Empirical performance modelling of a lithium-ion battery of a solar car

I Kasatkin¹, M Egorov², E Zakhlebaev¹, *, E Kotov¹, I Selin², M Kukolev²

¹Youth Design Bureau, Peter the Great St.Petersburg Polytechnic University, Polytechnicheskaya 29, St. Petersburg, 195251, Russian Federation
²Peter the Great St.Petersburg Polytechnic University, Polytechnicheskaya 29, St. Petersburg, 195251, Russian Federation

* E-mail: egorov12m2u@mail.ru

Abstract. The aim of the work is to ascertain a solar car battery performance. The student engineering team of Peter the Great Petersburg Polytechnic University designs the car. Parameters as terminal voltage, operating current, power losses and efficiency are determined depending on battery state of charge (SOC) and operating power. For electrochemical transient modelling, an equivalent RC-circuit is included based on Thevenin battery model. It is assumed in the model that internal resistance, open circuit voltage and the RC-circuit voltage drop depends only on the SOC. Experimental data was obtained from the LG INR18650 MJ1 battery discharge curves. Modelling was performed for SOC values in the range of 0.17 to 0.95 since the terminal voltage dependence on SOC is nearly linear there. The proposed model is sufficient for state of charge estimating and battery performance determination.

1. Introduction

Electric vehicles and renewable energy sources offer great potential for increasing energy efficiency, reducing greenhouse gas emissions and relieving reliance on hydrocarbon fuel reserves [1]. But applying these green technologies could be difficult without efficient and reliable energy storage method [2].

Lithium-ion battery is considered as one of the most promising secondary battery technologies due to its high energy density, charge retention capabilities and long cycling life [3]. It is commonly used in electric vehicles, uninterruptible power supply systems, renewable energy storage systems and so on.

Within a student engineering project «Polytech Solar» of Peter the Great St. Petersburg Polytechnic University a solar electric car is constructed that is powered by a storage lithium-ion battery which is charged by a solar photovoltaic panel [4].

The performance and utility of systems using lithium-ion batteries is principally dependent on the performance and efficiency of the battery pack [5]. Battery models are used for optimal usage of batteries, predicting the amount of stored energy and safe charging and discharging.

2. The design and principle of operation of the DFIM

There are various types of battery models to calculate the battery performance parameters and its efficiency at different operating conditions. There are physical models that simulate the internal
electrochemical processes in the battery and empirical models replicating battery behavior as a «black box» [6-8].

Physical models are sophisticated and contain quite a large number of parameters but they allow to achieve high accuracy. Empirical models significantly simplify the modeling of physical processes in the battery but at the same time they give acceptable accuracy for battery performance estimation [9]. Most empirical models are based on equivalent circuits. In this paper the modelling is based on Thevenin empirical battery model.

2.1. Thevenin battery model
Thevenin battery model is a commonly used battery equivalent circuit model based on resistive and capacitive properties of batteries. The capacitive impedance produced from polarization phenomena can be simulated with the resistor \( R \) and the capacitor \( C \), as shown in Figure 1. Where \( R_{in} \) is the internal ohmic resistance of the battery, \( R \) and \( C \) are the polarization resistance and the polarization capacitance, both of which form the \( RC \) circuit to describe the polarization of the battery [10-11].

![Figure 1. Thevenin equivalent battery electrical diagram: \( U_{OC} \) — open circuit voltage, \( U_T \) — terminal voltage.](image)

Proposed battery model is basically Thevenin model considering the voltage across the parallel components \( R \) and \( C \) a voltage \( U_d \) that is function of \( SOC \). The following parameters are also considered as function of \( SOC \):

\[
U_{OC} = f(SOC); \quad R_{in} = f(SOC); \quad U_d = f(SOC).
\]

Cubic dependence on \( SOC \) is reviewed. Cubic dependence is \( f(SOC) = k_1 \cdot SOC + k_2 \cdot SOC^2 + k_3 \cdot SOC^3 + k_4 \), where \( k_i \) — constant coefficients identified by experimental data.

\( SOC \) is defined as the ratio of the remaining capacity of the battery to the rated capacity at a standard discharge rate [12]. For the studied LG INR18650 MJ1 battery the standard discharge rate by specification is 0.2C. The formula is as follows:

\[
SOC = \frac{Q_c}{Q_N},
\]

where \( Q_c \) is the battery remaining capacity, \( Q_N \) is the capacity under standard discharge rate.

2.2. Analysis of proposed battery model
It is considered that the battery can be connected to both the charger and the load at the same time.

The battery cannot simultaneously be charged and discharged literally, i.e., the current cannot flow through the battery in reverse directions, so there is either a discharge or a charge, depending on charge power \( P_{in} \) and discharge power \( P_{out} \) values.

At the beginning of the calculation, the values of \( SOC \), charge and discharge power are known and it is required to find the terminal voltage \( U_T \), operating current \( I_{dis} \) or \( I_{ch} \), power losses \( P_{loss} \) and efficiency \( \eta \).

2.3. Charge model
First, discharge model is considered, \( P_{in} < P_{out} \).
Looking at the Figure 1, the following equations can be written for discharge process:
\[ U_T = U_{OC} - U_d - I_{dis} \cdot R_{in} \]  

(1)

where \( I_{dis} \) is discharge current.

\[ U_T = \frac{P}{I_{dis}} \]  

(2)

where \( P = P_{out} - P_{in} \).

Based on (1) and (2) equations the quadratic equation is compiled:

\[ I_{dis}^2 \cdot R_{in} - I_{dis} \cdot (U_{OC} - U_d) + P = 0. \]  

(3)

Solving the equation, the discharge current value is calculated, using the input power value:

\[ I_{dis} = \frac{(U_{OC} - U_d) - ((U_{OC} - U_d)^2 - 4R_{in}P)^{1/2}}{2R_{in}} \]  

(4)

2.4. Discharge model

The discharge model slightly differs, and the equation for the terminal voltage is:

\[ U_T = U_{OC} + U_d + I_{dis} \cdot R_{in}. \]

Now, \( P_{in} < P_{out} \) and \( P = P_{in} - P_{out} \).

In the same way as in equations (3) in clause 3.1, the charge current \( I_{ch} \) value is:

\[ I_{ch} = \frac{-(U_{OC} + U_d) + \left( (U_{OC} + U_d)^2 + 4R_{in}P \right)^{1/2}}{2R_{in}} \]  

(5)

2.5. Power losses

Power losses for both charge and discharge consist of losses on the internal resistance and on the RC circuit:

\[ P_{loss} = I^2 \cdot R_{in} + I \cdot U_d \]  

(6)

And the battery efficiency is

\[ \eta = 1 - \frac{P_{loss}}{P} \]  

(7)

It remains to find the dependencies \( U_{OC} = f(SOC) \); \( R_{in} = f(SOC) \); \( U_d = f(SOC) \) by processing the experimental data.

2.6. Dynamic model

To calculate \( SOC \) in dynamic process, measuring each \( \Delta t \) time interval:

\[ SOC = \text{old \( SOC \) + \( I \cdot \Delta t \)/}Q_N, \]

where \( I \) can be positive or negative whether it is charging or discharging [13].

3. Results and discussions

3.1. Experimental data processing

The discharge performance of the LG INR18650 MJ1 battery was obtained by fully discharging the battery cell at constant load of 0.7, 1, 3, 3.5, 5 A and 7 A currents, the 5 A discharge curve is shown on Figure 2.

The dependence \( U_T (SOC) \) was found for each curve, data was obtained with a step of 0.1 V.
SOC values were selected in the range of 0.17-0.95, since processes are relatively stable in it, and a simplified model can be applied [14].

For each constant SOC value with a step of 0.1 (or 10%) the dependence \( U_T(I) \) was approximated as cubic, then \( U_{OC} \) is found by clause that \( U_{OC} = U_T(I=0) \) [15]. An example for SOC=0.6 is shown in Figure 3, in this case \( U_{OC} = 3.8293 \) V.

The dependence \( U_T(I) \) after approximation is \( U_T = -0.0005 \cdot I^3 + 0.0087 \cdot I^2 - 0.0946 \cdot I + 3.8293 \).

Then, \( P_{\text{loss}}(I) \) is found as \( P_{\text{loss}}(I) = I \cdot R_{\text{in}} + U_d = U_{OC} - U_T \), this dependence is approximated linearly and the \( R_{\text{in}} \) and \( U_d \) values are obtained for each SOC value, an example is shown in Figure 4, and the \( R_{\text{in}} = 0.0537 \) Ohm and \( U_d = 0.0288 \) V for SOC=0.6.

The dependence \( P_{\text{loss}}(I) \) after approximation is \( P_{\text{loss}} = 0.0537 \cdot I + 0.0288 \)

Now the dependences \( U_{OC} = f(SOC) \); \( R_{\text{in}} = f(SOC) \); \( U_d = f(SOC) \) can be found by cubic approximation. Knowing these dependences and using the (1) and (4-7) equations, desired parameters can be calculated.

The modelling and experimental results comparison is performed. The example of comparison for 3 A discharge current is shown in Table 1.
Table 1. Modelling and experimental results comparison for 3A discharge current.

| SOC  | \( U_T \), V, modelling values | \( U_T \), V, experimental values | Model error |
|------|--------------------------------|-------------------------------|------------|
| 0.18 | 3.253                         | 3.204                         | 0.015      |
| 0.26 | 3.312                         | 3.300                         | 0.004      |
| 0.39 | 3.420                         | 3.399                         | 0.006      |
| 0.51 | 3.535                         | 3.502                         | 0.009      |
| 0.60 | 3.623                         | 3.600                         | 0.006      |
| 0.69 | 3.721                         | 3.704                         | 0.005      |
| 0.78 | 3.806                         | 3.803                         | 0.001      |
| 0.88 | 3.904                         | 3.900                         | 0.001      |

4. Conclusions

Battery performance parameters as terminal voltage, operating current, power losses and efficiency were determined depending on battery state of charge and operating power values. The linear dependence of terminal voltage on operating current was studied in the SOC range of 0.17 to 0.95. The model error does not exceed 2%. The proposed model is sufficient for state of charge estimating and battery performance determination.

In future researches it is planned to consider other types of terminal voltage dependencies on operating current.

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