Journal of Energy Storage 18 (2018) 40–49

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

A high frequency model for predicting the behavior of lithium-ion batteries connected to fast switching power electronics

Pablo Korth Pereira Ferraz[a,*], Robert Schmidt[a,b], Delf Kober[c], Julia Kowal[a]

[a] *Electrical Energy Storage Technology (EET), Department of Energy and Automation, Technische Universität Berlin, Einsteinufer 11, D-10587 Berlin, Germany*
[b] *Power System Engineering, Bergische Universität Wuppertal, Rainer-Grünter-Str. 21, D-42119 Wuppertal, Germany*
[c] *Chair of Advanced Ceramic Materials, Institut für Werkstoffwissenschaften und -technologien, Technische Universität Berlin, Hardenbergstr. 40, D-10623 Berlin, Germany*

ARTICLE INFO

Keywords:
Lithium-ion battery
Power electronics
Electrochemical impedance spectroscopy
Equivalent circuit modeling
Ripple current
High frequency

ABSTRACT

Battery powered energy systems such as electric vehicles utilize power electronics for controlling energy flows between the battery and the load or generation, respectively. Therefore, the battery is under high frequency stress due to fast switching power electronic devices. However, most battery models throughout the literature are not able to cope with high frequency excitation. This paper proposes an easy to implement equivalent circuit model that covers aforementioned frequency regions with a series of inductors that are each connected in parallel with an ohmic resistance. This circuit is parameterized by electrochemical impedance spectroscopy (EIS) up to 100 kHz. For further regions that reach regions of megahertz a skin effect model is investigated and compared to the *RL*-model. It is shown that such semi-empirical models can be motivated by geometrical considerations that can be found in the literature. Moreover, the proposed model is validated by simulating the voltage response from an input current that originates from an actual back-to-back half bridge DC/DC converter. The promising results indicate that such models might be implemented in future battery energy systems to improve insights on how batteries react to perturbations such as EMI noise or high frequency current ripple.

1. Introduction

It is commonly accepted that lithium-ion batteries are going to be a crucial factor for the energy transition from fossil fuels towards renewable energies regarding either the necessity to buffer fluctuating feed-ins from solar and wind power plants, improving grid quality and grid stability or as one feasible energy storage for electric mobility [1,2]. Given that distributed generation is an immanent feature of renewable energies, a paradigm shift towards new forms of electrical energy networks such as microgrids [3] has been initiated and batteries are commonly seen as a self-evident part of such smaller scaled networks to guarantee uninterrupted service or increase the degree of utilization of renewable power plants [4]. One example is to equip electric cars with back-to-back battery chargers [5] instead of the nowadays widely used unidirectional vehicle battery chargers [6] so that the car's traction battery can be used as a backup storage which is known as the concept “vehicle to grid” (V2G) [7,8].

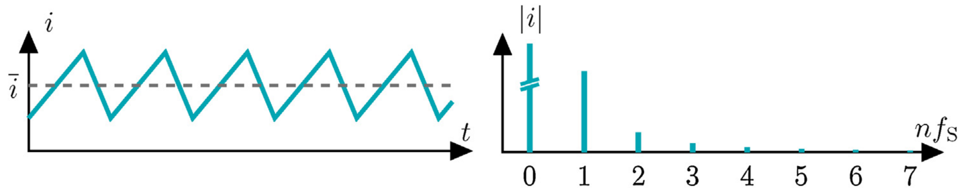
Regardless of all the aforementioned ideas being future concepts or already commercially available, they have one vital similarity: The design of energy systems cannot be done without taking power electronics into account. In principle, power electronic devices convert a mostly arbitrary current or voltage signal into another with power switches such as field-effect transistors (FET) or insulated gate bipolar transistors (IGBT) that are turned on and off periodically, e.g. controlled by pulse-width modulation (PWM) [9]. The switching frequency is within the magnitude of several kilohertz and therefore induces high-frequency noise and current ripple as shown for a half bridge based DC/DC converter in Fig. 1.

Thus, batteries that are connected to power electronics face high-frequency excitation. Therefore, a novel model that is able to represent a battery's high-frequency behavior with a satisfactory explanation for its elements needs to be developed. In order to achieve a model that is easy to parameterize and is potentially simple enough to be implemented in online battery monitoring systems without inducing too much computational burden [10], two well established methods for modeling and parameterizing batteries, respectively, have been chosen. In this work, electrochemical impedance spectroscopy (EIS) is used to measure the voltage response due to a harmonic input current to calculate the cell's impedance which is then passed to a fitting algorithm so that an equivalent circuit model can be implemented [11]. In the past, this practice has been discussed thoroughly in the literature, e.g. in [12–14]. Yet, only a few researchers have dealt with models that take

---

[*] Corresponding author.
E-mail address: pablo.korthpereiraferraz@tu-berlin.de (P. Korth Pereira Ferraz).

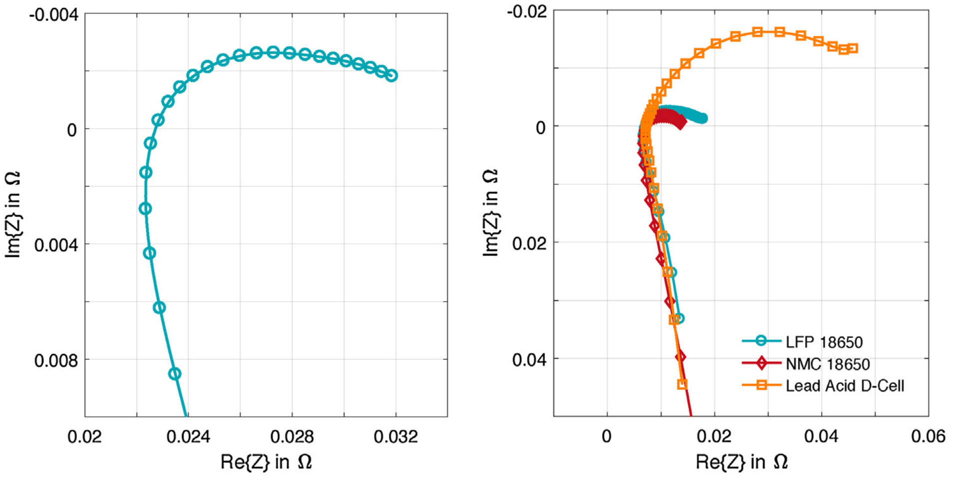
https://doi.org/10.1016/j.est.2018.04.024
Received 23 March 2018; Received in revised form 23 April 2018; Accepted 23 April 2018



(a) Typical current wave form of a DC/DC-converter

(b) Corresponding harmonic spectrum

Fig. 1. The left side shows a qualitative diagram of a typical battery current waveform if connected to a DC/DC-converter, e.g. a boost converter. On the right side, the corresponding harmonic spectrum is shown qualitatively, too. It declines in orders of $1/n^2$.



(a) Excerpt of an EIS-measurement for a LiFePO$_4$-cell, frequency range is shown from $f_{\text{min1}} = 10\,\text{Hz}$ to $f_{\text{max},1} = 20\,\text{kHz}$.

(b) Different EIS-measurements for varied cylindrical cells, frequency range is shown from $f_{\text{min},1} = 1\,\text{Hz}$ to $f_{\text{max},2} = 100\,\text{kHz}$.

Fig. 2. Exemplary impedance spectra clearly show significant growth of the real part for high frequencies for various cylindrical cells.

the inductive branch, i.e. the high-frequency behavior, into account. In [15,16] and to some extent [17] an impedance analysis with high-frequency excitation has been undertaken and an inductance in parallel to an ohmic resistance is proposed as an equivalent circuit model. Their conclusions are motivated by an increasing real part at high frequencies, as illustrated in Fig. 2, which seems to be imminent for a lot of cell technologies, since a regrowth of the real part at higher frequencies has been observed in the past and is clearly visible for every measurement throughout this work. However, a deep analysis is missing in the literature. Moreover, it is established to provide aforementioned inductive equivalent circuits to achieve an exceedingly precise fitting result but neglecting them in the following simulation for reasons concerning simulation stability [18].

Further battery models that are based on transmission line approaches are also discussed. In case of [19], the effect of EMI on the battery is investigated so that its primary frequency range is by far higher than a typical switching frequency of power electronics, which normally operates in the range of several kilohertz. The authors of [20] provide a more promising concept for a lower band which is based on the geometrical concept of a spiral-wound cell [21]. Therefore, another goal of this work is to provide an equivalent circuit model that is usable in simulations of power electronic battery systems as it uses *RL*-circuits not only in terms of an improved parameterization but as a key part of the simulation as well. With this modeling approach, a more precise prediction of the battery's voltage response due to high frequency current ripple is achieved.

In Section 2 the carried out electrochemical impedance measurements are presented. It is followed by the modeling approach with an equivalent circuit and its parameterization in Section 3. Afterwards, the developed model is evaluated and discussed in Section 4 as it is tested with measurement data of a real life battery system, based on a half-bridge DC/DC converter.

2. Experimental

2.1. Cell characteristics and equipment used

All measurements presented in this work are done with commercial spiral wound cylindrical cells with varying chemistry, see Fig. 2b. Albeit the proposed model has been derived for any given cylindrical cell, only a 18,650 spiral wound cylindrical high power lithium-ion cell is investigated further to focus on the properties of the model. The anode consists of graphite and the cathode is made of lithium iron phosphate (LFP). The nominal properties of the identical cells are listed in Table 1. They are both cycled and characterized by a *Zahner Zennium* impedance spectroscope. This device has also been used to conduct the EIS-measurements. The cells are connected in a way to utilize four-terminal sensing. The wires for voltage and current are twisted in pairs respectively to minimize the stray effects. Ultimately, the cells are tested in a *Binder MK 240* climate chamber.

Table 1
Nominal features of the battery under test.

Value	Symbol	Quantity
Nominal capacity	C_N	1, 1 A h
Nominal voltage	U_N	3, 3 V
End-of-charge voltage	U_{EoC}	3, 6 V
Cutoff voltage	U_{CO}	2 V