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Energy Flow Control of Wind/PV/Batteries/Supercapacitors Autonomous Hybrid Power Sources using the Flatness Concept

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

Abstract— **In this paper, an autonomous Wind/Photovoltaic (PV) hybrid power sources using lead-acid batteries and supercapacitors as storage elements is presented. The lead-acid batteries are used to compensate the power demand which PV and wind generators can't provide. Supercapacitors are employed to relieve the batteries of repeated charging and discharging ensuring longer hybrid source lifetime. The system is designed to supply a residential load. The exchanged power among different components is managed using a nonlinear control based on the flatness concept. Simulation results are presented and discussed for different wind speeds and solar illuminations.**

I. INTRODUCTION

In the field of renewable energies, the Photovoltaic (PV) production cost is expensive. However, its use offers distinct advantages especially in remote areas, by the easy implementation and low maintenance requirements. In the other hands, the drawback consists on the storage need since the produced energy should be used at different (non-sunny) times. As a result, and in order to fully optimize the power production systems technically and economically, the designers combine multiple energy sources. The obtained combinations are called: Hybrid Power Sources.

The hybridization combines the advantages of both technologies: high specific energy and available power for significant periods during seconds allowing, then, to separate dimensioning of the average and transient power. So, the main interest is the resulting gain in terms of volume and mass [1].

According to the chosen combination, several configurations of hybrid power systems are possible to supply residential load [2-6]. The following combinations can be listed: Wind-Diesel, PV-Diesel, Wind-PV and Wind-PV-Diesel.

In this paper, an autonomous "Wind-Photovoltaic" hybrid power sources using batteries and supercapacitors as storage elements is presented. The connection of different components through static converters allows the main source and storage elements to have different voltages and a power flow actively controlled [1]. The system is designed to supply a house use load. A nonlinear control based on the flatness principle is used to ensure the energy flow control between sources and load. The advantage of this technique is when the trajectory is known, evolution of state and control variables are well controlled.

II. PROPOSED AUTONOMOUS HYBRID SYSTEM

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

- A DC link (bus), assuring power segmentation between load, main source (wind and PV sources), and storage unit (lead-acid batteries and supercapacitors).
- A wind generator connected to the DC bus through a single-phase full-bridge AC-DC converter.
- 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.

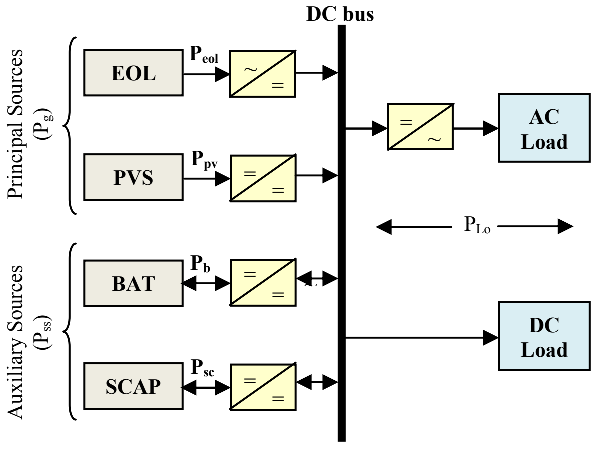

Figure 1. Synoptic of the autonomous hybrid system.

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III. MODELLING AND SIZING

A. *Wind generator*

A wind generator is a system that produces electricity from the available wind energy [7-8] given by:

$$E_d = \frac{1}{2}\rho S v^3 \Delta t \tag{1}$$

ρ: air density ($\rho = 1.225 kg/m^3$ at 15°C)
S: swept area [m^2]
v: wind speed [m/s]

The energy provided by a wind generator can be written as [7-8]:

$$E_{eol} = C_p \eta_a E_d \tag{2}$$

η_a: wind generator efficiency
C_p: Betz coefficient ($C_p = 0.593$)

B. *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 [9]:

$$E_{pv} = n_e P_c \tag{3}$$

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.

C. *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) [10].

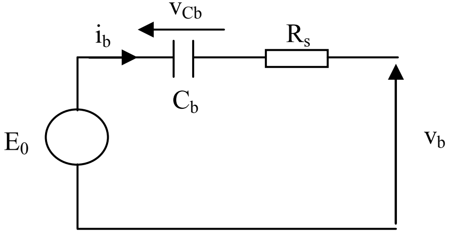

Figure 2. R-C model of the lead-acide batteries.

- The batteries voltage is written as follows:

$$vb = E_0 - v_{Cb} - R_s i_b \tag{4}$$

The batteries State of Charge, SOC_b, is written in [%] as follows:

$$SOC_b = \left(1 - \frac{Q_{dB}}{C_B}\right) \times 100 \tag{5}$$

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

D. *Supercapacitors*

The basic and commonly used equivalent model of a supercapacitor is a capacitor (C_{elem}) in series with a resistor (R_{elem}) [10].

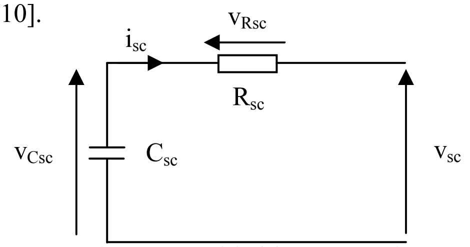

Figure 3. Model of the supercapacitors.

- The supercapacitors voltage is written as follows:

$$v_{sc} = v_{Csc} - R_{sc} i_{sc} \tag{6}$$

- The supercapacitors State of Charge, SOC_{sc}, is written in [%] as follows [12]:

$$SOC_{sc} = \left(\frac{4}{3}\left(\frac{E_{sc}}{E_{sc\,max}} - \frac{1}{4}\right)\right) \times 100 \tag{7}$$

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

E. *Supervision system*

P_g is the power supplied by the whole "Wind and PV generators", and P_{Lo} is the consumed power. By adopting the "generator" convention (the current supplied by the storage elements is positive), then:

$$P_{ss} = P_{Lo} - P_g \tag{8}$$

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 threshold for stop charging batteries	52V
V_2	Low threshold for stop discharging batteries	47.2V
V_3	High threshold for stop charging supercapacitors	30V
V_4	Low threshold for stop discharging supercapacitors	15V

F. *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

Different characteristics of the autonomous hybrid system, obtained using the worst month, are summarized in Table III.

TABLE III. CHARACTERISTICS OF THE AUTONOMOUS HYBRID SYSTEM

Wind generator: Whisper200 is chosen				
Daily produced energy at 3.5 m/s [Wh/d]	**Elements number**	**Swept surface [m²]**	**Efficiency [%]**	
5237	3	21.2	65	
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 is chosen				
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			

IV. CONTROL STRATEGY

A. *Structure of the autonomous hybrid system*

Fig. 4 shows structure of the studied system.

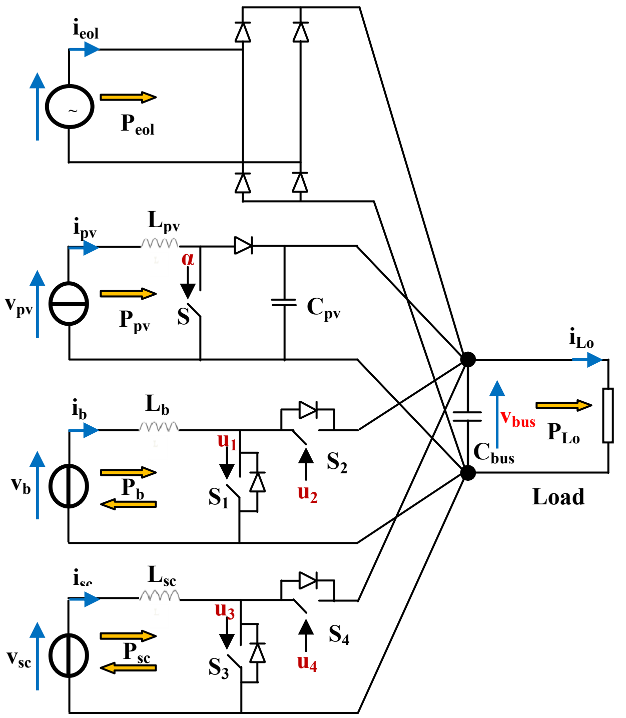

Figure 4. Structure of the autonomous hybrid system.

B. *System control*

The flatness concept was introduced by Michel Fliess [1], and has been used in different applications of electrical engineering such as hybrid sources based on Fuel Cell/ Supercapacitors [13-16] and Batteries/Supercapacitors [1][17].

The major advantage of the flatness approach is to plan the desired trajectory of the flat output variable. If the modeling is without error, it is possible to know the evolution of all variables without having to solve any differential equation [13], 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 flatness control applied to Wind/PV autonomous hybrid sources with batteries and supercapacitors 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:

$$v_{bus} = \sqrt{\frac{2y_{bus}}{C_{bus}}} = f_{v_{bus}}(y_{bus}) \tag{9}$$

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

$$P_{sc} = \sqrt{\frac{2y_{bus}}{C_{bus}}}.i_{Lo} + \dot{y}_{bus} - P_{eol} - P_{pv} - P_b = h_{p_{sc}}(y_{bus}, \dot{y}_{bus}) \tag{10}$$

$v_{bus} = f_{v_{bus}}(y_{bus})$ and $P_{sc} = h_{P_{sc}}(y_{bus}, \dot{y}_{bus})$ → The energy system model can be considered as « differentially flat » [18-19].

- The reference trajectory planning:

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

$$y_{busref}(t) = \frac{1}{2} C_{bus} v_{busref}(t)^2 \tag{11}$$

- The flat output variable tracking:

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

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

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

$$s^2 + k_{11}s + k_{12} = 0 \tag{13}$$

With:

$$\begin{cases} k_{11} = 2\xi w_n \\ k_{12} = W_n{}^2 \end{cases} \tag{14}$$

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:

$$\begin{cases} P_b = P_{b\,max} \\ P_{sc} = P_{ss} - P_b \end{cases} \text{ if } \ P_{ss} \geq P_{b\,max} \tag{15}$$

$$\begin{cases} P_b = P_{ss} \\ P_{sc} = 0 \end{cases} \text{ if } \ 0 \prec P_{ss} \prec P_{b\,max} \tag{16}$$

$$\begin{cases} P_b = 0 \\ P_{sc} = P_{ss} \end{cases} \text{ if } \ P_{ss} \prec 0 \text{ and } v_{sc} \prec V_3 \tag{17}$$

$$\begin{cases} P_b = P_{ss} \\ P_{sc} = 0 \end{cases} \text{ if } \ P_{ss} \prec 0 \text{ and } v_{sc} \geq V_3 \text{ and } v_b \prec V_1 \tag{18}$$

- The inductive currents tracking:

To generate signals u_1, u_2, u_3 and u_4, two hysteresis comparators with fixed bandwidths are used.

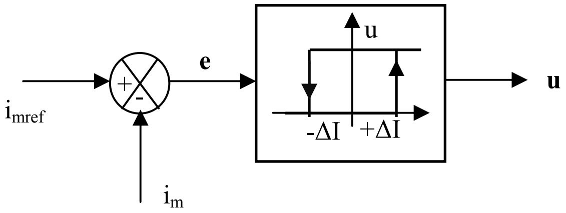

Figure 5. Principle of a hysteresis comparator.

E. Simulation results and discussion

The simulation results are shown in the next figures.

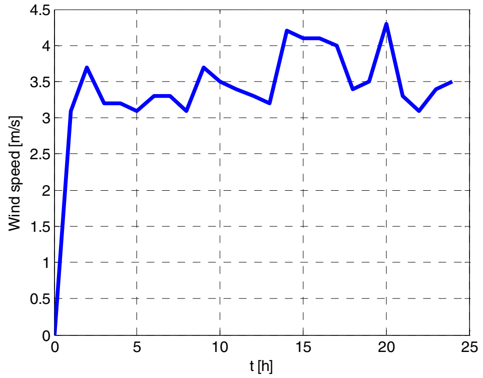

Figure 6. Wind speed profil.

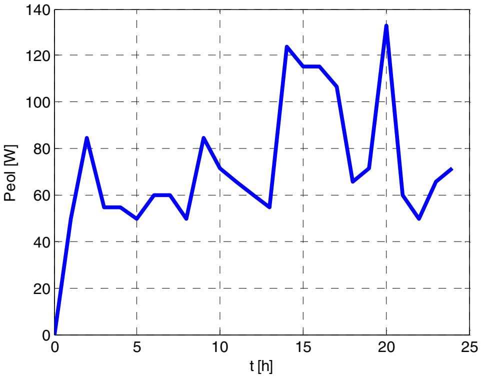

Figure 7. Daily wind production.

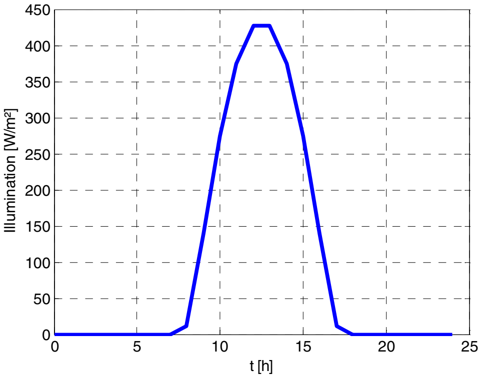

Figure 8. Solar illumination profil.

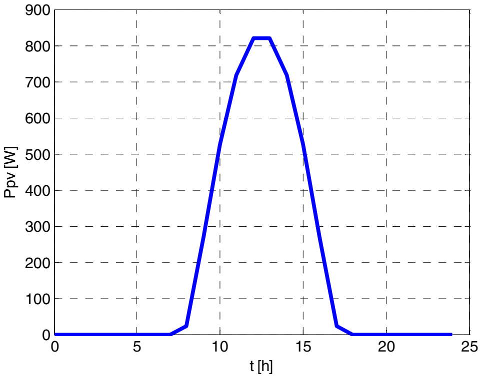

Figure 9. Daily PV production.

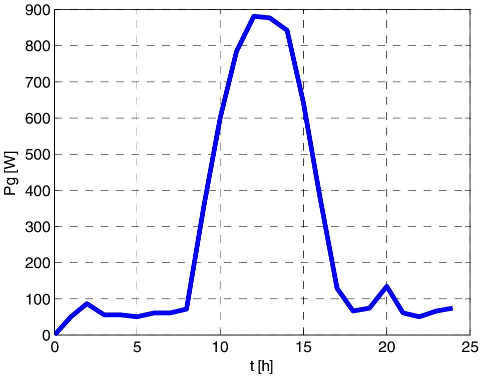

Figure 10. Daily production.

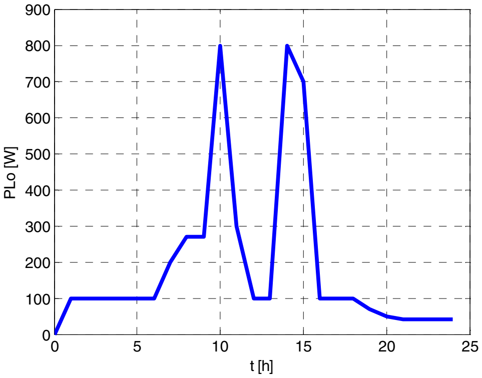

Figure 11. Consumption profile.

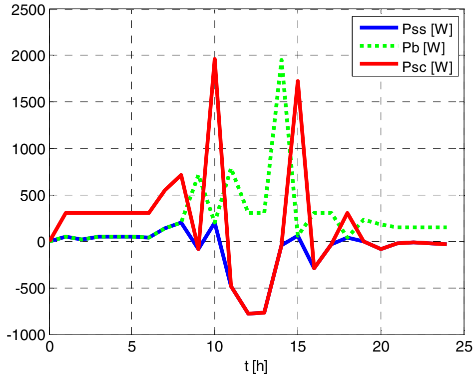

Figure 12. Power curves of the hybrid storage system.

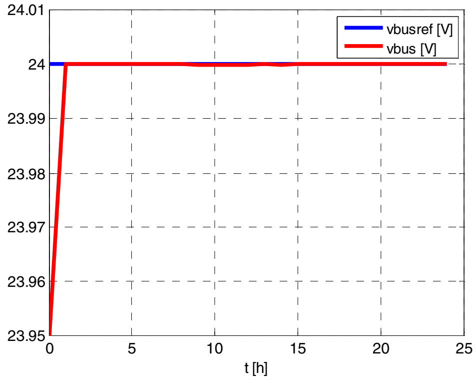

Figure 13. DC bus voltage and its reference.

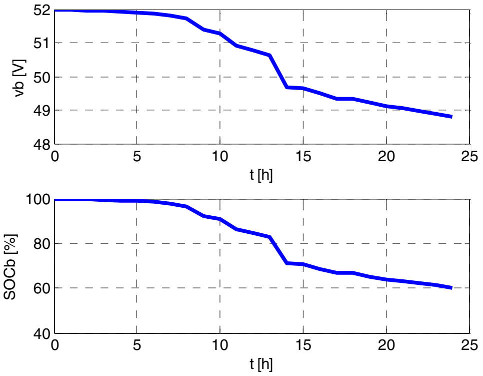

Figure 14. Batteries voltage and state of charge.

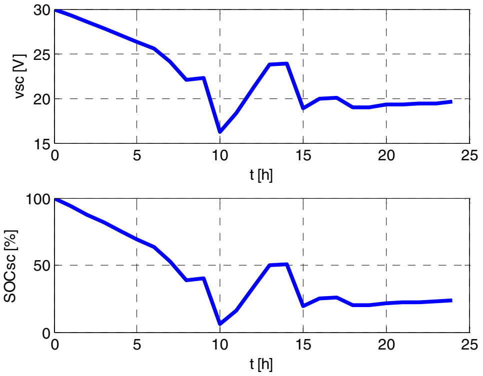

Figure 15. Supercapacitors voltage and state of charge.

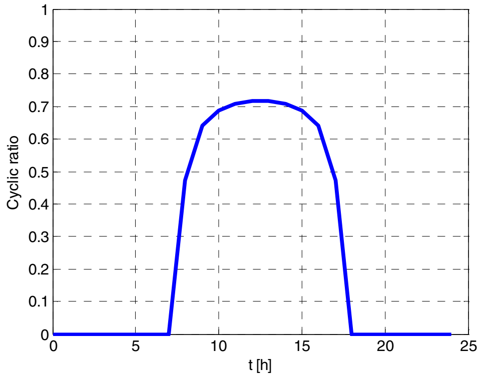

Figure 16. Photovoltaic converter duty cycle changing.

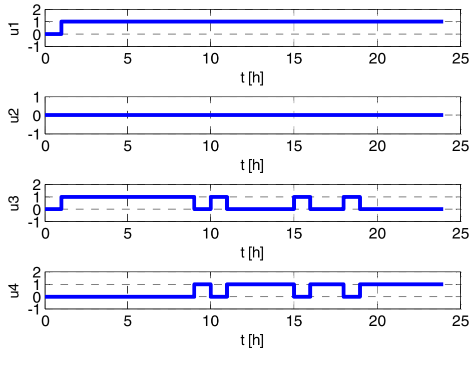

Figure 17. Switching sequences of S_1, S_2, S_3 and S_4.

Fig. 13 shows that the DC bus voltage is well regulated to its reference. In fact:

- If P_{ss} is positive and less than the maximum power that can provide batteries, they provide the housing power demand, while supercapacitors deliver two powers: one to compensate the difference between the consumer, main source and batteries, and the other is needed to control v_{bus}. Therefore, voltages and states of charge are decreasing.
- If P_{ss} is positive and greater than the maximum power that can provide batteries, they supply the difference between the load and main source, while supercapacitors deliver the necessary power to regulate v_{bus}. Thus, voltages and states of charge decrease.
- If P_{ss} is negative, it is absorbed by the supercapacitors (lower constant time), then by batteries (higher constant time). Figures 14 and 15 explain that the excessive power produced by the primary source is always stored in supercapacitors because they never reach the fully charge.
- The process of charging/discharging is respected since: v_b Є $[V_1, V_2]$ and v_{sc} Є $[V_3, V_4]$.

V. CONCLUSION

In this work, a nonlinear control strategy to manage flow in a hybrid power system supplying an autonomous house and combining a main (Wind and photovoltaic generators) and an auxiliary (lead-acid batteries and supercapacitors) sources, is presented.

The control strategy called: the flatness control is used to generate reference trajectories for the electrostatic energy stored in the output capacitor. These trajectories are used to define the evolution of all variables without having to solve any differential equation, simplifying, then, the system control.

Through different results, it is shown that whatever the change of the required power is, the DC link voltage is controlled and regulated to its reference, with voltages and states of charge maintained in their admissible intervals. Therefore, the hybrid source lifetime is theoretically increased.

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