Energy management of solar panel and battery system with passive control

Mohamed Becherif*, Damien Paire† and Abdellatif Miraoui†
*SeT, UTBM, Belfort, FRANCE
†L2ES, UTBM, Belfort, FRANCE
damien.paire@utbm.fr
Tel:+33 (0)3 84 58 33 96, Fax:+33 (0)3 84 58 34 13

***Abstract*— The objective of this paper is to determine a simple controller for street lighting application using an energy shaping method (Passivity-Based Control (PBC)). The idea is to supply such lights with clean electricity and isolated from the network. To answer this problem, one solution consists on the association of photovoltaic (PV) panel and battery. Battery can store energy from PV panel during the day and give it back during the night. First, the system model is presented then Port-Controlled Hamiltonian (PCH) form is written. This form allows to exhibit system characteristics and to simplify the stability proof. Then the control law is deduced using passivity theory and simulation results are shown. Contrary to PI or hysteresis control usually applied for these systems, here no sensor device is used for the control.**

***Index Terms*—Hybrid system, Passivity-Based Control, Photovoltaic cells**

I. Introduction

Nowadays, street lighting is become essential in our society in order to ensure comfort and security. The installation of street lighting in a city involves complex and expensive work. Moreover, to supply the lights, it needs an electrical network (usually produced by power plants generating carbon dioxide emissions). To reduce environment impact and the use cost of street lighting, renewable energies can be a good alternative. A system (Figure 1) composed of photovoltaic panel and battery is proposed in this paper to answer this demand.

The use of storage device like battery is essential because solar energy is transformed and stored during the day and it is used when it is getting dark. The day, the battery is charged and it is discharged during dark period. Once installed and according to the chosen scenario, the system do not consume any electricity from network (null operation cost) and just needs periodical maintenance of the battery.

The aim of this paper is to determine a simple controller for street lighting application using an energy shaping method (PBC). First, the system model is presented then PCH form is written. This form allows to exhibit system characteristics and to simplify the stability proof. Then the control law is deduced using passivity theory and simulation results are shown. Contrary to PI or hysteresis control usually applied for these systems, here no sensor device is used for the control.

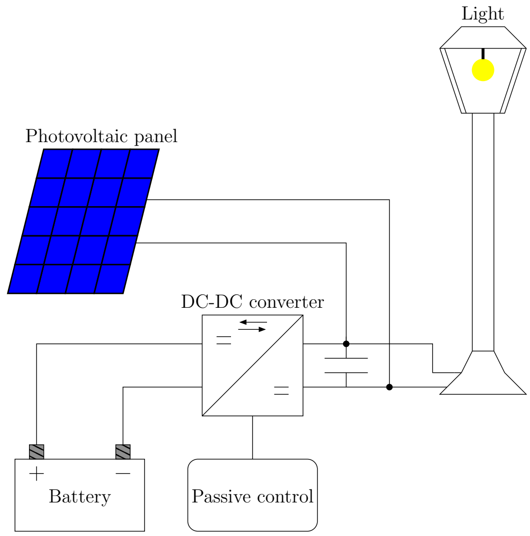


Fig. 1. System structure

II. Architecture of the System

A. Structure

As shown in Figure 2, the studied system comprises photovoltaic panel, battery and a load. A bidirectional DC-DC converter connected to a DC bus allows to hybridize these two sources of energy and to charge the battery. It consists of an inductor L_b, a capacitor C_{dc}, diodes and transistors controlled with the input u_b. The load is a $50\,\mathrm{W}$ light modelled by a resistor R_L. So it is important to underline that the load is constant.

B. Photovoltaic panel model

The PV panel can be modeled by a photo-current source I_{ph} (proportional to illumination) connected in parallel with a diode and with a shunt resistor R_{sh} [1]. This resistor models the disturbance currents in the cell. So the output current of the panel can be expressed by equation (1) where I_d is the direct current in the diode given by the function (2).

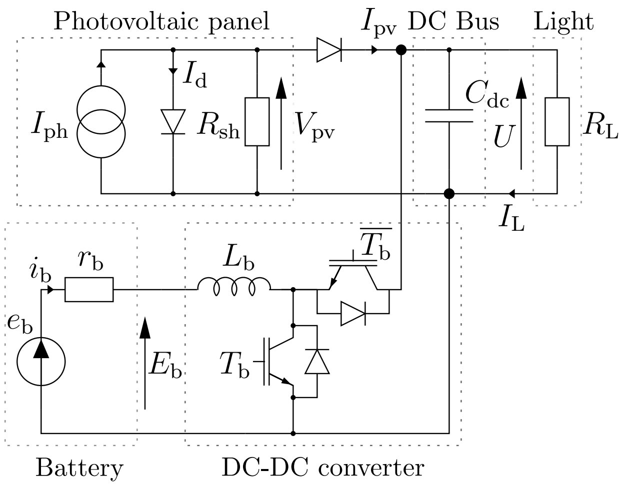


Fig. 2. System electrical model

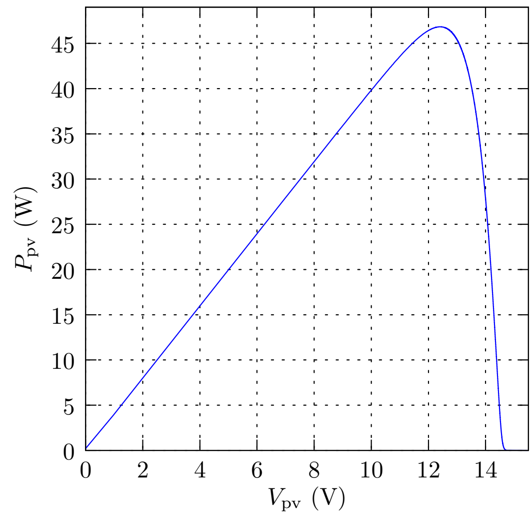


Fig. 4. P-V curve for the PV module

$$I_{\mathrm{pv}} = I_{\mathrm{ph}} - I_{\mathrm{d}} - \frac{V_{\mathrm{pv}}}{R_{\mathrm{sh}}} \quad (1)$$

$$I_{\mathrm{d}} = I_{\mathrm{s}}(e^{aV_{\mathrm{pv}}} - 1) \quad (2)$$

$$a = \frac{q}{20kT}$$

where q is the elementary charge, T is the cell temperature, k is Boltzmann's constant, I_{s} is the saturation current and V_{pv} is the output voltage.

The I-V and P-V characteristics are shown in Figure 3 and Figure 4. The PV panel power is around 50 W. An illumination of 1000 $\mathrm{W/m^2}$ is assumed during the day. An additional diode is used to connect the PV panel on the DC bus. This diode insure that no reverse current will go in the PV panel which can cause a detrimental effect. It is not taken into account in modeling, it is just used for the simulation. Indeed, it correspond to $I_{\mathrm{pv}} = 0$ for the modeling.

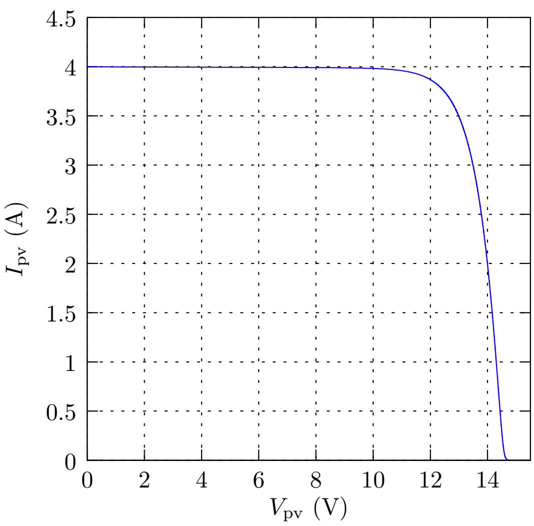


Fig. 3. I-V curve for the PV module

C. Battery model

The model used for the battery is an electromotive force e_{b} with a series resistor r_{b}. The PV panel recharges the battery through the converter during the day. And during the dark, the battery supplies the load. If the light is turned on during the day, the PV panel supplies the load directly. The battery provides or absorbs the rest depending of the illumination.

D. State space model of the system

The model of the hybrid system can be written in a state space model by choosing the following variables:

$$x = \begin{bmatrix} x_1, & x_2 \end{bmatrix}^T = \begin{bmatrix} U, & i_{\mathrm{b}} \end{bmatrix}^T \quad (3)$$

The control input is u_{b} where $u_{\mathrm{b}} \in [0,1]$ with $u_{\mathrm{b}} = 1$ means the associated transistor (T_{b}) is closed and $u_{\mathrm{b}} = 0$ means the transistor is opened (T_{b} and $\overline{T_{\mathrm{b}}}$ work in complementarity). Let's define $\mu_{\mathrm{b}} = 1 - u_{\mathrm{b}}$.

Using Kirchhoff's laws, the 2^{nd} order state space model is then :

$$\begin{aligned} \dot{x}_1 &= \frac{1}{C_{\mathrm{dc}}}\Big[I_{\mathrm{ph}} - I_{\mathrm{s}}(e^{ax_1} - 1) - \frac{x_1}{R_{\mathrm{sh}}} \\ &\qquad - \frac{x_1}{R_{\mathrm{L}}} + \mu_{\mathrm{b}} x_2\Big] \\ \dot{x}_2 &= \frac{1}{L_{\mathrm{b}}}\left[e_{\mathrm{b}} - r_{\mathrm{b}} x_2 - \mu_{\mathrm{b}} x_1\right] \\ y &= x_1 \end{aligned} \quad (4)$$

To simplify the equations, $I_{\mathrm{eq}}(x_1)$ and R_{eq} are defined as shown in (5). x_1 is measurable and it is bound in the interval $[0; V_{\mathrm{d}}]$ (V_{d} is the desired DC bus voltage).

So it can be considered that $I_{\mathrm{eq}}(x_1) = I_{\mathrm{eq}}$. I_{eq} is a measurable input for the system and it is no longer explicitly a function of x_1. From physical consideration, it comes that $I_{\text{eq}} \in [0; I_{\text{ph-max}}]$ ($I_{\text{ph-max}}$ is the maximum value of I_{ph}).

$$\begin{aligned} I_{\text{eq}}(x_1) &= I_{\text{ph}} - I_{\text{s}}(e^{ax_1} - 1) = I_{\text{eq}} \\ \frac{x_1}{R_{\text{eq}}} &= \frac{x_1}{R_{\text{sh}}} + \frac{x_1}{R_{\text{L}}} \end{aligned} \tag{5}$$

So the model can be rewritten as follow:

$$\begin{aligned} \dot{x}_1 &= \frac{1}{C_{\text{dc}}}\left[I_{\text{eq}} - \frac{x_1}{R_{\text{eq}}} + \mu_{\text{b}} x_2\right] \\ \dot{x}_2 &= \frac{1}{L_{\text{b}}}\left[e_{\text{b}} - r_{\text{b}} x_2 - \mu_{\text{b}} x_1\right] \\ y &= x_1 \end{aligned} \tag{6}$$

E. Equilibrium

In the steady state, the equilibrium points are reached. The following calculations explain their determination. Consider that $\overline{(.)}$ is the equilibrium value of the variable $(.)$.

$$\bar{x}_1 = V_{\text{d}} \quad \Rightarrow \quad \dot{\bar{x}}_1 = 0 \tag{7}$$

where V_{d} is the desired DC bus voltage.

Form equations (6) and (7), the following equations can be deduced:

$$\begin{aligned} \frac{V_{\text{d}}}{R_{\text{eq}}} - I_{\text{eq}} &= \bar{\mu}_{\text{b}} \bar{x}_2 \\ e_{\text{b}} - r_{\text{b}} \bar{x}_2 &= \bar{\mu}_{\text{b}} V_{\text{d}} \end{aligned} \tag{8}$$

So $\bar{x}_2$ is the root of the equation:

$$r_{\text{b}} \bar{x}_2^2 - e_{\text{b}} \bar{x}_2 + \frac{V_{\text{d}}}{R_{\text{eq}}} - I_{\text{eq}} V_{\text{d}} = 0$$

$\Rightarrow \bar{x}_2 = \dfrac{e_{\text{b}} \pm \sqrt{\Delta}}{2r_{\text{b}}}$ with $\Delta = e_{\text{b}}^2 - 4r_{\text{b}} V_{\text{d}} \left(\dfrac{V_{\text{d}}}{R_{\text{eq}}} - I_{\text{eq}}\right)$ because $\Delta \geq 0$ due to physical considerations.

Thus, the equilibrium points are:

$$\begin{aligned} \bar{x}_1 &= V_{\text{d}} \\ \bar{x}_2 &= \frac{e_{\text{b}} \pm \sqrt{\Delta}}{2r_{\text{b}}} \\ \bar{\mu}_{\text{b}} &= \frac{e_{\text{b}}}{V_{\text{d}}} \end{aligned} \tag{9}$$

III. Problem Formulation

The purpose of the study is the control of the DC voltage U (consequently the load voltage) and the energy management between the PV panel, the battery and the load. During the day, the PV panel charges the battery through the DC-DC converter and can also supply the light if this last one is turned on. During the night the battery supplies the lights. The voltage U has to be maintained at the desired voltage V_{d} in order to supply correctly the load.

IV. Port-Controlled Hamiltonian representation of the system

After model determination, the system can be rewritten in a PCH form in order to identify interconnexion and damping function. PCH theory [2] allows to describe electrical, mechanical and electro-mechanical systems. Once the system is written in PCH form, the stability problem can be solved using the IDA-PBC (Interconnection and Damping Assignment Passivity-Based Control) method. The control is chosen in order to preserve structure properties of the PCH system.

Consider the nonlinear system given by:

$$\dot{x} = f(x) + g(x)u \tag{10}$$
$$y = g^T(x)\nabla H(x) \tag{11}$$

where y is the considered output, $x \in \mathbb{R}^n$ is the state vector, $f(x)$ and $g(x)$ are locally lipschitz and $u \in \mathbb{R}^m$ is the control input. A PCH form of the system (10) is given by:

$$\dot{x} = [\mathcal{J} - \mathcal{R}]\nabla H(x) + g(x)u \tag{12}$$

where $\mathcal{J}(x)$ is an $n \times n$ skew symmetric matrix ($\mathcal{J}^T(x) = -\mathcal{J}(x)$) and represents the natural interconnection of the system. $\mathcal{R}(x)$ is a positive semi-definite symmetric matrix ($\mathcal{R}(x) = \mathcal{R}^T(x) \geq 0$) and it symbolizes the damping. $\nabla H(x)$ is the gradient of the energy function $H(x)$ of the system (10) and (11). PCH systems with $H(x)$ non-negative, are passive systems [1].

V. Passivity and Natural energy of the system

The natural energy function of the system is :

$$H = \frac{1}{2}x^T Q x = \frac{1}{2}x^T \begin{bmatrix} C_{\text{dc}} & 0 \\ 0 & L_{\text{b}} \end{bmatrix} x \tag{13}$$

The desired closed loop energy function is:

$$H_{\text{d}} = \frac{1}{2}\tilde{x}^T Q \tilde{x} \tag{14}$$

where $\tilde{x} = x - \bar{x}$ is the new state space defining the error between the state x and its equilibrium value $\bar{x}$. The dynamic equations of the equilibrium are:

$$\begin{aligned} \dot{\bar{x}}_1 &= \frac{1}{C_{\text{dc}}}\left[I_{\text{eq}} - \frac{\bar{x}_1}{R_{\text{eq}}} + \bar{\mu}_{\text{b}} \bar{x}_2\right] = 0 \\ \dot{\bar{x}}_2 &= \frac{1}{L_{\text{b}}}\left[I_{\text{eq}} - r_{\text{b}} \bar{x}_2 - \bar{\mu}_{\text{b}} \bar{x}_1\right] \end{aligned} \tag{15}$$

By subtracting equations (6) and (15), the following equations can be deduced:

$$\begin{aligned} \dot{\tilde{x}}_1 &= \frac{1}{C_{\text{dc}}}\left[-\frac{\tilde{x}_1}{R_{\text{eq}}} + \mu_{\text{b}} x_2 - \bar{\mu}_{\text{b}} \bar{x}_2\right] \\ \dot{\tilde{x}}_2 &= \frac{1}{L_{\text{b}}}\left[-r_{\text{b}} \tilde{x}_2 - \mu_{\text{b}} x_1 + \bar{\mu}_{\text{b}} \bar{x}_1\right] \end{aligned} \tag{16}$$

[1]Passive system cannot store more energy than is supplied to it from outside, with the difference being the dissipated energy

In order to preserve the PCH structure in closed loop, the following control is chosen for the system:

$$\mu_{\mathrm{b}} = \bar{\mu}_{\mathrm{b}} \tag{17}$$

Finally, the dynamic of the error can be written:

$$\begin{aligned} \dot{\tilde{x}}_1 &= \frac{1}{C_{\mathrm{dc}}}\left[-\frac{\tilde{x}_1}{R_{\mathrm{eq}}} + \mu_{\mathrm{b}}\tilde{x}_2\right] \\ \dot{\tilde{x}}_2 &= \frac{1}{L_{\mathrm{b}}}\left[-r_{\mathrm{b}}\tilde{x}_2 - \mu_{\mathrm{b}}\tilde{x}_1\right] \end{aligned} \tag{18}$$

The representation in function of the gradient of the desired energy is given by:

$$\dot{\tilde{x}} = [\mathcal{J} - \mathcal{R}]\, \nabla H_{\mathrm{d}} \tag{19}$$

$$\text{with} \quad \begin{aligned} \mathcal{J}(\mu_{\mathrm{b}}) - \mathcal{R} &= \begin{bmatrix} \dfrac{-1}{R_{\mathrm{eq}}\, {C_{\mathrm{dc}}}^2} & \dfrac{\mu_{\mathrm{b}}}{L_{\mathrm{b}}\, C_{\mathrm{dc}}} \\ \dfrac{-\mu_{\mathrm{b}}}{L_{\mathrm{b}}\, C_{\mathrm{dc}}} & \dfrac{-r_{\mathrm{b}}}{{L_{\mathrm{b}}}^2} \end{bmatrix} \\ \nabla H_{\mathrm{d}} &= \begin{bmatrix} C_{\mathrm{dc}}\, \tilde{x}_1 \\ L_{\mathrm{b}}\, \tilde{x}_2 \end{bmatrix} \end{aligned}$$

$\mathcal{J}(\mu_{\mathrm{b}}) = -\mathcal{J}^T(\mu_{\mathrm{b}})$ is a skew symmetric matrix and $\mathcal{R} = \mathcal{R}^T \geq 0$ is symmetric positive semi definite matrix.

Proposition 1 *The origin of the closed loop PCH system (19), with the control laws (17) and the radially unbounded energy function (14), is globally asymptotically stable.*

Proof: The closed loop dynamic of the PCH system (19) with the laws (17) with the radially unbounded energy function (14) is:

$$\dot{\tilde{x}} = [\mathcal{J} - \mathcal{R}]\, \nabla H_d \tag{20}$$

$$\text{where} \quad \mathcal{J}(\mu_{\mathrm{b}}) = \begin{bmatrix} 0 & \dfrac{\mu_{\mathrm{b}}}{L_{\mathrm{b}}\, C_{\mathrm{dc}}} \\ \dfrac{-\mu_{\mathrm{b}}}{L_{\mathrm{b}}\, C_{\mathrm{dc}}} & 0 \end{bmatrix} = -\mathcal{J}^T(\mu_{\mathrm{b}})$$

$$\text{where} \quad \mathcal{R} = \begin{bmatrix} \dfrac{1}{R_{\mathrm{eq}}\, {C_{\mathrm{dc}}}^2} & 0 \\ 0 & \dfrac{r_{\mathrm{b}}}{{L_{\mathrm{b}}}^2} \end{bmatrix} = \mathcal{R}^T \geq 0$$

The derivative of the desired energy function (14) along the trajectory of (20) is:

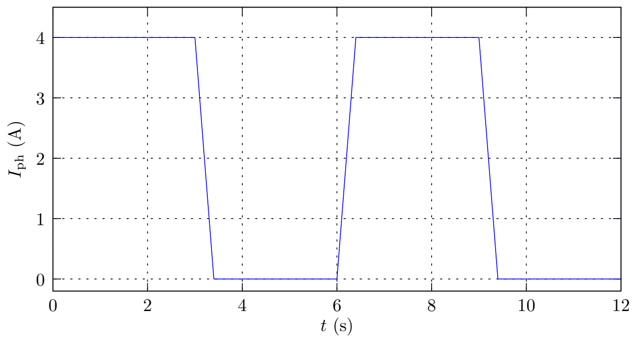
$$\dot{H}_d = \nabla H_d^T \dot{\tilde{x}} = -\nabla H_d^T \mathcal{R} \nabla H_d \leq 0 \tag{21}$$

∎

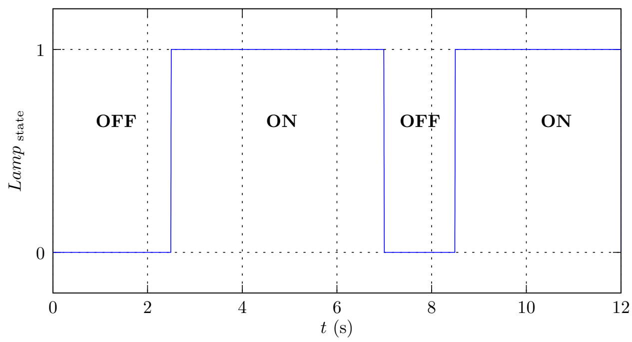
VI. Simulations results

A. Simulations

In order to simulate the behaviour of the system, a 12 seconds simulation is done. In our scenario, illumination is assumed to be present fifty pourcent of time. The following simulations present the system response obtained with two cycles (2 days and 2 nights). The light is turned on before a dark period, as shown in Figure 5.



(a) Illumination



(b) Load state

Fig. 5. External conditions

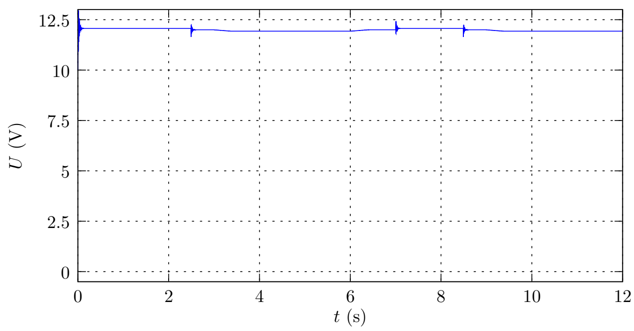


Fig. 6. DC bus Voltage

Figure 8(a) presents the desired voltage V_{d} (reference) and the voltage U obtained. A small overshoot appears when the light is turned on or off.

The battery output voltage remains around 9 V as it is shown in Figure 8(b). The battery is charged during the day (between 0 s and 2.5 s). Then the load is supplied by PV and

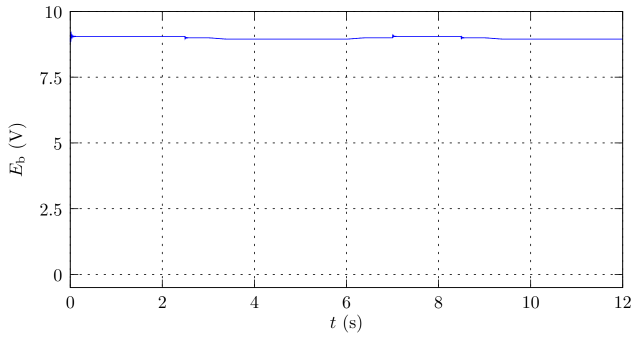
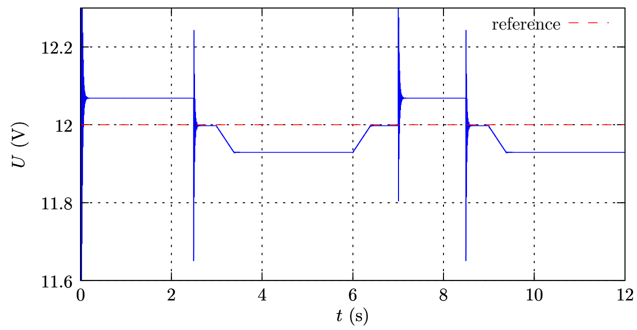
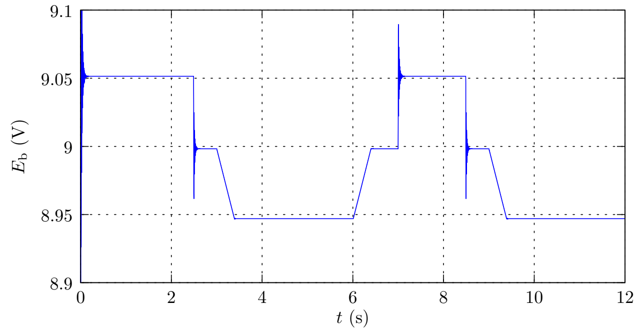


Fig. 7. Battery voltage



(a) Zoom on DC bus voltage and its reference (V_d)

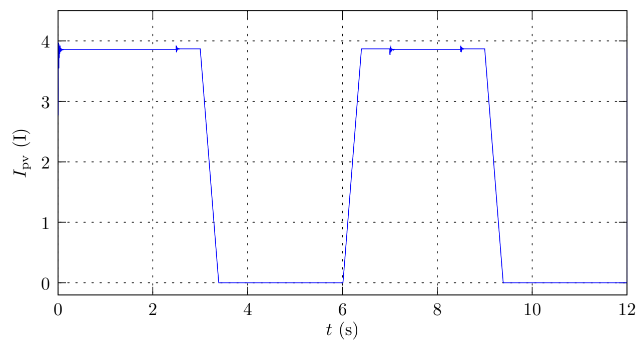


(b) Zoom on Battery voltage

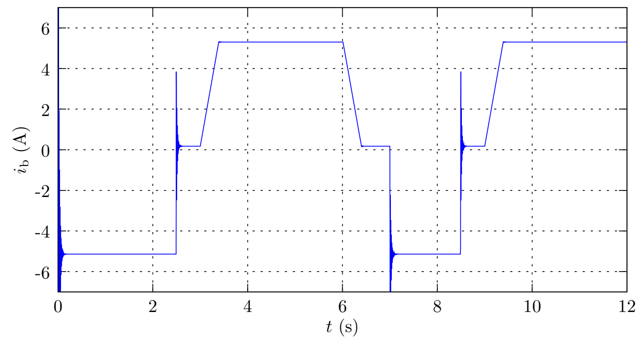
Fig. 8. Voltage curves

battery during a short time and after the battery provides all the energy needed ($t = 3.4$ s). When the sun comes back at $t = 6$ s, the battery current decreases to 0 and at the same time, the PV current increase to the maximum. After a delay, the light is turned off and the battery goes on charge and so on. In Figure 9, the current provided by the two sources and the load current are shown. It illustrates that the battery is used as a buffer in order to supply the load or to store the energy.

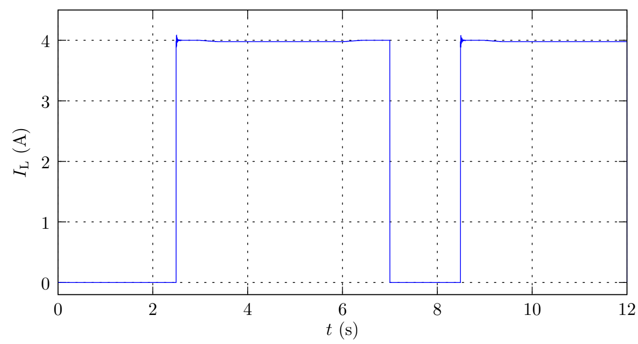
Figure 10 shows the power transfer between the battery, the PV panel and the load demand. When the light is off, the power from PV panel goes directly to the battery. Before night, the PV power decrease, at the same time, the battery power increases, that insure a constant power for the load.



(a) PV current



(b) Battery current



(c) Load current

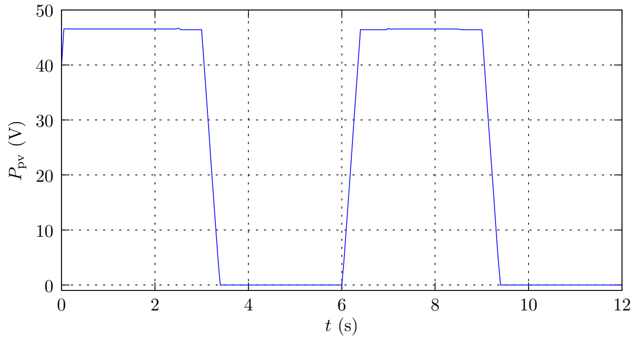
Fig. 9. Current curves

B. *Energy transfers*

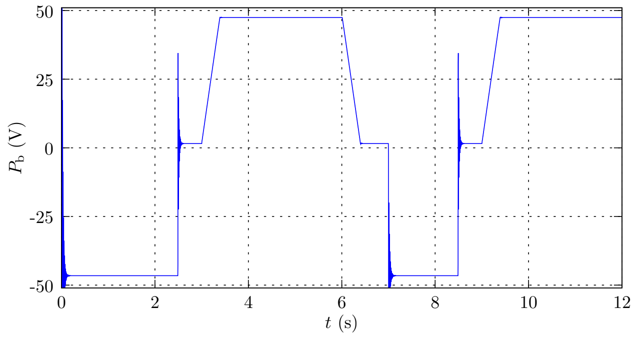
During the scenario, the PV panel provide 287.4 J. 186.1 J is absorbed by the battery and it provides 280.3 J. The load uses 381.6 J during the test (287.4 J + 280.3 J − 186.1 J = 381.6 J). It illustrates that the battery is used as storage device to insure light operation during the night. This is the worst case because the light is turned on during a long time (the ON state (67%) is longer than the OFF state (33%)). In an other scenario, where the ON and OFF state of the lamp will be equal, the charge of the battery will be complete (in the hypothesis that there is light during the day).

VII. Conclusion

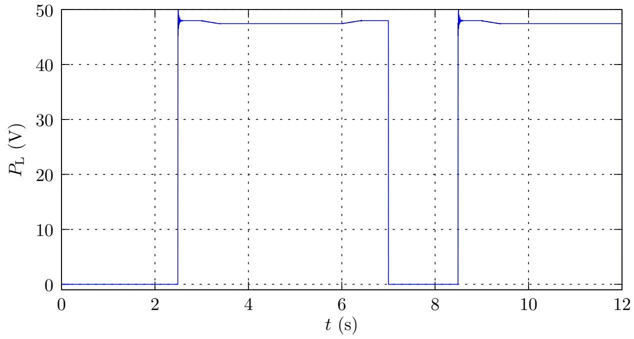
A modeling of hybrid sources system composed of a PV source and battery is presented. PCH structure of the system is given exhibiting important physical properties. The desired



(a) PV power



(b) Battery power



(c) Load power

Fig. 10. Power curves

objectives are reached and good results are obtained using a simple linear open loop controller and no sensor device is used for the control. This simple controller can reduce the set-up costs and manage energy between different sources. This solution has the advantages of consuming clean electricity and makes the lighting application autonomous (no network). In the case where there is not enough light during the day to the charge of the battery, the MPPT (Maximum Power Point Tracking) can be adopted to use the maximum power of the PV panel. Experimental tests are in progress.

References

[1] Protin L.; Astier S.: *Convertisseurs photovoltaiques*, Techniques de l'Ingénieur, vol. D3360, Aug. 1997.

[2] Ortega R.; Garcia-Canseco E.: *Interconnection and damping assignment passivity-based control: A survey*, European Journal of Control, 2004.

[3] Becherif M.; Ayad M.; Miraoui A.: *Modeling and passivity-based control of hybrid sources: Fuel cell and supercapacitors*, in the 2006 IEEE Industry Applications Conference 41st IAS Annual Meeting, Conference Record of, vol. 3, Oct. 2006, pp. 11341139.

[4] Becherif M.: *Passivity-based control of hybrid sources: Fuel cell and battery*, in the 11th IFAC Symposium on Control in Transportation Systems, Netherlands, Aug. 2006.

[5] Djerdir A.; Elkadri K.; Miraoui A.: *Alimentation par biberonnage solaire photovoltaique dune chaine de motorisation électrique*, in Revue des Energies Renouvelables, vol. 9, no. 2, 2006, pp. 6374.

[6] Paire D.; Becherif M.; Miraoui A.: *Passivity-based control of hybrid sources applied to a traction system*, in Workshop on Hybrid and Solar Vehicles, Italy, Nov. 2006.

[7] Walker G. :*Evaluating MPPT converter topologies using a MATLAB PV model*, in Journal of Electrical & Electronics Engineering, vol. 21, no. 1. Australia: IEAust, 2001, pp. 4956.