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Sliding-Mode Control Based MPPT for PV systems under Non-Uniform Irradiation

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Sliding-Mode Control Based MPPT for PV systems under Non-Uniform Irradiation

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Abstract— **A fast and robust maximum power point tracking scheme with ability to track maximum power point (MPP) under partially shaded condition (PSC) is proposed for photovoltaic (PV) systems. The fast dynamics and robustness are attained by a sliding mode control and ability to track maximum power point under PSC by a MPPT algorithm with variable steps. In response to irradiance variations, the proposed algorithm recognizes shading and activates the scanning phase of the algorithm to find the global maximum power point (GMPP). In order to verify the accuracy and validity of the proposed method, different simulations are carried out in MATLAB-Simulink environment for various atmospheric conditions.**

Keywords- photovoltaic (PV) generator; MPPT; partial shading condition (PSC); sliding mode control (SMC)

I. INTRODUCTION

Nowadays due to environmental and economical reasons, the focus on renewable energy has increased rapidly. Photovoltaic (PV) energy is a kind of sustainable energy and works by converting the solar irradiation into electrical power. This technology has progressed over the last decades but still has some problems. Its nonlinearity and dependency on temperature and irradiation makes it difficult to extract maximum available power. It is the purpose of the MPPT system to sample the output of the cells and apply the proper resistance (load) to obtain maximum power for any given environmental conditions.

MPPT devices are typically integrated into an electric power converter system that provides voltage or current conversion. As a consequence, the control strategy of the converter is one of the most important components that facilitate the system to meeting the user requirement. It is designed to control and accurate the DC voltage, and provides a suitable quality of power [1].

Sliding mode control offers a very good way to implement a control action which exploits the inherent variable structure nature of DC-DC converters [2]. This mode occurs on switching surface, and the system remains insensitive to parameter variations and disturbance.

Although a lot of research publications are available in the literature on the SMC, those ones focused in photovoltaic applications are few and mainly devoted on the control of the DC/AC stage for regulating the current injected into the grid. In [3,4] adaptive total sliding-mode control system is designed for the current control of the PWM inverter to maintain the output current with a higher power factor and less variation under load changes. And some publications focus on Maximum Power Point Tracking (MPPT) [5] using simple algorithms such as P&O [6].

However, when some modules on the PV array receive less irradiation than others, local maximum power points appear on the P-V curve. These points can entrap simple algorithms such as P&O. In order to avoid such problems, special algorithms must be developed that can recognize local maxima and be able to track the global maximum power point (GMPP).

Some GMPPT techniques [7,8], recognize partially shaded condition and use a predetermined function to move the operating point to the vicinity of the Global Maximum Power Point (GMPP). These methods track the GMPP relatively fast but, under complex shading patterns that lead to many peaks in the PV power curve, they may move the operating point near one of the local MPPs and consequently, track the wrong MPP. Also, the algorithm proposed in [7] requires measuring open-circuit voltage V_{oc} and short-circuit current I_{sc} which causes power loss.

Other GMPPT algorithms use different methods to scan some parts or the whole PV power curve to search for the GMPP, and distinguish between local and global maximum power points. In [9] the sign of ${\partial P}/{\partial V}$ at different points is used to search around the MPPs for possible GMPP. The dividing rectangles (DIRECT) technique proposed in [10] utilized a Lipschitz condition to track the GMPP as a function of the PV voltage [11]. The power increment technique proposed in [12] is based on controlling a dc/dc converter connected at the PV array output, such that it behaves as a constant input-power load. These scanning algorithms are always able to track the global maximum power point and usually have a simple structure. However, due to searching on a large portion of the power curve, they cause power loss, and are not fast enough under rapidly changing irradiation and also for mobile applications.

In this paper, a MPPT technique for partially shaded PV arrays is proposed that employs sliding mode control instead

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of PWM for converter switching. The proposed controller offers a fast and accurate convergence to the MPP in steady state and during varying environmental conditions and even in presence of disturbance. A DC/DC boost converter is utilized as a control actuator for the MPP. The paper is organized as follows: in second section, we introduce sliding mode control and the proposed controller for the boost DC-DC controller. In the third section, simulation results show the fast response and accuracy of the proposed controller even under PSC. Finally, the conclusions are summarized in section IV.

II. SLIDING MODE CONTROL

In the sliding mode theory, the objective is to find a control input signal u such that the state vector x tracks a desired trajectory x* in the presence of model uncertainties and disturbances. The sliding surface may then be set to be of the form:

$$S(x) = x - x^* \tag{1}$$

In general, maximum power point tracking of photovoltaic systems is performed using a step up converter in order to increase PV voltage to a suitable value which allows the suitable behavior of the DC/AC stage.

In order to track maximum power point, the power converter that in this paper is a dc/dc boost converter, must be controlled. Schematic diagram of DC-DC boost converter is shown in Figure 1. Its dynamic model in state space is obtained by the application of basic laws governing the operation of the system [1]. The dynamic equations of this converter can be written as:

$$\frac{di_L}{dt} = -(1-u)\frac{v_c}{L} + \frac{E}{L} \tag{2}$$

$$\frac{dv_c}{dt} = (1-u)\frac{i_L}{C} - \frac{v_c}{RC} \tag{3}$$

Where i_L is the inductor current, v_c is the output capacitor voltage, E is the input voltage and u the control signal. If the switch is ON, $u = 1$ and if it is OFF, $u = 0$.

Taking $x_1 = i_L$ *and* $x_2 = v_c$ as the state variables of the system and using the state equations given in equations (2) and (3) with the aim of achieving a desired constant output voltage v^*, the state variable x_2 can be obtained as follows:

$$x_2 - v^* = 0 \tag{4}$$

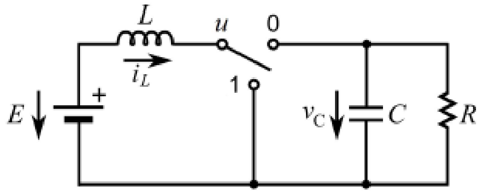

Figure 1. Schematic diagram of DC-DC boost converter [1]

Thus, according to (1), the sliding surface is defined as follows:

$$S = i_L - i_{ref} \tag{5}$$

The reference value x_1^* is derived internally to the controller from the output of the linear voltage controller. Figure 2 shows a control strategy operating on the inductor current of the dc/dc converter in order to regulate PV current value [13].

But this method requires two high-bandwidth current sensors for i_{PV} and i_L, both affecting the value of control signal. Bianconi et.al. [14] suggests a more simple method (Figure 3), in which the i_{Lref} is replaced by i_{Cin} and i_{vr} according to Kirshhoff current law. Therefore, the sliding path can be rewritten as:

$$S = i_{C_{in}} - i_{vr} \tag{6}$$

This simplification is important for practical implementation because *u(t)* only depends on the instantaneous value of i_{Cin}, so, only one high band-width current sensor is required. However, this method still needs an extra current sensor compared with conventional MPPT techniques.

In the proposed method the same sliding surface is used but the input capacitor current i_{Cin} is estimated using v_{Cin} (7) which is measured for MPPT anyway.

$$i_{C_{in}} = C_{in}\frac{dV_c}{dt} \tag{7}$$

Therefore, the need for a high-bandwidth current sensor is eliminated.

In order to ensure that the state trajectory is always moving towards *S=0*, the following conditions must be ensured:

$$S = 0 \tag{8}$$

$$\frac{dS}{dt} = 0 \tag{9}$$

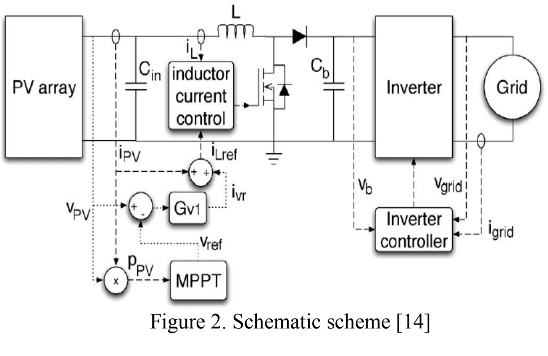

Figure 2. Schematic scheme [14]

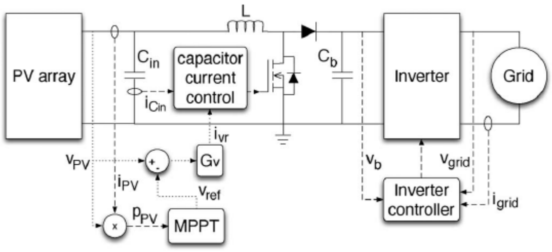

Figure 3. System scheme based on input capacitor current control [14]

Thus, the switching law will be considered:

$$\begin{cases} S < 0 \Rightarrow i_{C_{in}} > -i_{vr} \Rightarrow u = 1 & (12) \\ S > 0 \Rightarrow i_{C_{in}} < -i_{vr} \Rightarrow u = 0 & (13) \end{cases}$$

According to the classical boost converter input-output voltage relationship:

$$\frac{di_L}{dt} = \frac{v_{PV}}{L} - \frac{v_b.(i-u)}{L} \tag{14}$$

Where v_b is the output voltage and u is the control signal which is 1 switch is ON and 0 when the switch is OFF.

According to the equivalent control technique [15], the constraints ensuring sliding-mode operation, are fulfilled by ensuring that the average control signal u_{eq} fulfilles the inequality $0 < u_{eq} < 1$ which leads to:

$$\frac{v_{PV} - v_b}{L} < \frac{di_{sc}}{dt} + \frac{di_{vr}}{dt} < \frac{v_{PV}}{L} \tag{15}$$

This inequality shows that maximum i_{vr} and i_{sc} slopes depend on inductor current derivatives in the OFF and On switch states. Therefore, the voltage controller can be designed to fulfill this dynamic constraint.

A. PI controller

According to [8] the PI controller (16) is designed by considering the relation between settling time t_s and minimum switching period T_{sw}.

$$G_v(s) = k_p + \frac{k_p}{s} \tag{16}$$

$$\begin{cases} k_p = 2C_{in}\zeta\omega n & (17) \\ k_i = C_{in}\omega_n^2 & (18) \end{cases}$$

Therefore, the time constant is : $\tau = 1/\zeta\omega_n$

B. MPPT algorithm

The objective of MPP algorithms is to obtain the maximum power of the PV modules. In this work, a MPPT algorithm based on perturb and observe but with different v_{ref} steps is proposed. Flowchart of this MPPT algorithm is shown in Figure 4. The different steps of this method are:

- If the system is working under nominal condition, small v_{ref} steps are used to accurately track the maximum power point.
- If the system recognizes non-uniform irradiation, the algorithm first uses large Δv_{ref} to scan the P-V curve and after finding the approximate global MPP, switches to normal MPP to accurately track the actual MPP.

According to the PV characteristic equation, the PV current is linearly dependant on the irradiation. Thus, when irradiance on some parts or the entire array changes, the current variation (19) is considered as shading condition and the scanning phase of the proposed algorithm is activated.

$$\frac{I_{PV}[k] - I_{PV}[k-1]}{I_{sc,n}} < \Delta I_{SET} \tag{19}$$

Where I_{PV} is the PV array output current, $I_{sc,n}$ is the short-circuit current of the PV array under nominal condition and ΔI_{SET} is a preset parameter depending on PV array type.

Since every local and global MPP voltage in a PV array is a multiple of MPP voltage of a PV module, the size of large step changes in the V_{ref} are MPP voltage of the PV module at the standard condition that can easily be obtained from the module datasheet.

After observing several shaded P-V curves with many local maxima, it can be concluded that power of local maximum power points increases as they get closer to the Global MPP, and after that power of local maxima keeps decreasing. Therefore, the proposed algorithm does not need to scan the entire P-V curve because the same as traditional P&O algorithm, once power starts decreasing, it means GMPP is passed.

In order to generate a dynamic behavior of v_{ref} and remove the switching frequency components, all the P&O input and output signals are filtered using $G_{fv}(s)$:

$$G_{fv}(s) = \frac{V_{ref}(s)}{P\&O(s)} = \frac{1}{\tau_f s + 1} \tag{20}$$

Where P&O(s) is the P&O control signal [8].

I. SIMULATION RESULTS

To verify the proposed MPP tracking control performance, simulations are carried out using a MATLAB/Simulink environment. At first, the control algorithm is implemented assuming steady state under the STC. Then another simulation is performed with partial shading at different values of irradiances.

The PV system consists of a 4 × 2 PV array with 2 strings, each with four PV modules and its parameters are shown in table I.

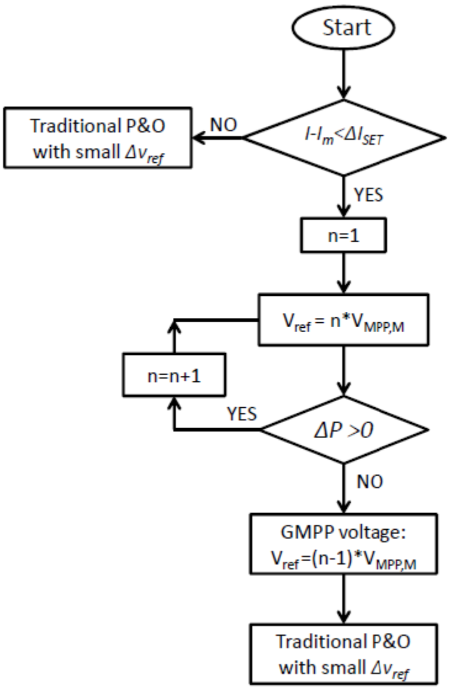

Figure 4. Proposed MPPT algorithm

According to [1], minimum switching frequency is 100 kHz, $\Delta v_{ref-large} = 16.56\ V$ and $\Delta v_{ref-small} = 0.4\ V$, so, the PI controller design considerations lead to $t_s = 40$ ms and the following controller:

$$G_v(s) = 0.2\frac{s+10000}{s} \qquad (21)$$

TABLE I. SYSTEM PARAMETERS AND NOMINAL CONDITIONS

PV Array	Values at STC
Short-circuit current I_{SC}	2.55 A
Open Circuit Voltage V_{OC}	21.24 V
MPP Current	2.25 A
MPP Voltage	16.56 V
Boost Parameters	**Nominal Values**
Input Capacitance	110 uF
Output Capacitance	2*22 uF
Inductance L	13.8 mF
Operating Conditions	**Nominal Values**
Nominal Switching Frequency	100 kHz
Average Output Voltage	100 V

In order for the PV power to reach its steady state, the MPPT controller period T_a is chosen as $1.5t_s$ which in this example is $T_a = 60$ ms and the time constant is set to $\tau_f = \tau = 110\ \mu s$.

Another important feature of sliding-mode control is disturbance rejection. Therefore, low frequency voltage variations back propagating from the bulk voltage towards the PV voltage are added to the system. Δv_b is assumed to oscillate in the range [-10, 10] with 100 Hz frequency.

First, the system works under standard test condition, and suddenly; it experiences partial shading condition at time 2 s. As shown in Figure 5, two modules from the first string and two modules from the second string receive lower irradiation (300 and 400 w/m^2 irradiance respectively) while other modules receive nominal irradiation. The shaded array P-V characteristic is given in Figure 6. It is shown that there is also one local maximum power point in which the conventional P&O algorithm might be trapped.

To prove the proposed system's better performance, it is compared with a conventional MPPT under PSC algorithm proposed in [8]. In this algorithm changes in current and voltage mean partially shaded condition. When shading occurs at 2 s and current and voltage drop, the algorithm detects shading and moves the operating point to the reference voltage calculated by the linear function (22), and then employs Incremental Conductance algorithm to track the GMPP

$$V^* = \frac{N_s V_{oc}}{N_p I_{sc}} I[n] \qquad (22)$$

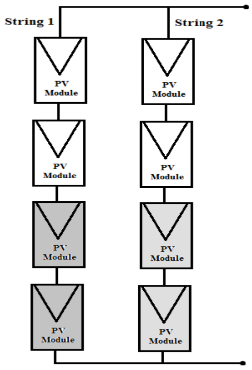

Figure 5. P-V curve under partial shading condition

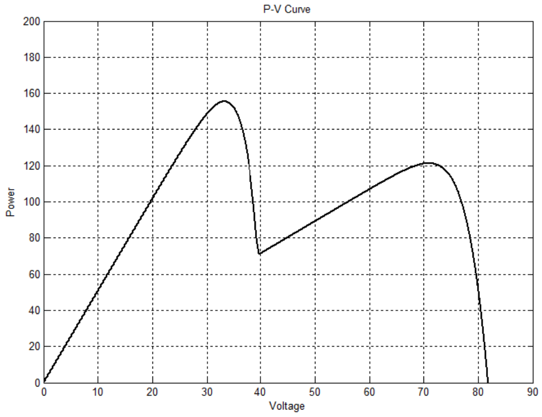

Figure 6. P-V curve under partial shading condition

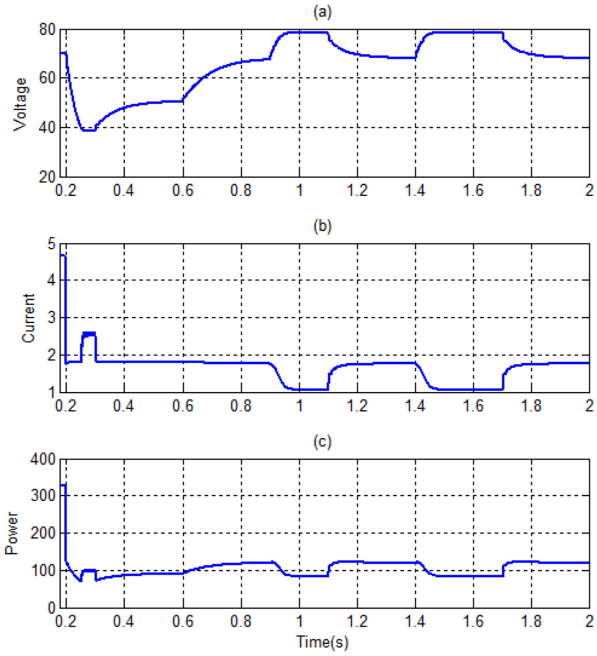

Figure 7.Conventional algorithm performance under PSC

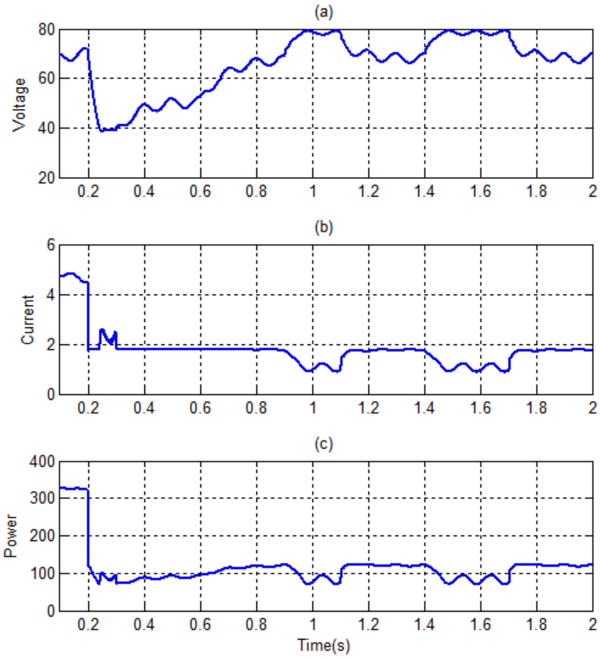

Figure 8. Conventional algorithm performance with disturbance

Figure 7 illustrates the conventional algorithm performance under shading condition. It correctly identifies partial shading, but the reference voltage is moved to the point $V^* = 43\ v$ which is far from the global maximum power point. Consequently the local MPP is tracked instead, which leads to almost 30 W power losses. It can be deduced that this algorithm is not able to track GMPP under all shading patterns. The conventional MPPT system's performance in presence of low frequency disturbance is illustrated in Figure 8. It shows that the conventional PWM based algorithm cannot reject disturbance and it will cause error in measuring and power loss.

Now, the system with the proposed algorithm is simulated under non-uniform irradiation, the low frequency voltage variations are also added to the system to confirm the disturbance rejection ability of the system. The results are given in Figure 9. It is illustrated that instantly after shading occurs on some PV modules, the controller recognizes shading from current drop and activates PSC MPPT, thus maintaining the power at its maximum in presence of local maxima by first scanning the PV curve and then accurately tuning the MPP voltage. As it can be seen in Figure 9, the proposed MPP maintains the power at its maximum under different irradiance values after only a few iterations and its tracking time is 0.8 s which is faster than the conventional method.

As a final consideration, the upper and lower limits of the slopes di_{sc}/dt and di_{vr}/dt as appear in (15) have been calculated for the numerical example considered in this section. In this case it is:

$$-1956 < \frac{di_{sc}}{dt} + \frac{di_{vr}}{dt} < 5298\ A/ms \tag{23}$$

Also, by considering the perturbation amplitude imposed by the proposed MPPT algorithm which is $\Delta v_{ref} = 16.5$, the boundaries for di_{vr}/dt can be calculated as:

$$\left.\begin{aligned} \min\left(\frac{di_{vr}}{dt}\right) &= -29.4\ A/ms, \quad \Delta v_{ref} > 0 \\ \max\left(\frac{di_{vr}}{dt}\right) &= 29.4\ A/ms, \quad \Delta v_{ref} > 0 \end{aligned}\right\} \tag{24}$$

It means that the system is able to track short circuit current perturbations with slopes between [-1900, 5260] A/ms therefore, very fast irradiation perturbations. These inequalities confirm the proposed system's ability to track global maximum power point under very fast varying irradiation.

Finally, the simulation results show that estimating the input capacitor current using its voltage has not affected the system performance and MPP is tracked fast and very accurately. The reason is that i_{Cin} is only used to be compared with $-i_{vr}$ and since both i_{Cin} and its estimation have the same mean value, the system performance does not change.

II. CONCLUSION

In this paper, a controller for tracking maximum power point of a PV array under non-uniform irradiation is proposed. The MPPT algorithm recognizes shading condition and uses reference voltage steps to approximately scan the P-V curve in search of the global MPP and then uses small steps for fine tuning. The switching method used in this paper is based on sliding mode control and only uses voltage and current of the PV array. The proposed controller does not require additional sensors, is easily implemented, has fast dynamics and is able to reject low frequency disturbances. Simulation results have also confirmed its effectiveness and convergence speed.

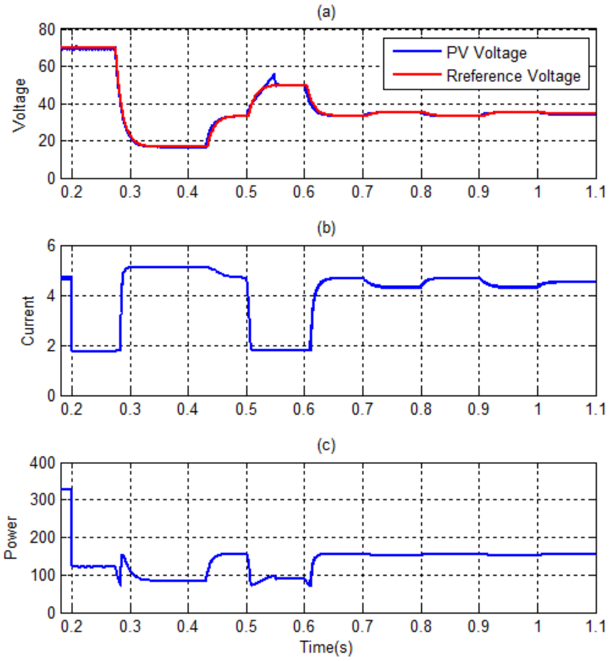

Figure 9. Proposed system performance under PSC

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