charging and Discharging

Constant current pulse charge-discharge is similar to HPPC pulse test. In discharging, we use the Pulse Generator module to provide the required rectangular waves as Figure 10 shown and we set the simulation time to 500 seconds.

![FIGURE 10. Constant current pulse discharging curve](image1)

![FIGURE 11. Constant current pulse charging curve](image2)
After the simulation, observe the oscilloscope waveform. It can be seen from Figure 12 that after each cycle of the rectangular wave, the drop valley value of the battery terminal voltage and the rise peak are constantly decreasing, which is caused by the drop of the battery discharge terminal voltage. It can also be seen from the changes of the battery SOC value in Figure 13 that the battery SOC value decreases gradually with the addition of impulse current.

When the battery is charged with constant current, the initial value of SOC is set to 0.02, and the pulse waveform is shown in the Figure 11. We set the simulation time to 500 seconds.
After the simulation, observe the oscilloscope waveform. As shown in Figure 14, after each cycle of the rectangular wave, the rising peak value of the battery terminal voltage and the falling valley value are constantly rising, which is caused by the rising voltage of the battery charging terminal. It can also be seen from the changes of the battery SOC value in Figure 15 that the battery SOC value is gradually increasing with the addition of the impulse current.

3.2.2.2 Constant Voltage Charging

Constant voltage charging is more common in battery applications. There are many DC and AC variators that enable the battery to maintain a constant voltage at the charging end during charging. In this test, we adopted 3.7V constant voltage charging and set the initialSOC at 0.02. The simulation time is set to 500 seconds.
Measuring the battery terminal voltage is meaningless because it is charged at constant voltage. The current IL waveform of the battery main circuit is shown in Figure 16, and the waveform of the battery SOC value is shown in Figure 17. As the charging process goes on, the voltage of the open circuit in the battery increases gradually. The difference between internal potential and external potential decreases gradually, so the discharge current decreases gradually. And the battery SOC value approximately increases linearly with time.

![Cell main loop current IL waveform](image1)

**FIGURE 16.** Cell main loop current IL waveform

![SOC values in Constant voltage charging](image2)

**FIGURE 17.** SOC values in Constant voltage charging

### 3.2.2.3 Battery discharge under city condition

In the operation process of electric vehicles, they are not in a simple constant current and constant pressure environment, but in a more complex discharge environment. We performed discharge test using discharge current data in UDDS operating condition in the United States [5]. The initial value of SOC is set to 0.99, and the simulation time is set to 500 seconds. We get the corresponding waveform.
The main work of this chapter is to optimize and simulate the PNGV equivalent circuit model. And the corresponding parameter identification model is given. Under the appropriate initial value of SOC, we tested the HPPC impulse response of the model, the constant current impulse charge-discharge response, the constant pressure charging response and the response under the operating condition. It is proved that the improved PNGV model can characterize the battery characteristics well, and has reference value to the related research.
REFERENCES