Internal resistance of cells of lithium battery modules with FreedomCAR model

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Abstract

Internal resistance is usually calculated by EIS (Electrochemical Impedance Spectroscopy) method, which gives unrealistic low internal resistance values. In this paper internal resistance will be calculated from the voltage drop with FreedomCAR method where the validation of the results is much better (99%) than EIS method\cite{1}\cite{12}. Batteries are often tested per cell. But in most cases more than one single cell is needed for an application and the characteristics of a module of cells is not the same. In other cases the whole module is examined as one big cell, without looking on the individual cells. But the weakest cell affects the performance of the whole module. This research goes deeper than the module approach on batteries: the behavior of \textit{individual cells} is examined while they are working together \textit{in a module}. The battery model consists in most researches of an ideal voltage source and a simple internal resistance\cite{2}. In this work the advanced FreedomCAR battery model, created by Idaho National Laboratories (USA), is used: the cell is represented by an ideal voltage source with two internal resistances and two capacitors. Usually batteries are tested with very low constant currents (till 5% of the nominal current value) to show a high capacity value to the customer, while the customer needs the characteristics of the battery in \textit{real conditions}. Here the parameters are calculated by testing the battery packets in high \textit{pulse conditions}. The matching between the predicted and the measured voltage is proportional with the quality of the model. This was 99% (+-0.9%) in the tests. This means that the model is very close to the reality. Three types of Lithium-ion battery packets with 6-7 cells were tested.

\textbf{Keywords:} lithium battery, internal resistance, FreedomCar model, cell parameters

\textbf{ABBREVIATIONS}

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>OCV</td>
<td>Ideal battery voltage [V]</td>
</tr>
<tr>
<td>C</td>
<td>Capacity [Ah]</td>
</tr>
<tr>
<td>(I_{\text{max}})</td>
<td>Maximum charge current [A]</td>
</tr>
<tr>
<td>(I_{\text{dis}})</td>
<td>Discharge current [A]</td>
</tr>
<tr>
<td>(I_{\text{b}})</td>
<td>Battery load current [A]</td>
</tr>
<tr>
<td>(I_{\text{p}})</td>
<td>Current through polarization resistance [A]</td>
</tr>
<tr>
<td>OCV'</td>
<td>Variation of OCV per exchanged capacity [V/As]</td>
</tr>
<tr>
<td>(R_{\text{c}})</td>
<td>Internal resistance (general, total) [\Omega]</td>
</tr>
<tr>
<td>(R_{\text{p}})</td>
<td>Battery internal &quot;ohmic&quot; resistance [\Omega]</td>
</tr>
<tr>
<td>(R_{\text{p}})</td>
<td>Battery internal &quot;polarization&quot; resistance [\Omega]</td>
</tr>
<tr>
<td>SOC</td>
<td>State of Charge [As]</td>
</tr>
<tr>
<td>V</td>
<td>Voltage [V]</td>
</tr>
<tr>
<td>(V_{\text{cc}})</td>
<td>Closed circuit voltage</td>
</tr>
<tr>
<td>(V_{\text{t}})</td>
<td>Battery terminal voltage [V]</td>
</tr>
<tr>
<td>(V_{\text{o}})</td>
<td>Open circuit voltage</td>
</tr>
<tr>
<td>(\tau)</td>
<td>Polarization constant = (R_{\text{p}} \times C) [s]</td>
</tr>
</tbody>
</table>
1 Introduction

The evolution of the cell parameters are determined as a function of the number of cycles and as a function of SOC. The parameters are calculated at the package level and at the cell level. Three types of lithium batteries are listed in Table 1. Six (seven for type 2) cells are placed in series.

<table>
<thead>
<tr>
<th>Type</th>
<th>V</th>
<th>C</th>
<th>I_{Ah,\text{max}}</th>
<th>I_{Ah,\text{max}}</th>
<th>I_{Ah,\text{max}}</th>
<th>R_{i}</th>
<th>M</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.3V</td>
<td>2 Ah</td>
<td>70 A cont.</td>
<td>10A cont.</td>
<td>10A cont.</td>
<td>8 mΩ</td>
<td>70 g</td>
<td>66-26-26 mm</td>
</tr>
<tr>
<td>2</td>
<td>3.2V</td>
<td>3.2 Ah</td>
<td>12 A cont.</td>
<td>2A cont.</td>
<td>2A cont.</td>
<td>&lt;19 mΩ</td>
<td>82 g</td>
<td>65-26-26 mm</td>
</tr>
<tr>
<td>3</td>
<td>3.2V</td>
<td>10Ah</td>
<td>140 A 10 s</td>
<td>28 A 30 s</td>
<td>28 A 30 s</td>
<td>6 mΩ</td>
<td>400 g</td>
<td>138-40-40 mm</td>
</tr>
</tbody>
</table>

Table 1: Datasheet of the batteries

2 Battery model

The FreedomCAR linear battery model is shown on Fig. 1. A high pulsing current I_L (Fig. 2), has to be loaded according to this model [3][4][5].

\[ V_L = OCV - OCV' \left[ I_L \text{d}t \right] - R_0 \left[ I_L \right] - R_P \left[ I_P \right] \]  \tag{1}

After discretisation of equation (1), the next simplified equation can be written:

\[ \frac{d I_P}{d t} = \frac{I_L - I_P}{\tau} \quad \text{or} \quad \frac{d I_L}{d t} = \frac{dt}{\tau} \]  \tag{2}

In (1):
- \( V_L, I_L \) and \( t \) are measured
- \( I_P \) comes from (4)
- \( OCV, OCV', R_0, \) and \( R_P \) are calculated by linear regression method

Discretising and solving the differential equation (2), with the starting condition \( I_P(t=0) = 0 \), gives for every sample i:

\[ I_{P,i} = \left( 1 - \left(1 - \frac{\Delta t}{\tau} \right) \right) \cdot I_{L,i} + \left( \frac{1 - \Delta t}{\Delta t} \cdot e^{-\frac{\Delta t}{\tau}} \right) \cdot I_{L,i-1} + \left( \frac{-\Delta t}{\Delta t} \cdot e^{-\frac{\Delta t}{\tau}} \right) \cdot I_{P,i-1} \]  \tag{4}

\( \tau \) is chosen or calibrated in the model so that the fitting between the measured and estimated voltage (Fig. 3) would be optimal. The difference between the measured and the estimated voltage \( V_L \) in [%] (Fig. 3) is proportional with the quality of the model. This is around 99% in the tests.
3 TEST RESULTS: Internal resistance

3.1 Internal Resistance

There are 205 FreedomCar tests (Fig. 2) done on the three battery types, which corresponds to 685Ah. The temperature is kept constant at approximately 25 °C by a fan and is also measured. As mentioned in chapter 2 the voltages of the cells will be measured as well as the current and the temperature of one cell. This data is filled in in a spreadsheet, where OCV’, Rp, Ro and OCV will be calculated.

The result is shown on Table 2.

3.2 Influence of SOC

The table shows that when the SOC decreases from 100 to 15% the total internal resistance Ri (=Rp+Ro) increases with 50-100%, especially due to Rp. Rp has a more dynamic character in comparison with Ro which stays nearly constant.

3.3 Comparison with the datasheets

The calculated resistance is 50-100% higher than the value measured by the producer. Type 3 has the lowest internal resistance and the value provided from the producer is much closer to the one which is calculated by FreedomCar model.

3.4 Imbalance between the cells

Type 3 has the lowest internal resistance imbalance between the cells. At full SOC the variation of Ri between the cells was 0.7mΩ. For type 1 and 2 it was 13 and 10mΩ. That means a battery management system (to balance cells) is less needed in case of type 3 than in case of type 1 or 2, which is an advantage of type 3.

3.5 Cell versus pack

Consider a pack which is capable to deliver 10Ah at 24V with only one type of cell by placing the right number of cells in parallel and/or in series, then the three types can be compared at package level (Table 3). The combination manner is written at the top of the columns. E.g. for type 1 8 cells are placed in series and form a group; there are 4 such groups placed in parallel. This is abbreviated as “8s4p” in Table 3. 8 cells are needed to get 24V and 4 groups in parallel are needed to reach 10Ah. For type 2 3 parallel placed groups contain each 8 in series placed cells (8s3p).

The internal resistance increases with approx. 50% when the SOC decreases from 100% to 15% for both (10Ah and 120A) packs. The internal resistance value on the datasheets is the half of the one from the FreedomCar model. Now it is type 1 which has the lowest internal resistance value because of many parallel placed cells (4 parallel groups of cells, each containing 8 cells in series). Putting so many cells in a pack asks for a good battery management, which is a disadvantage.

3.6 Influence of resting cells

Fig. 4, Fig. 5 and Fig. 6 show Rp, Ro and OCV’ of type 1 as a function of SOC in case when the cells
have rested for 1 day ("1 day of no load time") and in case when the cells have already done 5 non-stop discharge cycles and have only rested for half an hour ("30min. of no load time").

When the parameters are measured before and after 5 discharge cycles, \( R_p \) and \( R_o \) increase with approx. 20%.

OCV’ (Fig. 6) is the decrease of the cell voltage per discharged Ah. It decreases with 40% when the SOC decreases from 100% to 33% and it increases with 15% in case when the batteries have not rested.

### 3.7 Influence of current

Changing the load profile does increase the internal resistance of a battery, even if the new profile is less heavy than the previous one. Fig. 7 shows \( R_p \) for type 3. The FreedomCar tests are done at 120A until 509 Ah, also written in red on the figure. From 509 Ah to 556 Ah the tests are done at 60A. From 556 Ah on the tests are done at 40A.

When the cycle profile changes for the first time from 120A to 60A \( R_p \) increases with 25%. But after a few cycles it comes back to the original value.
4 Influence on discharge time

4.1 Influence of exchanged capacity on discharge time

When the exchanged capacity increases, the battery can deliver the maximum current for shorter time (Fig. 8).

![Fig. 8: Discharge time as a function of the exchanged capacity](image)

4.2 Influence of SOC on discharge time

When the SOC of the battery decreases, the battery provides the requested current during a shorter time (Fig. 9).

![Fig. 9: Discharge time = f(SOC)](image)

5 Temperature and ageing

The temperature increases with 2°C when several tests are done continuously with less pause despite of the fan. This has the same effect as decreasing the SOC: Rp and Ro increases with the increasing temperature.

![Fig. 10: Temperature[°C] as a function of time[h:min] for type3](image)

![Fig. 11: Temperature[°C] and capacity as a function of time [h:min] for type 3](image)

Fig. 11 shows that the decrease of the capacity at high discharge currents is not only due to the high current but also due to the high temperature, which increases up to 45°C [6]. The fan was not sufficient to cool the battery when it was discharging with 80A CC until he was empty. The temperature increased till 45°C. No ageing test were performed neither was the influence of temperature analysed at the moments. This will be carried out in future work. But the producer did a ageing test for type 1 (Fig. 12).
6 Energy and efficiency

6.1 Energy

Fig. 13 show the energy imbalance between the cells for type 3 cells. Cell 5 and 3 got the lowest energy input because of their little higher internal resistance in comparison with other cells. The efficiency of cell 3 and 5 is also low on Fig. 15.

6.2 Efficiency

Fig. 14 and Fig. 15 show the efficiency of type 1 and type 3 cells.

6.3 Energy loss

Energy loss of the considered packs (§3.5) is calculated by their internal resistance from Table 3. The current and the time is taken from the capacity tests.

\[ E_{loss} = R_i I^2 t = R_i I^2 \frac{Cap}{I} \]  

The energy loss due to the internal resistance is between 4 kWs and 33 kWs. Type 1 has the lowest loss. The percentages are also calculated, referred to the maximum energy that the packs contain.
Table 4: Energy loss in [kWs] and in [%] for packs

7 Capacity

Fig. 16, Fig. 17 and Fig. 18 show the capacity for the three cell types. They are in the order of what is written on the datasheet, except type 2. It has a lower capacity than on the datasheet because the cells were charged to 3.55V instead of 3.65V in order to be safe.

8 Voltage imbalance

Voltage imbalance between the cells is maximum 0.2V (Fig. 19). It decreases when the cells are charged with a low current.
9 CONCLUSION

The internal resistance is 50-100% higher than the value on the producers’ datasheet. Moreover it increases with 50-100% when the battery gets empty. Furthermore it increases with 20% when the cells have not rested for long time.

Type 3 cell has the lowest internal resistance and shows also that the producers can provide the realistic value for internal resistance.

The internal resistance imbalance is lowest for type 3 cell. This can be correlated with the voltage imbalance. If the voltage imbalance is low, then there is less need for a battery management or the energy system is less dependent from a battery management system.

Decreasing the load current increases the internal resistance for few cycles. After few cycles the internal resistance drops down to the original value. So it is only the change of the load profile that increases the internal resistance in this case.

The temperature only increases with 2°C during one FreedomCar test.

The energy loss is calculated from the internal resistance value.

The efficiency of the cells are around 88%.

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