Performance comparison between proportional-integral and backstepping control of maximum power in photovoltaic system

Omar Diouri[1], Ahmed Gaga[1,2], Mohammed Ouazzani Jamil[1]

[1]Laboratory of Intelligent Systems, Energy and Sustainable Development, Department of Electrical Engineering,
Private University of Fez, Fez, Morocco
[2]Laboratory of Physics and Engineering Sciences, Research team in Embedded Systems Engineering, Automation, Signal,
Telecommunications and Smart Materials, Department of Physics, Polydisciplinary Faculty, Sultan Moulay Sliman University,
Beni-Mellal, Morocco

Article Info	ABSTRACT
	The major problem with photovoltaic systems is to extract the maximum power with better performance and good efficiency as long as there are large variations in atmospheric conditions. To do this, we made a comparative analysis between two controllers, proportional-integrator (PI) and backstepping based on a photovoltaic system made up of two parts, the first is the photovoltaic (PV) panels which are used to convert solar irradiation to an electric current, the second is a boost converter which is used to provide the maximum power. The perturb and observe (P&O) algorithm is used to generate the reference voltage in order to follow it by the two controllers (PI and backstepping) and therefore generate the maximum power. We are considered some parameters for this comparison such asthe efficiency of the controllersto follow the reference power despite the rapid change in atmospheric conditions as well as the response time of the system and the ripples in the transient phase. *This is an open access article under the [CC BY-SA](#) license.*

Corresponding Author:

Omar Diouri
Laboratory of Intelligent Systems, Energy and Sustainable Development
Department of Electrical Engineering, Private University of Fez
Lotissement Quaraouiyine Route Ain Chkef, Fez, Morocco
Email: diouri@upf.ac.ma

1. INTRODUCTION

During the past few years, electricity consumption and the number of distributed generation systems have also increased across the world. As a result, in comparison to traditional energy systems, the usage of green energy systems is critical [1]–[5]. The photovolatic energy is widely used green energy technologies because it is inexhaustible, cleanand cheap. It may be controlled and supervised using the new technologies as machine and learning internet of thing [6]. I have already some books of people direct current (DC/DC) converters come in a variety of topologies [7], [8]. In this paper, a boost converter is used in this work to have the desired input voltage value to follow the most powerful (MPP) and regulate the output voltage of the solar arrays as per the requirements. The purpose of a DC-DC boost converter is to help the photovoltaic generator, through maximum power point tracking (MPPT) techniques, to provide maximum power [9]–[13]. There are multiple algorithms to track the MPP point in a very efficient way; some research proposes two types of use of MPPT techniques: indirect MPP monitoring, such as fractional open-circuit voltage technique [14] and the second technique is direct MPP point tracking, such as incremental conductance [15]–[20] or the perturb and observe (P&O) method [21]–[23] which is used in this study. There are other research which are focused on fuzzy logic algorithm to control the MPPT [24]–[26].

The proportional and integral control (PI) is another widely used regulation technique [27], [28]. This control is simple to set up. Martin and Vazquez [29] demonstrated that backstepping produces reasonable performance. The The power curve of a photovoltaic panel has a decreasing nature to the right of the MPP point and it has an increasing nature to the left of this same point. So the P&O algorithm takes advantage of this nature to get the maximum power. The disadvantage of using this algorithm is that the MPP point is never stable or fixed. Small variations or disturbances around the MPP point allow used to have more precision. Another drawback is that the output voltage of this DC-DC converter is not controllable from this MPPT algorithm, as mentioned in Kaouane *et al*. [30]. The reference voltage is produced by the P&O algorithm block for use by the backstepping controller. In addition, the control of the boost converter transistor makes it possible to cause the photovoltaic generator to produce or supply the same voltage as the MPPT block.

Some academic papers have focused on back-stepping control because of its ability to design stability control for nonlinear dynamical systems [31]–[37]. Alexsandr Lyapunov's theory of dynamic system stability is used as one of the approaches for modeling nonlinear controllers. The designer's aim is usually to find a positive definite function known as "the Lyapunov candidate function," whose derivative is restricted to be a negative definite function using the system's inputs [38], [39].

The remainder of this paper is structured as follows: section 2 describes the photovoltaic (PV) system which contains two essential parts, PV array and boost converter. The design of both controllers, PI and backstepping are discussed in section 3. Finally, simulation findings in section 4 demonstrate test and simulation of the robust control of MPP. A conclusion is used at the end of this article.

2. SYSTEM DESCRIPTION

The block diagram of a PV structure is seen in Figure 1. It consists of two main components: a power electronic converter and a photovoltaic array. We applied, at the beginning, to this converter the PI regulator, then the backstepping controller. The objective is to compare between the two controllers in order to provide the total power to the electrical load. The DC-DC type boost converter makes it possible to force the photovoltaic panels to provide the maximum power according to the different weather conditions. However, the MPPT block generates the reference voltage to be followed by PI and backstepping controllers.
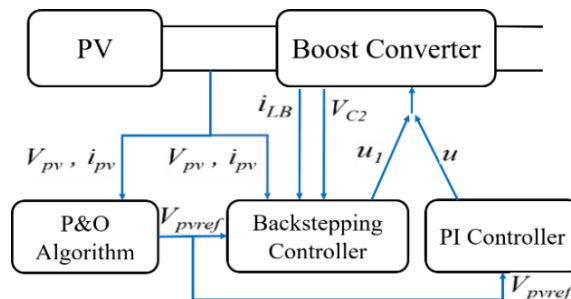

Figure 1. Block diagram of boost converter with controllers

2.1. The PV array and MPPT algorithm

The conversion of photons into electricity using semiconductor materials is the concept for photovoltaic radiation. The photovoltaic generators are made up of several solar cells; the basic part is the solar cell, which can only produce a few watts. Consequently, the series and parallel assembly of several solar cells allows the voltage and the current to be maximized respectively. This assembly makes it possible to build a photovoltaic panel.

There is one power point that is known to be the most powerful (MPP). Using a very specific algorithm called maximum power point tracking (MPPT), photovoltaic panels can generate maximum power and track it despite changing weather conditions. In this study, the P&O algorithm is applied by increasing or decreasing the voltage with an offset to always have the maximum power, as shown in Figure 2.

2.2. Boost converter

There are many types of DC-DC converters that could convert voltage value to desired levelhave been described in the literature. Voltage boosters and step down converters are two examples [28]. After the PV panel, a boost converter is used which boosts the voltage from the PV array's low input voltage to the

load's high output voltage. In order to obtain the MPP in various atmospheric environments, the boost converter's input is attached to the PV array. The synoptic block of the DC-DC converter with two controllers (PI and backstepping) is shown in Figure 1. These controllers may use a pulse width modulation (PWM) generator to produce exactly a desired duty cycle to control the gate ofthe power transistor.
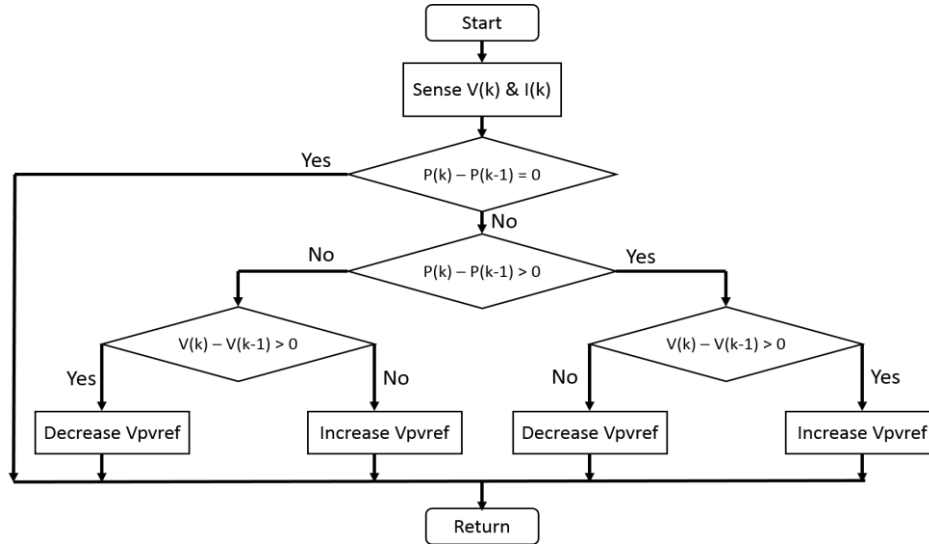

Figure 2. Algorithm of perturb and observe

3.   DESIGN OF MPPT CONTROLS

To have a very good photovoltaic system, the main role of MPPT algorithms is to follow the optimal MPP even there are rapid changes in climatic conditions. The most commonly used system, P&O is compared with the PI control and proposed backstepping control. This comparison will provide an idea which controller is better for tracking the power generated by PV.

3.1. Design of PI control

In several industrial systems, the PI regulator is widely used and well known. In our case, it is used to ensure that the voltage generated by the PV panels matches the reference voltage [27] by commuting the DC/DC converter switch, the PI control should be able to meet the reference voltage. This last one is that produces the most power, and is determined based on the ambient conditions, temperature and irradiance.

The PI regulator is known by two terms, proportional

$$G(s) = K_P + K_I \frac{1}{s} \tag{1}$$

$$G(s) = K_P \left(1 + \frac{1}{T_I s}\right) \tag{2}$$

Where K_P is the proportional gain, K_I the integral gain and T_I the integral time constant. For optimum and good quality of performance, K_P, K_I (or T_I) are mutually dependent in tuning. The PI parameters are configured in this study using a tuning method in Simulink, which is based on system measurements and several iterations. In a convergence field, this approach can obtain PI parameters that are similar to the optimal values.

3.2. Design of backstepping control

Figure 3 presents the schematic of boost converter used in this study. Which i_{pv} and V_{pv} are two parameters generated by PV array corresponding to current and voltage respectively. C_1, C_2 are respectively the capacitors of input and output of boost converter and L_B is the boost inductor. V_{C2} represents the output voltage of the system and i_{LB} the current in the inductor.

Using the Kirchhoff theorem on the boost model seen in Figure 3, (1) and (2) reflect the boost's dynamic model:

$$C_1 \frac{dV_{pv}}{dt} = i_{pv} - i_{LB} \tag{3}$$

$$L_B \frac{di_{LB}}{dt} = V_{pv} - (1 - u_1)V_{C2} \tag{4}$$

the (3) and (4) can be rearranged as follows using u_1 as the control signal for the boost converter and the voltage V_{pv} as the system state:

$$\dot{x}_1 = \frac{1}{C_1} i_{pv} - \frac{1}{C_1} x_2 \tag{5}$$

$$\dot{x}_2 = \frac{1}{L_B} x_1 - \frac{(1-u_1)}{L_B} V_{C2} \tag{6}$$

where x_1 and x_2 are the average value of V_{pv} and i_{LB} respectively.

By using the backstepping controller to follow the reference voltage and force the PV array to generate maximum power. e_1 is the error, which is defined as:

$$e_1 = x_1 - V_{pvref} \tag{7}$$

$$\dot{e}_1 = \dot{x}_1 - \dot{V}_{pvref} = \frac{1}{C_1} i_{pv} - \frac{1}{C_1} x_2 - \dot{V}_{pvref} \tag{8}$$

V_1 is the first Lyapunov function, and it is defined as:

$$V_1 = 0.5e_1^2 \tag{9}$$

$$\dot{V}_1 = e_1 \dot{e}_1 = e_1 \left(\frac{1}{C_1} i_{pv} - \frac{1}{C_1} x_2 - \dot{V}_{pvref} \right) \tag{10}$$

it is necessary to get $\dot{V}_1 = -k_1 e_1^2 < 0$ for this raison we obtain the (9), where k_1 is positive.

$$\frac{1}{C_1} i_{pv} - \frac{1}{C_1} x_2 - \dot{V}_{pvref} = -k_1 e_1 \tag{11}$$

The system's virtual control is x_2^*, which is equal to:

$$x_2^* = i_{pv} + C_1 k_1 e_1 - C_1 \dot{V}_{pvref} \tag{12}$$

where the second error is defined as follows between the second state variable x_2 and its desired value x_2^*:

$$e_2 = x_2 - x_2^* \tag{13}$$

the derivative of error e_1 is:

$$\dot{e}_1 = \frac{1}{C_1} i_{pv} - \frac{1}{C_1} (x_2^* + e_2) - \dot{V}_{pvref} = \frac{1}{C_1} i_{pv} - \frac{1}{C_1} \left(i_{pv} + C_1 k_1 e_1 - C_1 \dot{V}_{pvref} \right) - \frac{1}{C_1} e_2 - \dot{V}_{pvref} \tag{14}$$

as a result, the two error's system equation is:

$$\dot{e}_1 = -k_1 e_1 - \frac{1}{C_1} e_2 \tag{15}$$

$$\dot{e}_2 = \dot{x}_2 - \dot{x}_2^* = \frac{1}{L_B} x_1 - \frac{(1-u)}{L_B} V_{C2} - \dot{x}_2^* \tag{16}$$

the second Lyapunov function V_2 and its derivative are:

$$V_2 = V_1 + \frac{1}{2} e_2^2 \tag{17}$$

$$\dot{V}_2 = \dot{V}_1 + e_2 \dot{e}_2 = e_1 \dot{e}_1 + e_2 \dot{e}_2 \tag{18}$$

new expression of the derivative of V_2 is given in (19) by combining (15) and (16) in (18).

$$\dot{V}_2 = -k_1 e_1^2 + e_2 \left(-\frac{1}{C_1} e_1 + \frac{1}{L_B} x_1 - \frac{(1-u_1)}{L_B} V_{C2} - \dot{x}_2^* \right) \tag{19}$$

It is necessary to get $\dot{V}_2 = -k_1 e_1^2 - k_2 e_2^2 < 0$, where k_1 and k_2 are two positives:

$$-\frac{1}{C_1} e_1 + \frac{1}{L_B} x_1 - \frac{(1-u_1)}{L_B} V_{C2} - \dot{x}_2^* = -k_2 e_2 \tag{20}$$

the boost converter's control law corresponding to "u_1" is specified in (21).

$$u_1 = 1 - \frac{1}{V_{C2}} \left[x_1 - L_B \dot{x}_2^* - L_B \left(\frac{1}{C_1} e_1 - k_2 e_2 \right) \right] \tag{21}$$

The u_1 is the appropriate control signal that can be used in order to control the transistor gate of boost converter.
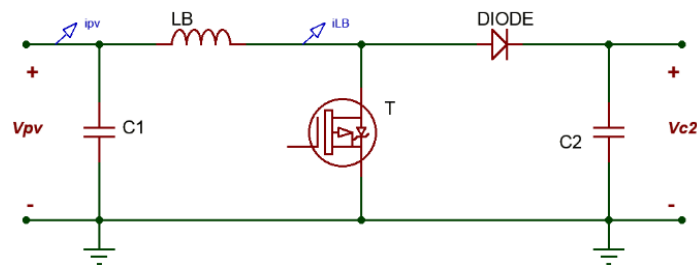

Figure 3. Electric circuit of boost converter

4. SIMULATION RESULTS

To compare the performance of backstepping and PI two simulations are used as shown in Figure 4. In order to track the MPP in different values of sun irradiation without partial shading in terms of response time in the transient phase and the rate of ripples in the steady state, a PV system using PI and backstepping controllers are simulated using Simulink platform as shown in Figure 4. The parameters of P&O algorithm are the same for two tests. The Figure 4(a) represents the PV system using PI controller and Figure 4(b) represents the same PV system but using the backstepping controller.

The monocrystalline 215 W solar panel is used in this study, and the PV array's total power is 100 kW. Table 1 lists the electrical properties of the PV array. The entire system is checked and validated using the system parameters specified in Table 2.

Figure 5 shows the profil chosen of sun irradiation in order to verify the performance of tracking the MPP. Figure 6 illustrates the photovoltaic power of the PV array using two controllers. Figure 6(a) shows the simulation over the course of one second. The irradiance is initially set at 900 W/m^2, indicating that the reference power of PV array is 90.4 kW.

Both of controllers should provide a suitable duty cycle control to boost converter in order to track the reference power since the transient process incorporates several ripples. In Figure 6(b), the reaction time to obtain the maximum value of power is about 11 ms for backstepping and 35 ms for the PI. The irradiance changed its value to 700 W/m^2 at 0.25 s, and the power immediately decreased, so the current value of the PV array's power produced is 70.8 kW. In comparison to the PI controller, the power provided by the backstepping controller easily reaches its reference value with minimal ripples, as shown in Figure 6(a).

The power value is 40.5 kW at 0.5 s, which corresponds to 400 W/m^2 of sun irradiance. The PI exhibits large variations of ripples in the transient phase, which can reach 1000 W and 610 W of error between reference power and PV array power. At 0.75 s, the reference power increase and its reaches 80.7 kW which is caused by increasing in sun irradiance to 800 W/m^2, backstepping control effectively tracks the MPP, demonstrating the high robustness and efficiency of backstepping control in terms of generating optimum power to the load as opposed to PI control.

Table 3 shows the performance of the MPPT method with PI and backstepping control in various solar irradiation conditions. When compared to a PI controller, our backstepping MPPT system controller has

the higher percentage of efficiency and a fast way for tracking the power. As shown in Figure 6(a), despite there is a high speed of variation of the solar irradiation, the backstepping remains the fastest controller to follow the maximum power and Figure 6(b) represents a zoom to verify this speed.
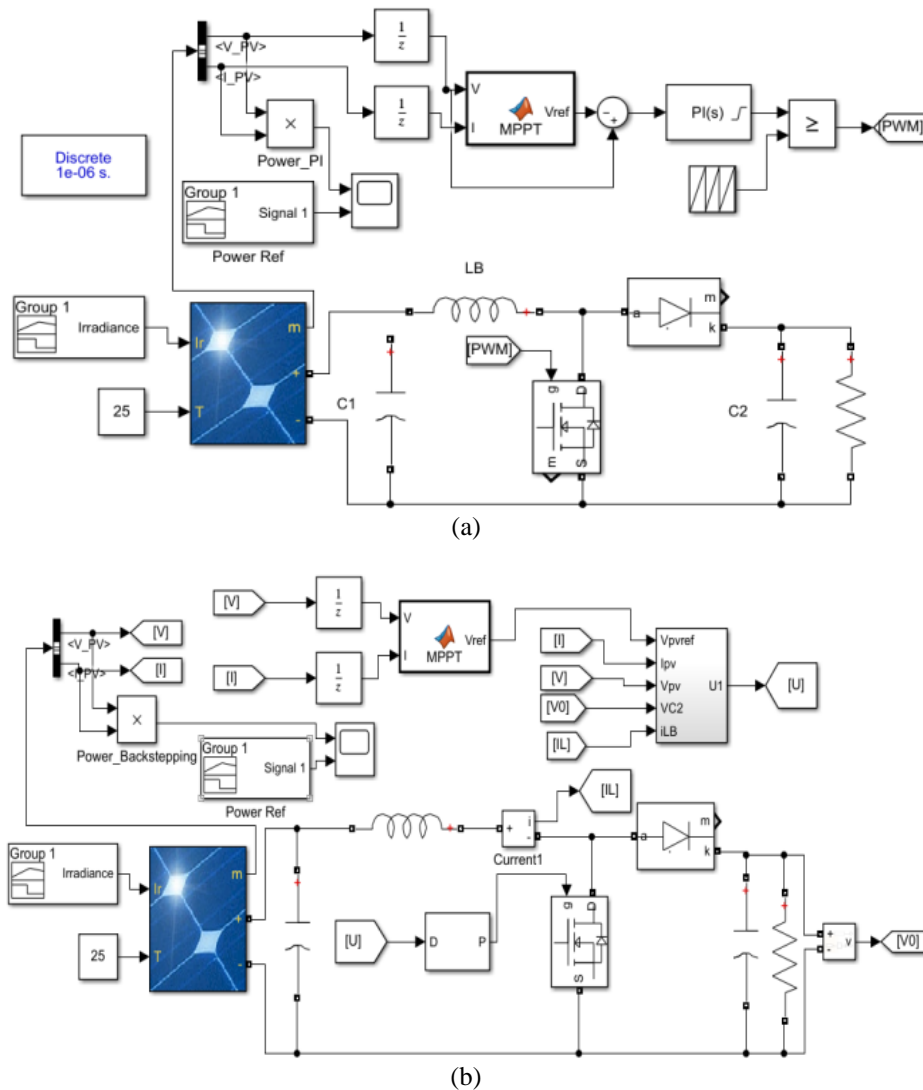
(a)

(b)

Figure 4. Simulation of two controllers PV with (a) PI controland and (b) backstepping control

Table 1. Electrical properties of the PV array

Typical electrical characteristics	Value
Maximum Power per module (Pmax)	215 W
Parallel strings	47
Series-connected modules per string	10
Maximum power of PV array	100 kW
Voltage at MPP of PV array	120.7 V
Current at MPP of PV array	8.2 A

Table 2. System parameters

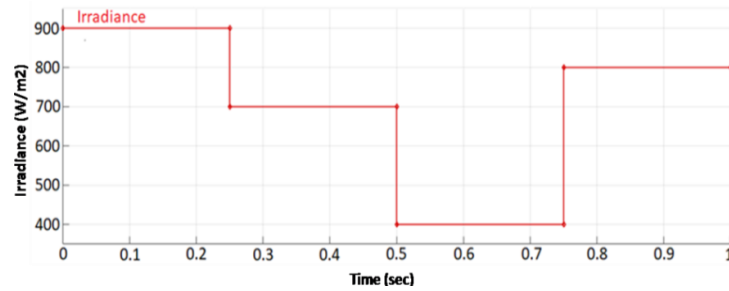| Parameter	Value	Parameter	Value
LB	1.45e-3 H	k1	9000
C1	1000e-6 F	k2	9000
C2	3220e-6 F	Kp	0.001
Fpwm	20 kHz	Ki	0.01
T	25 °C	Sample time	1e-6 s
Offset (MPPT block)	1 V		

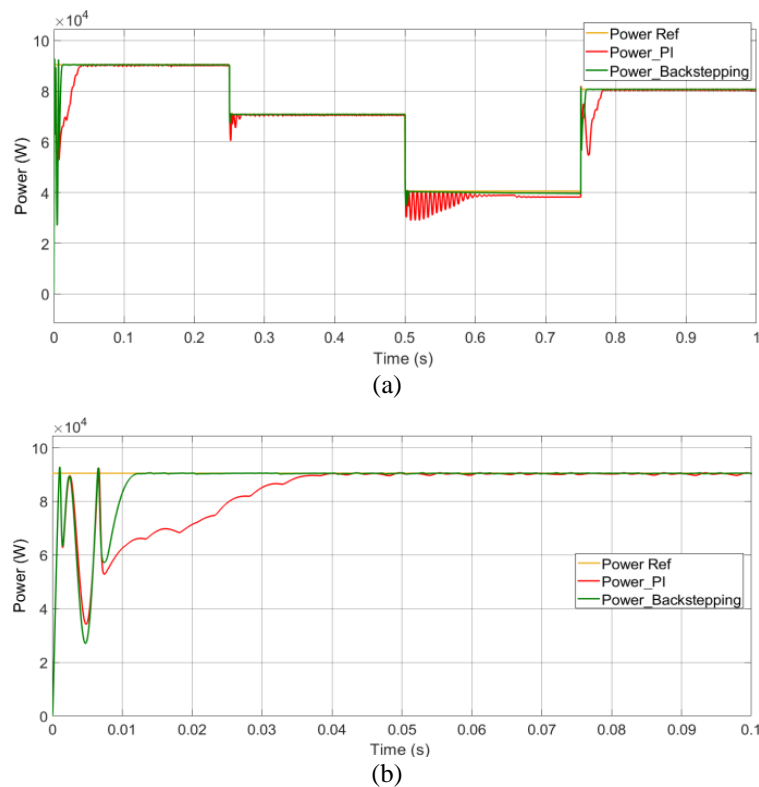Figure 5. Profil chosen of sun irradiance

(a)

(b)

Figure 6. Power generated by PI and backstepping with (a) power variation during 1 s and
(b) zoom from 0 to 0.1 s

Table 3. Efficiency of two controls in different solar irradiation

Solar irradiation (W/m²)	Efficiency of PI control (%)	Efficiency of backstepping control (%)
900	98.1	99.3
800	97.9	99.4
700	96.8	98.6
400	80.4	96.7

5. CONCLUSION

In this article, a rigorous control scheme with a high-performance PV system is introduced and compared to standard control. Backstepping control, which can easily track the reference, is used to achieve the successful results. To measure the robustness of this controller, we subjected it to rapid changes in solar irradiance, and the results show that our proposed system controls the reference power perfectly using backstepping. The results of this paper can be improved by considering implementing the backstepping control strategy in an electronic board for better control of the PV system as well as regulating the output voltage of the boost converter in order to supply loads such as batteries.

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BIOGRAPHIES OF AUTHORS

Omar Diouri 🆔 📇 SC Ⓟ received his PhD from Sidi Mohamed Ben Abdellah University in 2020. Currently, he is an Assistant Professor at Private University of Fez, Fez, Morocco. He works in electrical engineering. His research interest is electronics; and control theory. He can be contacted at email: diouri@upf.ac.ma.

Ahmed Gaga 🆔 📇 SC Ⓟ he is an Assistant Professor at USMS University, Beni Mellal, Morocco. He is with Department of Physics, He works in electrical engineering, especially embedded systems. He can be contacted at email: gaga.ahmad@gmail.com.

Mohammed Ouazzani Jamil 🆔 📇 SC Ⓟ is a Dean of Faculty of Engineering Sciences and Vice-President of Private University of Fez, Morocco. Mohammed does research in condensed matter physics, hamiltonian système, chaos. Their current project is 'dynamic systems'. He can be contacted at email: ouazzani@upf.ac.ma.