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Influence of Pulse Variations on the Parameters of First Order Empirical Li-Ion Battery Model

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Abstract

Battery performance and safety constitute a bottleneck for electric vehicles to penetrate the car market. Online battery models are one of the engineering tools to enhance their performance. Empirical battery models form the subject of many scientific publications. In this paper a study, is performed of the usefulness of the first order impedance model through the consistency of the parameters under changes in the calibration signal, i.e. the current pulse. It can be concluded that simple first order models show little potential to really increase battery performance. Only the equivalent series resistance of the first order impedance model is insensitive to small variations of the calibration signal.

Keywords: Li-Ion battery, empirical modelling, Equivalent Circuit, First-Order Model, HPPC test

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1 Introduction

Since the introduction of Lithium-Ion Batteries (LIB) a range of mathematical and computational modeling tools have been developed in order to improve their design or performance. These modeling tools can be categorized in three main areas: empirical models, physics-based models and computational chemistry. Empirical models, also known as black box models, are used to address the issue of battery performance and State-Of-Health (SoH) estimation [1]. This work is limited to isothermal empirical modeling.

Empirical models rely upon experimental data (current-voltage) of a battery that has already been built and tested. A mathematical framework is chosen which can reproduce corresponding input-output behavior. Common used mathematical frameworks are neural nets [2], Electric Circuit Models (ECM) [3] or a combination of methods [2]. Electric Circuit Models however are by far the most used model. Their popularity is due to their conceptual and computational simplicity and relative high accuracy [4]. They also serve well as a state-space model in SoC estimation algorithms such as Kalman Filtering [5, 6]. Additional they are easy to use in co-design of interfacing electric equipment.

The empirical modeling problem can be formulated more rigorously as followed: a LIB represents a voltage source with a non-linear time varying impedance. Knowing and predicting the impedance allows us to increase battery performance. The goal is to develop an impedance model which allows us to accurately relate the state (SoC and SoH) of a cell with its current-voltage response. In this context it’s important that the selected model gives us reliable information on the state of the cell. The impedance of a cell varies over its life time and thus provides us information about the SoH. Here we studied the influence of the calibration signal (the current) on the parameters of the commonly used First Order Model (FOM) which is also known as Thévenin model, see Figure 1.

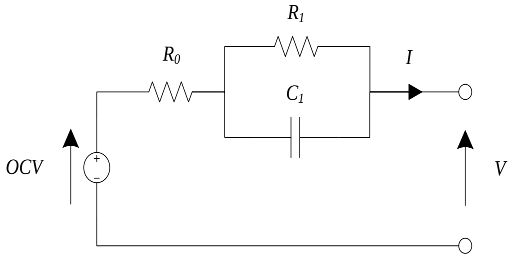

Figure 1: First Order Equivalent Circuit model

2 First-Order Model

The First Order Model (FOM) is characterized by the Open Circuit Voltage (*OCV*) and the R_0-R_1C_1-circuit. The OCV is equal to the terminal cell voltage after long resting periods (> 1h) and is a function of the SoC. It is assumed that in a certain working point the R_0-R_1C_1-circuit characterizes the dynamic change of the potential difference between the OCV and terminal cell voltage (*V*) when the cell is under load.

Although a LIB has a non-linear electric impedance, it is assumed that for a certain SoC, current rate and temperature it can be approximated by a linear ECM [4, 7-9]. Even more, because the parameters (internal resistance for instance) of the ECM will change over the life of a cell, it is suggested that their values are representative for the SoH [4]. The Nyquist plot of a LIB however, is different than that of a FOM [9]. Their sole justification for the model is the relative small value of the difference between the measured and experimental voltage. This error may not be the sole pillar on which the justification of an empirical model rests, at least if one wants to do anything more than simply reproducing I-V simulation. If the latter is the case, one should not bear any meaning to the numerical values of the electric circuit parameters. In addition, an extrapolation of the parameters over the lifetime of the battery under different load conditions would be impossible.

A second pillar can be the consistency of the parameter values under small changes of the working point and the calibration signal, i.e. the current pulse. Changes in the working point are mainly related to the SoC and the current rate at which the ECM is calibrated.

2.1 Calibration signal

One has the choice to characterize the input and output in the time domain (Pulse Tests) or in the frequency domain (Electrochemical Impedance Spectroscopy). Both approaches have their advantages and disadvantages. Step functions, in this case current pulses, are the preferred input signals for time domain characterization. Based on current and terminal cell voltage measurement the parameters of the ECM are determined. We investigated the influences of changes of the calibration signal in the time domain.

2.2 Parameter estimation

The parameter values are determined by an algorithm which minimizes the difference between the measured voltage and simulated voltage [9, 10]. In the domain of all possible model parameters this algorithm looks for these which minimize the sum of the squares of the errors, or at least a local minimum which is near to the starting values and satisfies convergence criteria.

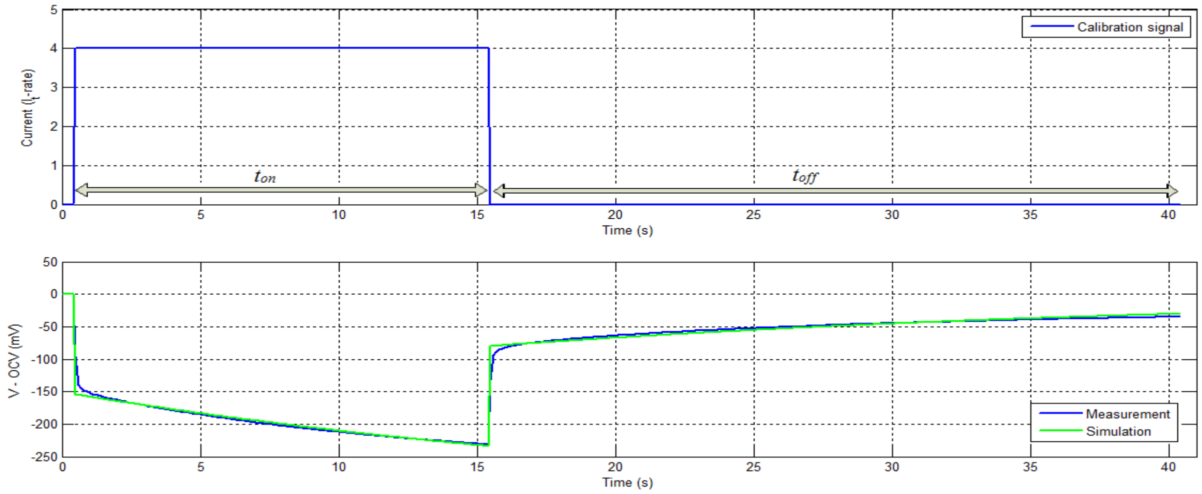

Figure 2: The figure above is the input (calibration) signal, lower figure is the measured output and fitted ECM response

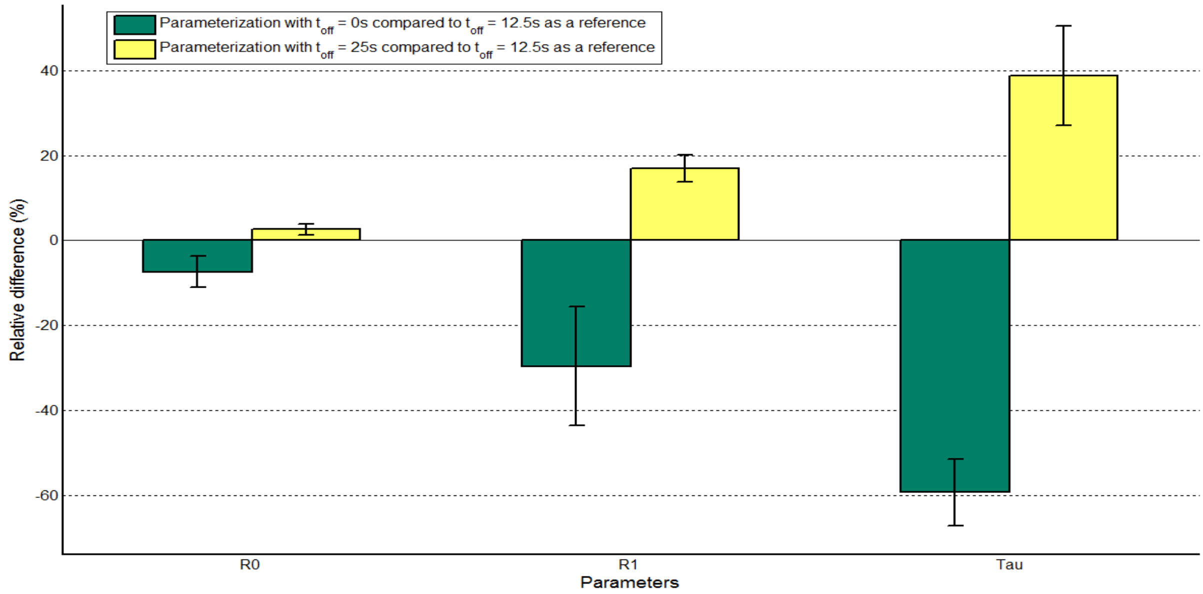

Figure 3: Influence of t_{off} on the ECM parameters for a *2It* discharge pulse averaged over the SoC window. The height of the bars is mean value of the relative difference; the error bars have a width of two times the standard deviation of the relative difference

3 Sensitivity Analysis

If an impedance model would be representative for a LIB response in a certain working point then a small change in the calibration signal should not result in major variations of the model parameters (R_0, R_1, $\tau = R_1.C_1$ in the case of a FOM). Small changes of the calibration signal can be changes in the amplitude or length of the pulse. To analyze this matter more rigorously we will use following notations: t_{on} and t_{off} defined in Figure 2. t_{on} is the time in which the charge or discharge current is applied to the cell and t_{off} is the time after the pulse during which no current is applied.

We studied the influence of variations in t_{off} and t_{on} on the parameter values of FOM over a SoC window from 20 to 90% and for three current rates ($1I_t$, $2I_t$ and $4I_t$) for five new Li-Ion cells.

First the influence of t_{off} was investigated by comparing parameter values fitted over the signal $t_{on} + t_{off}$ with t_{off} respectively equal to *0*, t_{on} and $2.t_{on}$ ($t_{on}= 12.5s$). We took the parameters for $t_{off} = t_{on}$ as a reference when calculating the relative change of the parameters. The trend of the change of the parameters is the same over the whole SoC window, hence we averaged out the relatively change of parameters over the SoC window. The results are shown in Figure 3. The influence on the ohmic resistance R_0 is relative small (less than 10%). The influence on R_1 (20 to 30%) and the time constant τ (40 to 50%) is significantly larger. The latter clearly indicates that the relaxing of the voltage is of much slower dynamic because the time constant τ rises as t_{off} increases. Therefor we concluded that the parameters should only be fitting during the period t_{on} in which the current is applied.

Next we studied the influence of t_{on} by determining the parameters for t_{on} equal to *10*, *12.5* and *15s* with t_{off} being *0s*. If the real dynamic response of cell would be the same as that of FOM then these small variations in the calibration signal should not result in big changes of the parameters. The results are shown in Figure 4. One can observe that variations in the length of the pulse result in small variations of R_0 (around 2%) and in considerable variations of R_1 (10 to 20%) and τ (30 to 50%) of the FOM.

Finally to quantify the quality of the different parameters fitted over short and longer pulses we applied a life-cycle current profile to the FOM as well as to a real cell. Three different groups of parameters were compared: parameters estimated over a short (t_{on} = 10s) middle-long (t_{on} = 12.5s) and long (t_{on} = 15s) pulse.

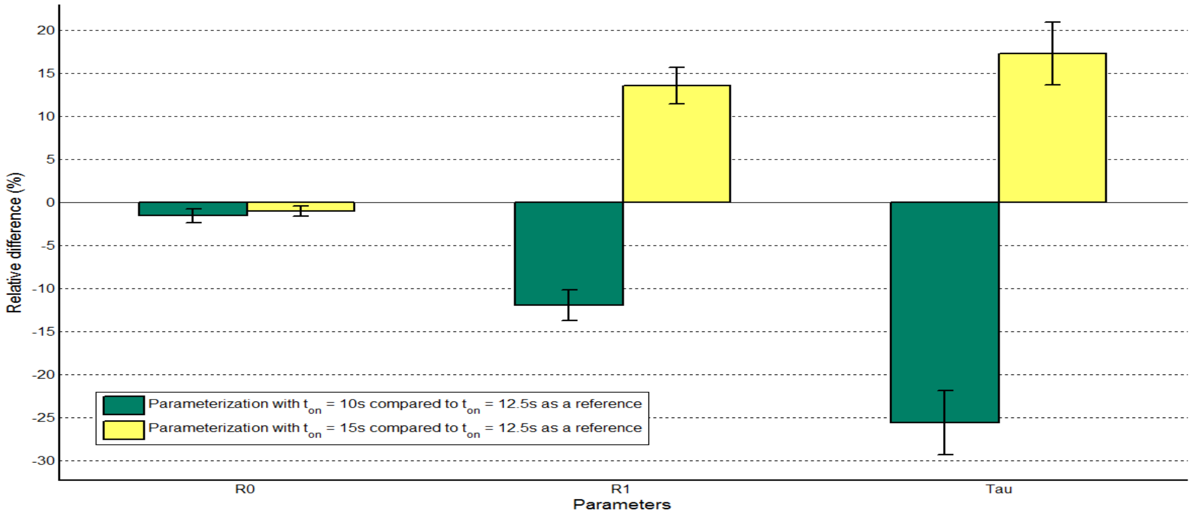

Figure 4: Influence of t_{on} on the ECM parameters for a *2It* discharge pulse averaged over the SoC window. The height of the bars is mean value of the relative difference; the error bars have a width of two times the standard deviation of the relative difference

On the first plot of figure 5 one can see the terminal cell voltage response of the real cell as well as the simulation of this voltage. In the second plot one can see the relative error defined by the difference of the measured (V_m) and simulated (V_s) terminal cell voltage divided by the usable voltage range of the cell.

$$\varepsilon = \frac{V_m - V_s}{V_{max} - V_{min}} \tag{1}$$

The usable voltage range of a cell is the difference of the maximum cell voltage (4.2V) and minimum cell voltage (2.7V). To compare the three different groups of parameters the Root Mean Square (RMS) of the difference of the measured and simulated cell voltage was determined. The RMS value as well as the maximum value of the relative error is given in Table 1. From Table 1 it can be seen that parameters fitted over longer pulses result in a slightly lower but not significant difference between the simulated and measured cell voltage.

Table 1: Maximum relative error and RMS value of the difference of the measured and simulated cell voltage for three different groups of parameters

Parameter group	1	2	3
t_{on} (s)	10.0	12.5	15.0
Max. |ε| (%)	5.39	5.33	5.23
RMS V_m-V_s (mV)	22.8	21.2	20.4

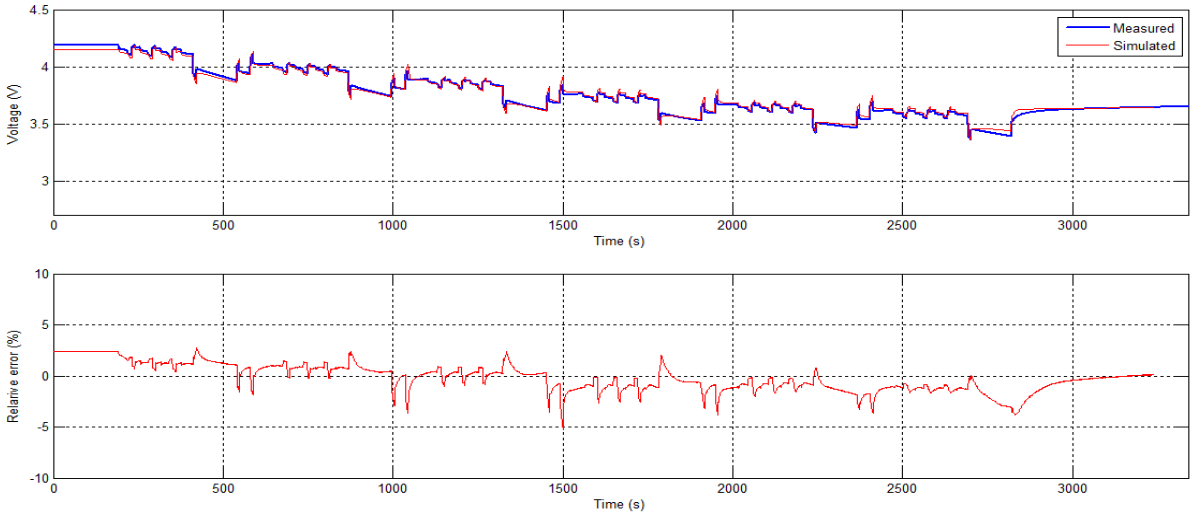

Figure 5: above are the real and simulated cell voltage are plotted, below the relative error is plotted. The simulated cell voltage was obtained by a First Order Model. In this figure the parameters fitted over 15s pulses were used.

4 Conclusion

In order to enhance the performance of current state-of-the-art Li-Ion batteries accurate battery models are required. These models should be able to simulate the output voltage and provide us with reliable information on state of the battery cell (SoC and SoH). The ease of calibrating the model as well as calculation time are in this context of great importance. First order models require low simulation time and are easy to calibrate. However if one looks for a consistent empirical model, the parameters should have some degree of consistency in the working point. Obtaining parameters of an empirical first order model trough fitting in the time domain does not result in consistent results for two of the three parameters. This means that slight variations of the working point or calibration signal do not have major influence on the parameter values. From this work we concluded that the parameter values should only be determined over the length of the pulse on which current is switched on. Further we saw that the length of the pulse great influence on the parameter values of the *RC*-circuit but does not result in big differences in the simulation of a voltage response.

No value can be attached to the first order model parameters for state determination except to the equivalent series resistance.

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