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Online parameter identification for real-time supercapacitor performance estimation in automotive applications

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ABSTRACT

This paper focuses on synthesizing a real-time adaptive process for supercapacitor performance estimation using a dynamic model describing the SC behavior which can vary within each experiment. We develop a simple and linear-recursive model that proved its efficiency regarding the comparison between simulation results and real data from power cycling tests. Based on a recursive least squared algorithm with a time-variant forgetting factor, the on-line estimation of the dynamic supercapacitor-model parameters, mainly the internal resistance, served as a state of health indicator. Model shows very good performances since the maximum relative modeling error do not exceed 3%. Results from state of health indicator are compared to those issued from IEC standard and electrochemical impedance spectroscopy methods.

1. Introduction

In order to reduce the environmental impact of their fleet, many companies have made investments in researching and testing alternative technologies such as hybrids as well as electric vehicles. These technological innovations rely on a common component, the energy storage system (ESS), designed to meet the requirements of each application and enhance on-board energy management (auxiliaries, regenerative braking energy, etc.) [1]. Electrochemical energy storage, such as lithium-ion batteries, fuel cells and SCs, has been identified as a critical enabling technology for these systems [2].

SCs are gaining more attention as electrical energy storage elements for renewable energy sources which tend to have a high charge–discharge cycle frequency, and demand high cycle efficiency and good depth-of discharge (DOD) properties [3]. Moreover, recently, several researches focused on hybrid ESS system, where the advantages of the high power capabilities of supercapacitors (SCs) would store the surplus energy that can be combined with the suitability of a high volumetric energy density Li-ion battery that can effectively work in variable high power applications such as EV, fuel cell vehicles and HEV [4,5].

In such a system, fuel cell or lithium battery is only operating in nearly steady state conditions. However, the SCs are functioning during transient energy delivery or transient energy recovery [6,7]. The role of the SC is to supply transient power demand and peak loads required during acceleration and deceleration.

The drawback of the SC technology concerns the electrical performances prediction which remains sophisticated as they depend strongly on the selected chemistry and technology. Nevertheless it remains a must in the design of energy storage system used on EV or HEV as the environmental conditions (power profiles, temperature and life time) affect them strongly [8]. Thus, in order to ensure that SCs operate in a reliable range and are capable of delivering the required power and energy, an accurate determination of its state of health (SOH) information are crucial in practical applications [9]. In addition, there is obviously an acute need for tools able of simulating SCs behavior based on current understanding of the phenomena involved and taking into account the environmental conditions [10].

In all cases, the challenge remains the same, how can we directly infer accurate SOH values from measurements of the SC voltage, its temperature and the current?

This work focuses on synthesizing an adaptive process for SC performance estimation using a dynamic model describing the SC behavior.

In the first part, based on real-life experiments data from power cycling on SC module and using recursive least squared algorithm (RLS) with a time-variant forgetting factor, a dynamic model describing SC behavior is proposed. In the second part, the adaptive model helps to develop a SOH indicator based on the identified dynamic parameters mainly the internal resistance. Results from SOH

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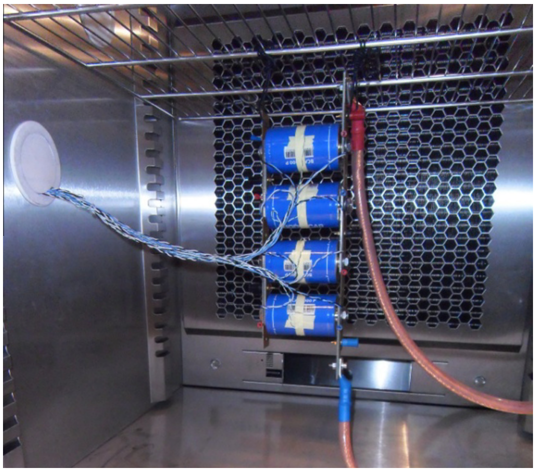

Fig. 1. SC module under test in the climatic chamber (Maxwell module).

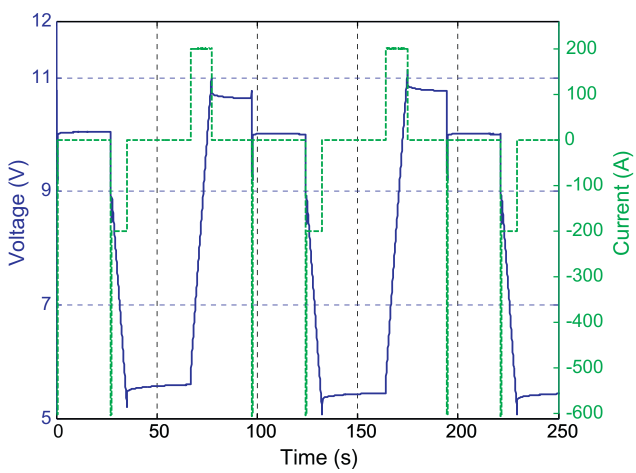

Fig. 2. Measured SC module current and corresponding voltage response.

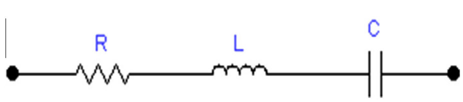

Fig. 3. Simple RLC equivalent circuit model for SC.

indicator are compared to those issued from IEC standard and electrochemical impedance spectroscopy (EIS) method.

2. Experimental setup

Experimental studies are conducted on a SC module (see Fig. 1) composed of 4 cells connected in series with 3000F/2.7V each. This module is associated with a balancing circuit that operates above the rated voltage value. Each cell is equipped with a thermocouple to measure its temperature. The cells in question are commercial ones and used in a HEV application. The Digatron Battery Testing System, BTS-600, is the power processing system which has the flexibility to implement virtually any electrical driving cycle, and can offer a voltage range of 70 VDC and a current range of ±1000 ADC.

SC module is charged and discharged at several current levels inspired from the IEC standard for SC electrical performance testing [11]. More importantly, the current profile, illustrated in Fig. 2, has been defined to make accelerated aging of SCs according to the specifications expected by car manufacturers for a typical microhybrid electric vehicle (micro-HEV). This profile is linked to the main functionalities of such vehicle like start/stop, boost and regenerative braking. The width and the level of the current pulses, the duration of the rest phases and the period of the cycle have been defined in order to obtain a given self-heating of the cells at the beginning of the aging tests.

During the experiment, the current, the voltage and the temperature data are collected by the (BTS-600). The SCs are placed in an isothermal chamber during tests to ensure temperature control. Experiment is carried out at 59 °C in order to optimally accelerate devices aging taking into account self-heating and avoid on the other hand limits for device damage such as electrolyte decomposition.

Fig. 2 represents the current profile applied to the module and the corresponding voltage respectively. These experimental results serve for the development of the adaptive dynamic modeling of the SC and the SOH monitoring process presented in next sections.

3. Adaptive supercapacitor modeling for SOH monitoring

On one hand, it is difficult to build an accurate model for SC, due to their complex physico-chemical characteristics [12]. For example, the dynamic behavior of a SC is strongly related to the ion mobility of the electrolyte used and the porosity effects of the porous electrodes [13]. These factors require a very complex electrochemical model to be considered. On the other hand, we have to ensure that SC operates in a reliable range and are capable of delivering the required power and energy in a safe way.

Therefore, in a first step, SC dynamic behavior is followed using dynamic-parameters on a simple and linear-recursive model. Basically, we conduct many simulations tests on adaptive model based from existing models in the literature in order to achieve a direct relationship between the SC voltage and respectively its current and temperature. In a second part, we profit from the identified parameters to have an indication on the available performances.

Actually, the challenge remains the same, how can we directly infer accurate SOH values from measurements of the SC voltage, its temperature and the current? Here, our contribution consist in the development of an adaptive dynamic model associated with a powerful identification algorithm that uses dynamic parameters in order to estimate the SOH of the SC.

3.1. Dynamic supercapacitor model

Several axes in researches on SCs aging have been tracked in order to understand, analyze and model this phenomenon [14,15]. For example, EIS and frequency models which are reported in many studies [16]. This technique is very helpful to identify aging sources such as heterogeneity of the electrode surface but it cannot run online. Furthermore, artificial intelligence techniques such as

Table 1
Temperature effects on dynamic supercapacitor modeling performance.

Model	Max relative error (%)	Mean relative error (%)
$Y(k) = K_0(k)Y(k-1) + K_2(k)Y(k-2) - R(k)I(k-1) + K_1(k)I(k-2) + K_3(k)T(k) + e(k)$	2.56	0.046
$Y(k) = K_0(k)Y(k-1) + K_2(k)Y(k-2) - R(k)I(k-1) + K_1(k)I(k-2) + e(k)$	4.07	0.096