Energy Management of Fuel cell/ Supercapacitor Hybrid Power Sources Based on The Flatness Control

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Abstract— **This paper presents a flatness control algorithm for a DC hybrid power sources used in Electric Vehicle (EV). The studied hybrid sources is composed by both electric sources, the first one is PEM fuel cell as the main sources, and the second one is supercapacitors pack considered as the auxiliary source. The load is connected directly in the DC link. The control algorithm is based on the flatness properties of the system. The advantage of this control algorithm is that the state variable and control system are downright estimated by the trajectories of the flat output derived from these outputs without the need to integrate any different equation. The results obtained by the new proposed control of hybrid source under Matlab/Simulink software tool are given.**

Keywords- Flatness control; Fuel Cell; Supercapacitors; Batteries; Electric Vehicle; Energy management; Flat system; Hybrid source.

I. INTRODUCTION

Recently, an interest toward Fuel Cell (FC) studies has grown, as FCs are clean and efficient sources of electricity, and have a wide range of vehicle and stationary applications [1]. FCs generates electrical energy from a chemical reaction, unlike the battery technology; FC provides the added advantages of refuel ability, little maintenance and no problems with disposal as is faced batteries and other power solution [2]. However, their use is still limited in daily applications because of their slow dynamics during the transient load changes (due mainly to the auxiliaries) and high initial cost. The slow response associated with the dynamic loading can be addressed by the use of energy (or power) storage system such us batteries and supercapacitors (SCs) [3]. Many researches shown that FC association with SC [4], with batteries [5] or with batteries /SCs [6], can combine the advantages of each source. The control of the hybrid source is one of essential area of research; several literatures have addressed the different type of control algorithm. Becherif and al. [7] studied the control based on passivity-based control of hybrid sources FC and SC. Ayad and al.[8] studied the sliding mode control of two types of hybrid source: SC /FC/ batteries and SC /FC. D'arco and al. [9] addressed the energy management of stand-Alone power systems with renewable Energy sources. Tofighi and Kalantar[10] studied the control based on adaptive passivity-based control of PEM FC/battery hybrid power source. Adhikari and al [3] were interested by a multi-level supervisory control of a FC hybrid power sources. Wong and Idris [11] studied a parallel energy-sharing control for FC /battery/ SC system. Thonthoung and al. [12] studies focus on the energy management based on differential flatness control of FC/solar cell/SC hybrid power sources.

The main idea in this paper is the modeling and energy management of hybrid sources of EV composed a FC as the main source, and SCs storage as a transient power source, by using the differential flatness control. The advantage of this control algorithm is that the state variable and control laws are downright estimated by the trajectories of the flat output derived from these outputs without the need to integrate any different equation.

II. HYBRIDIZATION OF POWER SOURCES FOR ELECTRIC VEHICLE APPLICATIONS

The hybrid power sources are attractive solution for EV applications, the hybridization of sources combines two or more embedded electrical sources and energy storage devices[13] that work together to deliver power and energy to the load or to store the excess or braking energy in order to:

- Improve vehicle performance.
- Capture regenerative braking energy.
- Enhance fuel economy.
- Provide a more flexible operating strategy.
- Potentially lower the cost per unit power.

The hybridization between sources has advantages and disadvantages. "Fig.1"shows different sources used in EV.

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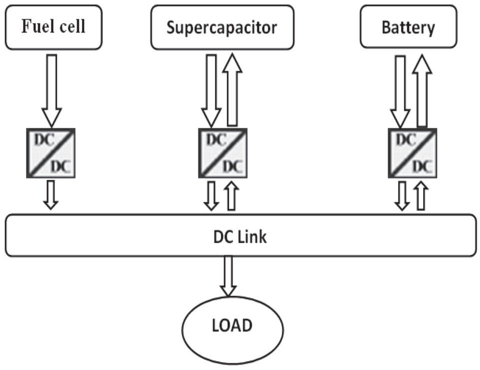

Figure. 1 - Hybrid sources for EV.

- The hybridization between FC and battery has the advantage of providing a high energy to the load, but has lower power; slow transient response and battery limited lifespan.
- Fc and SC hybrid sources has the disadvantages of the low and short time of energy storage in the SC but allows the peak load to be shaved and can compensate for the intrinsic limitations of FC [14].
- Combinations of SC and batteries in hybrid power source can reduce the size, weight, and the number of batteries in EV. SCs have a very high capacitance density and are able to provide a large amount of power. In the other hand, battery has a high specific energy and the disadvantages of its hybridization are that the battery performance can be affected by high discharge currents.

III. HYBRID POWER SOURCE

A. Structure of the hybrid power source

As shown in "Fig. 2", the studied hybrid power source comprises:

- Main source is the PEM FC (energy source) connected to the DC link by means unidirectional converter (BOOST).

- The electrostatic energy y_{bus} stored in the DC link:

$$y_{bus} = \frac{1}{2} C_{bus} v_{bus}^2 \quad (3)$$

- Auxiliary source is SCs (power source) connected to the DC link by through a reversible current DC-DC converter. The SCs power can be positive or negative; wish allows energy to be transferred in both directions [12].
- A capacitive DC link (Cbus),
- A RLE load.

The role of FC is to supply the mean power to the load, whereas the storage device is used as a power source: it supplies load power peak required for the system.
In order to manage energy exchanges between the DC link and the storage devices, three operating modes are defined [7]:
- The Energy ybus according to Pfc, P_{SC} and Pch:

$$\dot{y}_{bus} = P_{fc} + P_{SC} - P_{ch} \quad (4)$$

Where:

$$P_{fc} + P_{SC} = \dot{y}_{bus} + P_{ch} \quad (5)$$

$$P_{fc} = v_{fc}.\,i_{fc} \quad (6)$$

$$P_{SC} = v_{SC}.\,i_{SC} = \sqrt{\frac{2y_{SC}}{C_{SC}}}\,.\,i_{SC} \quad (7)$$

$$P_{ch} = v_{bus}.\,i_{ch} = \sqrt{\frac{2y_{bus}}{C_{bus}}}\,.\,i_{ch} \quad (8)$$

- The supercapacitors energy y_{SC} is given by:

$$y_{SC} = \frac{1}{2} C_{SC} v_{SC}^2 \quad (9)$$

C_{bus} : DC bus capacity [F]
P_{fc} : FC power [W]
P_{SC} : SC pack power [W]
P_{ch} : Load power [W]
Vfc : FC voltage [V]
v_{SC} : SCs pack voltage [V]
v_{bus} : DC bus voltage [V]
Ifc : FC current [A]
I_{SC} : SCs pack current [A]
I_{ch} : load current [A]

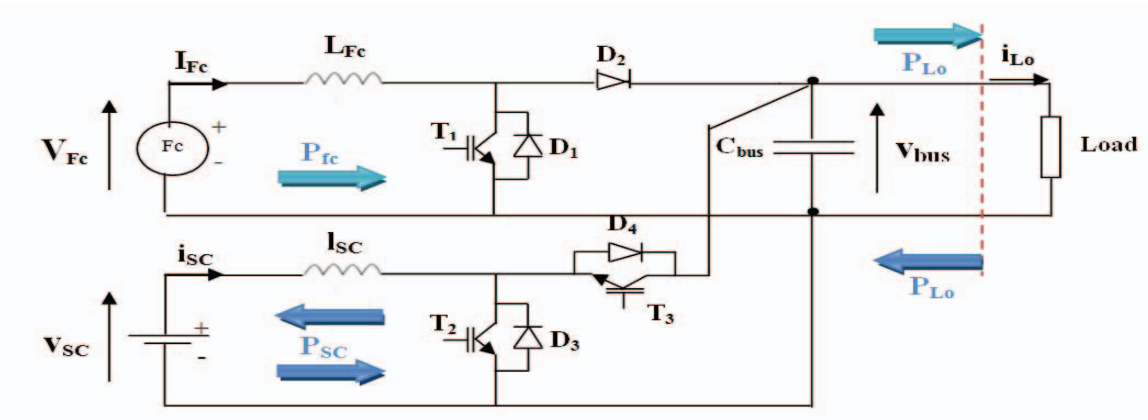

Figure 2. Structure of the hybrid power source.

IV. Control Law Of The Hybrid Power Sources

A. Brief definition of flatness theory:

The flatness property of a system is a relatively new concept in automatic control. It was proposed and developed by M. fliess and al. [15]. A system of ordinary differential equations is said to be differentially flat if there are variables such as:

$$\dot{x} = f(x, u) \quad (10)$$

$$x = [x_1, x_2, \dots, x_n]^T \qquad x \in R^n \quad (11)$$

$$u = [u_1, u_2, \dots, u_m]^T \qquad u \in R^m \quad (12)$$

$$y = [y_1, y_2, \dots, y_m]^T \qquad y \in R^m \quad (13)$$

x is the vector of random variables, u is the control vector, y is the vector of flat outputs, and $(n, m) \epsilon N$.

- The vector y can be written as a function of x and u as follows:

$$y = \emptyset\left(x, u, \dot{u}, \dots, u^{(s)}\right) \quad (14)$$

Where s is the finite number of derivatives.

- The vectors x and u can be expressed in terms of the vector of flat outputs y and finite number of its derivatives as follows:

$$\begin{cases} x = \varphi\left(y, \dot{y}, \dots, y^{(r)}\right) \\ u = \Psi\left(y, \dot{y}, \dots, y^{(r+1)}\right) \end{cases} \quad (15)$$

Where r is the finite number of derivatives.

- There is no differential equation of the form:

$$0 = \varsigma\left(y, \dot{y}, \dots, y^{(k)}\right) \quad (16)$$

Where k is the finite number of derivatives.

The vector of flat outputs y and the derivatives of these outputs offer the representation of the dynamics of the system so that if the flat output profiles are known as a function of time, then the profiles of all states of the system and the corresponding entries can be obtained. This property is used to calculate the trajectories of the flat outputs.

B. Flatness control of the proposed hybrid power system

To apply the flatness control for our system, it is necessary to verify that it is always possible to express all state and all control variables of the system according to the flat ouput variable and a finite number of its derivatives. For this purpose y_{bus} is supposed to be the flat output variable, P_{SC} as the variable of control and v_{bus} as the state variable of the system.

- From equation (3), the state variable v_{bus} can be written as follows:

$$v_{bus} = \sqrt{\frac{2y_{bus}}{C_{bus}}} = F_{v_{bus}}(y_{bus}) \quad (17)$$

-From equations (8) and (11), the control variable P_{SC} can be written as follows:

$$P_{SC} = \sqrt{\frac{2y_{bus}}{C_{bus}}}.i_{ch} + \dot{y}_{bus} - P_{fc} = h_{P_{SC}}(y_{bus}, \dot{y}_{bus}) \quad (18)$$

$v_{bus} = F_{v_{bus}}(y_{bus})$ and $P_{SC} = h_{P_{SC}}(y_{bus}, \dot{y}_{bus})$ → The system is flat.

C. Energy Regulation of the DC link

To control the energy of the DC link using the flatness law a desired reference trajectory for the DC link energy is defined. Consequently, consider by y_{busref} as the reference trajectory for the desired flat output variable y_{bus} (stored energy in the DC bus). y_{busref} is given by:

$$y_{busref}(t) = \frac{1}{2} C_{bus} v_{busref}(t)^2 \quad (19)$$

The figure 3 shows in block diagram allowing, the generation of the reference trajectory y_{busref}.

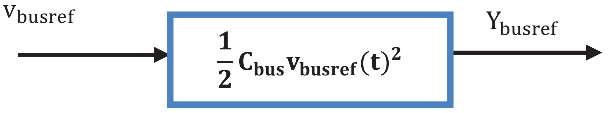

Figure 3. Generation of the reference trajectory $y_{busréf}$

To ensure that the flat output variable y_{bus} follow its reference y_{busref}, the following control law is adopted:

$$(\dot{y}_{bus} - \dot{y}_{busref}) + k_{11}(y_{bus} - y_{busref}) + k_{12}\int_0^t (y_{bus} - y_{busref})dt = 0 \quad (20)$$

Where k_{11} and k_{12} are the controller parameters chosen by studying the roots of the characteristic equation as follows:

$$s^2 + k_{11}s + k_{12} = 0 \quad (21)$$

Those are written:

$$\begin{cases} k_{11} = 2\xi w_n \ [rad.s^{-1}] \\ k_{12} = {w_n}^2 \ [rad.s^{-2}] \end{cases} \quad (22)$$

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

D. Control of the supercapacitors power

In order to manage energy during power flow between the SCs pack and the load three modes are considered:

- Normal mode: In this mode, the load power is positive and minimal than the maximum power that can provide the main source (FC). The power P_{SC} is given by:
  $P_{SC} = 0$ if $0 < P_{ch} < P_{fc\,max}$ (23)
- Discharge mode: In this mode, the load power exceeds the maximum power that can provide the main source. The power P_{SC} is given by:
  $P_{SC} = P_{ch} - P_{fc\,max}$ if $P_{ch} > P_{fc\,max}$ (24)
- Recovery mode: In this mode, the load is negative and must be absorbed by the storage device of the system (SCs). The power P_{SC} is given by:
  $P_{SC} = P_{ch} + \dot{y}_{bus}$ if $P_{ch} < 0$ (25)

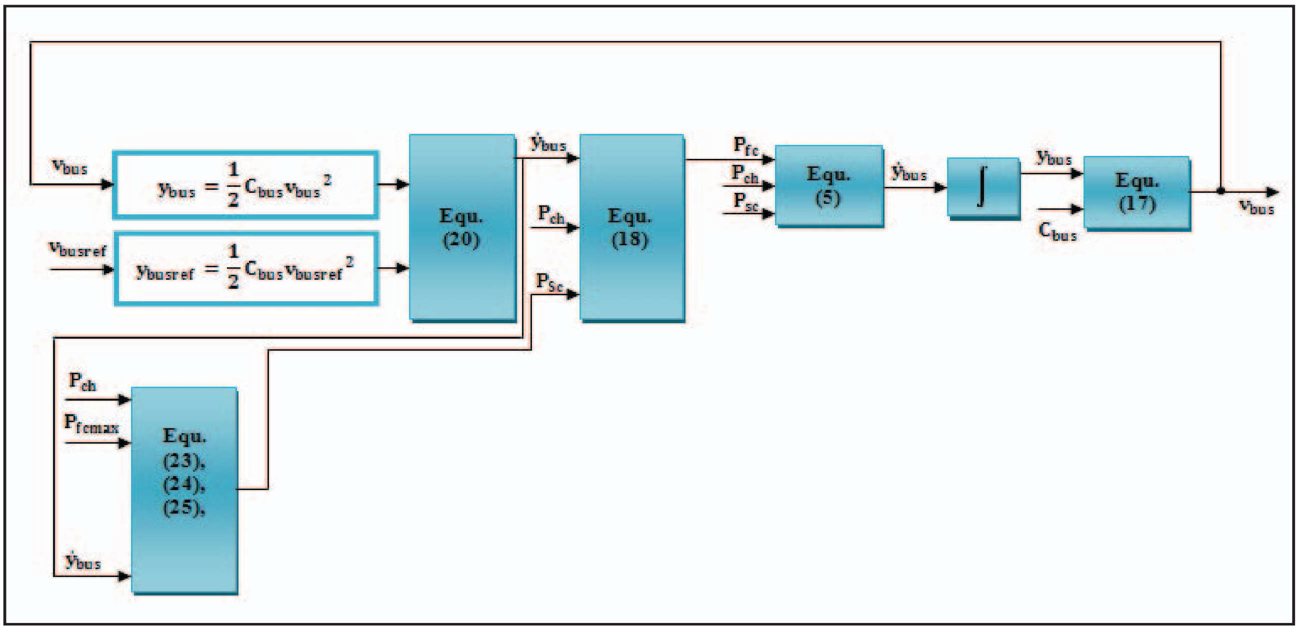

Figure 4. Control scheme for the proposed hybrid source.

V. SIMULATION AND RESULTS

In the following simulations, the shopper and gears are considered ideal and without losses. The parameters of the power hybrid sources system are given in Table I. For the simulation of the proposed control law a profile load power is considered. The simulation result shows that the DC bus voltage is regulated to its reference"figure.6".

At the starting of the system, when the load power is positive and less than the maximum power of the main source, only FC provides the mean power to the load. The storage device power is equal to zero (normal mode). After that, the load power becomes greater than the power of the main source. The storage device supplies the lack of power between the FC and the requested load power (case of discharging mode). In the charging mode, when the power required by the load is negative the SCs absorb the recovered energy "figures. 8-10". The "figure.11" shows a comparison between the DC link energy and its reference. It can be seen that the DC link energy follows its desired reference with relative acceptance state error.

TABLE I. PARAMETERS OF THE MULTI-SOURCES SYSTEM

Parameter	Value
Maximum power of the FC (P_{fcmax})	*500W*
Maximum voltage of the FC (V_{fcmax})	*24 V*
Reference voltage of the DC bus ($V_{busréf}$)	*42 V*
Maximum power of the SCs pack (P_{SCmax})	*1.5 kW*
Maximum voltage of the SCs pack (V_{SCmax})	*24 V*
Minimum voltage of the SCs pack (V_{SCmin})	*12 V*
SCs initial state of charge	*100%*
SCs final state of charge	*50%*

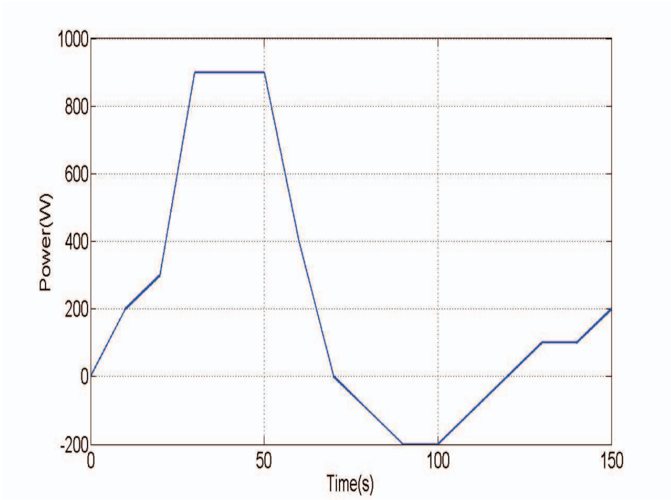

Figure 5. Power profil of load.

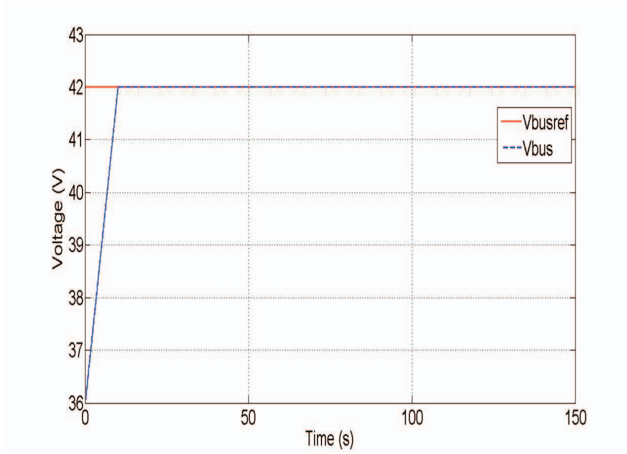

Figure 6. DC link voltage and its reference.

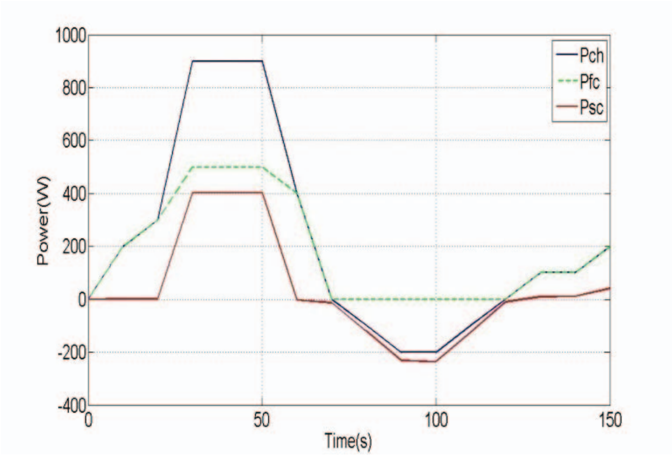

Figure 7. Power curves of the system.

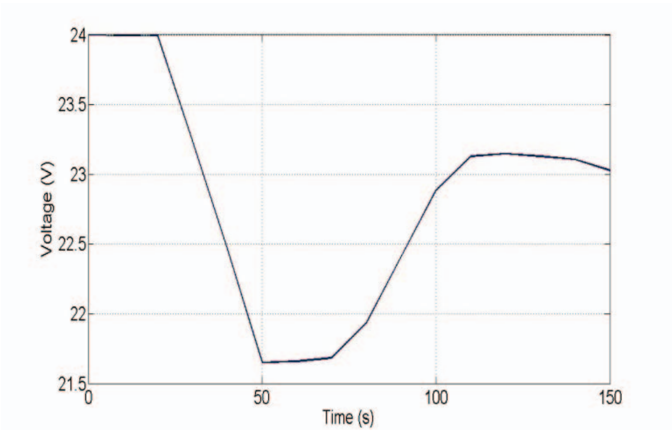

Figure 8. Supercapacitors voltage.

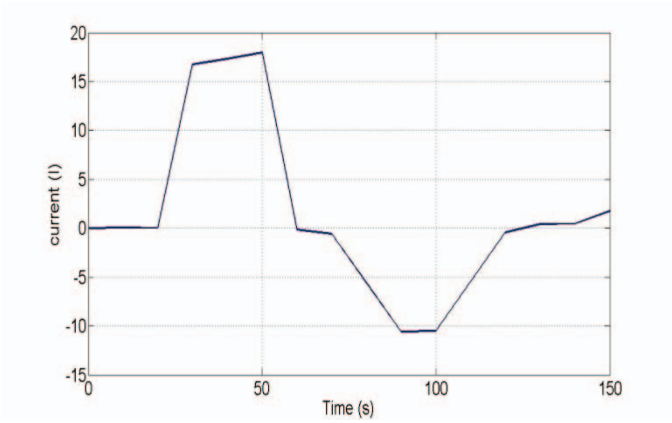

Figure 9. Supercapacitors currents.

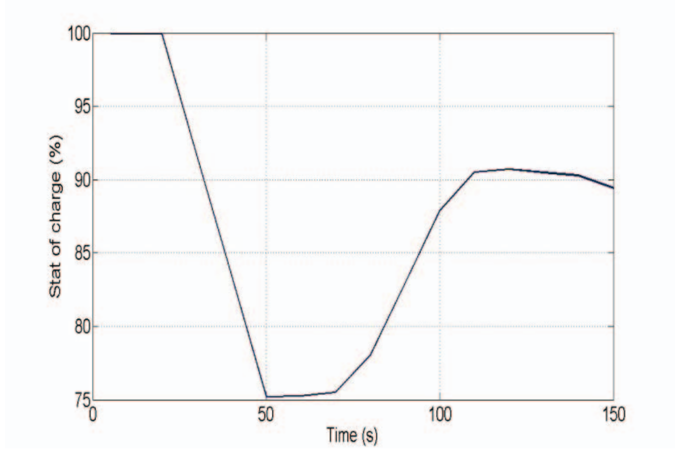

Figure 10. Supercapacitors state of charge

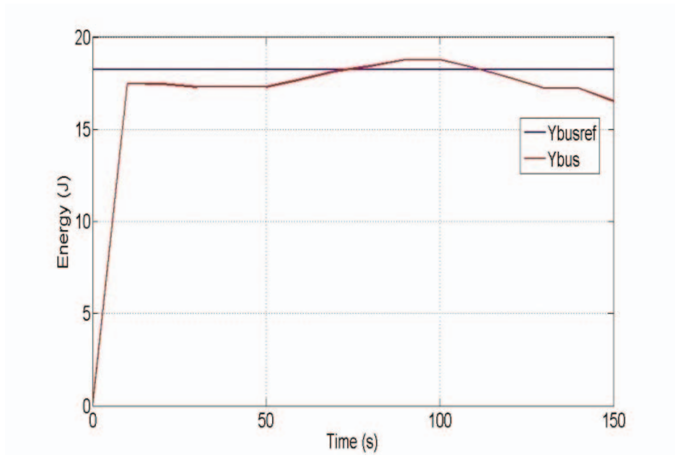

Figure 11. energy of the DC link voltage and its reference

VI. CONCLUSION

In this paper, an energy management strategy is presented to control and manage the energy between a fuel cell, load and supercapacitor as hybrid power sources of Electric Vehicle, the fuel cell have been used as mean energy source and SCs as auxiliary power sources. The energy management strategy used for the studied sources is based on flatness theory which offers a robust, simple controller, stability, and efficiency. The aim of this strategy is to plan the trajectory of the flat output variable. Knowing this trajectory, and if the modeling of the system is without error, then it is possible to know the evolution of state and control variables without having to solve any differential equation.The simulation results show a good agreement of the energy management of the system is by flatness control.

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