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Online supercapacitor health monitoring using a balancing circuit

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ABSTRACT

In this paper, a novel online technique for the state of health monitoring of supercapacitors energy storage systems is presented. It is based on measuring the equivalent series resistance of the energy storage element representing its aging. The suggested approach uses a suitable balancing circuit connected to the terminal of the storage element in order to extract its actual parameters. This new method is characterized by its simplicity which makes it convenient for industrial applications. A test bench is developed in order to prove the new method's reliability and accuracy. Experimental results taken from the test bench and from an offline classical laboratory characterization method shows that the differences between both responses do not exceed 7%.

Contents

1. Introduction

Due to their high energy and power density, supercapacitors [1], also known as ultracapacitors [2], or electrochemical double-layer capacitors (EDLC) [3–5], are nowadays becoming a popular new generation of storage systems for high-power applications [6,7].

In spite of their good electrical performances, supercapacitors are limited by their terminal voltages not exceeding 3 V. So, they are placed in a chain structure in order to obtain a suitable voltage. Thus, the supercapacitor storage system is composed of an association of elementary cells, called storage string, pack or stack [8].

For security and reliability reasons, a supercapacitor storage system, like most of storage systems, should be monitored and controlled by a management system. This system may be called SCM (Supercapacitor Manager), equivalent to the BMS (Battery Management System). SCM is composed of software and hardware units. It includes monitoring, state estimating and balancing functions for each pack element (cell) [9,10].

Temperature and voltage monitoring prevent the elements from exceeding their maximum operating range and ensure both user and system's safety.

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Users need information about the state of their system. Therefore, the state of charge (SOC) is required to verify the autonomy of the system. The state of health (SOH) is needed to prevent the replacement of the system. Those indications are provided by the SCM software unit which treats the measured data, such as system temperatures, currents and voltages, to estimate the state of cells.

In addition to monitoring and states' estimation, balancing functions adjust the voltage or the state of charge between the elements of a unique pack. It is compulsory to include this function on the SCM. Indeed, even if cells in the string are subject to the same current, a dispersion of voltage or SOC is obviously present and must be reduced. The principal reason of this dispersion is the differences between cells intrinsic characteristic due to manufacturing tolerance. In addition, during an operation, the differences between cells become more and more pronounced due to the temperature dispersion inside the stack and the aging of each element.

The balancing circuit reduces voltage imbalances between chain elements, thus prolonging the system's lifetime [11]. Depending on the circuit architecture, the balancing function is classified in a dissipative or non-dissipative category [12,13]. The dissipative one dissipates the excess of energy through the balancing resistor [14,15]. The non-dissipative one distributes the excess of energy between elements using capacitors, inductors or transformers [16,17]. The non-dissipative balancing seems more attractive, but the dissipative one remains widely used in the marketplace due to its simplicity and low cost. For supercapacitor energy storage systems, dissipative equalization method is the only technique existing in the market today.

The aim of this paper is to incorporate a new function in the balancing circuits to deal with SOH identification problem. Nowadays the online state estimation is one of the main focuses of research in the area of energy storage system applications. The research tries to develop mathematical algorithms (observers) based on automatic theories to estimate the aging of a storage element. However, in most cases these algorithms are greedy in terms of the computation time and their performances depend highly on the chosen model accuracy [18,19].

The presented work proposes a new method for estimating the SOH of an energy storage element. It uses a dissipative balancing circuit, the switched shunt resistor circuit which is composed of a serial association of a resistor and a switching MOSFET. This circuit is connected to the terminals of each storage system cell. The new strategy of health monitoring focuses on quantifying online the supercapacitor specific impedance which represents the aging of the element. Thus, in the first part of this paper, the supercapacitor impedance behavior and the aging effect will be introduced. In the second part, the principle of a new approach for the SOH and the estimated life duration (ELD) determination will be presented. In the third part, the test bench realization and the new approach implementation will be presented. Then, a comparison between famous laboratory results and the new method will be carried out in order to evaluate the accuracy of this new approach.

2. Supercapacitor aging effect

The supercapacitors offer higher lifespan than electrochemical accumulators. Indeed, they can support hundreds of thousands deep discharge and charge cycles thanks to the theoretical lack of chemical reactions at the electrodes. However, there are some impurities inside the supercapacitor called functional groups due to manufacturing imperfect process [20]. During aging, functional groups produce solid and gaseous reactions damaging the supercapacitor [21]. The aging process of supercapacitors affects mainly the capacitance and the equivalent series resistance (ESR) [22,23]. The capacitance, C, represents the supercapacitor ability to store an electrical charge. The equivalent series resistance is the resistance corresponding to all the resistive components within the supercapacitor. Experiments demonstrate a slow evolution of the capacitance and the ESR simultaneously over aging until failure depending on the solicitation [24,25]. The supercapacitor is defined as defective by the manufacturer when its equivalent series resistance generally increases to a value equal to twice its initial value or when its capacitance falls below 80% of its initial value. These ESR and C failure values could be different according to the application requirement [26]. Hence, the state of health monitoring is realized by following the evolution of at least one of those parameters. The comparison between instantaneous and initial values reflects the actual age of the element.

The method presented focuses on the estimation of the actual ESR in order to evaluate the supercapacitor's state of health. The instantaneous ESR estimated is then compared to its initial value obtained under same environmental conditions to estimate the aging of the cell. Thus, the method could also predict the life duration under specified conditions and forecast a replacement.

In the following section, offline characterizations and the new suggested approach are introduced in order to analyze supercapacitor's ESR behavior. Thereafter, results obtained by the classical offline characterization will be used as references for results validation.

3. Electrochemical impedance spectroscopy and supercapacitor frequency behavior

There are two main methods used to analyse the performance of supercapacitors: the temporal characterization method based on the electrical behaviour when charging and discharging the cell and the frequency method based on the electrochemical impedance spectroscopy. Both methods lead to the acquisition of parameters that are considered sufficient to describe the properties of the supercapacitor in time and spectral domain [27,28].

The temporal method is not presented in this paper. The frequency method is used since the impedance spectroscopy is more precise and gives further information.

Electrochemical Impedance Spectroscopy (EIS) is an accurate state evaluation method for supercapacitors and other electrical energy storage systems [29,30]. It determines the system's impedance for different frequencies. Its principle consists on injecting a sinusoidal signal of low amplitude in a range of frequencies in order to represent the impedance of the element for each frequency as in (1).

$$\underline{Z}(f) = \frac{\underline{V}(f)}{\underline{I}(f)} = \mathrm{Re}(\underline{Z}(f)) + jIm(\underline{Z}(f)) \quad (1)$$

Collected data allow different representations of the impedance. Figs. 1 and 2 show the Bode representations for different supercapacitors, characterized at 2.7 V and 25 °C.

According to the impedance phase diagram presented in Fig. 2, the curves can be divided into three principal parts (mostly capacitive, inductive and resistive impedance). When the phase's curves cross zero degree, the behavior of the supercapacitor is purely resistive (absence of imaginary part). The frequency corresponding to this real impedance is called resonance frequency. The corresponding module of impedance represents the ESR at the resonance frequency and will be named Ro. The internal parameter monitored by the characterization approach presented in this paper is the parameter Ro.

First, for a frequency band Δfr, ranging from approximately 10 Hz to 1 kHz, the supercapacitor impedance modulus represented in Fig. 1 is quasi constant and close to Ro values (less than 1%