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Robust Backstepping MPPT for Photovoltaic System

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ABSTRACT

This work focus on robust control applied to photovoltaic system for operating at maximum power point in all conditions. The boost converter is driven by robust backstepping controller to realize this objective. To make the control initially faster, a variable step-size is used to estimate the reference voltages that must be obtained to achieve the MPP and guarantee the maximum power extraction, modifying the conventional Perturb and Observe (P&O) method. The performance of the developed system has been analyzed by means a simulation platform in Matlab/Simulink helped by SimPowerSystemsBlockset. The obtained results illustrate that the used approach can effectively improve the MPPT in terms of tracking speed (in transitory) and efficiency (in steady state) simultaneously.

Keywords: Photovoltaic Generator, MPPT, Variable step-size, Backstepping, Robust Control.

1. INTRODUCTION

The photovoltaic (PV) energy is a perfect solution to power the autonomous devices and isolated houses, as well as to produce electricity on a large scale through distribution networks for grid-connected systems. The power–voltage (P-V) characteristic of a PV array is nonlinear and time varying with the changing of atmospheric conditions [1]. Maximum power point tracking (MPPT) techniques are used in photovoltaic systems for maximize the PV output power which depends on weather conditions (irradiance and temperature). Among all the MPPT strategies, P&O techniques are widely used due to its low cost and ease of implementation. With its conventional algorithms using fixed step-size, it is impossible to satisfy both performance requirements of fast dynamic response and good accuracy during the steady state. This is because, for big perturbation steps, the maximum power point is reached quickly, but, the power loss caused by perturbation in the steady state will also increase. With a smaller perturbation step can reduce the power loss caused by perturbation in the steady state but will slow down the tracking speed.

In order to overcome the disadvantages of the conventional P&O algorithm, various approaches have been proposed in literature, between them, Predictive & Adaptive method [2-4], modified P&O method with adaptive duty cycle step size [5, 6], fuzzy logic controller [7-10], adaptive P&O method with variable step-size [11-19], as well as, a new direction in development of MPPT is to use the artificial intelligent control algorithms such as fuzzy logic, neural network and neuro-fuzzy, amongst others.

The variable step-size method is able to improve the steady-state performance and the dynamic response. However, to solve the convergence problem of the tracking process, it is necessary to use a constant value. The choice of this constant is very significant, it makes the response time of the PV system slow in the fast changing irradiation. Thus reducing the overall output power [19].

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Further, diverse sliding mode approaches to track the MPPT have been addressed in many literatures. Among these algorithms, a robust control of the photovoltaic system with improved maximum power point tracking [20], where the second order sliding mode controller based on super twisting algorithm is applied, a first order sliding mode controller is presented in [21-23].

In addition, for robust control based in backstepping MPPT [24-33], in [24] a desired array voltage is designed on line using an extremum-seeking algorithm, in [26] the MPOP is managed through the use of an incremental conductance algorithm that generates the desired cell current, in [24, 27, 29] the reference voltage is synthesized on line by fixed step-size P&O technique.Some recent control methods are addressed in [34-40].

The different parts of this paper correspond to the following guide line. In the next section, we present the PV system, including the used PV array model and the design of reference voltages, this section also includes the dynamic model boost converter. The proposed design of the control for make the system operating at maximum power point is developed in Section 3, where the robust backstepping controller is detailed. Section 4 presents the simulation results and the corresponding analysis. And finally section 5 describes the main conclusions.

2. PHOTOVOLTAIC SYSTEM MODELING

A block diagram of the proposed controller system is illustrated in Figure 1. A DC/DC boost converter is used to interface PV output power to the load (resistive load in this paper) to track the maximum power of the PV array. The MPPT controller keeps adjusting the duty cycle of the power converter to reach the MPP of the solar panel.

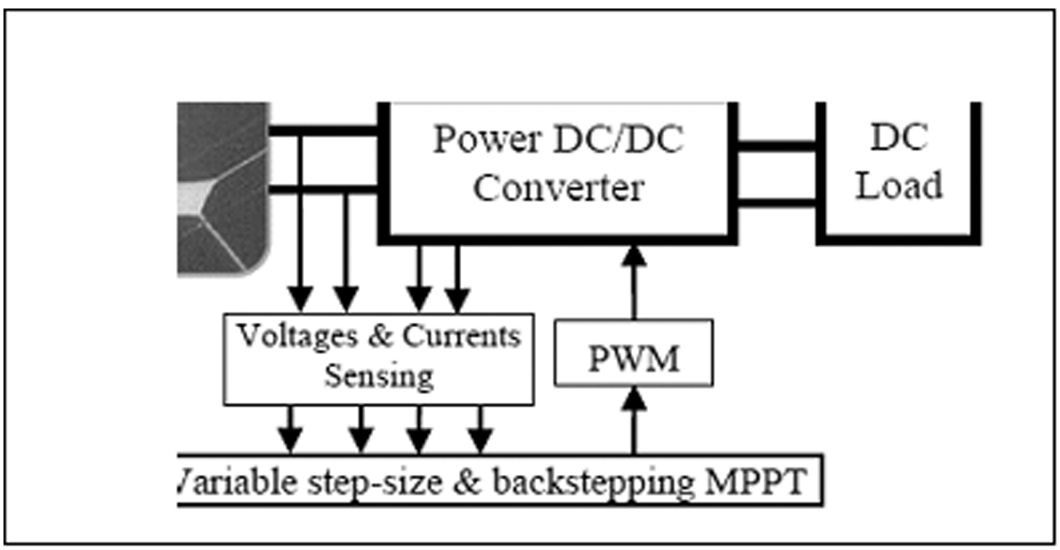


Figure 1: Block diagram of PV system

2.1. PV generator modeling

Figure 2 shows the equivalent circuit of the solar cell. The mathematical model of PV generator involving an array of cells connected in series and in parallel is,

$$I_{pv} = n_P I_{ph} - n_P I_o \left[\exp\left(\frac{q(V_{pv} + \frac{n_S}{n_P} R_S I_{pv})}{n_S AKT} \right) - 1 \right] - \frac{V_{pv} + \frac{n_S}{n_P} R_S I_{pv}}{\frac{n_S}{n_P} R_P} \tag{1}$$

V_{pv} is the panel voltage, I_{pv} is the panel current, R_s is the equivalent series resistance of the module, R_P is the equivalent shunt resistance, A is the ideality factor, K is the Boltzmann's constant, q is the electron charge, T is the temperature in Kelvin and I_{Ph}, I_s are the photocurrent and saturation current, respectively.

2.2. DC/DC Boost Converter

The DC-DC converter is a necessary stage in the PV systems, which is used as a power interface between the PV panel and the load, to operate at maximum power when the MPPT algorithm adjusts the duty cycle. The regulation is achieved by PWM and the switching device MOSFET or IGBT.

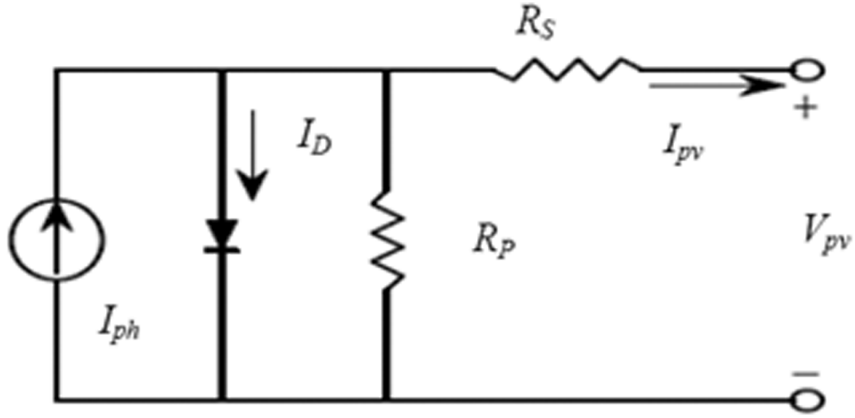


Figure 2: Equivalent circuit of PV cell

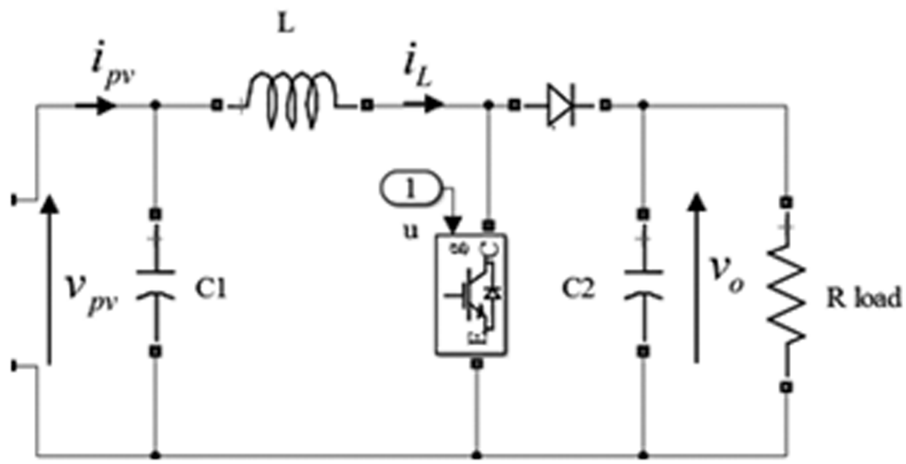


Figure 3: Model of DC/DC boost converterunder SimPowerSystems

The output voltage v_o is expressed by following relationship,

$$v_o = \frac{v_{pv}}{1-d} \tag{2}$$

Since the duty ratio d is between 0 and 1 the output voltage is higher than the input voltage.

The dynamic model for the boost converter can be illustrated by,

$$\begin{aligned} C_1 \cdot \dot{v}_{pv} &= i_{pv} - i_L \\ L \cdot \dot{i}_L &= v_{pv} - d' \cdot v_o \end{aligned} \tag{3}$$

Where d' is averaging value of (1-d), v_{pv} and i_{pv} are the average states of the output voltage and current of the PVG, i_L is the average state of the inductor current.

2.3. Variable step-size MPPT

The operating principle of P&O MPPT is summarized in three positions and two directions as shown in Figure 4 and Table I demonstrate the possible positions and directions during the perturbation and observation process and also the required action in each case to achieve the maximum power output [14].

Table 1
Operating Principle of P&O Mppt

Position	*Variation*	*Action*
1	dp=0	No action
2	+dp/+dv	Increase C
3	+dp/-dv	Decrease C
4	-dp/-dv	Increase C
5	-dp/+dv	Decrease C

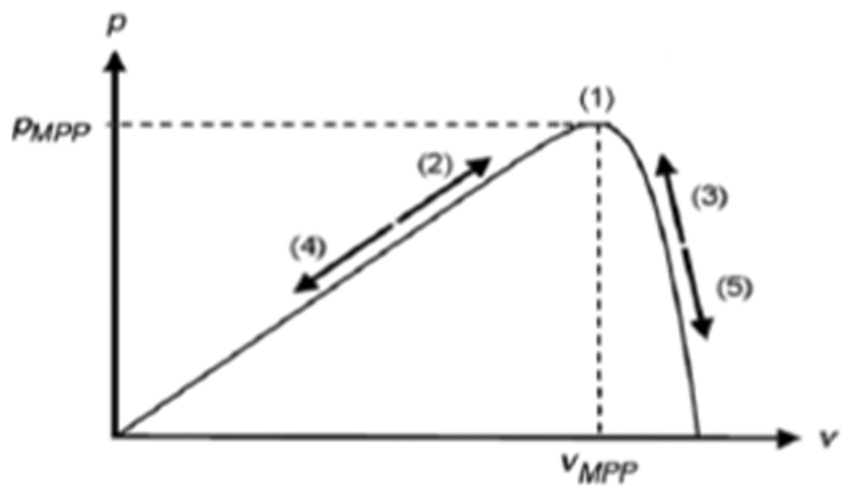


Figure 4: P&O MPPT positioning [14].

In the conventional P&O algorithm, the duty cycle perturbation step size is a fixed value as,

$$v_{ref}\left(k\right)=v_{ref}\left(k-1\right)\pm C \tag{4}$$

During steady-state MPPT operation, small perturbation reduces the power losses caused by the oscillations around the MPP. However, during transient MPPT operation, larger perturbation is chosen for faster convergence to the new MPP. Variable step-size algorithms are usually developed in order to achieve compromise between the speed and the accuracy of the tracking.

In This study, the variable step-size used to solve the problem mentioned above is shown as follows[15]:

$$v_{ref}\left(k\right)=v_{ref}\left(k-1\right)\pm N\cdot\left|\frac{\Delta p}{\Delta v}\right| \tag{5}$$

where N is the scaling factor determines the performance of the MPPT system and is adjusted at the design process [10].

3. BACKSTEPPING CONTROLLER DESIGN

The aim of backstepping technique is to identify a virtual control state and force it to become a stabilizing function, this procedure generates a corresponding error variable. As a result, the error variable can be stabilized by proper selection of control input via Lyapunov stability theory.

Step one:

The first error considered in designing the backstepping controller is voltage error,

$$e_1 = v_{pv} - v_{ref} \tag{6}$$

By deriving (6), we obtain the following error dynamics equations:

$$\dot{e}_1 = \dot{v}_{pv} - \dot{v}_{ref} = \frac{i_L}{C_1} - \frac{v_{pv}}{C_1} - \dot{v}_{ref} \tag{7}$$

Choose Lyapunov function candidate as $V_1 = 0.5 \cdot e_1^2$, its time derivative is computed by,

$$\dot{V}_1 = e_1 \dot{e}_1 = e_1 \left(\frac{i_L}{C_1} - \frac{v_{pv}}{C_1 r_{pv}} - \dot{v}_{ref} \right) \tag{8}$$

The choice of $\dot{e}_1 = -k_1 e_1$ lead us $\dot{V}_1 = -k_1 e_1^2 < 0$ and consequently the first subsystem is asymptotically stable (for $k_1 > 0$).

$$\frac{i_L}{C_1} - \frac{v_{pv}}{C_1 r_{pv}} - \dot{v}_{ref} = -k_1 e_1 \tag{9}$$

In (9), i_L behaves as a virtual control input, for $i_L = i_{ref}$ we can find the stabilizing function:

$$i_{ref} = k_1 \cdot C_1 \cdot e_1 + i_{pv} - C_1 \cdot \dot{v}_{ref} \tag{10}$$

Step two:

The next error variable is defined as,

$$e_2 = i_L - i_{ref} \tag{11}$$

This represents the difference between the virtual control and its reference value. Now, Replacing (10) into (7), the dynamic of current error is given by,

$$\dot{e}_1 = \frac{e_2}{C_1} - \frac{i_{ref}}{C_1} - \frac{v_{pv}}{C_1} - \dot{v}o = -\frac{e_2}{C_1} - k_1 e_1 \tag{12}$$

The derivate of reference currant is,

$$\dot{i}_{ref} = k_1 \cdot C_1 \cdot \dot{e}_1 + \dot{i}_{pv} - C_1 \ddot{v}_{ref} \tag{13}$$

By deriving (11), we obtain the second error dynamics equations:

$$\dot{e}_2 = \dot{i}_L - \dot{i}_{ref} = \frac{v_{pv}}{L} - d' \frac{v_o}{L} - k_1 \cdot C_1 \cdot \dot{e}_1 - \dot{i}_{pv} + C_1 \ddot{v}_{ref} \tag{14}$$

The novel proposed Lyapunov candidate function is,

$$V_2 = V_1 + 0.5 \cdot e_2^2 \tag{15}$$

Its derivate is,

$$\dot{V}_2 = \dot{V}_1 + e_2 \dot{e}_2 \tag{16}$$

Substituting (8) and (14) into (16), gives that

$$\dot{V}_2 = -k_1 e_1^2 + e_2 \left[k_2 e_2 - d' \frac{v_o}{L} + \frac{v_{pv}}{L} - \frac{e_1}{C_1} - k_1 C_1 \dot{e}_1 - \dot{i}_{pv} + C_1 \ddot{v}_{ref} \right] \tag{17}$$

Finally, the backstepping control of DC-DC boost converter for maximum power tracking is given by

$$d' = \frac{L}{v_o} \left[\frac{v_{pv}}{L} - \frac{e_1}{C_1} + k_2 e_2 - k_1 C_1 \dot{e}1 - \dot{i}_{pv} + C_1 \ddot{v}_{ref} \right]$$

After replacement of synthesis control into (17), the derivate of Lyapunov function is negative $\dot{V}_1 = -k_1 e_1^2 - k_2 e_2^2 < 0$, consequently, the system is globally asymptotically stable (for $k_1 > 0$ and $k_2 > 0$).

4. SIMULATION EVALUATION

Experiments in Simulation have been performed in order to check the PV system performances. A performance comparative between the backstepping control and the well-known P & O variable step-size is shown to prove the validity of the proposed control. Tests are carried out to test the stability of the studied approach to track the MPP in different conditions fast varying insolation, temperature and resistive load.

The PV module parameters under the temperature of 25°C and the irradiation of 1000 W/m2 are listed in Table II.

Table 2
UDTS50 PANEL CHARACTERISTICS [34]

Standard irradiation	1000 W/m^2
Standard temperature	25°C
Short-circuit current	3.43 A
Open circuit voltage	21.28 V
Optimal voltage	16.65 V
Maximum power	52.66 W
Series resistor	0.4 Ω
Number of the cell	36

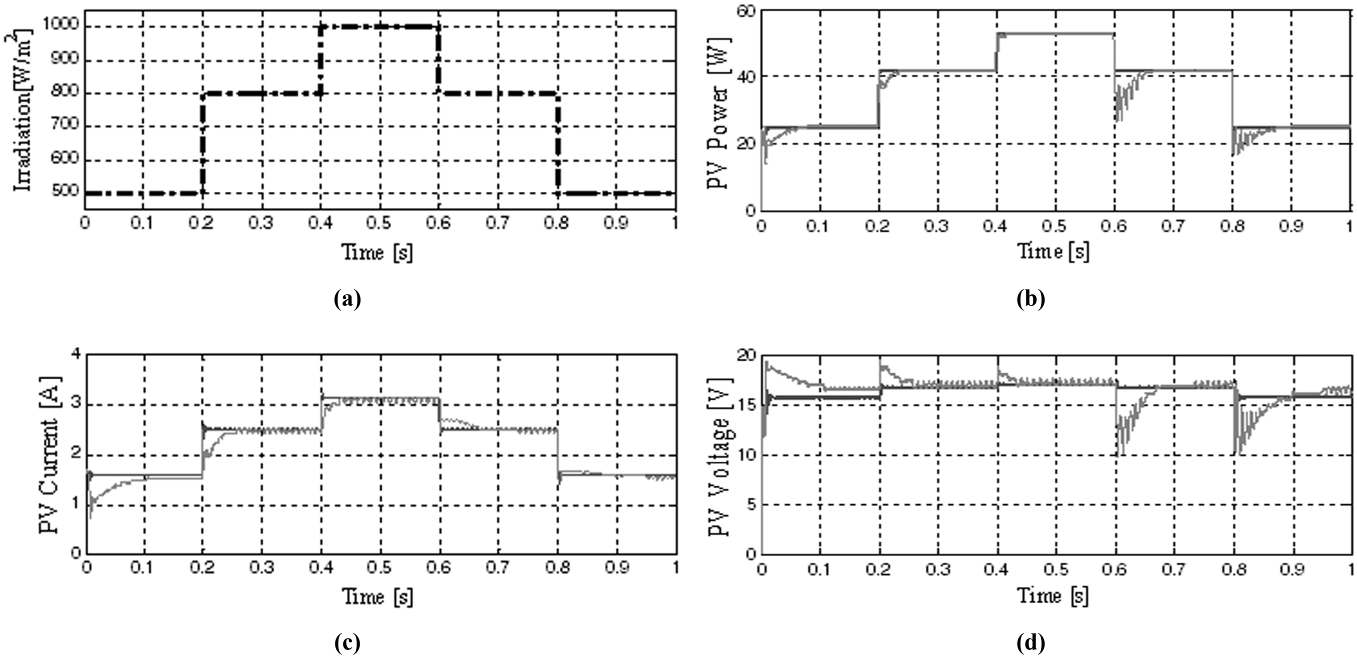
The Figures (b), (c) and (d) show the PV power, PV current and PV voltage, respectively (*for all three tests figures 5, 6 and 7*).

Figure 5 shows PV system performances for constant resistive load (20Ω), fixed temperature (298K) and fast varying irradiation levels. Figure 5(a) shows the irradiation variation profile (500, 800, 1000, 800, 500W/m^2).

It can be clearly seen from Figure 5(b) that, for both MPPT methods in steady state, the PVG achieves the maximum power, the tracking speed is very slow (between 0.03 and 0.06s) for the variable step-size method with N equal to 0.00001 when the irradiation is suddenly changed.

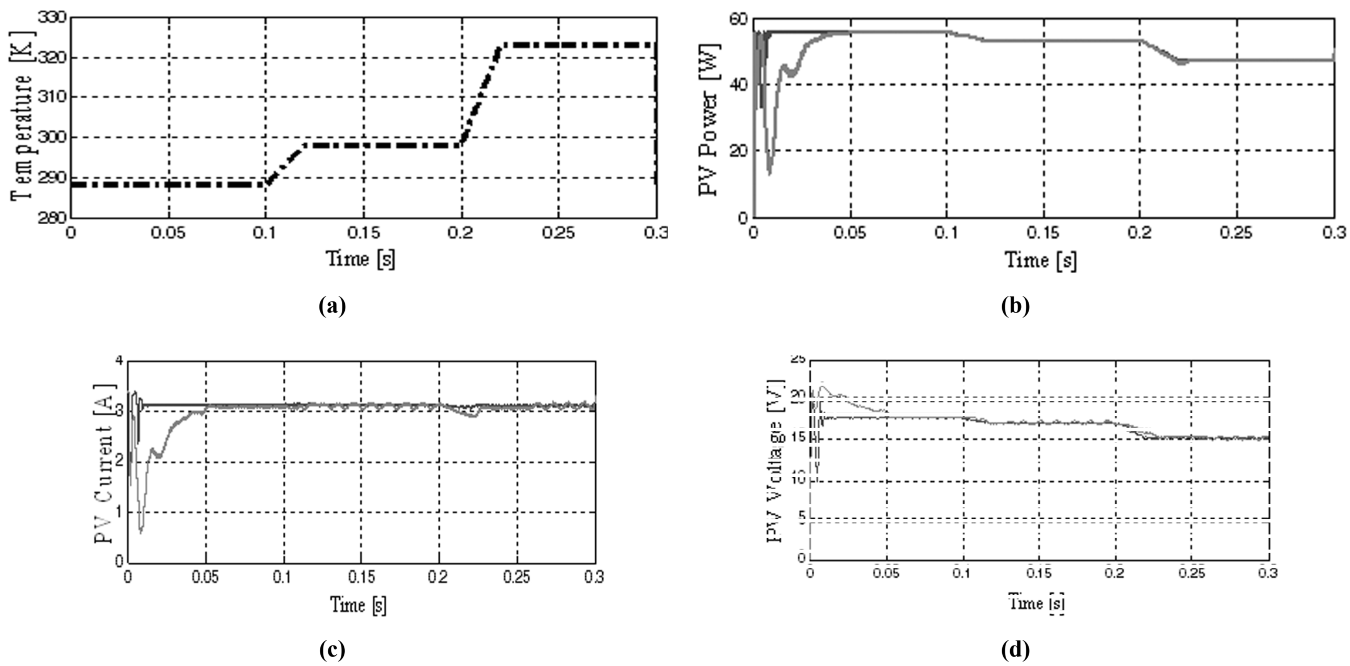
Figure 6 shows PVG performances for constant resistive load (R = 20Ω), fixed irradiation (1000W/m2) and fast varying temperature levels. Figure 6(a) illustrates the profile of temperature variations (288, 298, and 323 K).

We can see in Figures 6(b), 6(c) and 6(d) that, for both MPPT methods, in steady state, the PVG achieves the maximum power. However, the response time of classical variable step-size (for N=0.00001) is very slow (0.05s).



— variable step-size without backstepping control
— variable step-size with backstepping control

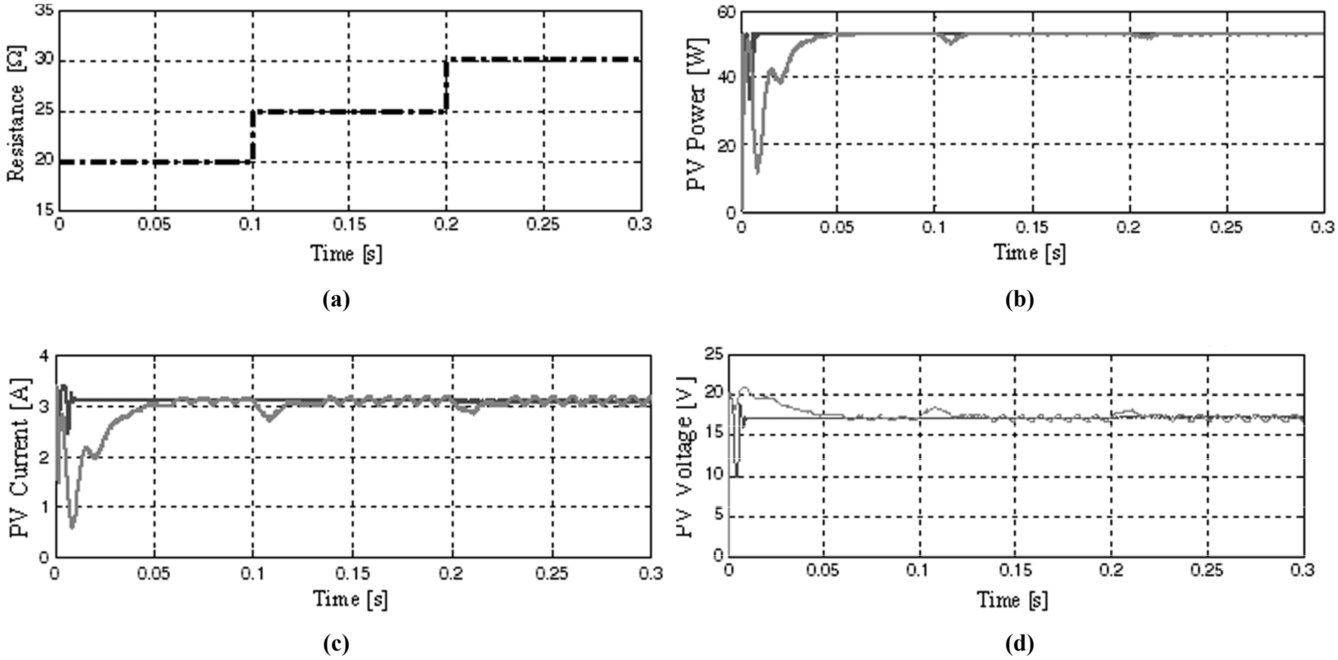
Figure 5: PV system performances with variable irradiation (T = 298K, *R*=20W), where (a): Irradiation [w/m²], (b): PV power [W], (c): PV current [A], (d): PV voltage [V].



— variable step-size without backstepping control
— variable step-size with backstepping control

Figure 6: PV system performances with variable temperature (G=1000W/m², *R*=20W), where (a): Temperature profile [K], (b): PV power [W], (c): PV current [A], (d): PV voltage [V].

Figure 7 shows PVG performances for constant irradiation (1000W/m2), fixed temperature (298K) and fast varying resistive load levels. The profile of resistive load variation (20, 25, and 30W), as shown in Figure 7(a). For both MPPT methods, in steady state the PV system achieves the maximum power as illustrated in Figure 7(b). However, the response time is very slow (0.05s) for variable step-size MPPT without backstepping controller (N=0.00001).



— variable step-size without backstepping control
— variable step-size with backstepping control

Figure 7: PV system performences with variable resistive load (G=1000W/m², T=298K), where (a): Resistive load profile [W], (b): PV power [W], (c): PV current [A], (d): PV voltage [V].

These results demonstrate very clearly that in all cases, the proposed scheme (variable step-size with backstepping controller) exhibits fast dynamic response and stable steady-state output power, even when the weather conditions are rapidly changed.

5. CONCLUSIONS

This paper has studied and justified a backstepping control design strategy. The control aim is to regulate the PV array output voltage in order to track the Maximum Power Point. This object is adopted by including the dynamic model of the DC-DC boost converter in photovoltaic system, for this, both fast dynamic and accuracy steady state performances under rapidly changing in weather conditions and load are achieved. Furthermore, the obtained simulation results clearly illustrate the robustness and effectiveness of the proposed method at any conditions than the conventional variable step-size method.

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