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Supercapacitors State-of-Health Diagnosis for Electric Vehicle Applications

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Short Abstract Summary

This paper presents an online diagnosis method for supercapacitors' aging problem. State-of-Health (SoH) estimation is an important feature since aging introduces degradation in supercapacitors' performance, which might eventually lead to their failure. The diagnosis model is based on a sliding mode observer as a well-known technique for its high nonlinear parameters estimation performance. The main objective of this paper is the online State-of-Health diagnosis based on supercapacitors' aging indicators estimation. The effectiveness of the proposed online observer is shown through experimental results.

Keywords: diagnosis, EDLC (electric double-layer capacitor or supercapacitor), internal resistance, energy storage, prediction.

1 Introduction

Supercapacitors, also called Electric Double Layer Capacitors (EDLCs), offer attractive performance to use them as a peak power source [1], [2]. They are able to store directly an important energy in its electrical form, with an immediate availability. In addition, supercapacitors are characterized by a large number of charge/discharge cycle that permits to have a longer lifespan [3], [4]. Unlike batteries, supercapacitors are more suitable for storing and supplying higher energy in short periods of time such as in acceleration and regenerative breaking conditions thanks to their higher power density. However, their performance is heavily dependent on their State-of-Health (SoH) [5].

Several SoH estimation techniques have been reported for supercapacitors used in various applications [6]–[8]. Computational intelligence techniques, such as neural network and fuzzy logic systems, have been credited in various applications as powerful tools capable of providing robust approximation for systems that may be subjected to uncertainties. Soualhi *et al*. present a supercapacitor aging prediction method using Artificial Neural Networks (ANNs) [9]. On the other hand, Nadeau *et al*. [10] present a supercapacitor state-of-charge estimation for solar application using Kalman filter. Three-branch supercapacitor equivalent circuit has been chosen to model the supercapacitor. The RC circuit parameters have been considered constant with aging time. In addition, Chiang *et al*. [11] use the extended Kalman filter to estimate the temperature and the state of charge of supercapacitors. The RC circuit parameters have been determined offline based on the impedance measurements at different operating temperatures. On the other hand, El Mejdoubi *et al*. [12] present an online supercapacitors state-of-health diagnosis using the extended Kalman observer to estimate the aging indicators, the resistance and the capacitance, whatever the operating temperature and the charging current profile.

The contribution of this paper is to propose an online SoH diagnosis technique for supercapacitors. SoH's information is important to determine supercapacitors' End-of-Life (EoL). The proposed technique achieves online SoH estimation with impedance and capacitance measurements using a sliding mode observer. The effectiveness of the proposed method is verified by experimental results. The rest of the

paper is organized as follows: The proposed online diagnosis method is detailed in section 2. In section 3, experimental results are reported and analyzed. Finally, section 4 presents conclusion with some remarks.

2 Proposed Sliding Mode Observer

2.1 Modeling of Supercapacitors

Several studies have been conducted for the electrical modeling of EDLCs and few models result in drastic increase in the system's nonlinear complexity [13]–[16]. As shown experimentally in [6], [13], the dynamics can be represented by an equivalent RC network circuit model, as revealed in Fig.1. It consists of a series resistance R and capacitance C, which represents storage capability of the supercapacitor. This model is suitable for both energy and electrical behaviors of supercapacitors as it has been validated with different charge/discharge durations for a given cycle period [6]. This model is equivalent to a lumped first-order transmission line model, but it takes into account the capacitance variation when the voltage charging/discharging evolves during time [15], [17]. This last point introduces a strong nonlinearity for the model.

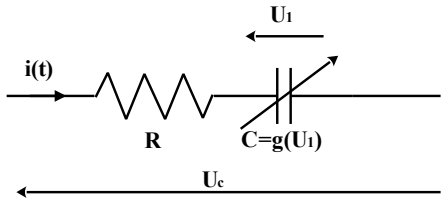


Fig. 1. Supercapacitor-RC circuit model

Therefore, the voltage-current characteristic dynamic model can be described by the following equations:

$$\begin{cases} U_c = U_1 + R.i(t) \\ U_1 = \frac{1}{C}.\int i(t)dt \end{cases} \quad (1)$$

Where, U_c (t) and i(t) are the supercapacitor voltage and its charge/discharge current, respectively. The equivalent series resistance and capacitance are represented, respectively, by R and C, with capacitance C defined by the following relationship [15], [17].

$$C = C_0 + \alpha.U_1 \quad (2)$$

2.2 Problem Statement

The aim of this study is to estimate the parameters R and C since they are directly correlated to supercapacitors' SoH. In this work, the system's parameters are assumed to be a priori unknown and the system's measurable states are the EDLC voltage and charge/discharge current. It is also assumed that the resistance is a slowly time-varying parameter such that $dR/dt = 0$ during a charge/discharge cycle. Also, the capacitance/voltage relationship evolves linearly with a constant or a slow time-varying slope α such that $d\alpha/dt = 0$.

2.3 Proposed Sliding Mode Observer

The main advantage of sliding-mode observers over their linear counterparts is that while in sliding, they are insensitive to the unknown inputs. Moreover, they can be used to reconstruct unknown inputs which could be a combination of system disturbances, faults or non-linearity. The reconstruction of unknown inputs has found impressive applications in diagnosis purpose [18]. The sliding mode observer principle consists in aligning the system to the sliding surface S defined as a function of the output error [19].
The sliding mode observer is used to estimate the state variables of a continuous nonlinear system defined by the system (Σ) defined already in the equation (9).

In fact, this model must combine all deterministic system information. Fig. 4 shows a block diagram of the sliding mode observer. It is noteworthy, from the nonlinear formulation (1), that the unknown state vector's variables are continuous.

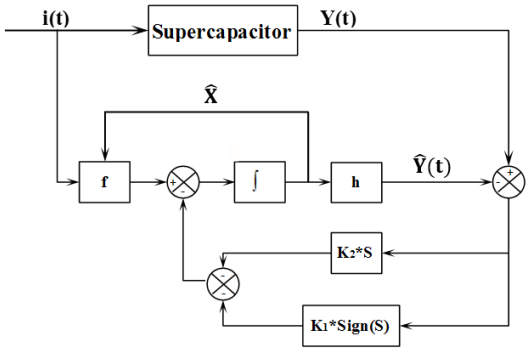


Fig. 2. Functional diagram of sliding mode observer

Where, K_1 and K_2 are positives sliding mode gain
Theorem: The convergence of the system is ensured to the sliding surface S defined by:

$$S = e - \lambda . \int e . dt \tag{3}$$

where, λ is a positive gain.
Proof: Choose the following Lyapunov candidate:

$$V(S) = \frac{1}{2} S^2 \tag{4}$$

Taking the derivative the Lyapunov function leads to:

$$\dot{V} = \dot{S}\, S \tag{5}$$

The system (Σ) is stable if $\dot{V} < 0$, so S must verify:

$$\begin{cases} \dot{S} < 0 \; et \; S > 0 \\ \quad ou \\ \dot{S} > 0 \; et \; S < 0 \end{cases} \tag{6}$$

So, $\dot{V} < 0$, if and only if

$$\begin{cases} \lambda < \dfrac{e}{\int e} \; et \; \lambda > \dfrac{\dot{e}}{e} \\ \quad ou \\ \lambda > \dfrac{e}{\int e} \; et \; \lambda < \dfrac{\dot{e}}{e} \end{cases} \tag{7}$$

We define the system stability area D_s such as:

$$D_s = \{\lambda \,/\, \dot{V} < 0\} \tag{8}$$

So,

$$D_s = \Re_+^* \cap \left\{ \left\{ \left]-\propto; \frac{e}{\int e}\right[\cap \left]\frac{\dot{e}}{e}; +\propto\right[\right\} \cup \left\{ \left]\frac{e}{\int e}; +\propto\right[\cap \left]-\propto; \frac{\dot{e}}{e}\right[\right\} \right\} \quad (9)$$

Thus, whatever $\lambda \in D_S$, the system (Σ) is stable in the sense of Lyapunov.

3 Experimental Results

3.1 Setup

Supercapacitors reliability is estimated by different electrical tests that provide complementary information. They are two test types: "DC voltage test" and "voltage cycling test". Calendar life testing is often mentioned in the literature [12]. The cells are prepared in different states of discharge (SOD) and are subjected to different temperatures. The cell parameters, i.e., resistance and capacitance, are measured periodically with well-defined charge/discharge conditions or with an Electrochemical Impedance Spectroscopy (EIS). In this study, two 350 F supercapacitors are used for tests. They are placed inside a temperature controlled chamber, which temperature is set to 70°C with a continuous applied voltage of 2.7V. These values were selected to accelerate aging without exceeding the electrolyte's boiling temperature point of 81.6°C for acetonitrile (at atmospheric pressure). Therefore, supercapacitors' calendar aging is carried out according to the following phases.

Since the voltage cannot be constant for the supercapacitor characterization, the supercapacitors are charged and discharged following a current profile with a constant temperature. It is important to note this occurs before starting the aging process. Then, the supercapacitors are placed inside the climatic chamber (70°C and 2.7V) and are connected to the voltage sources for few days. Finally, the supercapacitors are taken out of the climatic chamber to be characterized using the same current profile at ambient temperature. This process is repeated until the limit of aging is reached. Parameters such as the voltage and the current are measured before and after each aging phase using an acquisition board and LabView software as it illustrated in the test bench presented in Fig. 3.

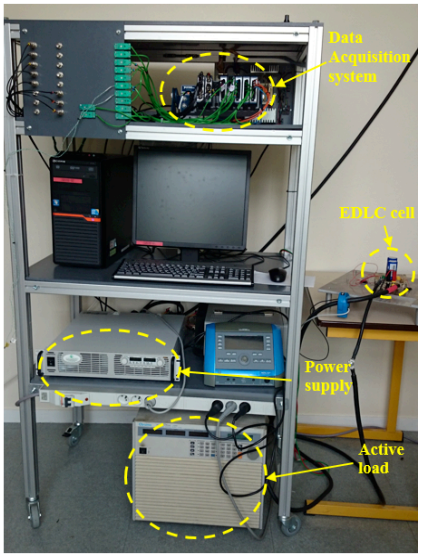


Fig. 3. Test bench used for characterization

In order to follow the evolution of the impedance R and the capacitance C during the aging process, the supercapacitors are characterized after each aging stage. Therefore, a piecewise charging current profile has been selected to age the supercapacitor under 70°C and 2.7V as it is depicted in Fig. 4. It is noteworthy that this profile introduces a nonlinearity (discontinuity) at each step, which is an additional burden compared to any smooth load profile.

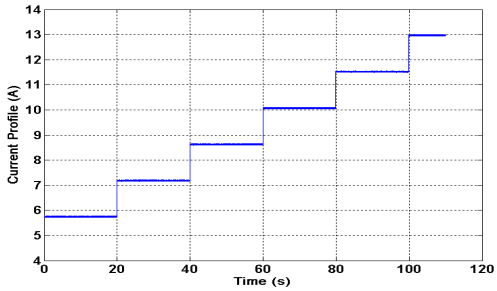
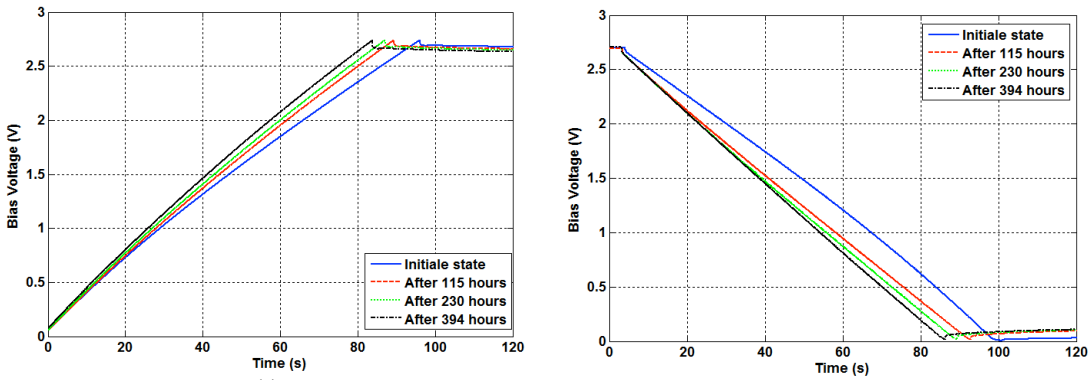


Fig. 4. Applied current profile

This profile introduces nonlinearities presented as an abrupt discontinuity at each step and provides continuous intervals to validate the proposed observer's performance in varying operating points. Four milestones are set to the aging process: 0 hour, 115 hours, 230 hours and 390 hours. The data measurements' sampling time is set to 0.1ms.

Experimental results for the supercapacitor voltage evolution in time during charge and discharge after each phase of calendar aging are depicted in Fig. 5. It is noteworthy that the charge and discharge time, i.e., capacitance, decreases as the supercapacitor ages. It also can be seen that at the beginning of the supercapacitor discharge, the drop of voltage increases with aging. This effect is due to the increase of the R, which is also an indicator of aging. The supercapacitor calendar aging is accelerated by increasing the temperature and by imposing a high bias voltage [13], [17], [20].



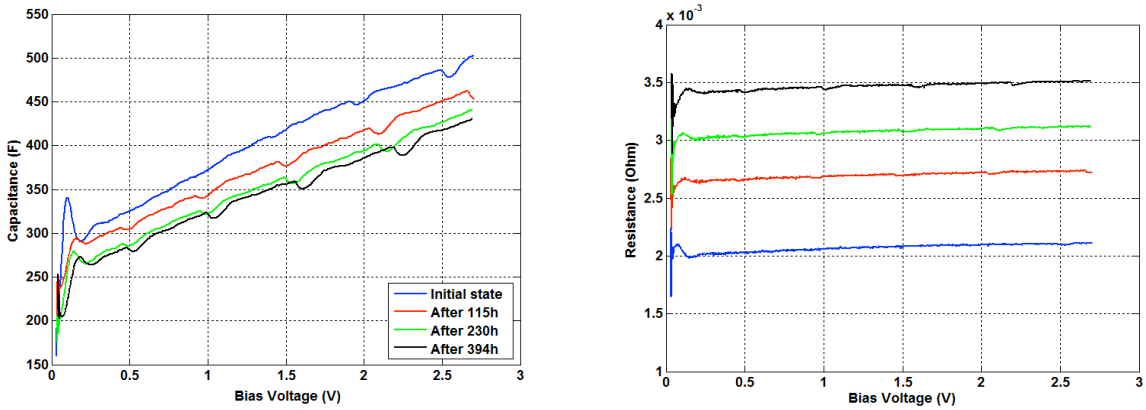
(a) (b)

Fig. 5. Supercapacitor cycles for different aging phases: a) charging; and b) discharging

On the other hand, high temperature leads to an important reactivity of the chemical component. At high bias voltage value, more impurities undergo a redox reaction and the decomposition of the electrolyte is accelerated. The physical origin of the aging is not well established. It is attributed to different phenomena as the oxidation of the carbon surface, the closing of the pores access, or/and the ionic depletion in the electrode [21]. When a supercapacitor is opened, after an aging period under large stress, the oxidation of the separator may be observed. A brown coloration appears on the surface, especially on the side exposed to the positive electrode. The electrolyte undergoes irreversible transformations which are accentuated with voltage and temperature. The electrochemical decomposition of the electrolyte generates a gas overpressure in the supercapacitor package (for example generation of H_2 in the case of acetonitrile [22] or CO_2 [23] or propylene carbonate [24]. This effect may be easily monitored by measuring the cell dimensions which increase with the pressure. To avoid a violent rupture of the can, the manufacturers introduce a controlled mechanical weakness in the design which acts as a mechanical fuse. Charging and discharging also create mechanical stresses in the electrode. It has been shown that the application of a voltage induces a reversible expansion of the electrode [25]. This mechanical motion, especially in the case of ionic insertion in the electrode, is known to be one of the origins of aging in the battery domain.

3.2 Estimated Results

An experiment is conducted using the aforementioned current profile. Results are depicted in Fig. 6. As it is revealed, both resistance and capacitance estimates show good convergence despite of current's profile nonlinearities. Then, comparison can be made for each aging milestone.



(a) (b)

Fig. 6. Estimation of the supercapacitor's parameters a) resistance, b) capacitance

As it is expected, resistance is shown to increase and capacitance to decrease as the supercapacitor ages. It is noteworthy from the theoretical model in (2) that the capacitance is proportional to the voltage, which is shown in experimental validation of Fig. 6(a).

Fig. 7 shows the measured and the estimated bias voltage. Perfect tracking is achieved and the error remains very small during all experiment. The high accuracy of the proposed observer is clearly shown in this experiment.

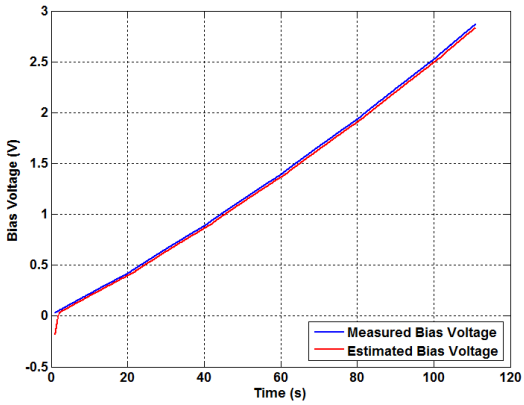


Fig. 7. Measured and estimated bias voltage

Thus, Fig. 8 presents the evolution of the initial error of the bias voltage estimated by sliding mode observer. The stability of the error is reached after one second with 0.2% as a maximum error. The sliding mode observer is fast and the estimated results are accurate, the value of the error after the transition phase reaches a constant value, i.e. 0.025%.

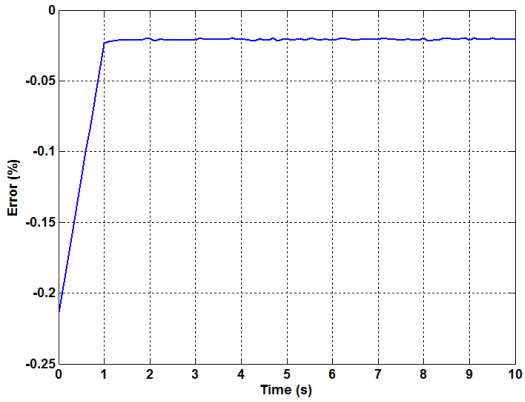


Fig. 8. Initial error of the bias voltage estimated by sliding mode observer

4 Conclusion

In this paper, an online aging diagnosis method is presented for supercapacitors. The proposed strategy capitalizes on the capabilities of the sliding mode for the design of a sliding mode observer. Therefore, online parameters' estimation is achieved, which yields SoH prediction. Unlike other methods such as electrochemical impedance spectroscopy, where estimation is performed offline and requires interruption of the system's operation, this paper presents an online diagnosis method. Moreover, only voltage and current measurements are required. The effectiveness of the proposed online observer is shown through a set of experiments. Results highlight its good performance in parameters estimation with robustness to current's nonlinearities.

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