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Hybrid characterization procedure of Li-ion battery packs for wide frequency range dynamics applications

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ABSTRACT

This paper presents a hybrid characterization procedure of battery packs capable of reproducing their behavior under different dynamic operation conditions. During the experimental procedure, both time and frequency tests are performed. These tests have been carried out on a commercial battery pack, instead of a single cell, in order to include packaging effects as well as performance of battery pack devices in real electrical applications. As a result of this procedure the battery pack model has been experimentally validated for four cases based on real electrified transportation and grid applications. Additionally, the model response has been compared with the widely used Partnership for a New Generation of Vehicles (PNGV) model. The validation tests show that the proposed battery pack model reproduces the dynamic battery response with better accuracy than the PNGV for all analyzed cases.

1. Introduction

Energy storage devices are becoming key elements for the developing of electrical mobility and smart grids. Advancements in new materials with competitive energy and power densities fostered the increase of commercial storage devices [1]. Lithium based batteries are the most promising energy storage technology because of their high specific power and energy, and long lifetime [2,3]. Large-scale applications such as electrical vehicles (EVs) or supporting electrical systems during voltage dips, require the setting up multi-cell battery devices composed by several individual Li-ion cells in a combination of series and parallel connections, to provide the required nominal voltage and capacity [4–6]. In practice, each of these individual cells are slightly different among them (due to manufacturing process), which can jeopardize the overall operation. Battery packs require a battery management system (BMS) [7,8] to control their dynamic behavior, monitoring and assuring a safe operation (preventing that voltage, temperature and charging/discharging current from exceeding their strict limits) and maximizing the battery performance using different cell-balancing algorithms. These factors, along with the non-linearity of the electrochemical processes that occurs inside Li-ion batteries, make the modeling of battery packs a difficult task.

Li-ion battery packs are forced to work under a variety of load cycles. Depending on the duration of these cycles, battery modules may operate over a wide range of dynamic regimes. For highly demanding dynamical applications such as EVs, electrical grids support, or frequency control in microgrids [9–11], battery packs performance is specially affected by the different processes that occurs inside the battery module. These electrochemical processes take place with different time constants which determine the transient response of the Li-ion battery module [12]. In electrified transportation and grid applications, there are three frequency ranges of special interest. The first one is related to the fast dynamic processes ranging from millisecond to second, which are relevant for the control and protection of the battery pack. The second refers to the operational regime associated to charge-discharge cycles, within a time horizon from minutes to some hours. Finally, aging effects due to chemical and mechanical degradation [3] that produce modification of the internal structure of the battery components and losses of active materials affect the state of charge (SOC) estimation (these phenomena take place during months or years). Because these processes occurs simultaneously during module operation, battery packs models should explicitly reflect these different time constants in order to accurately reproduce the dynamic behavior of the battery module.

Battery simulations are commonly used to predict the battery behavior and to optimize the required storage capacity, reducing development time and cost. Battery models are also used by the BMS to estimate the SOC. Different battery models have been proposed depending on the different applications. The most common battery models for simulation of power applications are based on electrical

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equivalent circuits [13,14], because they directly represent the terminal voltage and current of the battery.

There are two main strategies in the literature to determine the parameters of the equivalent circuit models, one based on time domain experimental tests and the other based on the frequency domain techniques.

1.1. Time domain modeling

Time domain models are obtained from the analysis of the battery voltage and current evolution during tests, predicting its dynamic behavior as a function of time [15–17]. Some examples of these kind of models are the RC model, the Thevenin model, the PNGV model or Dual polarization (DP) model, among others [18,19]. These models are relatively easy to obtain, but their validity is usually limited to some specific dynamic profile applications [20]. Probably the most popular time-domain test to perform the battery modeling procedure is the current interruption test [20,21]. In this time-domain test, a series of charge/discharge pulses of constant current is applied to the battery, usually starting from 100% SOC to 0% SOC. The subsequent analysis of the variations of terminal voltage vs. output current allows supposedly determining the parameters of the battery equivalent circuit. With this method, however, it is difficult to achieve a very precise model, because it relies, to a great extent, upon the exact determination of some singular points on the terminal voltage record. In the first proposed circuits, only a first-order model (RC model), as it is presented in Ref. [22], can be fitted with reasonable accuracy. In spite of this model is able to reproduce the voltage behavior of the battery in steady-state conditions, it fails to reproduce the dynamical behavior of battery voltage when a pulsed or dynamical current profile is applied [17].

To improve battery model accuracy a second RC network (DP model) or other electrical elements such as capacitors, controlled current or voltage sources can be added (PNGV model). In this case the electrical circuit parameters are determined using advanced simulation tools and could be on-line updated using estimation algorithms like Kalman filter, sliding-mode observer or so on [19,23–25]. These estimation algorithms predict battery behavior as a function of time, based on battery voltage evolution during specific charge–discharge tests and previous measurements. Internal battery behavior is not considered, and therefore their validity is usually limited to a narrow bandwidth.

In Ref. [23] a comparison of different electrical battery models has been done. This study reveals that computational times to find optimized parameters as a function of SOC increases by about four times when a second RC network is added. A similar analysis was performed by Refs. [17,19]. In these works, up to five different models of Li-ion batteries were used to simulate the voltage response of a battery in EVs. According to these comparative studies, equivalent circuit models that include two RC network or another electrical elements, improve simulation results in comparison with first-order models. These authors conclude that it is necessary to consider all internal processes of the battery in order to properly reproduce its dynamic performance. These studies show that it is necessary to use advanced algorithms to obtain an accurate model, thus involving even more computational time. Also, dynamical characteristics associated to electrochemical processes inside the battery can be taken into account in order to improve battery modules modeling.

1.2. Frequency domain modeling

The other way to evaluate the model parameters is performing a frequency domain analysis by Electrochemical Impedance Spectroscopy Tests (EIS). Li-ion battery cells present a nonlinear discharging characteristic curve, as it is shown in Fig. 1. If the battery cell is operating around a specific operating point, it is possible to obtain a simple linear model, linearizing the non-linear characteristic curve. During EIS tests, a small AC excitation signal (either current or voltage) is applied to the electrochemical system [26–28]. This excitation signal will cause the system to react, generating an AC voltage (if the excitation signal was initially a current) or AC current (if the excitation signal was initially a voltage). The AC excitation signal is usually applied as a variable frequency sweep. To keep linearity during the tests, the amplitude of the AC excitation signal applied to the battery cell is kept small enough (e.g. 5–10% of the rated voltage/current), as it is depicted in Fig. 1. In addition, this ripple is kept constant during the tests.

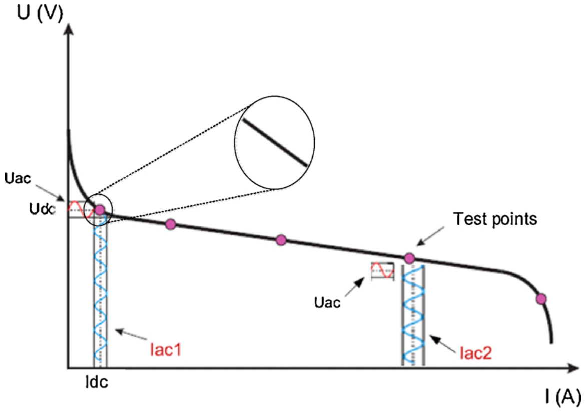

Fig. 1. Li-ion battery characteristic discharge curve.

The complex impedance is calculated as the ratio of the complex voltage and current ($Z(\omega) = \mathbf{U}_{ac}(\omega)/\mathbf{I}_{ac}(\omega)$). The subsequent impedance calculation and model fitting is time consuming and complex, so it is recommendable to use an impedance analyzer, which generates the excitation signal and evaluates the complex impedance. To study the influence of SOC variations in impedance parameters, EIS tests are done at different operating points. Furthermore, these tests can also be carried out at different temperatures to analyze other behaviors like thermal runaway or aging effects.

Although this procedure provides good simulation results, it presents some drawbacks. One of them is that the AC ripple used in most of commercial EIS analyzers are suitable for testing single battery cells of small capacity (maximum 100 mA), but it is too small to test full-size industrial battery devices. Also, some impedance elements (CPE or Warburg elements) [28] used to describe the electrochemical processes are only valid in the frequency domain and, for this reason, they must be approximated by real electrical elements in order to implement them in the standard simulation platforms.

According to the above analysis, battery pack model accuracy can be improved if the internal behavior that occurs inside the cells is considered. Also, the modeling procedure must be applied to battery packs in order to reproduce realistic operation conditions. However, most of the work available in literature only presents individual cell testing and modeling, neglecting the interactions between elements within the battery pack, which is the final assembly needed for a large-scale application, despite some recent investigations have revealed that considering BMS and packaging effects in Li-ion battery packs modeling, improves the model accuracy [29,30]. Moreover, only a few studies consider cells parameters variation. To accomplish these objectives, in this work, a battery pack modeling procedure based on time and frequency tests is proposed.

The main contribution of this work is to develop a hybrid experimental procedure based on both time and frequency tests to reproduce the dynamic behavior of a battery pack under different dynamic requirements and realistic scenarios. In this way the processes that occur inside the cells are taking into account to obtain the model parameters of the battery pack. Also, the interactions of all components of the module are considered because the characterization process is performed upon the whole pack. As a result of this procedure an electrical circuit of the battery pack is validated applying requirements for two