Proceedings of the 3rd International Conference on Systems and Control, Algiers, Algeria, October 29-31, 2013

Nonlinear Flatness Control Applied for Energy Management of PV/Batteries/Supercapacitors Hybrid Power Sources for Stand-Alone Applications

M. Benaouadj, M.Y. Ayad, M. Becherif, A. Aboubou, M. Bahri and O. Akhrif

Abstract—**This paper presents the hybridization of photovoltaic (PV) panels considered as the main source, with lead-acid batteries and supercapacitors used as storage system, for a stand-alone application. The aim is to supply a domestic load and energy management between different components.**
A nonlinear control strategy based on the flatness approach is applied to manage energy flows among the PV source, storage unit and load in the system. Simulation results are presented and discussed when applying different solar illuminations.

I. Introduction

The production of electrical energy by PV systems is highly dependent on weather conditions. Therefore, this energy should be stored during the day [1].

Presently, the lead-acid batteries are the most common electrochemical storage technology. Their use has been widely demonstrated, but costs and life-cycle characteristics are not yet satisfactory and need to be improved for stand-alone applications [2].

Developed at the end of the seventies for signal applications (for memory back-up for example), supercapacitors present a capacitance of some farads and specific energy of about 0.5 $Wh.kg^{-1}$. The power supercapacitors appeared during the nineties and brought components of thousands of farads and high specific power of several $kW.kg^{-1}$.

When lead-acid batteries are subjected to extreme conditions (high discharge current for example), their performance degrades rapidly. So, the use of a hybrid storage source is indispensable: batteries will be dedicated to store and supply the produced photovoltaic energy, while the auxiliary source (supercapacitors) would deal with high solicitations (deep discharge).

M. Benaouadj is with the Laboratory of Energy Systems Modeling, University of Mohamed Kheider, Biskra, Algeria (e-mail: b-mahdii@hotmail.fr).
M.Y. Ayad is an IEEE member, he is with Industrial Hybrid Vehicle Applications France (corresponding author: e-mail: ayadmy@gmail.com).
M. Becherif is an IEEE member, he is with FCLab FR CNRS 3539, FEMTO-ST UMR CNRS 6174, UTBM University, Belfort, France (e-mail: mohamed.becherif@utbm.fr).
A. Aboubou is with the Laboratory of Energy Systems Modeling, University of Mohamed Kheider, Biskra, Algeria (e-mail: a.aboubou@mselab.org).
M. Bahri is with the Laboratory of Energy Systems Modeling, University of Mohamed Kheider, Biskra, Algeria (e-mail: m.bahri@mselab.org).
O. Akhrif is with GREPCI Research Group, Ecole de Technologie Supérieure, Montréal, QC, Canada (e-mail: ouassima.akhrif@etsmtl.ca).

This paper presents a "PV/Batteries/Supercapacitors" hybrid power sources used to supply a house load. The energy management between the photovoltaic source, storage system and the load is assured by applying a nonlinear control based on the flatness approach.

II. Presentation of the Autonomous Hybrid System

The studied autonomous hybrid system combines, as shown in figure 1, a permanent source for energy production, and two intermediate storage elements. It includes:

- A DC link (bus), assuring power segmentation between load, main source (wind and photovoltaic sources), and storage elements (lead-acid batteries and supercapacitors).
- A PV source connected to the DC link using a DC-DC converter.
- Lead-acid batteries (electrochemical storage) connected to the DC bus by a current bidirectional DC-DC converter.
- Supercapacitors (electrostatic storage) connected to the DC link through a current bidirectional DC-DC converter.
- A supervision system used to control the batteries and the supercapacitors "charge/discharge".
- A house load modeled by a daily consumption profile.

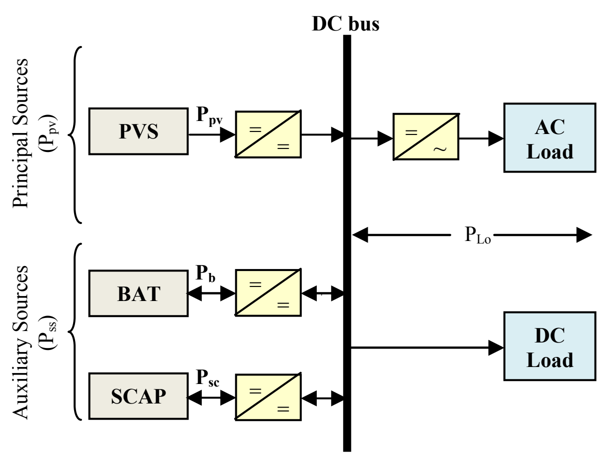

Figure 1. Synoptic of the autonomous hybrid system.

III. Modelling of the Autonomous Hybrid System

A. Photovoltaic source

A PV generator converts illumination energy into electric current. It is obtained by the combination of several PV cells to adapt the theoretical energy to the load demand.

The energy supplied by a PV generator is written as follows [3]:

$$E_{pv} = n_e P_c \tag{1}$$

978-1-4799-0275-0/13/$31.00 ©2013 IEEE

n_e: number of daily illumination hours [h/d]
P_c: Peak power [W]

A MPPT (Maximum Power Point Tracking) controller is used to allow operating the PV source under the maximum available power.

B. Lead-acid batteries

The electrical model of a lead-acid battery has an electromotive force (E_0) modelling the battery open circuit voltage, a capacitor (C_b) modelling the battery internal capacity, and an internal resistance (R_s) [4].

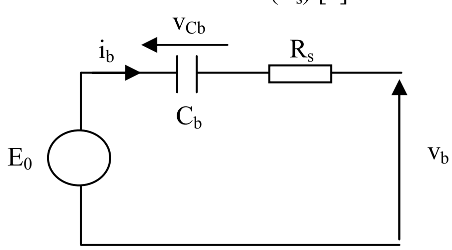

Figure 2. R-C model of the lead-acid batteries.

- The batteries voltage is written as follows:

$$v_b = E_0 - v_{Cb} - R_s i_b \tag{2}$$

- The batteries State of Charge, SOC_b, is written in [%] by:

$$SOC_b = \left(1 - \frac{Q_{dB}}{C_B}\right) \times 100 \tag{3}$$

C_B: nominal capacity [Ah]
Q_{dB}: Quantity of charge missing comparing to C_B

C. Supercapacitors

The basic and commonly used equivalent model of a supercapacitor is a capacitor (C_{elem}) in series with a resistor (R_{elem}) [5].

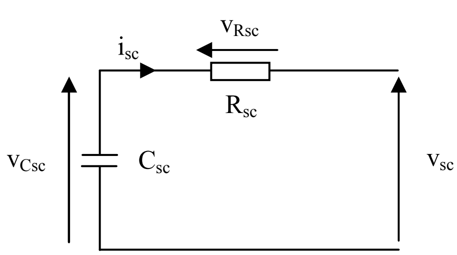

Figure 3. Model of the supercapacitors.

- The supercapacitors voltage is written as follows:

$$v_{sc} = v_{Csc} - R_{sc} i_{sc} \tag{4}$$

- The supercapacitors State of Charge, SOC_{sc}, is written in [%] as follows [6]:

$$SOC_{sc} = \left(\frac{4}{3}\left(\frac{E_{sc}}{E_{sc\max}} - \frac{1}{4}\right)\right) \times 100 \tag{5}$$

E_{sc}: stored energy [J]
E_{scmax}: maximal contained energy [J]

D. Supervision system

P_{pv} ist he power supplied by the PV source, and P_{Lo} is the consumed power. By adopting the "generator" convention (the current supplied by the storage elements is positive),then:

$$P_{ss} = P_{Lo} - P_{pv} \tag{6}$$

P_{ss} represents the available power for charging batteries and supercapacitors. Thus, when it is negative, the corresponding storage element receives power and, is, therefore in charge; it can be said that the principal source production exceeds the load demand. Different thresholds voltages of the supervision system are summarized in Table 1.

TABLE I. THRESHOLDS VOLTAGES OF THE SUPERVISION SYSTEM

Threshold	Definition	Value
V_1	High thresholdfor stop chargingbatteries	52V
V_2	Lowthreshold for stop discharging batteries	47.2V
V_3	High thresholdfor stop chargingsupercapacitors	30V
V_4	Lowthreshold for stop discharging supercapacitors	15V

E. Energy consumption

The energy balance of the chosen house is shown in Table II.

TABLE II. DAILY ENERGY CONSUMPTION

Load	Power [W]	Elements number	Use during [h/d]	Daily consumption [Wh/d]
Fluorescent	20	5	4	400
Refrigerator	70	1	10	700
Deep freeze	120	1	10	1200
TV	75	1	4	300
Washer	300	1	1	300
PC	40	1	4	160
Total				3060

IV. DESIGN OF THE AUTONOMOUS HYBRID SYSTEM

Different characteristics, obtained using the worst month, are summarized in Table III.

TABLE III. CHARACTERISTICS OF THE AUTONOMOUS HYBRID SYSTEM

PV source: AEG-40 is chosen		
Peak power [W]	Elements number	Surface [m²]
1920	50	19.2

Lead-acid batteries: Yuasa NP65-12 is chosen				
Nominal voltage [V]	Rated capacity [Wh]	Depth of discharge [%]	Autonomy days number	Elements number
48	4707.7	60	2	20

Supercapacitors: BCAP0100 P270 T07 ischosen				
Maximal power [W]	Maximal voltage [V]	Elements number	Resistance [Ω]	Capacity [F]
2400	30	44	0.04125	36.36

Converters			
Inductance L_{pv} [H]	Inductance L_b [H]	Inductance L_{sc} [H]	Capacity C_{pv} [F]
0.0007	0.0015	0.03	0.0002

DC link	
Nominal voltage [V]	Capacity [F]
24	0.025

V. Flatness Control of the Autonomous Hybrid System

A. *Structure of the autonomous hybrid system*

Structure of the studied system is showed in figure 4.

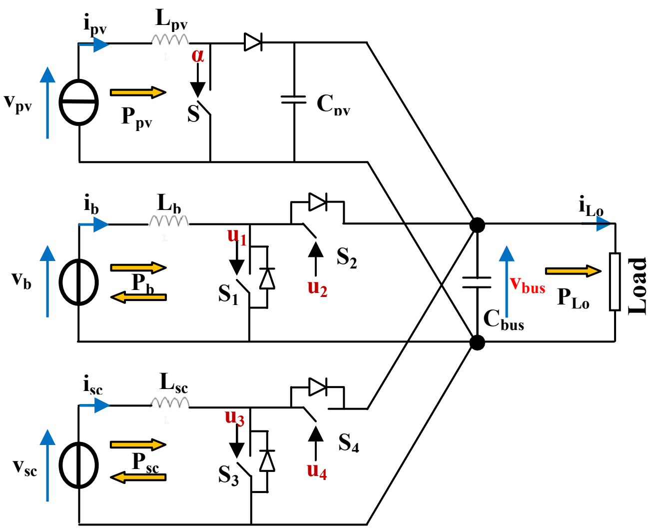

Figure 4. Structure of the autonomous hybrid system.

B. *System control*

The flatness concept was proposed fifteen years ago by Michel Fliess [1], and has been used in different applications of electrical engineering such as hybrid sources based on Fuel cell/Supercapacitors[7-10] and Batteries/Supercapacitors [11-12].

The major advantage of the flatness approach is to plan the desired trajectory of the flat output variable. If the modelling is without error, it is possible to know the evolution of all variables without having to solve any differential equation [7], simplifying, then, the system control.

C. *Energy management principle*

The proposed power management is based on:

- Use of the primary source for supplying power to consumer.
- Use of the auxiliary source to:
  - Compensate the difference in power between load and the main source.
  - Absorb the excessive power produced by the primary source.
  - Provide and absorb the power needed to control the bus capacitive voltage (v_{bus}).

D. *Control laws*

The nonlinear flatness control applied to PV/Batteries/ Supercapacitors autonomous hybrid sources follows the following steps:

- The flatness study:

To demonstrate the model flatness, it is necessary to verify that it is always possible to express all state and control variables according to the flat output variable and a finite number of its derivatives. So, y_{bus} is defined as the flat output variable, P_{SC} as the control variable and v_{bus} as the state variable.

➔ The state variable v_{bus} can be written as follows:

$$v_{bus} = \sqrt{\frac{2y_{bus}}{C_{bus}}} = f_{v_{bus}}(y_{bus}) \tag{7}$$

➔ The control variable P_{SC} can is given by:

$$P_{SC} = \sqrt{\frac{2y_{bus}}{C_{bus}}}.i_{Lo} + \dot{y}_{bus} - P_{pv} - P_b = h_{P_{SC}}(y_{bus}, \dot{y}_{bus}) \tag{8}$$

$v_{bus} = f_{v_{bus}}(y_{bus})$ and $P_{sc} = h_{P_{SC}}(y_{bus}, \dot{y}_{bus})$ $\rightarrow$ The energy system model can be considered as « differentially flat » [13-14].

- The reference trajectory planning:

The desired reference trajectory for the electrostatic energy y_{bus} is:

$$y_{busref}(t) = \frac{1}{2} C_{bus} v_{busref}(t)^2 \tag{9}$$

- The flat output variable tracking:

To track y_{bus} to its reference y_{busref}, the following law is used:

$$(\dot{y}_{bus} - \dot{y}_{busref}) + k_{11}(y_{bus} - y_{busref}) + k_{12}\int_0^t (y_{bus} - y_{busref})dt = 0 \tag{10}$$

The choice of $k_{11}$and$k_{12}$is done by studying roots of the following characteristic equation(roots placement):

$$s^2 + k_{11}s + k_{12} = 0 \tag{11}$$

With:

$$\begin{cases} k_{11} = 2\xi w_n \\ k_{12} = W_n{}^2 \end{cases} \tag{12}$$

ξ and w_n are, respectively, the desired dominant damping ratio and the natural frequency.

- The batteries power control:

The power supplied or absorbed by lead-acid batteries is obtained as follows:

$$\begin{cases} P_b = P_{b\,max} \\ P_{sc} = P_{ss} - P_b \end{cases} \quad \text{if} \quad P_{ss} \geq P_{b\,max} \tag{13}$$

$$\begin{cases} P_b = P_{ss} \\ P_{sc} = 0 \end{cases} \quad \text{if} \quad 0 \prec P_{ss} \prec P_{b\,max} \tag{14}$$

$$\begin{cases} P_b = 0 \\ P_{sc} = P_{ss} \end{cases} \quad \text{if} \ P_{ss} \prec 0 \ \text{and} \ v_{sc} \prec V_3 \tag{15}$$

$$\begin{cases} P_b = P_{ss} \\ P_{sc} = 0 \end{cases} \text{ if } P_{ss} \prec 0 \text{ and } v_{sc} \geq V_3 \text{ and } v_b \prec V_1 \qquad (16)$$

- The inductive currents tracking:

To generate signalsu$_1$, u_2, u_3 and u_4, two hysteresis comparators with fixed bandwidths are used.

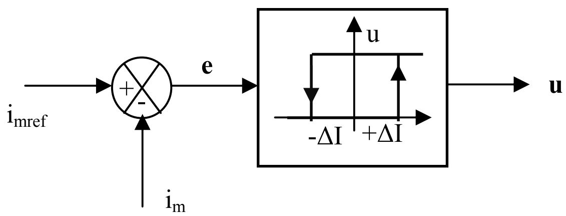

Figure 4. Principle of a hysteresiscomparator.

E. Simulation results and discussion

The simulation results are shown in the next figures.

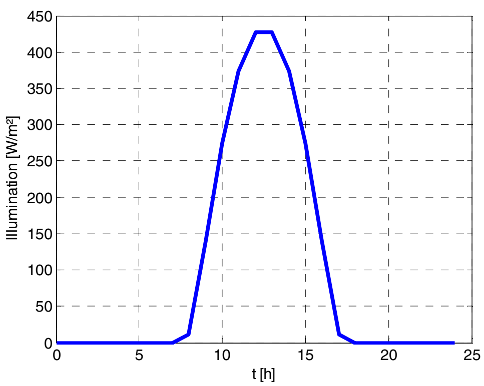

Figure 6. Solar illumination profil.

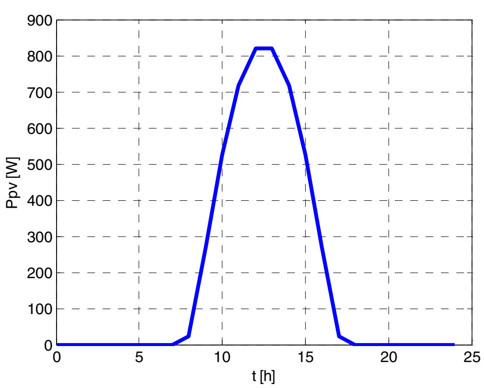

Figure 7. Daily PV production.

In figures 10, 11 and 12, and after a complete day of system operation, it is noted that the «charging/ discharging» process of the lead-acid batteries and the supercapacitors is respected as their states of charge are within admissible intervals, and the capacitive voltage v_{bus} is regulated to its reference:

- When the power P_{ss} is positive and the voltage across the supercapacitors is greater than V_4, resulting a decreasing of voltages and states of charge: batteries supply the load power demand, and supercapacitors deliver the necessary power to regulate v_{bus}.

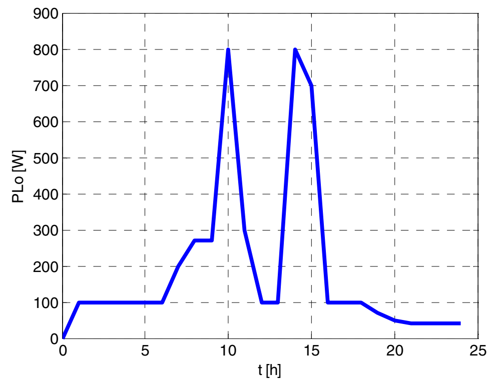

Figure 8. Consumption profile.

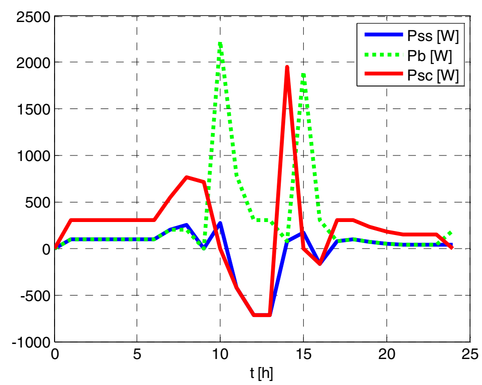

Figure 9. Power curves of the hybrid storage system.

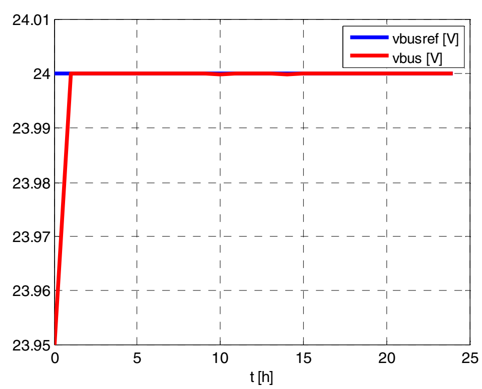

Figure 10. DC link voltage and its reference.

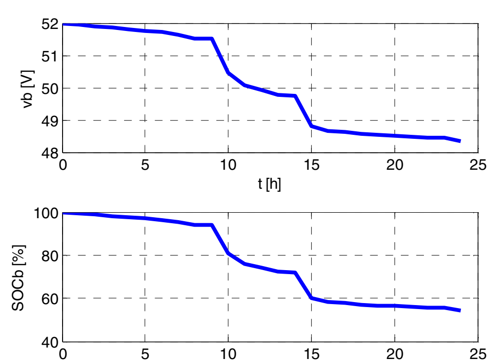

Figure 11. Batteries voltage and state of charge.

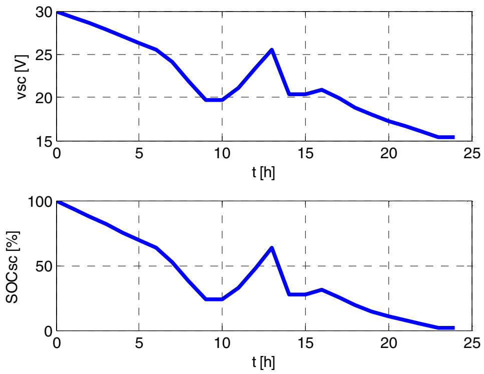

Figure 12. Supercapacitors voltage and state of charge.

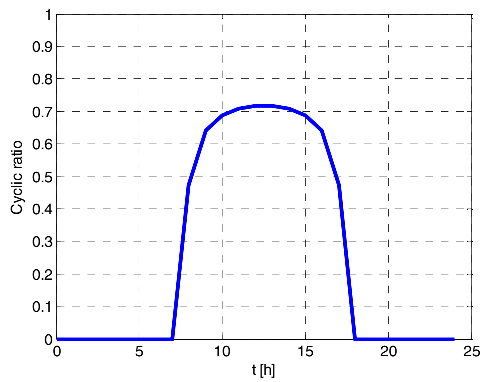

Figure 13. Photovoltaic converter duty cycle changing.

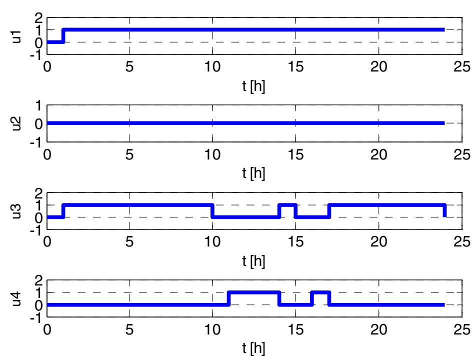

Figure 14. Switching sequences of S_1, S_2, S_3 and S_4.

- If P_{ss} is positive and the voltage across the supercapacitors is less than V_4, causing a decreasing of voltage and state of charge of batteries, and a constancy of those of supercapacitors: batteries supply power to the load and the DC bus, and no power is delivered by supercapacitors.
- When the power P_{ss} is negative, resulting a decreasing of the voltage and state of charge of the batteries, and an increasing of those of supercapacitors: batteries deliver power to the DC link, and the produced surplus is used to charge supercapacitors which never reach fully charge ($v_{sc} < V_3$).
- The supercapacitors are disconnected when their voltage is less than V_4.
- It is always verified that: $v_b \in [V_1, V_2]$ and $v_{sc} \in [V_3, V_4]$.

VI. Conclusion

In this paper, the flatness control was used to manage energy flows in a hybrid generation system which consists of a photovoltaic source, lead-acid batteries and supercapacitors.

After setting the DC bus voltage and supercapacitors power as state and control variables, respectively, and demonstrated that the system model can be considered as differentially flat, the reference trajectory planning for the electrostatic energy stored in the output capacitor allows to simplifying the system control without having to solve any differential equation.

The simulation results have proved that:

- The DC bus voltage is controlled and regulated to its reference,
- The batteries and supercapacitors voltages and states of charge are maintained in their admissible interval. Therefore, the hybrid system lifetime is theoretically increased.

References

[1] M. Benaouadj, A. Aboubou, M.Y. Ayad, M. Becherif, Z. Boumous and S. Boumous: "Modeling of self hybrid system for charging vehicle h2v", Second International Conference on New and Renewable Energies, (SIENR'12), Ghardaïa, Algeria, October 15-17, 2012.

[2] M. Benaouadj,A. Aboubou, M. Becherif, M.Y. Ayad, M. Bahri: "Recharging of Batteries/Supercapacitors Hybrid Source for Electric Vehicles Application using Photovoltaic Energy in a Stand-Alone Point", First International Conference on Renewable Energies and Vehicular Technology, (REVET'12), Hammamet, Tunisia, March 26-28, 2012, pp. 161-166.

[3] Jong Hwan Lim, ''Optimal Combination and Sizing of a New and Renewable Hybrid Generation System'', International Journal of Future Generation Communication and Networking Vol. 5, N° 2, June, 2012.

[4] A.T. Singo, ''Système d'alimentation photovoltaïque avec stockage hybride pour l'habitat énergétiquement autonome'', PhDthesis, University of Henri Poincaré, Nancy-I, France, February 2010.

[5] W. Hankache, ''Géstion optimisée de l'énergie électrique d'un groupe électrogène hybride à pile à combustible'', PhDthesis National Polytechnic Institute of Toulouse, France, December 2008.

[6] J. Lachaize, ''Etude des stratégies et des structures de commande pour le pilotage des systèmes énergétiques à Pile à Combustible (PAC) destinés à la traction'', PhDthesis, National Polytechnic Institute of Toulouse, France, September 2004.

[7] P. Thounthong, S. Pierfederici, J.P. Martin, M. Hinaje, B. Davat, ''Modeling and Control of Fuel Cell / Supercapacitor Hybrid Source Based on Differential Flatness Control'', IEEE Transactions on Vehicular Technology, July 2010, pp. 2700-2710.

[8] R. Saadi, M. Benaouadj, O. Kraa, M. Becherif, M.Y. Ayad, A. Aboubou, M. Bahri, A. Haddi: " Energy Management of Fuel Cell / Supercapacitors Hybrid Power Source Based on the Flatness Control", 4th International Conference on Power Engineering, Energy and Electrical Drives, (POWERENG 2013), Istanbul, Turkey, May 13-17, 2013.

[9] A. Payman, ''Contribution à la géstion de l'énergie dans les systèmes hybrides multi-sources Multi-charges'', PhDthesis, Polytechnic Institute of Lorraine, Nancy, France, July 2009.

[10] M. Zandi, "Contribution au pilotage des sources hybrides d'énergie électrique", PhDthesis, National Polytechnic Institute of Lorraine, Nancy, France, November 2010.

[11] M. Benaouadj, A. Aboubou, M.Y. Ayad, M. Becherif: "Flatness Control Applied to Batteries / Supercapacitors Hybrid Sources for Electric Vehicle Application", 4th International Conference on Electrical Engineering (ICEE'12), Algiers, Algeria, May 7-9 2012.

[12] M. Benaouadj, A. Aboubou, R. Saadi, M.Y. Ayad, M. Becherif, M. Bahri, O. Akhrif: "Energy Management Based on Flatness Approach

an Applied to Batteries / Supercapacitors Hybrid Source for Electric Traction", 4th International Conference on Power Engineering, Energy and Electrical Drives, (POWERENG 2013), Istanbul, Turkey, May 13-17, 2013.

[13] M. Fliess, J. Lévine, P. Martin, P. Rouchon, ''Flatness and defect of nonlinear systems: Introductory theory and examples'', Int. J. Control, 61(6), pp. 1327-1361, June 1995.

[14] M. Fliess, J. Lévine, P. Martin, P. Rouchon, ''A Lie-Bäcklund approach to equivalence and flatness of nonlinear systems'', IEEE Trans. Automat. Control 61, pp. 1327-1361, 1999.