JPE 15-6-18

http://dx.doi.org/10.6113/JPE.2015.15.6.1584
ISSN(Print): 1598-2092 / ISSN(Online): 2093-4718

Backstepping Control of a Buck-Boost Converter in an Experimental PV-System

Jesus R. Vazquez† and Aranzazu D. Martin*

†,*Department of Electrical Engineering, University of Huelva, Huelva, Spain

Abstract

This paper presents a nonlinear method to control a DC-DC converter and track the Maximum Power Point (MPP) of a Photovoltaic (PV) system. A backstepping controller is proposed to regulate the voltage at the input of a buck-boost converter by means of Lyapunov functions. To make the control initially faster and avoid local maximum, a regression plane 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. An experimental platform has been designed to verify the validity and performance of the proposed control method. In this platform, a buck-boost converter has been built to extract the maximum power of commercial solar modules under different environmental conditions.

Key words: Backstepping, Buck-Boost Converter, Experimental, Maximum Power Point, Photovoltaic

I. INTRODUCTION

The PV energy is used to power many autonomous devices and isolated houses, as well as to produce electricity on a large scale through distribution networks. A PV module generates electrical current from the solar irradiance, and the generated power is only maximum for an output voltage under changeable environmental conditions, [1].

In order to reach the Maximum Power Point, the control of this PV output voltage is usually achieved connecting a DC-DC converter at the PV module output, as shown in Fig. 1.

An adequate control of the digital switch of the DC-DC converter allows the converter voltage input, v_{PV}, to set at desired value to get the MPP Tracking (MPPT). The converter output voltage, v_O, will be supplied to the connected load. In grid-connected systems, a DC-AC converter is used to obtain a sinusoidal current to supply to the load or to inject it into the electrical network.

There are different topologies of the DC-DC converter, [2], [3]. In this paper, a buck-boost topology has been designed, which converts the DC power from one voltage level to another higher or lower according to the needs.

Manuscript received Nov. 14, 2014; accepted May 23, 2015
Recommended for publication by Associate Editor Hao Ma.
†CorrespondingAuthor:aranzazu.delgado@die.uhu.es
Tel: +34-959217586, University of Huelva
*Department of Electrical Engineering, University of Huelva, Spain

The MPPT can be implemented through different control algorithms in order to obtain the maximum power under all conditions, [4]. Many methods have been used. Some of them are based on the well-known principle of Perturb and Observe (P&O) [5]-[7], on Sliding Mode control method [8], Ripple Correlation Control (RCC) [9], Artificial Neuronal Networks or Fuzzy based algorithms [10]-[12], amongst others. The methods have different accuracy and complexity. Some of them can obtain local maximum instead of global maximum, and others have involved structures.

A new control method for MPPT of PV arrays using a buck-boost converter is proposed in this paper. A nonlinear backstepping controller [13], [14] has been designed to track the maximum power point with the help of an off-line calculated regression plane. This plane provides the PV array output reference voltages for different irradiance and temperature values using a modified P&O method. Thus, the MPP tracking is initially faster, a desirable goal of the control [15]. The robustness is increased, global asymptotic stability is guaranteed by means of Lyapunov functions, and the MPP can be ensured even with changeable conditions. A nonlinear control has been chosen due to the nonlinear, time-variant nature and variable structure of the buck-boost. Thus a linear control implies a model linearization that is simple, but cannot control the converter in a wide range.

An experimental platform has been designed to check the

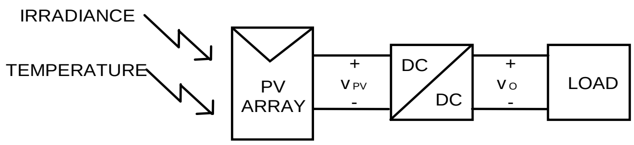

Fig. 1. Structure of an alone PV system.

TABLE I
ELECTRICAL PARAMETERS OF SOLAR MODULE

Parameter	Value
Maximum power (P_{max})	20 W
Maximum power voltage (V_{MPP})	17.5 V
Maximum power current (I_{MPP})	1.15 A
Open-circuit voltage (V_{OC})	21.6 V
Short-circuit current (I_{SC})	1.28 A

real performance of the proposed control. Some papers describe different experimental platform using acquisition & control commercial boards [16]-[18]. In this case, a PV module supplies power to a DC load through a buck-boost converter, and the backstepping controller has been implemented in a low cost microcontroller.

The paper is organized as follows. Section II presents the PV system, including the used PV array model to calculate the regression plane with the reference voltages and buck-boost converter. The proposed design of the control to make the system track the maximum power point is developed in Section III. The experimental platform and the different practical results will be presented in Section IV. Thus, the stationary and transient performance of the designed control will be checked. Finally, some conclusions will be described in Section V.

II. PHOTOVOLTAIC SYSTEM

The PV system includes a PV array (the solar generator) and a DC-DC converter, as shown in Fig. 1. Now the solar module is presented as well as its simulation model in order to obtain a regression plane with the desired PV output voltage under different environmental conditions. This plane will be used as initial reference for the control system. Moreover, the power block of the buck-boost converter is explained.

A. PV Array

First, the features of the solar module are detailed. In this work, a commercial solar module is used in the experimental analysis to test the DC-DC converter control. The maximum power of this photovoltaic module is 20 W, and its main electrical parameters are described in Table I for standard conditions, 1000 W/m^2 and 25 ºC.

The equivalent circuit which models the solar cell is presented in Fig. 2, where *i* is the solar cell output current in A, v is the solar cell output voltage, in V, i_1 is the current

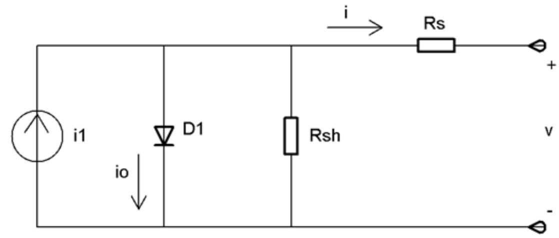

Fig. 2. Equivalent circuit of a PV cell.

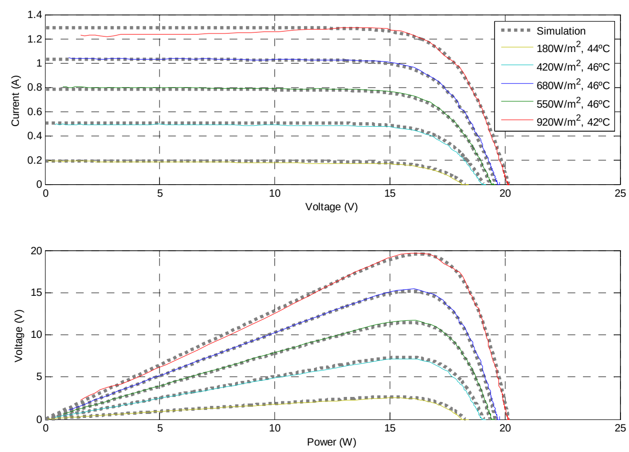

Fig. 3. Comparison between the I-V and P-V curves of the simulated PV model and the used PV module.

source in A (it depends on the irradiance and temperature), i_0 is the cell reverse saturation current in A, D_1 is an anti-parallel diode, R_{sh} is the shunt electrical resistor, and R_s is a series resistor. The resistors model the module power loss. This circuit is used to model the solar module in Matlab-Simulink, according to Vazquez et al. [10].

Fig. 3 shows the I-V and P-V curves of the simulated PV model and the characteristic curves of the used PV module in the experimental platform to prove the accuracy between them under different environmental conditions.

In order to make the control initially faster, a regression plane is achieved from I-V and P-V characteristic curves of the solar modules to obtain the theoretical voltage that supplies the maximum power, and a modified P&O is implemented to reach a reference practical voltage around the theoretical one and to get the maximum energy extraction. For that, the PV module was exposed to the sun under changeable irradiance and temperature to obtain the characteristic curves to know the peak of the curve under different environmental conditions. After that, by using the electrical parameters of the PV module, the PV array is modeled to obtain the regression plane. The simulation model was matched with the real module; thus, the characteristic curves obtained from the simulation and the laboratory measured real curves yield the same results, that is to say the same maximum power for each curve. Thus, the regression plane is calculated properly.

The solar module detailed in Table I has been considered

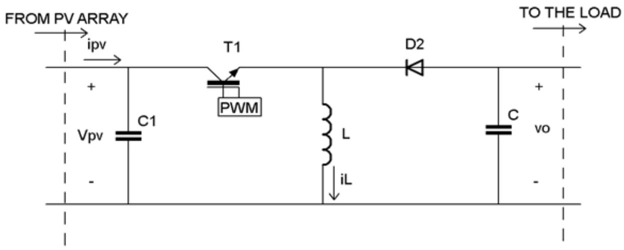

Fig. 4. Topology of a buck-boost converter.

to test the proposed control in the next section. The experimental platform has been designed for small-scale, and greater power solar arrays can be analyzed with series and shunt connection of this model.

B. Buck-Boost Converter

This DC-DC converter consists of power electronic components such as capacitors, an inductor, a transistor and a diode connected, as shown in Fig. 4, where its topology is presented. This converter behaves as a non-linear load due to the transistor and the diode.

In Fig. 4, v_{PV} is the PV output voltage in V, i_{PV} is the solar array output current in A, i_L is the inductor current in A. and v_0 is the buck-boost converter output voltage in V. L is inductor in H, and C_1 and C are capacitors in F and are constant parameters.

A Pulse Width Modulation (PWM) method is used to control the commutation of the transistor, allowing the energy to charge and discharge in the storage elements. The output voltage has opposite polarity to the input voltage, and this converter topology can supply a greater or lower voltage than the input voltage.

The main purpose of the proposed backstepping control is to regulate the PV output voltage modifying the buck-boost converter duty cycle, D, so as to obtain the voltage that makes the power maximum. The duty cycle is t_{ON} / t_C, with t_{ON} being the time which the switch is ON, and t_C is the switching period (0<D<1). The output/input voltage ratio is calculated as it is shown in (1).

$$v_o / v_{PV} = D/(1-D) \tag{1}$$

The DC-DC converter can work under two working modes, Continuous Conduction Mode (CCM) and Discontinuous Conduction Mode (DCM), depending on the inductor current in the operation period. In this work, the buck-boost converter works in CCM. Therefore, the inductor current is never zero.

Using the state averaging method [19], the equations of the converter model are defined in (2), (3) and (4).

$$\dot{v}_{PV} = \frac{1}{C_1} i_{PV} - \frac{1}{C_1} i_L D \tag{2}$$

$$\dot{i}_L = \frac{v_o}{L} + \frac{v_{PV} - v_o}{L} D \tag{3}$$

$$\dot{v}_o = -\frac{i_L}{C} - \frac{v_o}{RC} + \frac{i_L}{C} D \tag{4}$$

III. Buck-Boost Converter Control

The purpose of the designed control is to regulate the DC-DC converter voltage by means of a backstepping method, adjusting the PV array output reference voltage initially given by an off-line calculated regression plane. Therefore, the maximum power extraction of the solar modules is guaranteed.

A. Reference Voltage

In order to make the control initially faster and avoid local maximum, a regression plane provides the theoretical reference voltage required to achieve the MPP under any conditions of temperature and irradiance that ranges from 0 ºC to 80 ºC and from 200 W/m^2 to 1200 W/m^2, respectively. For that, the PV module used in the experimental platform has to be modeled to obtain the characteristic curves and to calculate the regression plane by linear interpolation for different environmental conditions. Thus, a voltage matrix is achieved which includes the reference voltages that supply the maximum power and, as a consequence, a maximum power matrix can be obtained as well, depending on the temperature and the irradiance.

Some tests have been developed in the lab to check the similarity between the simulated model and a real module. The I-V and P-V curves in both cases are the same under specific values of temperature and irradiance; thus, the solar cell is modeled correctly, as shown in Fig. 3.

Once the theoretical reference voltage is obtained, a practical reference voltage is proposed in this work. For that, by taking into account the PV output voltage and the PV output current, a modified P&O is implemented to obtain an incremental value of reference voltage instead of the duty cycle value. The addition of the theoretical reference voltage and the incremental value gives the practical reference voltage used in the backstepping control as it is described below.

B. Backstepping Controller

The purpose of this control is to regulate the converter input voltage to extract the PV maximum power, taking into account the practical reference voltage mentioned above. A non-linear backstepping controller is designed to control the duty cycle of the buck-boost converter switch to regulate the PV output voltage. Thus, the optimum voltage will be obtained, modifying the voltage around its reference. This type of control is used to design stable controls with a recursive methodology. It must stabilize the origin of a system by means of feedback control laws and using Lyapunov functions to prove the stability of the system. In order to design the controller, the next steps are followed:

The voltage tracking error is defined as it is shown in (5),

$$e_1 = v_{PV} - v_{PV}^{\;r} \tag{5}$$

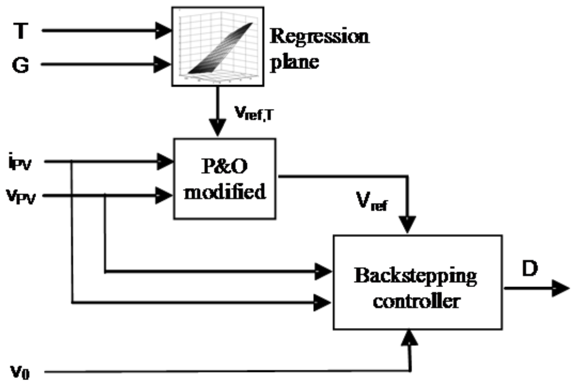

Fig. 5. Control scheme of the DC-DC converter.

where $v_{PV}{}^r$ is the reference output voltage of the PV modules, and it must be reached by the control. This error is defined to enforce the PV output voltage v_{PV} to track the reference voltage $v_{PV}{}^r$. Thus, the objective is to achieve zero tracking error.

By derivating e_1 with respect to time and accounting for (2), (6) is obtained, where i_L behaves as a virtual control input.

$$\dot{e}_1 = \dot{v}_{PV} - \dot{v}_{PV}{}^r = \frac{1}{C_1} i_{PV} - \frac{1}{C_1} i_L D - \dot{v}_{PV}{}^r \quad (6)$$

A Lyapunov function is selected. It must be positive definite and radially unbounded for all t, and the time derivative of Lyapunov function must be negative definite for all t to ensure the solution is locally asymptotically stable. The chosen function and its derivate are defined as below.

$$V_1 = 0.5 e_1{}^2 \quad (7)$$

$$\begin{aligned}\dot{V}_1 &= e_1 \dot{e}_1 = e_1 \left(\frac{1}{C_1} i_{PV} - \frac{1}{C_1} i_L D - \dot{v}_{PV}{}^r\right) = \\ &= -k_1 e_1\end{aligned} \quad (8)$$

$\dot{V}_1$ will be negative if k_1 is constant and positive. This way, the reference current for the control, α_1, the so-called stabilization function, can be obtained working out the value of the i_L from (8).

$$\alpha_1 = (C_1 k_1 e_1 + i_{PV} - C_1 \dot{v}_{PV}{}^r)\frac{1}{D} \quad (9)$$

Now, the behavior of the current error is studied, $z_1 = i_L - \alpha_1$, where the inductor current should reach α_1 to make the error vanish to achieve the control objective. The time derivative of this error is shown in (10).

$$\dot{z}_1 = \dot{i}_L - \dot{\alpha}_1 \quad (10)$$

The time derivative of α_1, (10), replacing i_L by $z_1 + \alpha_1$, yields (11).

$$\dot{\alpha}_1 = k_1 z_1 - \frac{C_1 k_1{}^2}{D} e_1 - \frac{C_1}{D} \ddot{v}_{PV}{}^r + \frac{1}{D} \dot{i}_{PV} - \alpha_1 \frac{\dot{D}}{D} \quad (11)$$

(11) with (2) gives the time derivative of z_1, as it is shown in (12).

$$\begin{aligned}\dot{z}_1 &= \frac{v_o}{L} + \frac{v_{PV} - v_o}{L} D - \\ &\left(k_1 z_1 - \frac{C_1 k_1{}^2}{D} e_1 - \frac{C_1}{D} \ddot{v}_{PV}{}^r + \frac{1}{D} \dot{i}_{PV} - \alpha_1 \frac{\dot{D}}{D}\right)\end{aligned} \quad (12)$$

Similar to what it is done in V_1, another Lyapunov function is defined with the same characteristics, being (13).

$$V_2 = V_1 + \frac{1}{2} z_1{}^2 = \frac{1}{2} e_1{}^2 + \frac{1}{2} z_1{}^2 \quad (13)$$

Its time derivative is (14), accounting for (6) and (12), and replacing i_L by $z_1 + \alpha_1$.

$$\begin{aligned}\dot{V}_2 &= -k_1 e_1{}^2 + z_1 \left[\frac{v_o}{L} + \frac{v_{PV} - v_o}{L} D + \right. \\ &e_1 \left(\frac{C_1 k_1{}^2}{D} - \frac{D}{C_1}\right) - k_1 z_1 + \frac{C_1}{D} \ddot{v}_{PV}{}^r - \\ &\left. \frac{1}{D} \dot{i}_{PV} + \alpha_1 \frac{\dot{D}}{D}\right] = -k_1 e_1{}^2 - k_2 z_1{}^2\end{aligned} \quad (14)$$

(14) will be negative when k_2 is positive, being a constant, to ensure the stability of the system. Therefore, the term between square brackets must be zero. From (14), the duty cycle derivative must be worked out from the term between square brackets, this term being equal to $-k_2 z_1$. Thus, $\dot{D}$ is worked out, yielding (15), where $0 < D < 1$ and $\alpha_1 \neq 0$.

$$\begin{aligned}\dot{D} &= \frac{1}{\alpha_1}\left[-\frac{v_o}{L} D - \frac{v_{PV} - v_o}{L} D^2 - \right. \\ &\left. e_1 \left(C_1 k_1{}^2 - \frac{D^2}{C_1}\right) + z_1 (k_1 - k_2) D - C_1 \ddot{v}_{PV}{}^r + \dot{i}_{PV}\right]\end{aligned} \quad (15)$$

The parameters design has been achieved empirically, and the used values, k_1 and k_2, are presented in table II.

The proposed control will be tested in Section IV in an experimental platform. (15) will be implemented, and the appropriate performance of the backstepping controller will be checked.

Fig. 5 shows the DC-DC converter control scheme. On the one hand, with the regression plane and T and G values, the theoretical reference voltage is obtained. On the other hand, by taking into account i_{PV} and v_{PV}, a modified P&O method is applied to provide an incremental value of reference voltage instead of the duty cycle value. The final value of the reference voltage is used in the backstepping control. Thus, (15) is implemented to obtain the duty cycle to control the DC-DC converter.

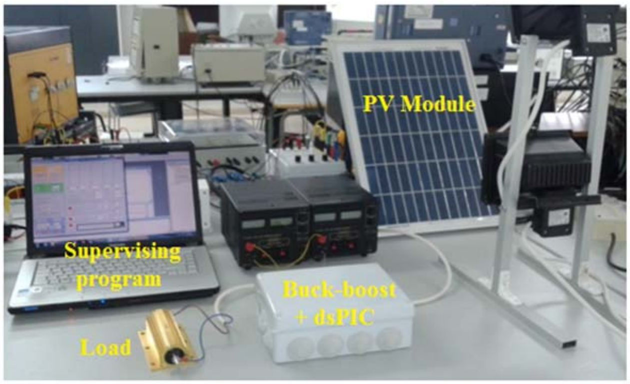

Fig. 6. Experimental system supervised by PC.

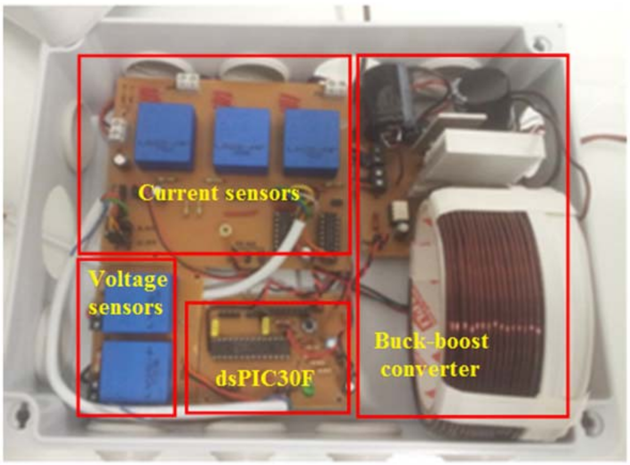

Fig. 7. Sensor, dsPIC and buck-boost converter.

Next section will detail the experimental implementation of the proposed control.

IV. MEASUREMENT RESULTS

A. Experimental Platform

The experimental platform consists of a commercial solar array (PV module), a buck-boost converter with the dsPIC and the voltage and current sensors in a box, a resistive load, and a PC to supervise the control parameters, as it is shown in Fig. 6. The PV array output is connected to the DC-DC converter input, and the buck-boost converter output is connected to the resistive load. The buck-boost converter input voltage range is 10 V – 40 V, and the maximum DC-DC converter output voltage is 80 V. The maximum power of the buck-boost converter is 50 W, and the output voltage ripple is 0.5% of v_o. The MOSFET used in the buck-boost converter is CSD19536KCS, driven by a FOD3180 driver, and the diode is the MBR10200.

Fig. 7 shows some details of the DC-DC converter box. The current and voltage values are measured using LEM sensors, LA25-NP (on the top left corner) and LV25-P (on the bottom left corner). The control program runs in a low-cost microcontroller, a dsPIC30F3013 controller (at the bottom centre), to control the DC-DC converter duty cycle of the power block (on the right side of the figure) to regulate the voltage. LM35 temperature sensor and a commercial irradiance meter (a compensated calibrated cell) are used. This cell provides a solar radiation with an accuracy of ±5%.

Moreover, a PC is connected to the PIC to supervise the control performance and all the parameters required. Fig. 8 presents a developed virtual instrument to supervise the tests via Wi-Fi. For that, Visual Basic programming was used.

Fig. 9 depicts a flow chart in order to summarize the design and implementation of the backstepping controller in the dsPIC. The sampling time for the control loop is 10 ms, and the PWM frequency is 25 kHz with a 10 bits PWM resolution. Besides, the duty cycle change rate is 10 ms, and it is updated with the sampling time.

The integrated development environment (IDE) is MPLAB and the programming language is C. As shown in Fig. 9, the PWM frequency and k_1 and k_2 constant values are defined. Then, the analogical digital converter reads the value of the PV module output current and voltage, the inductor current, the temperature, and the irradiance. After that, the regression plane and the modified P&O algorithm are applied to obtain the reference voltage that should be reached to achieve the maximum power. Once the reference voltage is known, the backstepping control calculates the time derivative of the buck-boost converter duty cycle, and then this value is integrated. Finally, the PWM is updated in each control loop.

B. Results

The proposed control has been implemented in the experimental platform detailed above to test its performance under changeable environmental conditions, such as a change in irradiance and consequently, in temperature. After some laboratory tests have been performed to obtain the regression plane described in this paper, the practical cases have been developed outdoors, under solar irradiation. Thus, the robustness of the system is evaluated.

The backstepping control parameters and inductor, the capacitors, and the resistive load values are presented in Table II. Constants k_1 and k_2 are the parameters used in backstepping method, in (15). L is the inductor of the DC-DC converter, and C and C_1 are the buck-boost converter output and input capacitors, as shown in Fig. 4.

1) Case 1 - Stationary Analysis: In this case, the proposed control has been tested to check the stationary response under constant irradiance and temperature, although their values fluctuate due to the environmental conditions. As it is shown in Fig. 10, the average irradiance is 835 W/m^2, and the average temperature is 38 ºC.

For these values of irradiance and temperature, the theoretical maximum power of the tested module is 18,5 W, about the 90 % of the module peak power, or 20 W_p in this case.

Fig. 11 shows the PV output current, i_{PV}, obtained in this

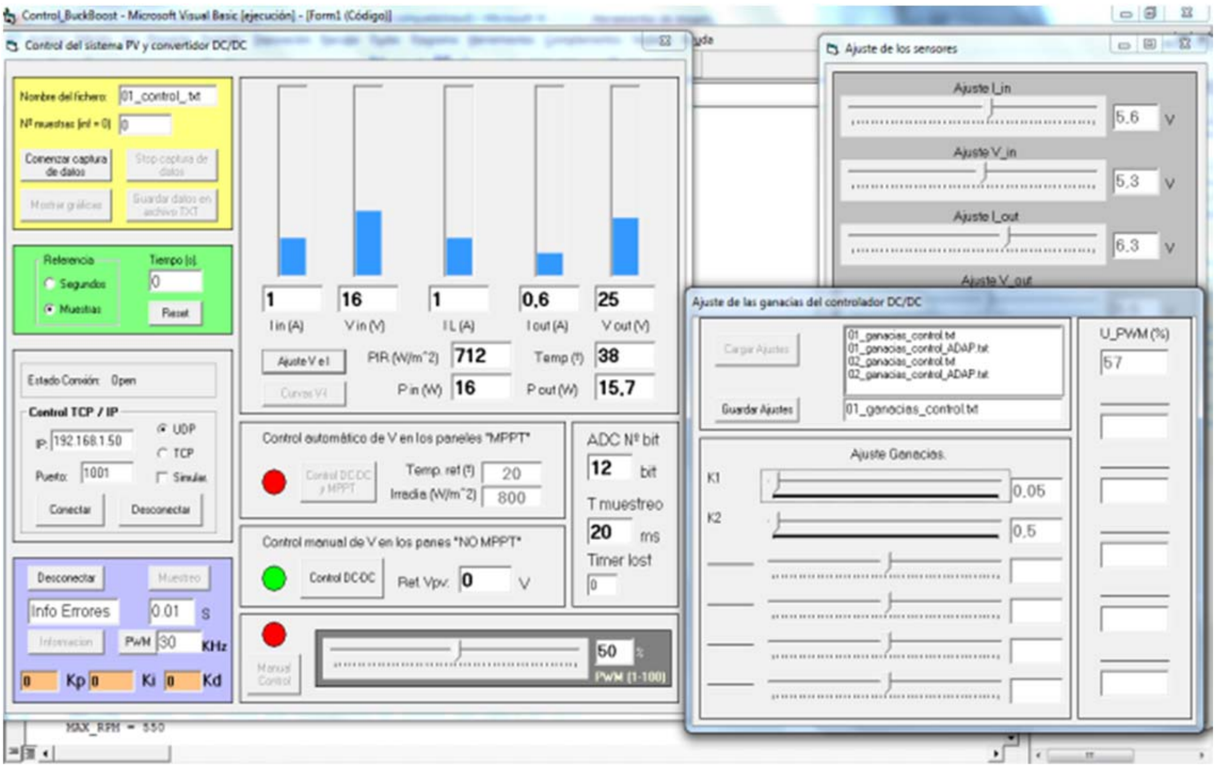

Fig. 8. Virtual instrument to supervise the control.

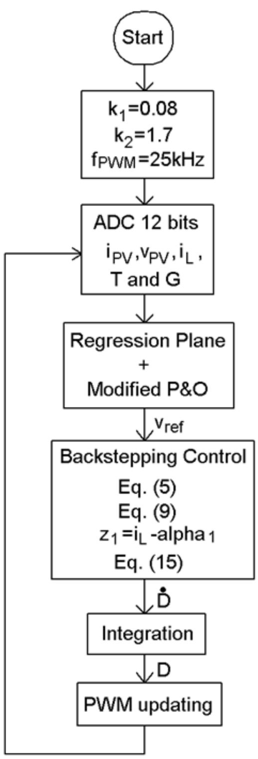

Fig. 9. Backstepping implementation flow chart.

TABLE II
ELECTRICAL AND CONTROL PARAMETERS

Parameter	Value
k_1	0.08
k_2	1.7
L	780 µH
C	1 mF
C_1	1 mF
R	50 Ω

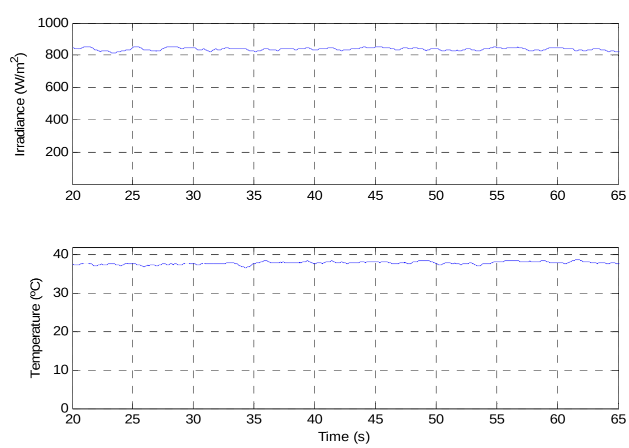

Fig. 10. Irradiance and temperature evolution.

case, and the buck-boost converter input voltage and the reference voltage that must be reached to obtain the MPP.

The reference voltage tracking efficiency, which is obtained by dividing the obtained voltage that supplies the maximum power by the reference voltage, is greater than 99%. Fig. 12 shows the buck-boost converter input and output power. Thus, the power converter efficiency, defined

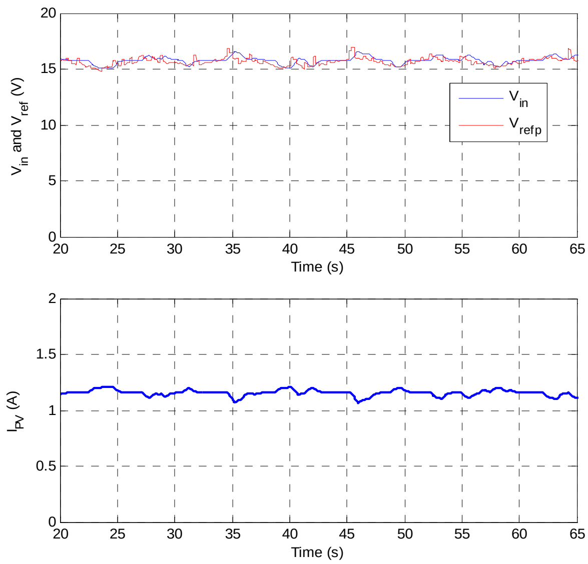

Fig. 11. DC-DC converter input voltage and reference voltage and PV output current.

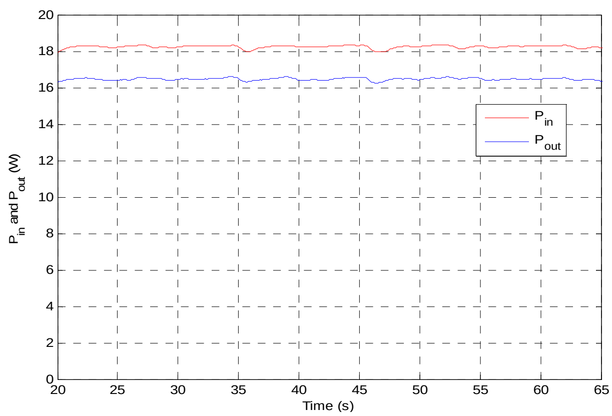

Fig. 12. DC-DC converter input and output power.

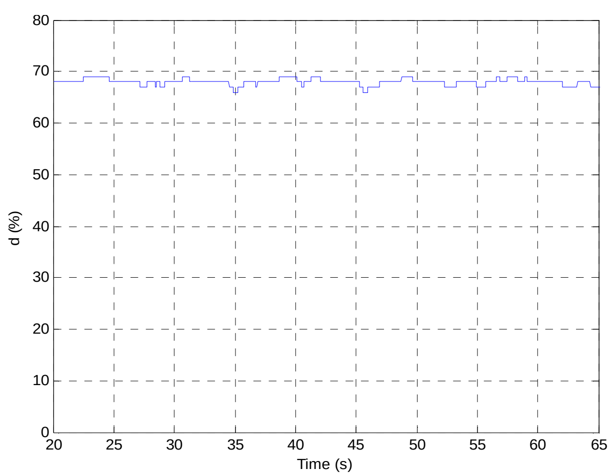

Fig. 13. DC-DC converter control signal.

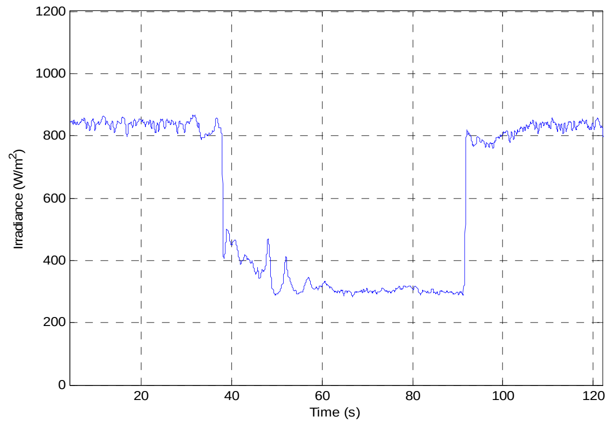

Fig. 14. Changeable irradiance.

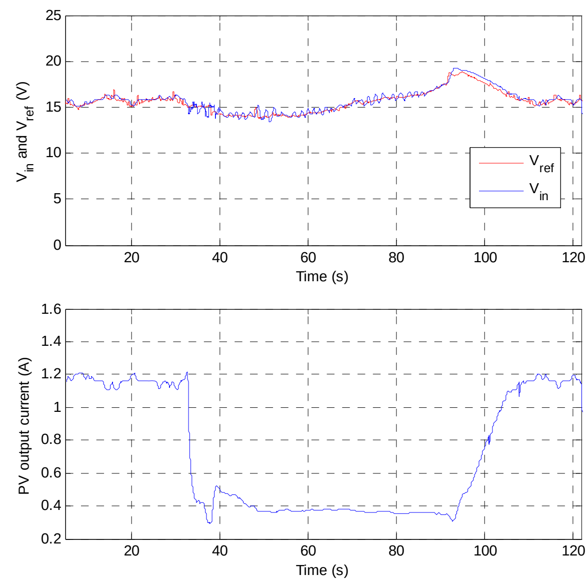

Fig. 15. DC-DC converter input and reference voltage and PV output current.

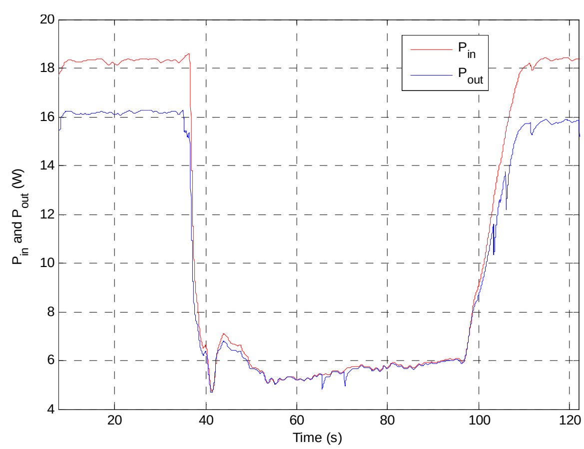

Fig. 16. DC-DC converter input and output power.

as the percentage achieved by dividing the DC-DC converter output power by the buck-boost input power, is about 90%.

Finally, the control signal is depicted in Fig. 13, where the percentage of the buck-boost converter duty cycle is shown.

2) Case 2 - Transient Analysis: In this case, the solar module was exposed to the sun during the two minutes in which the irradiance changed. The value of the irradiance is about 840 W/m^2 until 38 s, when it changes to 305 W/m^2

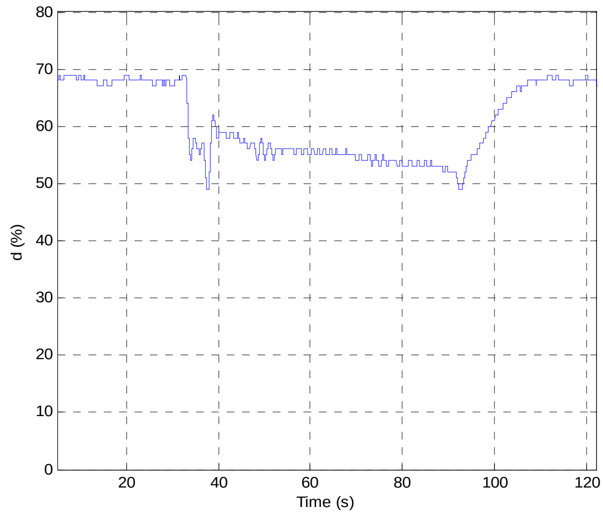

Fig. 17. DC-DC converter control signal.

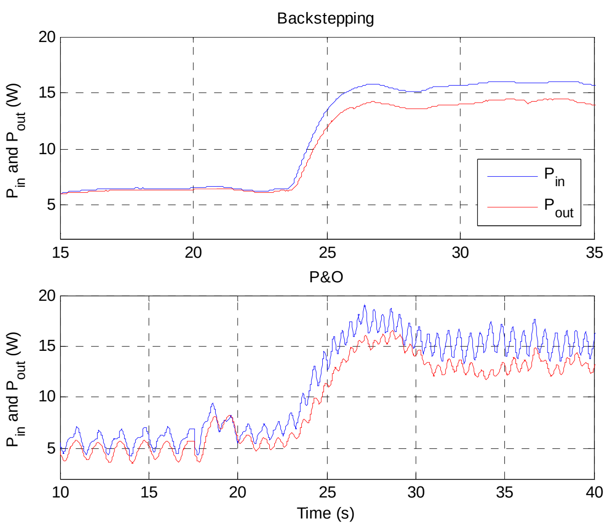

Fig. 18. DC-DC converter input and output power obtained with backstepping controller and P&O algorithm.

approximately. Then, the irradiance changes its value at 92 s to 840 W/m^2 again, as it is shown in Fig. 14.

Fig. 15 shows the PV output current, i_{PV}, obtained when there is a change in the irradiance. Aside from that, it depicts the PV output voltage and the reference voltage that must be tracked to achieve the maximum power point.

The DC-DC converter input and output power are shown in Fig. 16. Regarding the characteristics curves of the solar module, the maximum power for 840 W/m^2 and 38 ºC is 18.5 W, whereas the maximum power is 5.6 W when the irradiance is 305 W/m^2 and the temperature is 39.5 ºC, as in this case.

Therefore, the maximum power extraction is always achieved with a performance of about 90%, when the irradiance is 840 W/m^{2,} and of about 99% when the irradiance is 305 W/m^2. Moreover, the input and output power are stabilized after a smooth transient response. The duty cycle can be seen in Fig. 17. The buck-boost converter settling time when the duty cycle is changed is 100 ms.

Finally, a performance comparative between the backstepping control and the well-known P&O is shown to prove the validity of the proposed control. Fig. 18 presents DC-DC converter input and output power obtained with both methods.

The P&O algorithm has an oscillatory behavior, and it achieves a tracking efficiency of 96.1%, whereas the backstepping control does not oscillate, and obtains a tracking efficiency of 99%. Regarding the tracking time, the power is stabilized after 3.3 seconds under a change in the irradiance (from 400 W/m^2 to 700 W/m^2) when the backstepping control is used. When the P&O control is used under the same conditions of irradiance, the power is stabilized after 8.4 seconds.

V. Conclusion

In this paper, a nonlinear backstepping controller has been designed to control a buck-boost converter in a photovoltaic system. The control aim is to regulate the PV array output voltage in order to track the Maximum Power Point.

The proposed control includes an initial estimation of MPP using a simulation PV model and an off-line calculated regression plane under different temperature and irradiance conditions. The on-line control includes a modifying P&O method and a backstepping controller which calculates the duty cycle of the DC-DC converter switch device.

An experimental platform has been designed to verify the validity and performance of the proposed control method. The results confirm that the control works correctly because the reference voltage is always obtained for any environmental condition, including stationary and transient situations.

The control efficiency ratio or the tracking efficiency is greater than 99%, and the efficiency of power converter block is about 90%.

Acknowledgment

This work was supported by the Ministerio de Educación, Cultura y Deporte of Spain under FPU grant (Formación de Profesorado Universitario).

References

[1] Y. Tian, B. Xia, Z. Xu, and W. Sun, “Modified asymmetrical variable step size incremental conductance maximum power point tracking method for photovoltaic systems,” *Journal of Power Electronics*, Vol. 14, No. 1, pp. 156-164, Jan. 2014.

[2] T. F. Wu and Y. K. Chen, “Modeling PWM DC/DC converters out of basic converter units,” *IEEE Trans. Power Electron.*, Vol. 13, No. 5, pp. 870-881, Sep. 1998.

[3] J. Enrique, E. Durán, M. de-Cardona, and J. Andújar, "Theoretical assessment of the 18 maximum power point tracking efficiency of photovoltaic facilities with different 19 converter topologies," *Solar Energy*, Vol. 81, No. 1, pp. 31-38, Jan. 2007.

[4] T. Esram and P. L. Chapman, "Comparison of photovoltaic array maximum power point tracking techniques," *IEEE Trans. on Energy Conversion*, Vol. 22, No. 2, pp. 439-449, Jun. 2007.

[5] S. B. Kjaer, "Evaluation of the "hill climbing" and the "incremental conductance" maximum power point trackers for photovoltaic power systems," *IEEE Trans. Energy Convers.*, Vol. 27, No. 4, pp. 922-929, Dec. 2012.

[6] M. A. Elgendy; B. Zahawi; D. J. Atkinson, "Evaluation of Perturbe and Observe MPPT Algorithm Implementation Techniques," in *PEMD*, pp. 1-6, 2012.

[7] M. Momayyezan, H. Iman-Eini, "Developed MPPT Algorithm for Photovoltaic Systems without a Voltage Sensor," *Journal of Power Electronics*, Vol. 13, No. 6, pp. 1042-1050, Nov. 2013.

[8] M. I. Arteaga Orozco, J. R. Vázquez, P. Salmerón, "MPP Tracker of a PV System using sliding mode control with minimum transient response," *Int. Review on Modelling and Simulations*, Vol. 3, No. 6, pp. 1468-1475, Dec. 2010.

[9] T. Esram, J. W. Kimball, P. T. Krein, P. L. Chapman, P. Midya, "Dynamic maximum power point tracking of photovoltaic arrays using ripple correlation control," *IEEE Trans. Power Electron.,* Vol. 21, No. 5, pp. 1282-1291, Sept. 2006.

[10] J. R. Vazquez, A. D. Martin, and R. S. Herrera, "Neuro-fuzzy control of a grid-connected photovoltaic system with power quality," in *EUROCON*, pp. 850-856, 2013.

[11] R. Ramaprabha, B. L. Mathur, and M. Sharanya, "Solar array modeling and simulation of MPPT using neural network," in *Int. Conf. on Control, Automation, Communication and Energy Conservation*, pp. 1-5, 2009.

[12] T. L. Kottas, Y. S. Boutalis, and A. D. Karlis, "New maximum power point tracker for PV arrays using fuzzy controller in close cooperation with fuzzy cognitive networks," *IEEE Trans. Energy Convers.,* Vol. 21, No. 3, pp. 793-803, Sep. 2006.

[13] Y. Zhang, B. Fidan, and P. A. Ioannou, "Backstepping control of linear time-varying systems with known and unknown parameters," *IEEE Trans. Autom. Control,* Vol. 48, No. 11, pp. 1908-1925, Nov. 2003.

[14] Z. Pan, K. Ezal, A. J. Krener, and P. V. Kokotovic, "Backstepping design with local optimality matching," *IEEE Trans. Autom. Control*, Vol. 46, No. 7, pp. 1014-1027, Jul. 2001.

[15] M. Sokolov and D. Shmilovitz, "A modified MPPT scheme for accelerated convergence," *IEEE Trans. Energy Convers.*, Vol. 23, No. 4, pp. 1105-1107, Dec. 2008.

[16] J. Zeng, W. Qiao, and L. Qu, "A single-switch isolated DC-DC converter for photovoltaic systems," in *ECCE*, pp. 3446-3452, 2012.

[17] P. Pichlik and J. Zdenek, "Converter regulation of stand-alone photovoltaic system at low solar radiation," in *AE*, pp. 207-210, 2012.

[18] A. Daoud and A. Midoun, "Simulation and experimental study of maximum power point tracker based on a DC/DC buck converter," *Int. Review of Electrical Engineering.* Vol. 5, No. 2, pp. 514-520, Apr. 2010.

[19] R. Ortega, A. Lorai, P. J. Niklasson and H. Sira-Ramirez, "Passivity-based Control of Euler-Lagrange Systems," *Communications and Control Engineering*. pp. 168-171, Sept. 1998.

Jesus R. Vazquez was born in Huelva, Spain, on December 24. He received the degree in electrical engineering from the University of Seville, Spain in 1995. He obtained the Ph. D. degree in 2004. For one year, he was with the electrical department of Nissan Motor Ibérica S.A., Barcelona, Spain. Since 1996, he has been with the Electrical Engineering Department at the Escuela Técnica Superior de Ingeniería of the University of Huelva. He teaches Electric Circuits, Power Quality and Photovoltaic Systems, and his research interests include power quality, active power filters, renewable energy, distributed generation, and artificial network application.

Aranzazu D. Martin was born in Bollullos del Condado, Huelva, Spain. She received the degree in Industrial Engineering from the University of Huelva, Spain in 2008. She obtained her master's degree in Control Engineering, Electronic Systems and Industrial Computer Science in 2011. Since 2008, she has been with the Electrical Engineering Department at University of Huelva, working toward her Ph. D. She is currently working as a researcher with the FPU (Formación de Profesorado Universitario) grant. Currently, her research interests include renewable energy, control systems, distributed generation and power quality.