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Robust regulation of the photovoltaic voltage using discrete sliding mode control in part of a MPPT control

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Abstract— **The production cost of the photovoltaic energy is quite high and its performance is very low, hence the need to optimize the conversion process. This paper presents the synthesis of a discrete sliding mode control of the photovoltaic voltage which is added to a MPPT algorithm to maximize the generated power. The simulation results under Simulink confirm the effectiveness and robustness of the proposed control.**

Keywords— **Photovoltaic systems, robust control, discrete sliding mode control, photovoltaic voltage, perturb and observe MPPT algorithm.**

I. INTRODUCTION

Photovoltaic solar energy is one of the most dynamic markets in the renewable energy sector. It represents an alternative to traditional methods of producing electrical energy, which emit combustion wastes and pollutants harmful to the ecosystem.

Solar energy can be converted into electricity using solar panels based on photovoltaic (PV) cells. However, the conversion efficiency is low and the cost of panels is relatively high. For this reason, the photovoltaic energy conversion must be optimized to the maximum.

The output characteristic of a panel or PV generator (PVG) is nonlinear. It is characterized by a particular point for which the power supplied by the PVG is maximum. This is usually denoted MPP (Maximum Power Point). The MPPT (Maximum Power Point Tracker) is an electronic device that maintains the operating point of the system as close to the MPP. There are several MPPT control algorithms in the literature, the most used is the Perturb and Observe algorithm (P&O).

The purpose of this article is the synthesis of a robust and optimal control law for the photovoltaic voltage regulation. This is the discrete sliding mode control. This control law is added to the MPPT algorithm to optimize energy conversion minimizing power loss.

This paper is organized as follows: the photovoltaic generator is described in Part 2. The matching stage between PVG and a load is presented in Part 3. The MPPT converter together with the P&O MPPT algorithm is outlined in part 4. The synthesis of a nonlinear robust control for regulating the PV voltage and the simulation results are detailed in Section 5, followed by a conclusion in the last section.

II. THE PHOTOVOLTAIC GENERATOR

The PV cell is the basic element of a PV system. A plurality of electrically interconnected cells forms a PV module, several modules form a panel and several panels form a PV array. The term PV generator (PVG) is used in this article to designate a module or a PV panel.

A. *Modeling of the PV cell*

A PV panel is formed by properly connecting several PV cells. The mathematical model of the PVG is given by [1,2,3,4,5,6,7,12,17] :

$$I = I_{sc}\left[1-\exp\left(\frac{V-V_{oc}+IR_s}{N_s V_{th}^{C}}\right)\right] \tag{1}$$

B. *Current/Voltage (I/V) Characteristic of the PVG*

Figure 1 shows the I/V characteristics of a PVG and a resistive load R. The characteristic of R is a line of slope 1/R. The operating point is located at the intersection of the two curves. In the AB region of the curve the PVG behaves as a current generator and in the CD region it behaves like a voltage source. In the intermediate zone BC, the characteristic of the PVG is nonlinear, it is in this area that we find the MPP (Maximum Power Point) for which the PVG provide its full power for certain atmospheric conditions. The resistance value corresponding to this point is denoted R_{opt} [5].

In practice, in the case of a direct coupling of a PVG and a load, the OP rarely coincides with the MPP. For this reason, a matching stage, to transfer maximum power from the source to the load is necessary.

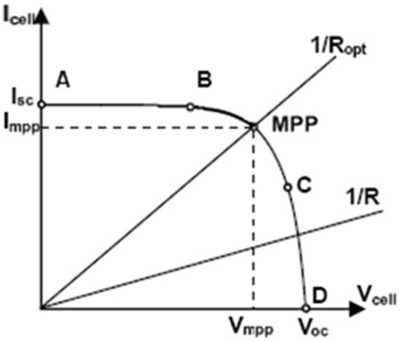

Fig. 1 I/V characteristics of a PVG.

III. MATCHING STAGE BETWEEN A PVG AND A LOAD

The commonly used adapter in PV systems is a DC/DC power converter. It ensures, through a control action, the transfer of the maximum of electrical power to the load. The structure of the converter is determined according to the load to be supplied. In this article we focus on the step-down DC/DC converter (Buck converter).

A. *DC/DC Buck converter*

A Buck converter (figure 2) is a switching power supply which converts a DC voltage into another DC voltage of lower value. This type of converter is used as an adapter between the source and the load, when the OP is to the left of the MPP in direct coupling [1,8,9,10,11].

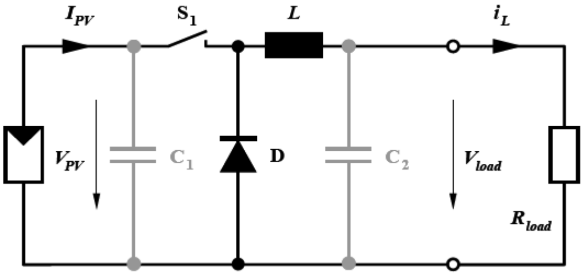

Fig. 2 Electrical circuit of a Buck converter.

In this case, the voltage across the load in continuous conduction mode is given by:

$$V_{load} = DV_{pv} \tag{2}$$

where $D = t_{on}/T$ is the duty cycle ($0 < \mathrm{D} < 1$)

$T = t_{on} + t_{off}$ is the switching period

IV. THE MPPT CONVERTER

The power delivered by a PVG depends greatly on the level of sunshine, temperature and also the nature of the load supplied. It is therefore highly unpredictable. The power characteristic has a maximum corresponding to the MPP.

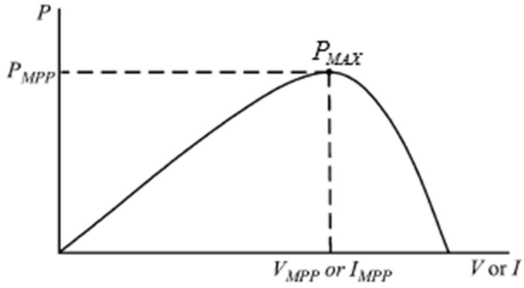

Fig. 3 Power Characteristic of the PVG.

The MPP position, depending on the various factors mentioned above, is never constant over time. The role of the DC/DC converter is to maintain the OP as close to the MPP for any operating conditions. An appropriate command will achieve this goal. Then we obtain a MPPT converter (Maximum Power Point Tracker). The MPPT converter is a power conversion system with a control algorithm for extracting the maximum power from the PVG. [1,8,9,10,11]. It regulates the input voltage V_{pv}. The reference voltage is then imposed by the control algorithm.

V. SYNTHESIS OF A NONLINEAR ROBUST CONTROL FOR PHOTOVOLTAIC VOLTAGE REGULATION

The switching power converters represent a particular class of variable structure systems (VSS). The latter are by definition nonlinear discrete systems that change structure or appear as various continuous nonlinear systems according to the state of the system [18]. Therefore, these converters can take advantage of nonlinear control techniques developed for this class of systems. Indeed, the power converters being endowed with a switching device, it is easy to design a discontinuous control law. The Sliding Mode Control (SMC) appeared in the Soviet Union in the 60s, which comes from the theory of VSS, allows accomplishing this task. This command leads to stability even in the presence of large variations in the supply or load, to good dynamic response and a simple implementation [19,20,21].

Nowadays the implementation of the control in practice is increasingly using microprocessors and microcontrollers. In this case, the information on the system (measurement) is only available at discrete times $t = kT_s$ (where k is an integer and T_s is the sampling period) and the control can only be updated at these moments. For this reason, the digital implementation of SMC in a system exhibits properties different from those seen in the continuous case [23, 24, 25]. This is called Discrete Sliding Mode Control (DSMC). The insensitivity of the controlled system against disturbances and uncertainties is reduced.

However, DSMC ensures a certain degree of robustness, most commonly measured in terms of oscillation amplitude of the variable to be regulated [26]. The main difference between SMC and DSMC is that the second is based on a discrete model of the system [27].

A. *Modelling of DC/DC buck converter*

The average model of the buck converter is given by the expression (3), with $x = [x_1 \quad x_2]^T = [I_L \quad V_{pv}\,]^T$ [9,11].

$$\begin{cases} \dfrac{dx_1}{dt} = \dfrac{D}{L}x_2 - \dfrac{V_{bat}}{L} \\ \\ \dfrac{dx_2}{dt} = \dfrac{1}{R_{pv}C_1}x_2 - \dfrac{D}{C_1}x_1 \end{cases} \tag{3}$$

with $R_{pv} = \frac{V_{pv}}{I_{pv}}$: equivalent load connected to PVG and V_{bat} : battery voltage.

The expression (3) can be written as follow:

$$\dot{x} = f(x) + g(x)d + H$$

Where: $f(x) = \begin{pmatrix} 0 \\ \frac{x_2}{R_{pv}C_1} \end{pmatrix}$, $g(x) = \begin{pmatrix} \frac{x_2}{\text{L}} \\ -\frac{x_1}{C_1} \end{pmatrix}$, $H = \begin{pmatrix} -\frac{V_{bat}}{L} \\ 0 \end{pmatrix}$

To obtain the discrete system model, the Taylor development series is used. One denotes by (k) a variable at time $t = kT_s$ where T_s is the sampling period. Taylor development series is given by [28]:

$$x(k+1) = x(k) + \dot{x}(t)|_{t=kT_s} + O_1(T_s) \tag{4}$$

Where $O_1(T_s)$ is the remaining higher order terms.

The application of this expression gives the following discretized system:

$$x(k+1) = \begin{cases} x_1(k) + \frac{d(k)T_s}{L}x_2(k) - \frac{V_{bat}T_s}{L} \\ \\ \left(1 + \frac{T_s}{R_{pv}C_1}\right)x_2(k) - \frac{d(k)T_s}{C_1}x_1(k) \end{cases} \tag{5}$$

B. *System Simulation*

The system used for our study consists of the Sharp SH-80 PV panel whose characteristics are given in Table 1, of a buck converter as an interface of adaptation and a lead acid battery with a voltage of 12 V as a load.

TABLE 1.

Number of cells	36 in series
Open circuit voltage (Voc)	21.6V
Short circuit current (I_{sc})	5.16A
MPP voltage (V_{MPP})	17.3V
MPP Current (I_{MPP})	4.63A
Maximum Power (P_{MPP})	80W

To perform the system simulation, one used the component library for standalone photovoltaic systems (Photovoltaic Systems Toolbox) that have been developed in Matlab/Simulink of Mathworks [17]. Regarding the parameters of Buck converter, their values are: $L = 120\mu H$, $C^1 = 660\mu F, C_2 = 100\mu F$.

To simplify the analysis, one used a piecewise linear approximation of the PVG I/V characteristic (Figure 4). The I/V curve is divided into four regions: current source region, power region I, power region II and voltage source region. In general, the normal operation of the MPPT converter starts from the voltage source region before moving to power regions I and II and remain there in steady state.

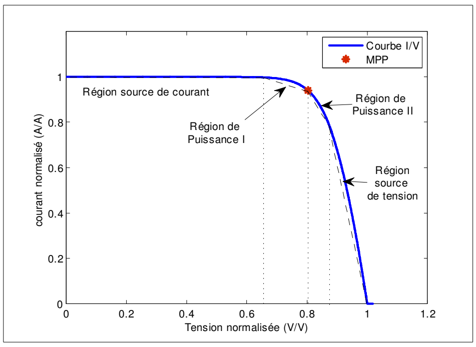

Fig. 4 Piecewise linear approximation of the PVG I/V characteristic

The simulation results using the linearized model are shown below. The figures illustrate the transient step response (open-loop) in the power regions for a 2% change in the duty cycle.

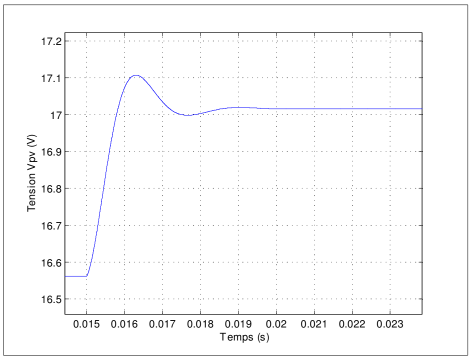

Fig. 5 System response in the power region II

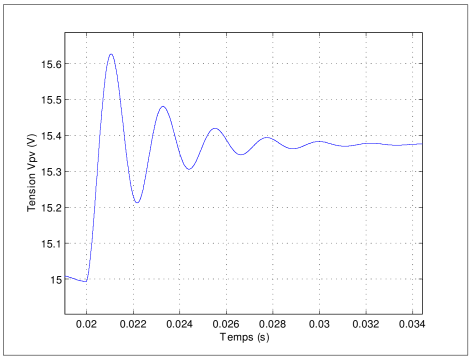

Fig. 6 System response in the power region I

One sees that in the power region II, the answer is averagely damped, while in power region I, it is slightly damped. The settling time is thereby affected. However, the settling time is an important parameter for the MPPT algorithm.

In addition, the observed oscillations generate a loss of the power generated by the PVG, which is not desirable. The time response of the system can be improved by using an appropriate control law.

C. *Synthesis of sliding mode control*

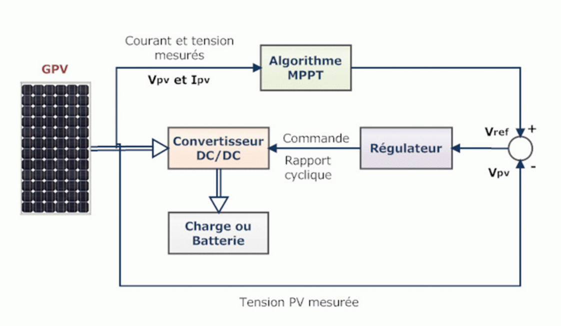

Fig. 7 Overall control loop

The figure 7 illustrates the overall control loop which includes the MPPT algorithm and the control law which will be synthetized in this section. The algorithm provides the reference voltage which is a tracking of the MPP. The control merely ensures voltage regulation according to specifications. The chosen switching function is the following:

$$\sigma(k) = x_2(k) - V_{ref}(k) \tag{6}$$

In our case, the reference voltage V_{ref} is provided by the P&O MPPT algorithm. In order to obtain a discrete nonlinear control law to reach the sliding surface in a finite time, a reaching law is used. We chose a linear reaching law (proposed by Hui and Spurgeon) [27] whose expression is:

$$\sigma(k+1) = \phi\sigma(k) \qquad \text{with } 0 \leq \phi < 1 \tag{7}$$

Substituting this expression in xx, one obtains:

$$\sigma(k+1) = x_2(k+1) - V_{ref}(k+1) = \left(1 + \frac{T_S}{R_{pv}C_1}\right)x_2(k) - \frac{d(k)T_S}{C_1}x_1(k) - V_{ref}(k+1) \tag{8}$$

from where the control law:

$$d(k) = \left(\frac{C_1}{T_S} + \frac{1}{R_{pv}}\right)\frac{x_2(k)}{x_1(k)} - \frac{C_1}{T_S}\frac{V_{ref}(k+1)}{x_1(k)} - \frac{C_1\phi}{T_S}\frac{\sigma(k)}{x_1(k)} \tag{9}$$

1) *Existence of discrete-time sliding mode*

The condition of existence of discrete-time sliding mode was proposed by Sarpturk & al (1987) [27]. It is given by:

$$|\sigma(k+1)| < |\sigma(k)| \tag{10}$$

This condition can be written as:

$$\begin{cases} [\sigma(k+1) - \sigma(k)]sign(\sigma(k)) < 0 \\ [\sigma(k+1) + \sigma(k)]sign(\sigma(k)) > 0 \end{cases} \tag{11}$$

Condition 1:
for $\sigma(k) > 0$:

$$\begin{cases} \phi < 1 \\ \sigma(k) > 0 \end{cases} \Rightarrow \phi\sigma(k) < \sigma(k) \Rightarrow \sigma(k+1) - \sigma(k) < 0$$

for $\sigma(k) < 0$:

$$\begin{cases} \phi < 1 \\ \sigma(k) < 0 \end{cases} \Rightarrow \phi\sigma(k) > \sigma(k) \Rightarrow \sigma(k+1) - \sigma(k) > 0$$

whence: $[\sigma(k+1) - \sigma(k)]sign\big(\sigma(k)\big) < 0$

Condition 2:
for $\sigma(k) > 0$:

$$\begin{cases} \phi \geq 0 \\ \sigma(k) > 0 \end{cases} \Rightarrow \phi\sigma(k) \geq 0 \Rightarrow \sigma(k+1) + \sigma(k) \geq \sigma(k) > 0$$

for $\sigma(k) < 0$:

$$\begin{cases} \phi \geq 0 \\ \sigma(k) < 0 \end{cases} \Rightarrow \phi\sigma(k) \leq 0 \Rightarrow \sigma(k+1) + \sigma(k) \leq \sigma(k) < 0$$

whence: $[\sigma(k+1) + \sigma(k)]sign\big(\sigma(k)\big) > 0$

Finally: $|\sigma(k+1)| < |\sigma(k)|$. The existence of discrete-time sliding mode is proved.

2) *Simulation Results*

The simulation results for a sampling frequency $f_s = 100kHz$ and $\phi = 0.9$ are given below. The reference voltage is equal to 17V at the beginning, increases to 18V after 3ms and then decreases to 17V at time 4ms. One sees that the DSMC manages to track the reference voltage with a settling time less than 0.5ms. One also notices that the static error is not null and is equal to 0.01. It is important to note that for a sampling frequency below 100 kHz (switching frequency) the DSMC don't give good results.

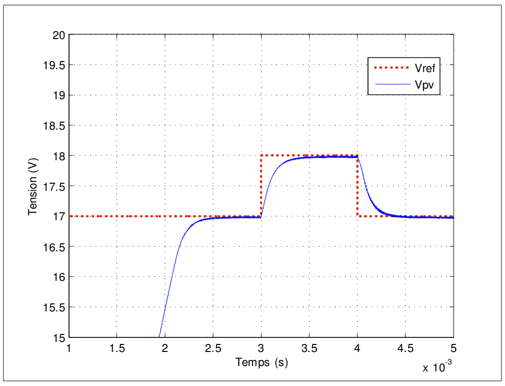

Fig. 8 Simulation result of the DSMC for a switching frequency equal to 100kHz

VI. CONCLUSION

In this article, a robust nonlinear regulation of the photovoltaic voltage using the discrete sliding mode control in the context of a MPPT algorithm has been presented. The component library "Photovoltaic Systems Toolbox" was used to perform the simulation. The simulation results in Simulink showed the effectiveness of the proposed control law.

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