EVS29 Symposium
Montréal, Québec, Canada, June 19-22, 2016

Supercapacitors State-of-Health Diagnosis for Electric Vehicle Applications

Asmae El Mejdoubi[1,2], Hicham Chaoui[3], Hamid. Gualous[1,*], Amarne Oukaour[1], Youssef Slamani[1], Jalal Sabor[2]
[1] Laboratoire LUSAC, Université de Caen Normandie, Cherbourg, France
[*] BP 78, rue Louis Aragon, 50130 Cherbourg-Octeville, France, *hamid.gualous@unicaen.fr*
[2] Equipe CP2S, ENSAM, Université Moulay Ismail, Meknès, Maroc
[3] Electrical & Computer Engineering Tennessee Technology University, Cookeville, TN, USA

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.

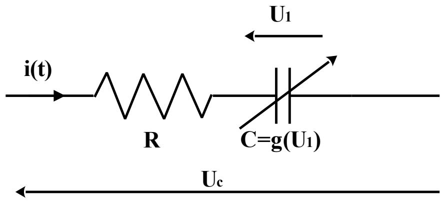


Fig. 1. Supercapacitor-RC circuit model

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

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

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.

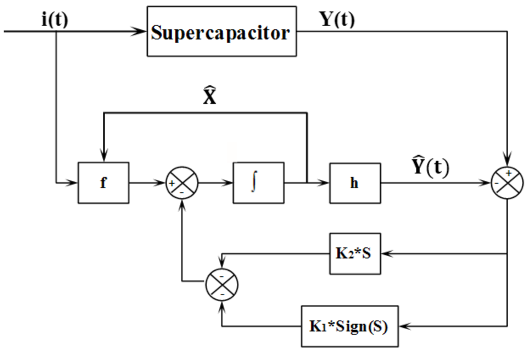


Fig. 2. Functional diagram of sliding mode observer

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,

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

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.

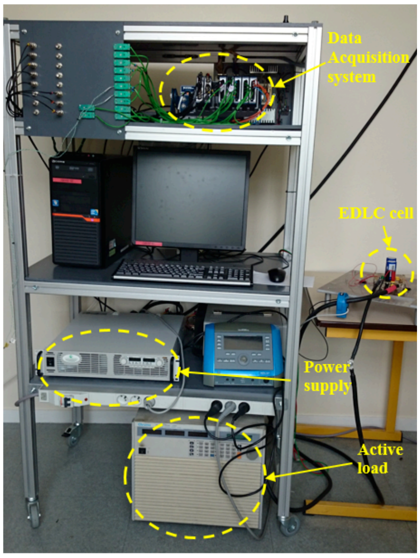


Fig. 3. Test bench used for characterization

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.

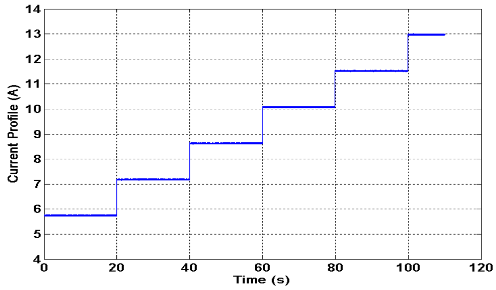
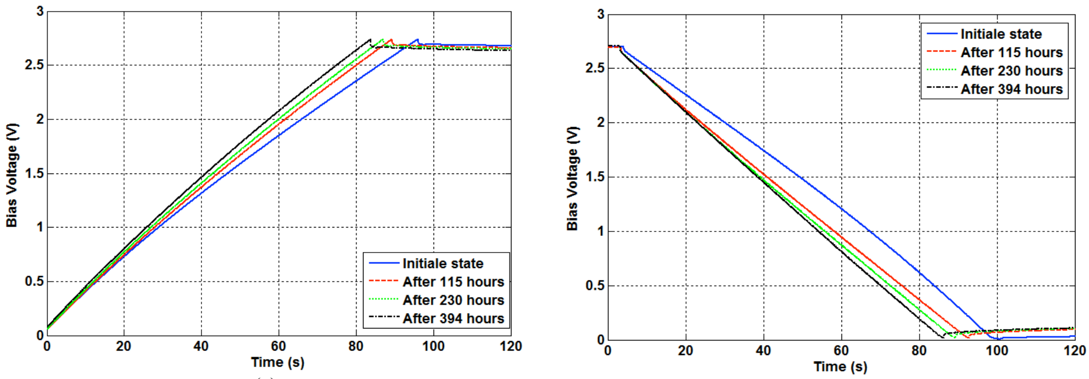


Fig. 4. Applied current profile

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].



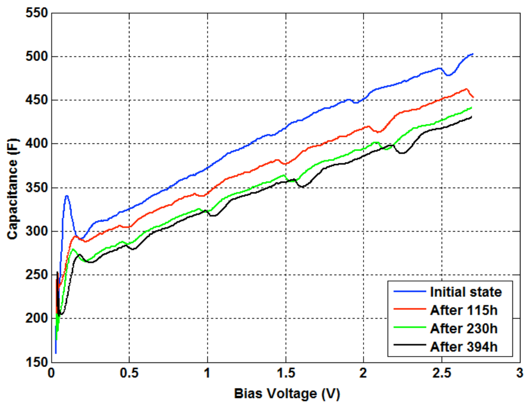
(a) (b)

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

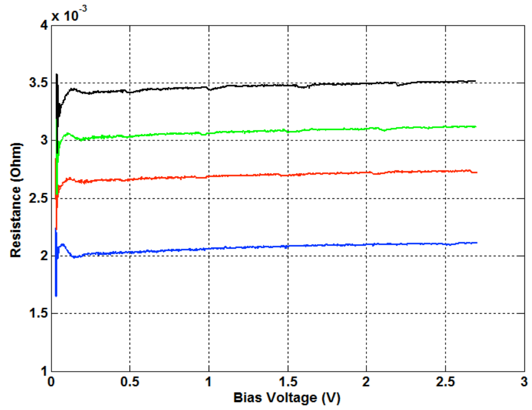
On the other hand, high temperature leads to an important reactivity of the chemical component. At high bias voltage value, more impurities undergo a redox reaction and the decomposition of the electrolyte is accelerated. The physical origin of the aging is not well established. It is attributed to different 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.

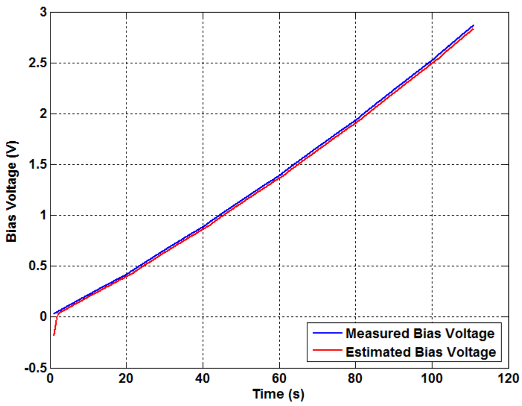


Fig. 7. Measured and estimated bias voltage

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%.

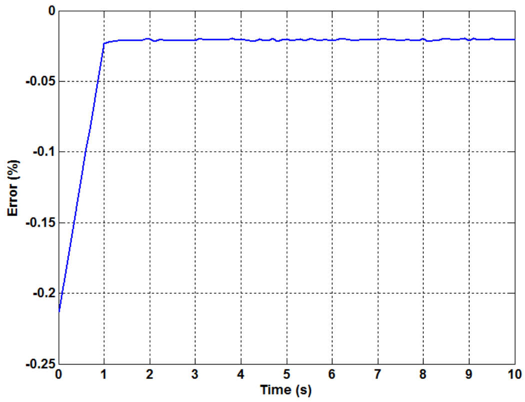


Fig. 8. Initial error of the bias voltage estimated by sliding mode observer

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.

References

[1] M.B. Camara, H. Gualous, F. Gustin, A. Berthon, "Design and New Control of DC/DC Converters to Share Energy Between Supercapacitors and Batteries in Hybrid Vehicles", *IEEE Transactions on Vehicular Technology*, vol. 57, Issue: 5, pp. 2721-2735, Sept. 2010.

[2] J.S. Martinez, D. Hissel, M.C. Pera, M. Amiet, "Practical Control Structure and Energy Management of a Testbed Hybrid Electric Vehicle", *IEEE Transactions on Vehicular Technology*, vol. 60, Issue: 9, pp. 4139-4152, Nov. 2011.

[3] R. Esteves Araujo, R. de Castro, C. Pinto, P. Melo, D. Freitas, "Combined Sizing and Energy Management in EVs With Batteries and Supercapacitors", *IEEE Transactions on Vehicular Technology*, vol. 63, Issue: 7, pp. 3062-3076, Sept. 2014.

[4] Jiabin Wang, B. Taylor, Zhigang Sun, D. Howe, "Experimental Characterization of a supercapacitor-Based Electrical Torque-Boost System for Downsized ICE Vehicles", *IEEE Transactions on Vehicular Technology*, vol. 56, Issue: 6, pp. 3674-3681, Nov. 2007.

[5] R. Carter, A. Cruden, P.J. Hall, "Optimizing for Efficiency or Battery Life in a Battery/Supercapacitor Electric Vehicle", *IEEE Transactions on Vehicular Technology*, vol. 61, Issue: 4, pp. 1526-1533, May 2012.

[6] Hanmin Liu, Zhixin Wang, Jie Cheng, D. Maly, "Improvement on the Cold Cranking Capacity of Commercial Vehicle by Using Supercapacitor and Lead-Acid Battery Hybrid", *IEEE Transactions on Vehicular Technology*, vol. 58, Issue: 3, pp. 1097-1105, March 2009.

[7] Wei Wang, Ming Cheng, Ya Wang, Bangfu Zhang, Ying Zhu, Shichuan Ding, Wei Chen, "A Novel Energy Management Strategy of Onboard Supercapacitor for Subway Applications With Permanent-Magnet Traction System", *IEEE Transactions on Vehicular Technology*, vol. 63, Issue: 6, pp. 2578-2588, July 2012.

[8] N. Rizoug, P. Bartholomeus, P. Le Moigne, "Modeling and Characterizing Supercapacitors Using an Online Method", *IEEE Transactions on Industrial Electronics*, vol. 57, Issue: 12, pp. 3980-3990, Dec. 2010.

[9] A. Soualhi, A. Sari, H. Razik, P. Venet, G. Clerc, R. German, O. Briat, J.M. Vinassa, "Supercapacitors ageing prediction by neural networks", *in Proc. IECON- IEEE 39th Annual Conference on Industrial Electronics Society*, Vienna, Austria, pp. 6812-6818, Nov. 2013.

[10] A. Nadeau, G. Sharma, and T. Soyata, "State-of-charge estimation for supercapacitors: A kalman filtering formulation", *in Proc. 2014 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP 2013)*, Florence, Italy, pp. 2213–2217, May 2014.

[11] Chia-Jui Chiang, Chia-Jui, Jing-Long Yang, and Wen-Chin Cheng. "Temperature and state-of-charge estimation in ultracapacitors based on extended Kalman filter", *Journal of Power Sources*, vol. 234, 234-243, 2013.

[12] A. El Mejdoubi, A. Oukaour, H. Chaoui, Y. Slamani, J. Sabor, H. Gualous, "Online Supercapacitor Diagnosis for Electric Vehicle Applications", *IEEE Transactions on Vehicular Technology,* vol. 99 pp, 1.

[13] P. Kurzweil, M. Chwistek, R. Gallay, "Capacitance Determination and Abusive Aging Studies of Supercapacitors Based on Acetonitrile and Ionic Liquids", *in Proc. 16th International Seminar On Double Layer Capacitors*, Deerfield Beach, USA, 2006, pp. 78.

[14] M. Hahn, R. Kötz, R. Gallay, A. Siggel, "Pressure evolution in propylene carbonate based electrochemical double layer capacitors", in *Proc. 56th Annual Meeting of the Intern. Soc. of Electrochemistry*, Busan, Korea 2005, pp. 1709-1712.
[15] [15] M. Hahn, O. Barbieri, R. Gallay, R. Kötz, "A dilatometric study of the voltage limitation of carbonaceous electrodes in aprotic EDLC type electrolytes by charge-induced strain", *Carbon*, vol. 44, pp. 2523-2533, October 2006.
[16] N. Rizoug, P. Bartholomeus, P. Le Moigne, "Study of the Ageing Process of a Supercapacitor Module Using Direct Method of Characterization", *IEEE Transactions on Energy Conversion* , vol. 27, pp. 220-228, June 2012.
[17] S. D. G. Jayasinghe, D.M. Vilathgamuwa, "Flying Supercapacitors as Power Smoothing Elements in Wind Generation", *IEEE Transactions on Industrial Electronics,* vol. 60, Issue: 7, pp. 2909-2918, July 2013.
[18] Karanjit Kalsi, Jianming Lian, Stefen Hui, Stanislaw H. Zak, "Sliding-Mode Observers for Uncertain Systems", in proc. American Control Conference, June 10-12, 2009, USA.
[19] J. Slotine, J. Hedrick et E. Misawa, "Nonlinear state estimation using sliding observers", *in proc. 25th IEEE Conf.* , Greece, 1986.
[20] Lei Zhang, Zhenpo Wang, Fengchun Sun, David G. Dorrell, "Online Parameter Identification of Ultracapacitor Models Using the Extended Kalman Filter." *Energies*, vol. 7, pp. 3204-3217, 2014.
[21] F. Rafik, H. Gualous, R. Gallay, A. Crausaz, A. Berthon "Frequency, thermal and voltage supercapacitor characterization and modelling" *Journal of Power Sources*, vol.165, Issue 2, pp. 928-934, 2007.
[22] O. Bohlen, J. Kowal, and D. U. Sauer, "Ageing behaviour of electrochemical double layer capacitors: Part I. Experimental study and ageing model", *Journal of Power Sources*, vol. 172, Issue: 1, pp. 468–475, Oct. 2007.
[23] D. Linzen, S. Buller, E. Karden, R.W. De Doncker, "Analysis and evaluation of charge-balancing circuits on performance, reliability, and lifetime of supercapacitor systems", *IEEE Transactions on Industry Applications*, vol. 41, pp. 1135 – 1141, Sept\Oct. 2005.
[24] M. Choi, J. Lee, S. Seo, "Real-Time Optimization for Power Management Systems of a Battery/Supercapacitor Hybrid Energy Storage System in Electric Vehicles", *IEEE Transactions on Vehicular Technology*, vol. 63, Issue: 8, pp. 3600-3611, Oct. 2014.
[25] L. Hardwick, M. Hahn, P. Ruch, M. Holzapfel, W. Scheifele, H. Buqa, F. Krumeich, P. Novák, R. Kötz. "An in situ Raman study of the intercalation of supercapacitor-type electrolyte into microcrystalline graphite". *Electrochimica Acta*, vol. 52, pp. 675-680, October 2006.

Asmae El Mejdoubi was born in Morocco in 1988. She received the Engineering degree in Electromechanical Engineering from the Ecole Nationale Supérieure d'Arts & Métiers "ENSAM", Meknès, Morocco, in 2012, and the Ph.D. degree in electrical engineering jointly from the University of Caen Normandie, Cherbourg-Octeville, France, and the l'ENSAM de l'Université Moulay Ismaïl, Meknes, in 2015
Her research interests are in the area of energy storage, more specifically, supercapacitors and Lithium-ion batteries, State-of-Health and State-of-Charge diagnosis and aging estimation.

Hicham Chaoui received the B.Sc. degree in electrical engineering from the Institut supérieur du Génie Appliqué (IGA), Casablanca, Morocco, in 1999, the M.A.Sc. degree in electrical engineering, the M.Sc. degree in computer science (with honors), the graduate degree in project management, and the Ph.D. degree in electrical engineering (with honors) all from the University of Quebec, Canada, in 2002, 2004, 2007, and 2011, respectively.
His career has spanned both academia and industry in the field of intelligent control and renewable energies. Prior to his academic career, he held various engineering and management positions including Vice-President Innovation and Technology Development. He is currently an Assistant Professor at Tennessee Technological University, TN, USA and an Adjunct Professor at the Université du Québec à Trois-Rivières, QC, Canada. His research interests include adaptive and nonlinear control theory, intelligent control, robotics, mechatronics, electric motor drives, and energy storage and management. He co-authored more than 70 journal and conference publications. He is a senior member of IEEE and serves regularly as a reviewer for many prestigious scientific editors.
Dr. Chaoui was a recipient of the Best Thesis Award (health, natural science, and engineering) and the Governor General of Canada Gold Medal Award.

Hamid Gualous (M'14) was born in Morocco in 1967. He received the Ph.D. degree in electronics from the university Paris XI Orsay, France, in 1994. From 1996 to 2009, he was an Associate Professor at the University of Franche-Comte in FEMTO-ST laboratory, France. He is currently a Full Professor at the University of Caen-Basse Normandie and the director of LUSAC laboratory. His main research activities include energy storage device, marine renewable energies, and energy management systems for smart grids.

Amrane Oukaour was born in Algeria 1963. He received Ph.D degree in electrical engineering from Pierre & Marie-Curie University (Paris IV), France in 1993.
From 1995 to 2003, he was an Associate Professor at the Antilles and French Guyana University. Since 2003, he has been an Associate Professor at the Caen Normandie University.
His current research interests are in the field of the diagnosis of the ageing states of power sources (Batteries – Supercapacitors – Fuel Cell).

Jalal Sabor received the Ph.D. degree in engineering science from the Institut National des Sciences Appliquées (INSA), Rouen, France in 1995. He is currently a Professor of industrial computer science at the Ecole Nationale Supérieure d'Arts & Métiers (ENSAM), Université Moulay Ismail, Meknes, Morocco. He is a member of the LSMI Laboratory, He is also the research team control steering and supervision systems head. His main research interests include intelligent management of energy, smart grid, control and supervision systems, architecture based on multi-agent systems and fuzzy logic.