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Advanced lithium ion battery modeling and nonlinear analysis based on robust method in frequency domain: Nonlinear characterization and non-parametric modeling

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ABSTRACT

Due to the importance of battery modeling and characterization and lack of an accurate and comprehensive method, which considers battery as a nonlinear model, this paper introduces a novel methodology for analysis in the frequency domain. This methodology looks to the battery from a different point of view and covers aspects of the battery that is often neglected in the previous work and research studies. Using periodic signals for system identification, allows separating noise and nonlinear distortions from the linear part of the system. Meanwhile random phase multisine signals are very popular as an arbitrary number of frequencies can be added together and applied to the battery at once. In addition to a shorter test time in comparison with conventional single sine EIS (electrochemical impedance spectroscopy), by performing extra periods and different phase realizations, transients are eliminated and noise disturbance and also nonlinear distortion is detected, quantified and qualified. Thanks to the statistical and averaging methods, the linear part of the system can be identified and distinguished from nonlinear noise source, which helps to improve model quality and accuracy. Furthermore this method is used for battery characterization and for evaluating the battery performance and its nonlinear behavior at different current rms values as well as at various state of charge levels.

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1. Introduction

Nowadays due to the price and availability of fossil fuels and because of environmental concerns, the demand for cleaner energy supply and for higher energy efficiency is ever increasing. Availability, certainty and efficiency of rechargeable electro-chemical energy systems, persuade us to consider them as alternative energy source in different applications such as electric and hybrid vehicles, heavy transportation systems, renewable energy systems and smart grids [1–4]. Therefore due to the wide range of applications, our understanding regarding the behavior of different types of energy storage systems under different operating conditions has to be extended. Lithium ion batteries, in the meantime, are promising for actual use and for many future applications. In order to have efficient and reliable performance of a lithium ion battery system, an autonomous management system is needed to monitor and control the status of each cell [5,6]. In order to efficiently control the state of a battery, it should be characterized carefully under many operating conditions. In this regard it is important to identify all aspects of the battery, considering both the linear and nonlinear behaviors. Furthermore an accurate and comprehensive model is needed to describe its behavior and predict the output based on arbitrary dynamic or static input load profile. Many papers describe the characterization of a battery based on conventional test procedures such as capacity test, hybrid pulse and dynamic performance tests and investigated battery specification mentioned in datasheet such as energy and power density, energy efficiency, discharge capacity and internal impedance [7–14].

Regarding electrical modeling of batteries and the associated parameter estimation, most of the publications rely on HPPC (hybrid pulse power) tests, described in time domain, and are based on a first or second order equivalent circuit, the measurement data have been fitted to the model and parameters have been identified [15–22]. In all of them the battery is considered as a linear system with variable parameters, while the nonlinear behavior and noise distortions are neglected. Also, test data is extracted and implemented in multi-dimensional lookup-tables, based on the

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condition applied to battery, such as SoC (state of charge) steps, current levels and temperature. Authors in Refs. [73–75] tried to improve the parameter identification process and model performance using different equivalent circuit configuration. However they keep using routine and conventional identification methods which have been mentioned above.

In Refs. [23,24] and [60–64] it is claimed that a nonlinear model is developed while it is still a linear model with variable parameter. The open circuit voltage, internal resistance and other parameters are identified based on a linear equivalent circuit with conventional ways such as pulse test. Then the parameters are fitted to a polynomial or exponential equations in function of SoC and/or temperature. Authors had to use high order polynomials in order to achieve good accuracy of modeled parameter in whole range of SoC. This causes generating lots of polynomial coefficients which brings no additional physical interpretation of parameters related to the battery behavior. Those parameters are fitted with a nonlinear function but still the essence of the electrical model is linear. In Refs. [65,66] the nonlinear model is developed based on an electrochemical concept of the battery. This method needs very complicated deferential equations and also pre-knowledge regarding the active materials, electrolyte and diffusion coefficients is essential. Artificial intelligence methods such as neural network and fuzzy logic are used in Refs. [67–72] for nonlinear battery modeling and SoC estimation. Although these methods can capture nonlinear behavior of battery, however they need to be trained with different load profile data and also the computational cost is high. Furthermore no additional information regarding physical meaning of model parameter is provided.

In contrast to identification in the time domain, identification in the frequency domain, frequency, amplitude and phase of each component of the identifier signal can be controlled. One can design an identifier signal containing arbitrary frequencies with specified amplitude and phase. This flexibility has made frequency domain suitable for identification of a wide range of nonlinear systems or complex systems such as linear dynamics with feedback or parallel feed forwards loops [25,26]. The possibility of optimal identifier signal design in the frequency domain in function of a specific application or system is very helpful and makes the identification process time efficient. Due to these advantages, a large number of research and investigations in field of EIS (electrochemical impedance spectroscopy) in the frequency domain have been done [27–35]. Karden et al. have performed galvanic EIS and measured impedance when DC current with different levels is added to the AC perturbation [36,37]. In the case of testing with high current levels, the impedance is distorted and in order to avoiding significant SoC changes during the test, the frequency range is limited to a rather small range of high frequency components. Andre et al. [38] investigated the effect of rest duration before measurement on impedance while they did not consider transient effects on the measurement during the experiment.

In recent years, RPMS (Random phase multisine) has been used for identification of different systems in many fields of technology [39–42]. In the Refs. [43–46] for instance indicate how multisine can be used for mechanical system identification. Here, the excitation signal is applied to the system in the form of mechanical vibrations. This mechanical system could be a car body, airplane wings or a metal structure. Multisine excitation is also very popular for electrical system identification as the system can be analyzed in a wide frequency spectrum at once. Further, this method has been applied in other fields such as medical system and devices, broadband power amplifiers and electronic circuits [47–50]. In addition to the previous mentioned applications, multisine has been applied also for electrochemical system identification. In Refs. [51–54] the effects of metallic coating and of corrosion and its influence on impedance variation and nonlinear behavior of the system has been analyzed and evaluated.

1.1. Contribution of the paper

Due to the lack of knowledge regarding battery characterizing and modeling with multisine excitation signals, this article focuses on lithium-ion battery nonlinear characterization under different operating conditions making use of high current multisine characterization signals. Further, this work investigates the linear nonparametric modeling of a battery cell by making use of the new robust frequency approach and its advantages in comparison with the existing methods. It has been supposed that system includes a linear dynamic plus disturbance noise and nonlinear distortion. At first step nonlinear distortions caused by high current and/or low SoC levels are quantified and then noise disturbance caused by environmental and measurement equipment are analyzed and modeled. Quantifying the distortion noises, enable us to extract linear part of the system that improves the model quality and accuracy. Furthermore, the nonlinear distortion presents new aspects of battery which can be used for performance evaluation and cell characterization.

1.2. Organization of the paper

In Section 2 of this manuscript, conventional EIS using single sine excitation applied to a 20 A h lithium ion pouch cell is discussed. Further this section the measured impedance at different SoC levels has been analyzed. The theory and design of the multisine is explained in Section 3 and also quality of applied multisine current to the cell and its voltage response is evaluated. In Section 4 formulation of linear approximation of system is presented and also it is shown how noise and nonlinear distortion can be detected. In Section 5 the theory explained in Section 4 has been applied to the cell and finally results are discussed and analyzed.

2. Single sine sweep excitation signal

Different types of excitation signals are being used for identification purposes in frequency domain, such as impulse, random Gaussian, periodic random and periodic sinusoidal signals [39]. Meanwhile, the periodic signal such as single and multisine signals are more applicable and consistent as noise disturbance level is reduced by averaging over multiple periods, and also the transient state can be eliminated by neglecting initial periods, until output reaches to the steady state. Single sine sweep is also a popular and effective method, which is easy to implement and also post analysis of the obtained results is quite simple. This method is very common and has being used in many applications and, as discussed in introduction, also a large number of publications address many aspects of this topic [32–36].

The theory of single sine identification is very simple and can be easily implemented. The measured AC voltage is divided on AC current in phasor form and the complex form of the associated impedance is calculated for each excited frequency [55].

For this manuscript, an NMC against graphite lithium-ion battery cell with a nominal capacity of 20 A h has been used. PEIS (Potential electrochemical spectroscopy) has been performed at different SoC levels (90, 70, 50, 30, 10 and 2%) on the considered cell, and measured impedances are shown in Fig. 1. For avoiding nonlinear effects, the amplitude of the AC perturbation signal has been kept at 10 mV and also the EIS has been performed in the frequency range between 2 kHz and 20 mHz. Due to the low value of the voltage amplitude, the corresponding current value is around 350 mA rms. In many papers it is described that how

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