A Sliding Maximum Power Point Tracker for a Photovoltaic System

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Abstract. This paper proposes a control strategy of a Maximum Power Point Tracking (MPPT) of a photovoltaic (PV) system. The system includes a photovoltaic array, a DC/DC converter and a DC/AC inverter connected to a load. The proposed strategy is based on the sliding mode control and it allows a direct control of power converter. The stability as well as the robustness of the system will be evaluated. This work is motivated by the need to use the maximal power of PV generator, which is a special source of energy that has a non-linear current-tension characteristic (I-V) dependent of temperature and solar irradiance. Some reliable simulation results are provided in this paper in order to demonstrate the efficiency of the proposed approach.

Key words: Photovoltaic system, boost converter, sliding mode control, maximum power point.

1. Introduction

Nowadays, photovoltaic (PV) systems are used as energy source in many cases. Most commonly applied PV systems can be found in remote and rural areas where no public grid is available. A typical small off-grid photovoltaic power system can contain the following components: solar PV array, with a number of series/parallel interconnected solar modules and protection elements, a DC/DC converter, a DC/AC inverter and a control system, figure 1.

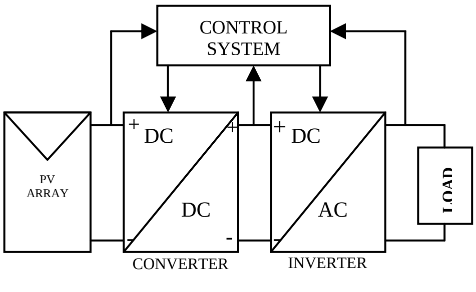

Fig. 1. Basic structure photovoltaic system

The target of control system is that the PV array will maximize the electrical power with a given irradiance. The control should guarantee that the dc power will be transformed with high efficiency to the load.

In order to archive this maximum power point (MPP) of the PV array, it is necessary to maintain it at their optimum point operating. This characteristic is difficult to reach because the PV array exhibit interesting dynamical properties. PV modules have nonlinear voltage-current characteristics, and there is only one PV operation point with a maximum output power under particular conditions of solar radiation and temperature. Such properties have attracted the interest of this work in the search a control that improves its dynamic performance.

Many methods have been developed to determine the MPP. For example, Ibrahimm and Houssing employed the look-up table on a microcomputer to track MPP, Midya et al. applied a dynamic MPP tracker to PV appliances, and Kuo and Liang proposed a single-stage MPP controller using the slope the power versus voltage, [1-3]. Dual boost converter based MPP tracking using fuzzy logic has been reported, [4]. Too, there is an approach based on a perturbation and observation method, where the reference voltage varies periodically when the MPP is reached, [5].

In this analysis, the sliding mode controller has been designed to search maximum power point and an adequate DC/DC converter output voltage. The control circuit adjusts the duty cycle of the switch control waveform for maximum power point tracking as a function of the evolution of the power input at the DC/DC converter. In this control system, it is necessary to measure the PV array output power and to change the duty cycle of the DC/DC converter control signal.

The paper is organized as follows. Section II introduces the basic principle of the PV system and a system description. Section III explains as the sliding mode control is applied. Section IV describes the proposed sliding controller. Simulation results and conclusions are finally discussed in the last sections.

2. System Description

A The photovoltaic system

A real PV array has been modelled. It consists of 30 PV modules with 36x2 monocrystalline silicon solar cells each one, connected in series and parallel. Each module can produce 106 W of DC electrical power with an area of 126.5 square centimetres. The array is configured as follows: fifteen modules are connected in series with a nominal operating voltage of 325 V. Then, 2 of these series strings are connected in parallel, resulting in a current of 6A. The rated power of the PV array is 2.6 kW (DC).

In order to allow the interaction between the DC/DC converter and the PV array, a simulation model for a PV array has been developed, including the dependence of the PV array output with the irradiance and temperature. The model was implemented in ®Simulink, helped by the SimPowerSystem blockset, figure 2.

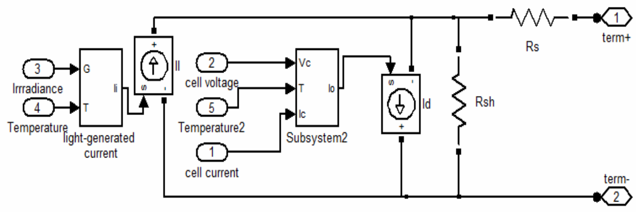

Fig. 2. Equivalent circuit of a PV cell

This equivalent circuit models the general form the equation that relates current and voltage [6] in a photovoltaic cell:

$$I = I_l - I_o\left(e^{q\frac{(V+R_sI)}{\eta K T_K}} - 1\right) - \frac{V+R_sI}{R_{sh}} \qquad (1)$$

where I_{PV} and V_{PV} are cell output current and voltage, I_0 is the cell reverse saturation current, I_L is the light-generated current, R_s and R_{sh} are series and shunt resistances, q is electronic charge, K is Boltzmann's constant and T_K is cell temperature in K.

Photovoltaic generator performance can be determined trough the characteristic curves. Figures 3 and 4 present the current-voltage and power-voltage output characteristics of a photovoltaic array for different solar isolation with temperature of 25ºC.

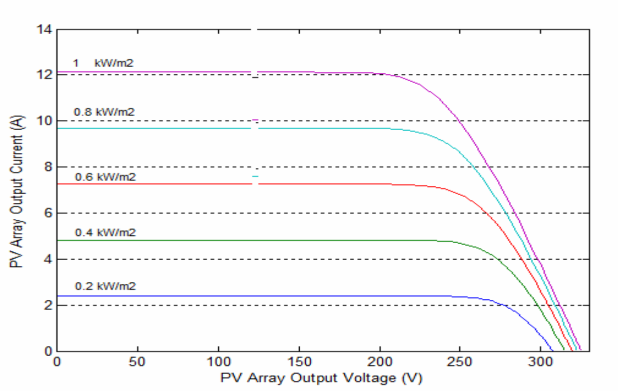

Fig. 3. Current-voltage curve of a PV array with constant irradiation and temperature of 25ºC.

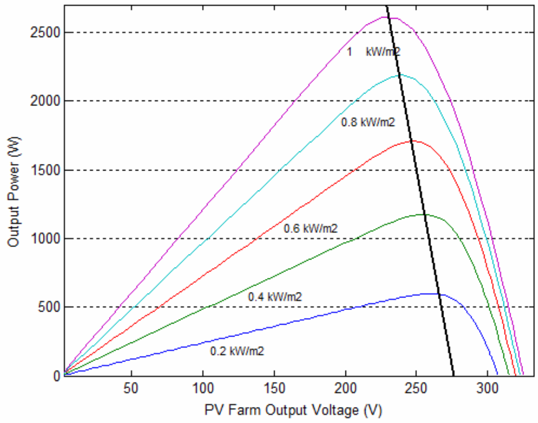

Fig. 4. Power-voltage curve of a PV array with constant irradiation and temperature of 25ºC.

The knowledge of these characteristic curves for different irradiations and temperatures allows knowing the maximal power what it possible to obtain, figure 4. The efficiency of the system will be the ratio between the measured real power and this maximal power.

In general, the PV modules have nonlinear voltage-current characteristics, and there is only one PV operating point with a maximum output power under particular conditions. For example, the maximum power points of the modelled system are:

TABLE I. Maximum power points to different irradiations and temperature of 25ºC

Radiation (W/m^2)	Maximal power (W)
200	588
400	1239
600	1700
800	2190
1000	2600

Based on characteristic curve shown in figure 4, the condition of maximum power point is given by:

$$\frac{\partial P}{\partial V_{PV}} = 0 \qquad (2)$$

where PV array output power P is defined as

$$P = I_{PV} \cdot V_{PV} \qquad (3)$$

where V_{PV} and I_{PV} are the voltage and current supplied by photovoltaic array.

The equation (2) can be written as follows:

$$\frac{\partial}{\partial V_{PV}}\left[I_{PV} \cdot V_{PV}\right] = I_{PV} + \frac{d}{dV_{PV}}\left[I_{PV}\right] \cdot V_{PV} = 0 \qquad (4)$$

B. Buck-Boost converter

In order to adapt the array photovoltaic to a large voltage range, the PV MPPT system adopts step up and down DC-DC converter topology, figure 5.

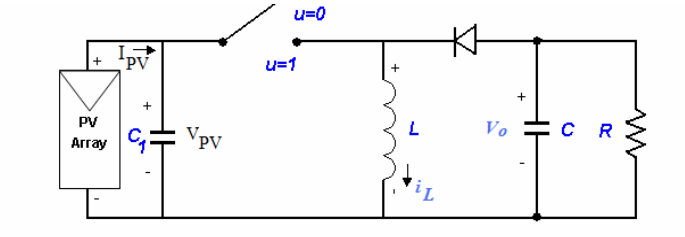

Fig. 5. Buck-boost converter

This converter can be modeled [8] as follows.

$$\frac{dV_{PV}}{dt} = \frac{I_{PV}}{C_1} - \frac{i_L}{C_1}u \qquad (5)$$

$$\frac{di_L}{dt} = -\frac{v_o}{L} + \frac{u}{L}(V_{PV} + v_o) \qquad (6)$$

$$\frac{dv_o}{dt} = (\frac{i_L}{C} - \frac{v_o}{RC}) - \frac{ui_L}{C} \qquad (7)$$

where i_L is the current across the inductor, v_0 is the voltage in the capacitor *C*. Parameters *R*, *L*, C_1 and *C* are supposed to be known constants. $u \in \{0,1\}$ defines the switch position.

The equations (5-7) can be written as follows:

$$\dot{x} = Ax + \delta + u(Bx + \gamma) \qquad (8)$$

where

$$A = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{L} \\ 0 & \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \quad \delta = \begin{bmatrix} I_{PV}/C_1 \\ 0 \\ 0 \end{bmatrix} \quad B = \begin{bmatrix} 0 & -\frac{1}{C_1} & 0 \\ \frac{1}{L} & 0 & \frac{1}{L} \\ 0 & -\frac{1}{C} & 0 \end{bmatrix}$$

$$\gamma = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \text{ and } x = \begin{bmatrix} V_{PV} & i_L & v_o \end{bmatrix}^T$$

When a buck-boost converter is used in PV applications, the input voltage changes continuously with the atmospheric conditions. Therefore, the duty cycle should change to track the maximum power point of photovoltaic array.

3. Sliding mode control

The Variable Structure Systems (VSS) are a special class of nonlinear systems characterized by a discontinuous control action which changes the structure on reaching a set of switching surfaces. If a system is forced to constrain its evolution on a predetermined switching surface, it results in a dynamic behavior that is largely determined by the design parameters and equations defining the switching surface. Consequently, new properties which are not present in the original system can be obtained for the controlled motions. Therefore, the system is robust and insensitive to disturbances and parameter variations, [7].

In order to design the sliding mode control considers the linear time-varying systems described by the equation:

$$\dot{x} = A_1 x + B_1 u \qquad (9)$$

where $x \in \Re^n$, $u \in \Re^m$. The matrices $A_1 \in \Re^n$ and $B_1 \in \Re^n$ are constants. The VSSs are characterized by a discontinuous control *u* which changes structure on reaching a set of predetermined switching surfaces in the state space. The control has the following form:

$$u = \begin{cases} u^+ & para \quad S(x) > 0 \\ u^- & para \quad S(x) < 0 \end{cases} \qquad (10)$$

where u^+ and u^- are components of *u* and *S(x)* is the switching surface which satisfies

$$S(x) = 0 \text{ and } \frac{dS(x)}{dt} = 0 \qquad (11)$$

The system finds in sliding mode if switching control signal is between u^+ and u^- satisfied (11). The figure 6 evidences an example of the commutation when there is a band of hysteresis.

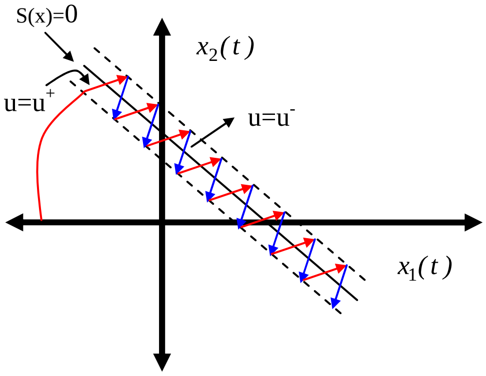

Fig. 6. Example with band of finite hysteresis in sliding mode

After selecting the switching surface, it selects the control law which ensures the existence of the sliding mode.

Applying the model of the converter (8), the equation (9) can be written as follows:

$$\dot{x} = A_1 x + B_1 u := Ax + \delta + u(Bx + \gamma) \qquad (12)$$

The equivalent control u_{eq} [4] of the system can be obtained as

$$u_{eq} = -\frac{<\nabla S,(Ax + \delta)>}{<\nabla S,(Bx + \gamma)>} \qquad (13)$$

where ∇S is the gradient (or gradient vector field) of the scalar function S, < , > is the inner product and $<\nabla S, Bx+\gamma> \neq 0$.

Ideally, equivalent control u_{eq} is a solution to the sliding mode control because it maintains the state on the sliding manifold at each instant and satisfied (11).

The sliding mode existence is ensured if

$$min(u^-,u^+) < u_{eq} < max(u^-,u^+) \qquad (14)$$

In the following section, it is presented a design method which will ensure the motion of the system (8) on the switching surface without using discontinuous control inputs *u*.

4. Controller Design

Considering the condition of MPPT (4) the following sliding surface *S(.)* is proposed:

$$S(.) = I_{PV} + \frac{\partial I_{PV}}{\partial V_{PV}} V_{PV} = 0 \qquad (15)$$

The sliding surface assures that the sliding motion is reached and regulates output voltage buck-boost converter. While, the switch control signal can be selected as

$$u = \begin{cases} u^+ & para \quad S(x) > 0 \\ u^- & para \quad S(x) < 0 \end{cases} \qquad (16)$$

Assuming that (15) as sliding surface and imposing the invariance conditions [7] *S(x)*=0 and *dS(x)*/*dt*=0 in (13) leads to the following expression of the equivalent control $u_{eq}(x)$:

$$u_{eq} = \frac{I_{PV}}{i_L} \qquad (17)$$

where the numerator and denominator of (13) correspond to

$$\langle \nabla S(.), Bx+\gamma \rangle = \left(\frac{\partial^2 I_{PV}}{\partial^2 V_{PV}} V_{PV} + 2\frac{\partial I_{PV}}{\partial V_{PV}} \right)\left(-\frac{i_L}{C} \right) \qquad (18)$$

$$\langle \nabla S(.), Ax+\delta \rangle = \left(\frac{\partial^2 I_{PV}}{\partial^2 V_{PV}} V_{PV} + 2\frac{\partial I_{PV}}{\partial V_{PV}} \right)\left(\frac{I_{PV}}{C_1} \right) \qquad (19)$$

From equations (17) and (8), it is possible to obtain the next equations:

$$\frac{di_L}{dt} = -\frac{v_o}{L} + \frac{I_{PV}}{Li_L}(V_{PV} + v_o) \qquad (20)$$

$$\frac{dv_o}{dt} = \frac{i_L}{C} - \frac{v_o}{RC} - \frac{I_{PV}}{C} \qquad (21)$$

We conclude that a sliding regime will exist if the converter works in continuous conduction mode, i.e., $i_L>0$. The expression (17) allows obtaining the ideal model of closed loop control systems and to demonstrate that the system could reach global stability.

5. Simulation results

The proposed control design was implemented in Simulink and SimpowerSystem. The figure 7 shows a block diagram of the PV system.

The PV array has been modelled with 30 PV modules, connected in series and parallel way. In order to adapt the photovoltaic array output voltage, a DC/DC converter is connected. This converter should support input voltages in a wide range, from 100 to 325 V. Under such conditions, the duty ratio *D* is adjusted to regulate the output voltage at 400 V. For the given range, *D* is in a range of [0.76-0.20] and the output current is maximal when *D*=0.33. The DC/DC converter has a sliding mode control that searches the maximum power point of the PV array as was detailed above. The input of the sliding control block is shows in figure 8.

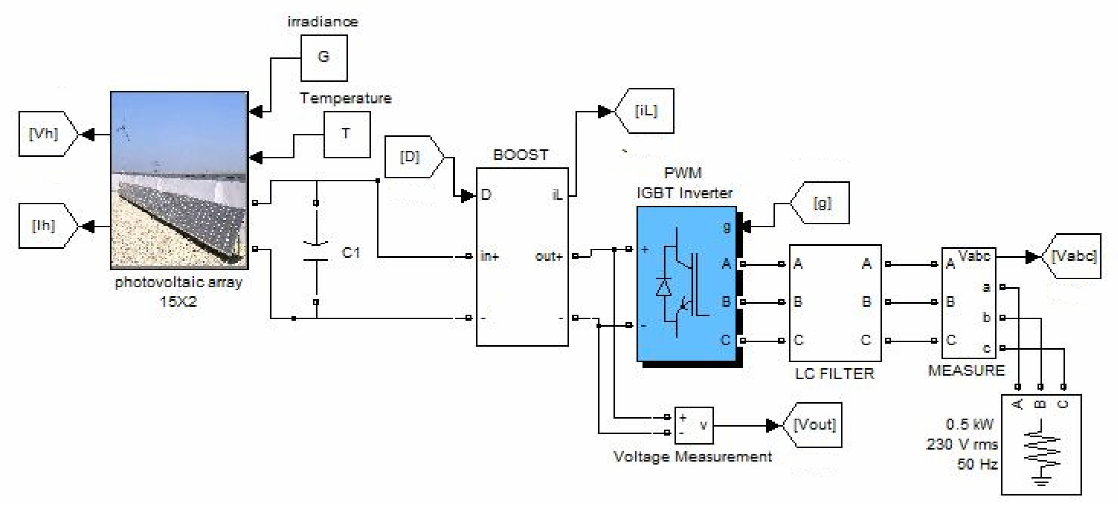

Fig. 7. Photovoltaic array interconnected to AC load

The 400 V obtained at buck-boost converter are applied to an IGBT two-level inverter to generate a sinusoidal output voltage of 50 Hz. The IGBT inverter uses Pulse Width Modulation (PWM) with a 1050 Hz carrier frequency. The circuit sample time was 1 µs. The IGBT inverter is controlled with a PI regulator, figure 9, in order to maintain 230 Vrms, 50 Hz, at the load terminals. This control loop is independent for the PWM inverter.

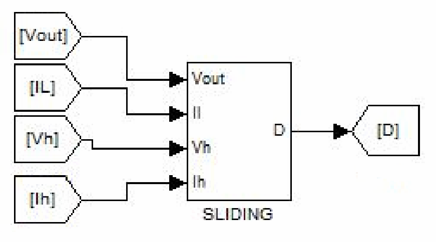

Fig. 8. Inputs of the sliding mode control

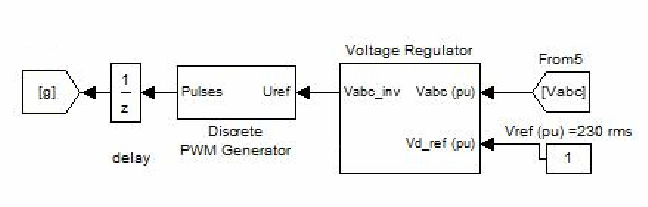

Fig. 9. PI regulator

The proposed design scheme was tested connecting a load of 0.5 KW, and some radiation steps in PV array. Simulation results have been observed in each case to view the influence of the sliding mode control in power and index modulation.

Figure 10 shows the evolution of current, voltage and power PV array for 1000 W/m^2 and for successive irradiance steps applied at t=0.06 seg (800W/m^2) and t=0.12 seg (600 W/m^2).

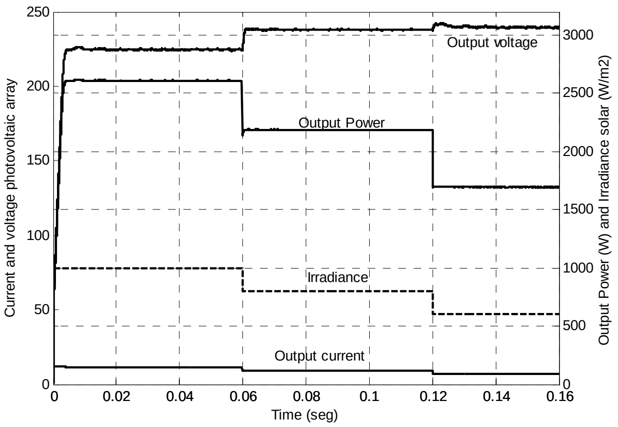

Fig. 10. Evolution of V_{PV}, I_{PV} and P_{PV}

Figure 11 shows the load voltage for the irradiance step and figure 12 shows the evolution of the modulation index. The time response is nearly 10 ms for a final output of 230 Vrms.

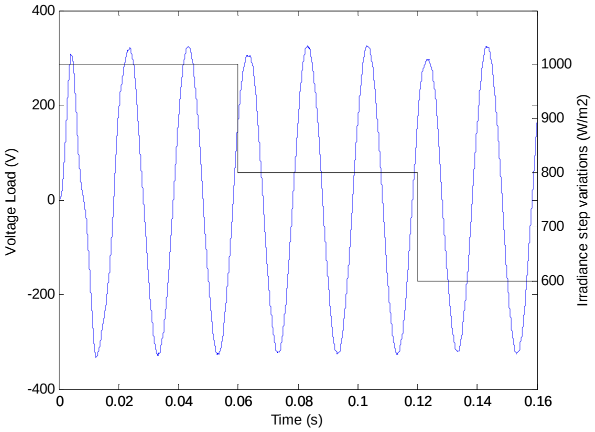

Fig. 11. Evolution of load voltage to difference irradiances solar

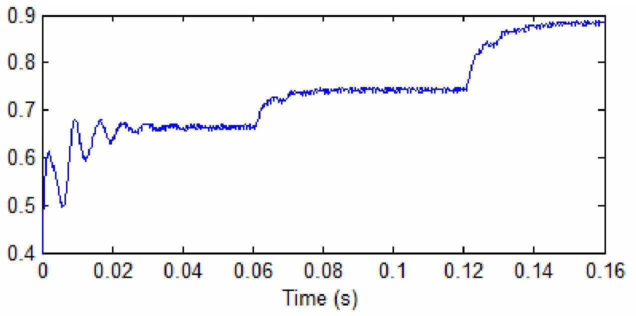

Fig. 12. Evolution of index modulation

6. Conclusions

In this paper, a sliding mode control of the boost converter in a PV system has been analyzed. The inputs of the controller are the PV array output voltage and its output power, and the output control is the switching signal os the DC/DC converter.

The control law provides voltage regulation at the converter output, and guarantees the maximum power point of the PV array, as the simulations result probed.

This control law could be implemented by means of standard operational amplifiers, analog multipliers and digital devices in an experimental platform, or using an acquisition and control DSP board.

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