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Complementary characterization methods for Lithium-ion Polymer secondary battery modeling

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ABSTRACT

This paper deals with the electrical modeling of Lithium-ion Polymer battery, from complementary characterization tests. The first aim of this work is to understand the electrical behavior of this battery through experimentations in the same environmental conditions as the final application's ones. The second goal of this work is to identify battery models with different precision levels and to implement them in specific models of the considered aircraft electrical network. In this paper, two equivalent electrical circuit models are presented: a quasi-static model, which is functional and sufficient for the electrical energy management in the aircraft; a dynamic model, which is behavioral and necessary for the analysis of the embedded network quality. The identification of their parameters is carried out with adapted characterization tests, such as chronopotentiometry at constant current and Electrochemical Impedance Spectroscopy at different temperatures. The complementarity of these tests is particularly underlined in this paper because it is useful for the parameter identification. The results from model simulation and from experimentation are compared through a mission profile and are analyzed. Eventually, this paper presents complete experimental data for a commercial 4.8 Ah Lithium-ion Polymer battery including the temperature influence.

Introduction

The management of an embedded electrical network requires the use of electrical storage systems, such as battery, in order to guarantee the network stability and quality, and the energy availability. In conventional aircrafts, electrical storage systems are helpful as support to engine start at the mission beginning or as electrical emergency back-up. For a couple of years, aircrafts have moved on "more electrical" aircrafts [1] due to the flexibility of use of electrical energy and due to the decrease of its operating cost. This evolution implies a higher consumption of electrical energy and a change of functional scope for storage systems.

As battery is considered as an energy source in regards to the application scale [2], it is necessary to know its electrical behavior in the aircraft environmental conditions. Therefore, battery must be characterized with a view to be modeled in a tractable way, in order to carry out numerical simulations and to anticipate its operation within the aircraft network.

Battery characteristics

This paper deals with a Lithium-ion Polymer battery. Their main characteristics are summed up in this paragraph. One of these characteristics is the Open-Circuit Voltage (OCV). This voltage is due to the redox potential difference between the electrode materials. For Lithium-ion Polymer battery, the nominal open-circuit voltage is about 3.7 V a cell. Another characteristic is the capacity, that is the quantity of charges that battery can provide (under constant voltage) during discharge time. The capacity range of Lithium-ion Polymer battery is between few Ah and few hundreds of Ah. The quantity of specific energy is in connection with both previous characteristics and in relation to the battery volume or weight. The major advantage of Lithium-ion Polymer battery is its high specific energy [3,4], which is about 120–180 $Wh.kg^{-1}$ or 200–300 $Wh.dm^{-3}$, and its specific power, which is between 10 and 1000 $W.kg^{-1}$. Its discharge time is about several minutes or hours, it depends especially on the discharge current-rate. The life duration of Lithium battery is higher than life duration of other

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battery technologies (Nickel or Lead). However, its number of cycles, which is about 1000–1500 cycles for a depth of discharge (DOD) of 80%, is rather low in comparison with other Energy Storage Systems. The life duration is the main drawback of Li-ion battery. Moreover, this kind of battery has also two advantages: an excellent energetic efficiency (close to 100% because of the non-aqueous electrolyte) and a low auto-discharge rate, which is between 0.1% and 0.5% a day.

The tested battery cells are provided by Kokam (Fig. 1). According to the datasheet [5], the nominal capacity is 4.8 Ah, the nominal voltage is 3.7 V and its maximal value is 4.2 V. The tested cell is classified as a high power density cell, where its specific power is higher than 2 $kW.kg^{-1}$ and its specific energy is about 155 $Wh.kg^{-1}$.

One of the aims of this paper is to give complete experimental data for this commercial high power battery including the temperature influence on its performance.

Battery modeling

Numerous models of battery are developed in literature [6]: electrochemical models and equivalent electrical circuit models. On Li-ion batteries, several models were developed. For instance, in [7], a mathematical model is developed to predict time response of battery in charge and at constant temperature. Another example is given in [8], where the diffusion phenomenon is modeled by a capacitive transmission line. In this case, the study focuses on electrode porosity and on concentration at the electrodes/electrolyte interfaces. A $LiFeO_4$ battery model is simulated in [9], for a PNGV (Partnership for a New Generation of Vehicles) application. On Li-ion Polymer (Li–Po) batteries, some models with electrical equivalent circuits were established recently. The model parameters are mathematically defined in function of temperature and state-of-charge [10,11]. In [12], a simple model is developed with linear parameters and nonlinear parameters (such as hysteresis phenomenon).

In this paper, the studied models are based on equivalent electrical circuits, according to the analogy between electrochemical and electrical fields. The global model implementation and its final use lead to a relevant choice of modeling and model granularity. Hence, two equivalent electrical circuit models are retained in this paper: a quasi-static model, which is simple, functional and sufficient for studying the battery operation during a mission profile; and a dynamic model, which is behavioral and necessary for studying the battery performance at transient steps and for the accurate analysis of the network quality.

Fig. 1. Example of a Kokam Lithium-ion Polymer 4.8 Ah cell.

The parameters of these different models can be determined through experimentations with adapted characterization methods.

Battery characterization

In literature, battery characterization tests are used to describe and to comprehend their electrical behavior at steady-state and in transient operation. They are based on several tests such as charge/discharge cycle tests at different current rates [13] and on Electrochemical Impedance Spectroscopy (EIS) [10,14]. In general [15], the kind of the characterization test depends on the method chosen for the analysis. For instance, time domain analysis needs experimental data such as voltage and current from charge and discharge tests. Another example, frequency domain analysis is carried out through Nyquist plots, which are obtained by impedance measurements (typically EIS).

Furthermore, investigations are usually carried out in different conditions in order to study the battery behavior and its evolution with state-of-charge [10,8], current rate [8], temperature [10,11], use frequency and cycling (or ageing).

In this paper, two equivalent electrical models are chosen according to their future use: a quasi-static model and a dynamic model. As these are models used in time domain, the Lithium-ion Polymer battery cells are characterized by using a chronopotentiometry at constant current. Moreover, the dynamic model is composed of complex impedance and its determination needs EIS. Otherwise, characterizations are carried out in experimental conditions which define the validity area of modeling, in relation with the application constraints. Hence, this study focuses on state-of-charge and temperature because their influence on model parameters is dominating.

Then, these models are assessed through a comparison of simulation and experimental results in response to a load profile, defined from aircraft mission profiles.

Finally, the experimental results are presented, analyzed and compared.

Experimentation and modeling

Firstly, charge and discharge tests at constant current are carried out to determine the battery capacity and to compare it with supplier's data.

Determination of battery capacity

Test procedure

Method. The test procedure consists in supplying the discharged battery with a constant current corresponding to 1 C-rate, until the voltage reaches its maximal value, which is 4.2 V. Then the battery voltage is regulated at its maximum value until the charging current tends to zero. At that time, the battery is considered as charged. Finally the battery is discharged by providing a constant current until the voltage equals its minimum value, which is 2.7 V (Fig. 2). Three tests are carried out with three values for the discharge current I_{bat} corresponding to 0.5 C, 1 C and 2 C rates.

Determination of capacity. As it is easier to know when the battery is completely charged, the capacity C_n (in Ah) is determined, according to (1), from a discharge test at constant current I_{bat} (in A) after a complete charge as described before (Fig. 3).

$$C_n = \left(\int I_{bat} \cdot dt \right) \Big/ 3600 \tag{1}$$

Results

The stored capacity, measured during discharge period, is about 4.15 Ah (at 2 C-rate), 4.2 Ah (at 1 C-rate) and 4.3 Ah (at 0.5 C-rate).