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Nonlinear backstepping control of a partially shaded photovoltaic storage system

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ABSTRACT

Many power converter architectures and control approaches, both traditional and unconventional, have been developed, investigated, and adjusted to handle the challenge of tracking the maximum power points of a partially shaded photovoltaic (PV) system, which fluctuates with meteorological conditions (radiation and temperature). A DC-DC converter was used as the power conditioning unit to determine the system's maximum efficiency. In this research, we focus on developing a nonlinear controller for a DC-DC converter to track the overall maximum power point in a PV storage system under partial shading situations. This study presents a combination of two MPP search algorithms with a backstepping controller. The particle swarm optimization (PSO) and variable step Perturb and Observe (P&O)with global scan (VSP&O/GS) algorithms supply the PV output reference voltage to the backstepping controller in order to recover the maximum power from photovoltaic (PV) systems. The simulation results of the methods compared to the proposed maximum power point (MPPT) algorithm are simulated and examined in the MATLAB/Simulink environment under non-uniform irradiation conditions. To demonstrate the performance and limits of each approach in tracking the maximum power point.

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Nomenclature:

RES	Renewable energy sources	I_{ph}	Current generated by the incident light
PV	Photovoltaic	I_0	Reverse saturation current
MPPT	Maximum power point tracking	K	Boltzmann's constant
P&O	Perturb and observe	q	Electronic load
PSO	Particle Swarm Optimization	T	Cell temperature
VSP&O/GS	Variable Step P&O and Global Scanning	R_s	Series resistance
PSC	Partial shading conditions	R_{sh}	Shunt resistance
GMPP	Maximum power point global	n	Diode ideality
LMPP	Maximum power point local	C_1	Input capacitor
PMW	Pulse width Modulation	C_2	Output capacitor
Irr	Irradiation	L	Bobbin
		D	Diode

Parameters:

DC	Direct-Current	I_L	Output current of the bobbin
S	Switch	V_s	Output voltage
		I_s	Output current
I_{pv}	PV output current	E_{Bat}	Battery generator
V_{pv}	PV output voltage	$V_{réf}$	Reference tension
R_{Bat}	Battery resistance	$\Delta V_{réf\,max}$	the largest perturbation of the $V_{réf}$
K_1,K_2	Positive constants (control parameters)	P_r	output PV power in real time
e_1,e_2	Tracking errors	a_i^k	the acceleration of particle
α	Virtual control	i	the particle
d	Duty cycle (control law)	w	the inertia weight
V_1, V_2	Lyapunov functions	r_1 , r_2	random numbers
N	Scaling coefficients	x_i	position of the particles
		m_1, m_2	the acceleration coefficients

1. INTRODUCTION

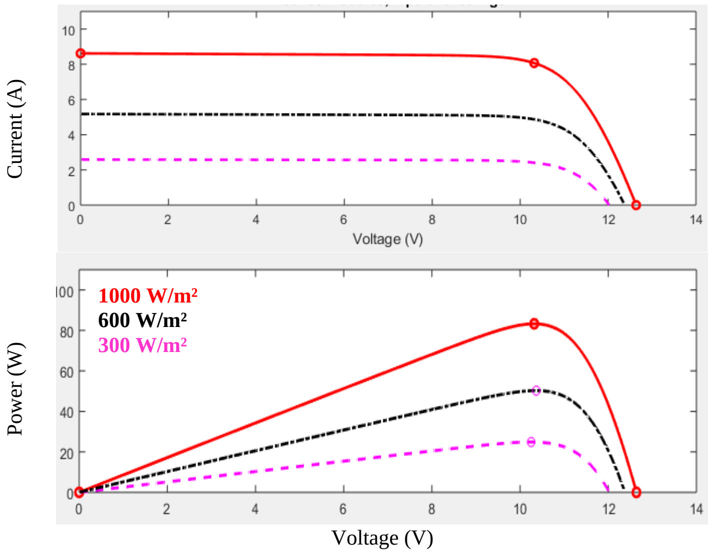
Having a clean environment, good economic performance, and interest in a stable and reliable sustainable energy source has become a global challenge in the energy field. In contrast to conventional energy sources based on fossil fuels. Renewable energy sources (RES) [1], especially solar energy, remain the most attractive. And this is because it is durable, clean, discreet, close to the user, and easy to use. Photovoltaic (PV) systems are based on several solar cells connected in parallel or in series, which convert solar radiation into electrical energy. This energy transformation has a main weakness because of the solar radiation and the atmospheric temperature. The role of photovoltaic systems is to power one or more consumers, such as smart homes, who use these systems to save energy or who are located in an area isolated from the electrical grid [2].

Due to the discontinuous and arbitrary nature of the solar source, the latter requires the use of a PV energy storage system, for the conservation of the energy produced by the photovoltaic generator, pending further application according to demand [3]. A storage system associated with PV generators in smart homes and electrical vehicles, responsible for ensuring the supply at all times and for several days despite the intermittent nature of the production. The reduction of the system cost, requires the use of a controller for a thorough and careful search of the maximum power point (MPPT) in changing atmospheric conditions .In order to increase the productivity and efficiency of a PV system [4], [5]. This control system consists of a power converter inserted between the PV source and the load; the maximum power point tracking (MPPT) is achieved by the duty cycle of the converter. In the literature, several methods of MPP tracking have been proposed and discussed [6], namely the Perturb and Observe (P&O) method [7], which is the best known, the most used and the most debated. And the biological-inspired algorithms, called non-conventional, namely the PSO method with its simplest structure and easy implementation [8]. Thus, the techniques dedicated to PV storage systems, which are based on sliding mode controllers such as the nonlinear backstepping control proposed by [9], [10],this control provides good stability to the system using the Lyapunov function. Since the 1990s, several authors have tried to evaluate and integrate energy storage systems with PV systems [11]. Others have done their comparative studies to investigate the performance and costs of different battery technologies [12] Nowadays, several technologies and studies on energy storage exist in the literature, showing their reliability and economic applicability. This makes PV systems competitive with other energy sources.

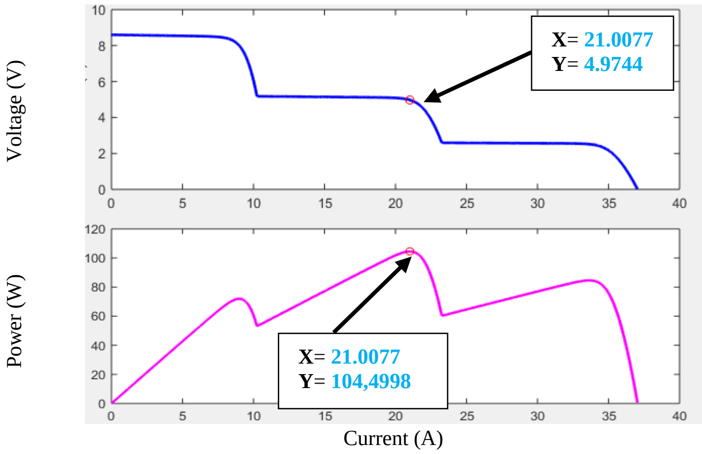
This work will focus on a comparative analysis of frequently used MPPT approaches. The implementation of a new control method for the MPPT of a PV storage system. The result is a non-linear backstepping controller with a combination of improved algorithms: i) VSP&O/GS which is an improved perturbation, observation and global scanning method; It tracks the maximum power point under shading which gives multi-peak characteristics of the curve (P-U) [13]; ii) the unconventional biologically inspired PSO algorithm with its simplest structure and easy implementation [14]. Both search algorithms are responsible for providing a reference voltage for the PV output, which the controller will regulate by changing the duty cycle of the inverter in response to changing environmental conditions. To solve the problem of partial shading. This paper is organized as shown in: in Section 2, a study of partial shading conditions is presented. Section 3 is devoted to photovoltaic system modeling. The backstepping control design, in Section 4. After that, in Section 5, we present our improved MPPT technique (VSP&O/GS) and the PSO technique based on artificial intelligence. In Section 6, numerical simulation results and comparison of the algorithms proposed are presented on MATLAB-Simulink in case of partial shading for photovoltaic storage system. And finally, In the conclusion, we encapsulated the main points of our article.

2. PARTIAL SHADING CONDITIONS (PSC)

Photovoltaic cells are responsible for converting solar energy into electrical energy. These cells' connection can have an effect on either the current (parallel) or the voltage (series). Due to the uniform radiation received by the PV cells; the P-V curve displays a single MPP in normal conditions. I-V and P-V characteristics curve as shown in Figure 1. As it is illustrated in Figure 1(a).



(a)



(b)

Figure 1. I-V and P-V characteristics curve for (a) various solar irradiance and (b) under partial shading conditions

Since it is uncommon to have uniform and steady radiation at all times in real life, passing clouds and birds, as well as trees and buildings, can provide a total or partial shading effect (PSC) on the solar panels as shown in Figure 2. This creates a contrast in radiation reception. So some modules in the PV array receive high radiation and other shaded modules receive low radiation [15]. The solar cells are connected in series, and the currents running through all modules in series must be equal, according to Kirchhoff's law of currents. In this regard, shaded cells (which receive less or no radiation) operate at a negative voltage to produce the same current as non-shaded cells. This part of the current given by the non-shaded cells must pass through the parallel resistance R_{sh} of the shaded modules. As a result, the system suffers a net voltage loss, leading in energy being consumed rather than produced, causing in a hot spot effect [4].

To solve this problem, inserting bypass diodes in parallel with each panel is the ideal method. In a PSC system, the polarization of these diodes ensures that current flows from non-shaded cells to shaded cells are reversed. In order to avoid reverse current, each PV string is linked in series with a blocking diode [16], [17]. However, in the case of PSC, the inclusion of the bypass diode introduces a new problem: the characteristic curves (P-V) become non-linear, with several maximum points Figure 1(b) that are proportional to the number of PV modules connected in series in the PV array [18]. Optimization algorithms, differential algorithms, artificial neural networks, artificial intelligence approaches, new inverter architecture, new PV module reconfiguration, and new PV modeling are used to produce a number of recent MPPT optimization algorithms. To address the issue of numerous peaks, which traditional MPPT optimization algorithms fail to distinguish between, GMPPs and LMPPs were developed [6].

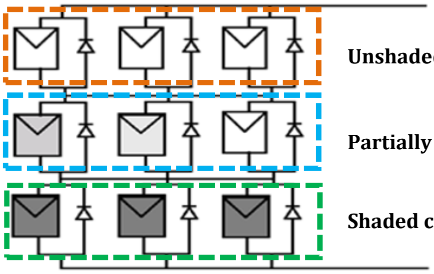


Figure 2. Structure of the photovoltaic panel

3. SYSTEM MODELLING

3.1. PV panels modeling

The schematic of a photovoltaic storage system is shown in Figure 3. These photovoltaic systems consist of a photovoltaic module, a DC-DC boost converter, a control system and batteries. According to (1), shows the relation between the current I_{pv} and the voltage V_{pv} of the corresponding circuit:

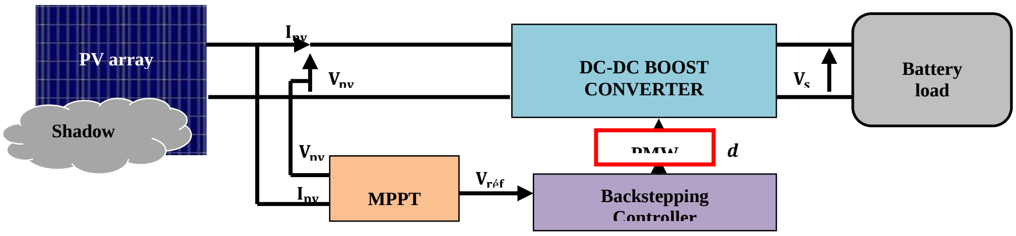


Figure 3. Model of the solar PV and, BOOST converter and load

$$I_{pv} = I_{ph} - I_0 \left[e^{\frac{V_{pv}+I_{pv}.R_s}{\frac{n.k.T}{q}}} - 1 \right] - \frac{V_{pv}+I_{pv}.R_s}{R_{sh}} \quad (1)$$

Where I_{ph} is the current generated by the incident light in Ampere,I_0 represent the reverse saturation current of the diode in Ampere, K is the Boltzmann's constant (1, 38×10^{-23} JK−1), q is the electronic load (1,602$\times10^{-19}$ C), T is the cell temperature in Kelvin, and R_s and R_{sh} These respectively are the series resistance and the shunt resistance in Ω. The set of five values that characterize the equivalent circuit of PV cells are reported in Table 1.

Table 1. Parameters of the PV array

Parameters	Nomenclature	Values
Light-generated	I_{ph}	8.6307 A
Diode saturation	I_0	$1.4176e^{-10}$A
Diode ideality	n	0.99132
Series resistance	R_s	0.098625 Ω
Shunt resistance	R_{sh}	82.1161 Ω

3.2. DC-DC boost converter modeling

In order to make the PV module work permanently at its maximum power point, it is necessary to use a DC/DC converter. This converter allows to adjust the voltage V_{pv} given by the PV to its reference value which provides the MPP [4]. The DC/DC converter is characterized by its high flexibility and efficiency to control power in direct current circuits DC. Its working principal changes according to the demand of the load. If the voltage will be converted to another of low value, then it is a (Buck)/(series) converter, and if the converted voltage is of higher value, then it is a (Boost)(parallel) converter. In this work, we are interested to using a BOOST DC/DC converter, considering its desirability for the adjustment of the MPPT. Figure 4 shows that the DC-DC boost converter consists of an LC filter (L,C_1) to filter the input voltage (V_{pv}) and to decrease the current ripple of I_L, a switch (S) to regulate the input voltage, a diode (D), a capacitor (C_2) [17].The dynamics of the BOOST DC/DC converter model is described by the following:

$$\begin{cases} \frac{dV_{pv}}{dt} = \frac{1}{C_1}(I_{pv} - I_L) \\ \frac{dI_L}{dt} = \frac{1}{L}(V_{pv} - (1-d)V_s \\ \frac{dV_s}{dt} = \frac{1}{C_2}(I_L(1- d) - I_s) \end{cases} \quad (2)$$

3.3. Battery energy storage system modeling

The integration of the PV system with a storage system the Figure 4 and shown in the (3), is the agitating solution in the conservation of energy in order to restore it at any desired time. Due to the intermittent and unpredictable nature of the electrical energy extracted by PV systems [18], [19]. Lead-acid batteries are still the most used in stand-alone systems, thanks to their profitability, performance and cost [20], [21].

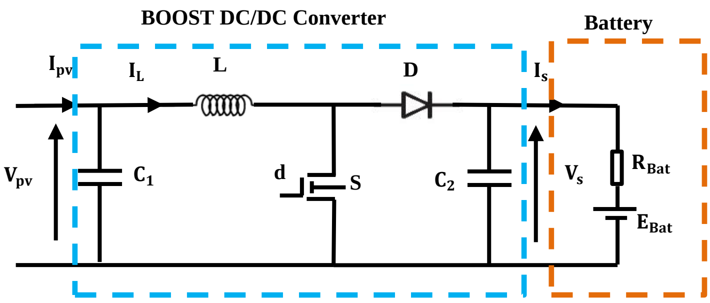


Figure 4. Equivalent circuit of a BOOST DC/DC Converter and a battery energy storage system

$$V_s = E_{Bat} + I_s \times R_{Bat} \quad (3)$$

4. BACKSTEPPING CONTROL

This type of controller achieves the objective of adjusting the output PV voltage to track the maximum power. This objective is realized by acting on the duty cycle d of the boost type DC-DC converter [22]. The steps of this control are presented in [17], [22].

4.1. Step 1

In the first step, we determine the reference tension $V_{réf}$ followed by V_{pv} , so we define below the tracking error:

$$e_1 = V_{pv} - V_{réf} \quad (4)$$

the derivative with time respect to e_1 is given by:

$$\dot{e_1} = \dot{V}_{pv} - \dot{V}_{réf} = \frac{1}{C_1}(I_{pv} - I_L) - \dot{V}_{réf} \quad (5)$$

we consider the first Lyapunov candidate function to ensure stability:

$$V_1(e_1) = \frac{1}{2}e_1^2 \quad (6)$$

time derivative of V_1 is given by:

$$\dot{V}_1(e_1) = e_1 \times \dot{e_1} = e_1\left(\frac{I_{pv}-I_L}{C_1} - \dot{V}_{réf}\right) \quad (7)$$

as shown in (7) must be negative. Or, $\dot{V}_1(e_1)$ can also be expressed as:

$$\dot{e_1} = -K_1e_1 \quad (8)$$

$$\dot{V}_1(e_1) = -K_1{e_1}^2 \leq 0 \quad (9)$$

with K_1 is positive constant (K_1 > 0) which represents a design parameter of the backstepping controller.

$$e_1\left(\frac{I_{pv}-I_L}{C_1} - \dot{V}_{réf}\right) = -K_1{e_1}^2 \quad (10)$$

Assuming a new variable α that represents the virtual control, with $\alpha = I_L$; hence; corresponds to the desired value of the state variable I_L **.** The time derivative of α would be:

$$\alpha = I_{pv} - C_1\dot{V}_{réf} + K_1C_1e_1 \quad (11)$$

And its derivative is:

$$\dot{\alpha} = \dot{I}_{pv} - C_1\ddot{V}_{réf} + K_1C_1\dot{e}_1 \quad (12)$$

4.2. Step 2

The second tracking error that represents the difference between I_L the state variable and its desired value α is defined by:

$$e_2 = I_L - \alpha \quad (13)$$

its time derivative:

$$\dot{e_2} = \dot{I}_L - \alpha = \frac{1}{L}\left(V_{pv} - (1-d)V_s\right) - \dot{\alpha} \quad (14)$$

the second Lyapunov function of the system to be controlled, in the state space $V_2(\mathrm{e}_1, \mathrm{e}_2)$ are written:

$$V_2(e_1, e_2) = V_1(e_1) + \frac{1}{2}\,{e_2}^2 \quad (15)$$

the time derivative of:

$$\dot{V}_2 = \dot{V}_1(e_1) + e_2\dot{e}_2 \quad (16)$$

the new expression of the time derivative of the Lyapunov function V_1 (e_1) can be obtained:

$$\dot{V}_1(e_1) = -K_1{e_1}^2 - \frac{e_1e_2}{C_1} \quad (17)$$

the time derivative of $V_2(\mathrm{e}_1, \mathrm{e}_2)$ becomes as follows:

$$\dot{V}_2(e_1, e_2) = -K_1{e_1}^2 + e_2\dot{e_2} - \frac{e_1e_2}{C_1} \quad (18)$$

$$\dot{V}_2(e_1, e_2) = -K_1{e_1}^2 + e_2\left(\dot{I}_L - \dot{\alpha} - \frac{e_1}{C_1}\right) \quad (19)$$

$$\dot{V}_2(e_1, e_2) = -K_1{e_1}^2 + e_2\left(-\frac{1}{C_1}e_1 + \frac{1}{L}\left(V_{pv} - (1-d)V_s - \dot{\alpha}\right)\right. \quad (20)$$

to ensure that the time derivative of the Lyapunov function $V_2(\mathrm{e}_1,\mathrm{e}_2)$ is negative, the previous expression must validate:

$$\left(-\frac{1}{C_1}e_1+\frac{1}{L}\left(V_{pv}-(1-d)V_s-\dot{\alpha}\right)=-K_2e_2\leq 0 \quad (21)$$

with: K_2 is a positive design parameter. Combining (20) and (21), the final control law d is obtained:

$$d=1-\frac{1}{V_s}\left[V_{pv}-L\alpha-L(\frac{1}{C_1}e_1-K_2e_2)\right] \quad (22)$$

the second Lyapunov function of the system:

$$\dot{V}_2(e_1,e_2)=-K_1e_1^2-K_2{e_2}^2 \quad (23)$$

The above expression, determines the control law that ensures the asymptotic convergence of the errors (e_1,e_2) to 0, which implies that V_{pv} converges asymptotically to the origin $V_{réf}$.

The main result of the proposed backstepping controller is summarized in the following theorem.

- Theorem: consider the closed-loop system consisting of the controlled system of Figure 3 represented by its nonlinear model (2) and the controller composed of the control law (22), Then, one has:
  a. The closed loop system is globally asymptotically stable, it follows that all closed loop signals are bounded and
  b. The tracking errors $\mathrm{e}=[\mathrm{e}_1,\mathrm{e}_2]$ converges to zero implying MPPT achievement.

5. GLOBAL MPPT ALGORITHMS UNDER PSC

Because the MPPT control system is a critical component of solar power generation systems, a variety of conventional and non-traditional MPPT algorithms. So therefore, have been tested in a variety of situations and environments.

5.2. Improved variable step P&O and global scanning (VSP&O/GS) algorithm

The VSPO&GS algorithm illustrated in the Figure 5, uses a global scanning approach to manage the multiple-peak MPPT of a PV array as irradiance varies (shading case). To determine the MPP, the VSPO&GS algorithm first employs the VSP&O method in Figure 6. The initial peak's power U_1, is recorded as P_{max}. The search continues until the power of the last peak is located, and each time the power recorded as MPP is compared with the new one found, it is updated to the maximum power point [13]. Since the power output varies depending to the irradiance, The VSPO&GS algorithm must be restarted so that the solar system may recover the MPP when the irradiation changes. As a result, the restart conditions are as shown in:

$$|\mathrm{P_r}-\mathrm{P}| > \mathrm{Q} \quad (24)$$

where: P_r is the output power of the photovoltaic panel operating in real time, P is the recorded power and Q is obtained when the shade circumstances vary, the variance in power must be more than the constant Q.

5.3. Particle swarm optimization algorithm

The particle swarm optimization (PSO) technique, created by Eberhart and Kennedy in 1995 [23],is an innovative, simple, and efficient meta-heuristic technique. This approach uses a collection of particles to solve issues in complicated and nonlinear systems [14]. Each particle is thoroughly described in this method based on its position and speed. The behavior of each particle is influenced by the movement of the particles around it (neighboring particles) as stated in Figure 7.

The particles update their accelerations and positions ,when the optimal solutions are found according to the equations given below [24], [25]:

$$x_i^{k+1}=x_i^k+a_i^{k+1} \quad (25)$$

$$a_i^{k+1}=wa_i^k+m_1r_1^k\left({P_{best}}_1^k-x_i^k\right)+m_2r_2^k\left({G_{best}}_i^k-x_i^k\right) \quad (26)$$

where a_i^k is the acceleration of particle i after k times of Iterations, w is the inertia weight, m_1 and m_2 are the acceleration coefficients for moving to each individual or global between]0 ; 2.05], respectively r_1 and r_2 are random numbers between 0 and 1 [25]. The particle swarm location and fitness are used in this study as the PV system's duty cycle and power production, respectively. When the stopping requirement is met, the PSO-based tracker comes to a halt and provides the best duty cycle corresponding to the total power[16]. Figure 8 illustrates PSO's flowchart.

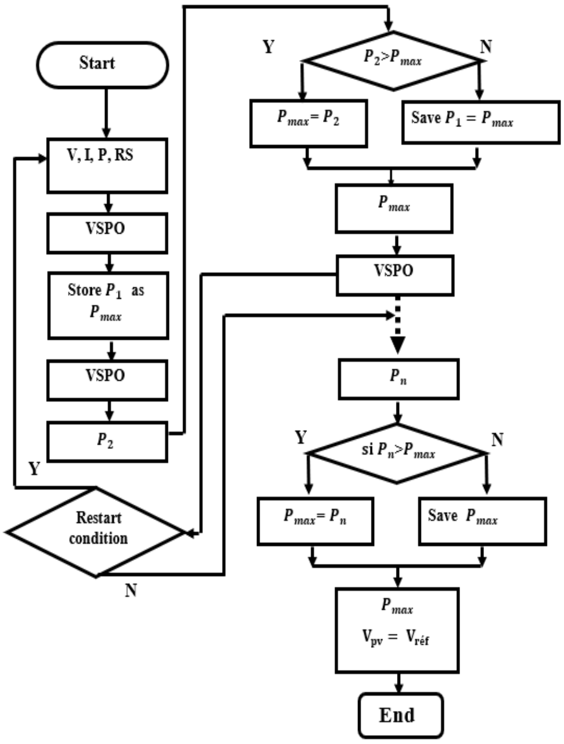


Figure 5. Flowchart for improved VSP&O and global scanning algorithm (VSP&O/GS)

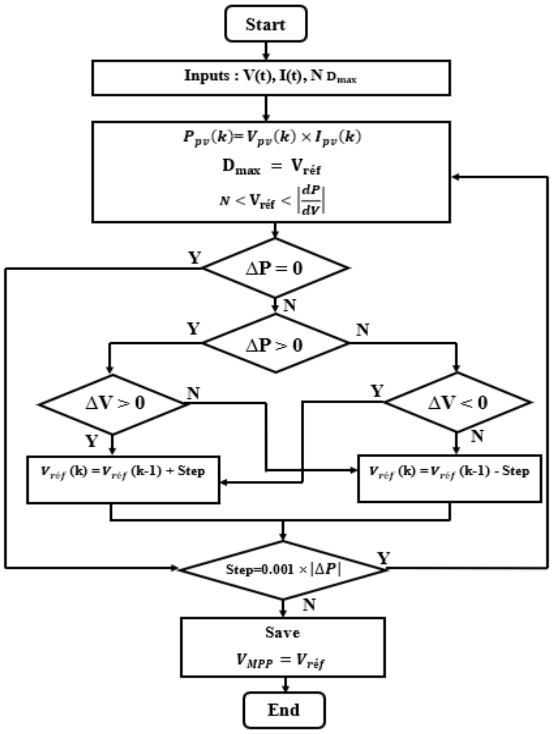


Figure 6. Flowchart for variable step P&O algorithm (VSP&O)

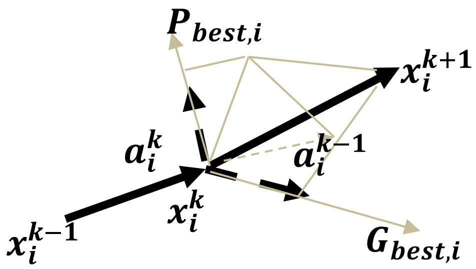


Figure 7. Movement of particles in a search space

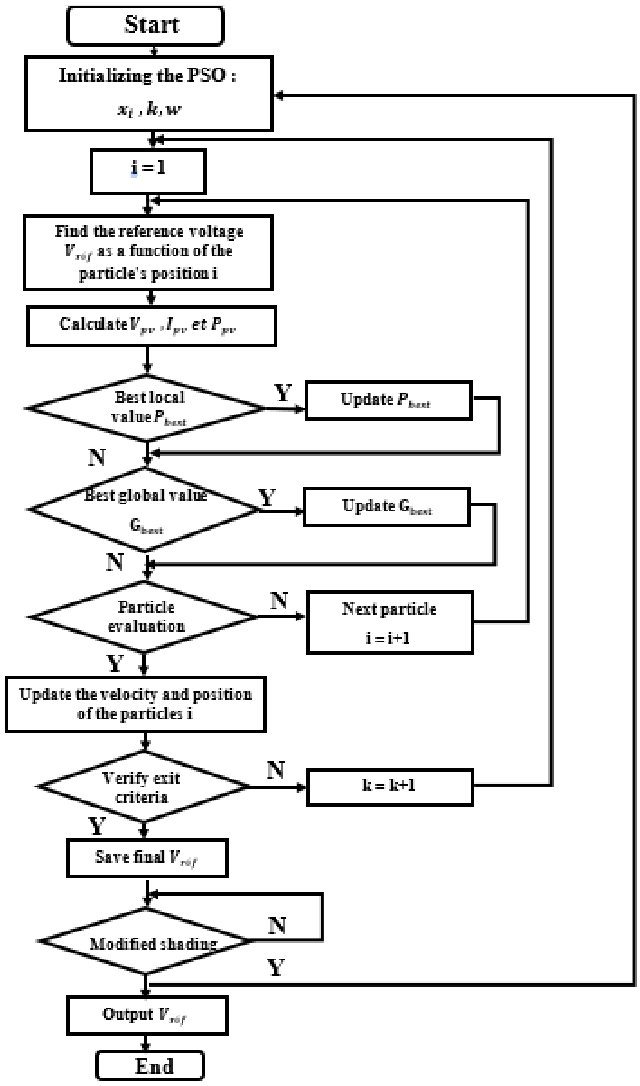


Figure 8. Flowchart of the PSO algorithm

6. SIMULATION RESULTS, DISCUSSION AND COMPARISON

6.1. Simulation results and discussion

The experimental setup is described by Figure 4, the nonlinear backstepping control law (22) will be now evaluated by simulation. It worth noting that the parameter $V_{réf}$ involved in (11) and (12) is generated using PSO and VSP&O/GS algorithms with the block diagram illustrated by Figure 9. The major properties of the completely loaded components at a temperature of 25 °C are presented in Table 2.

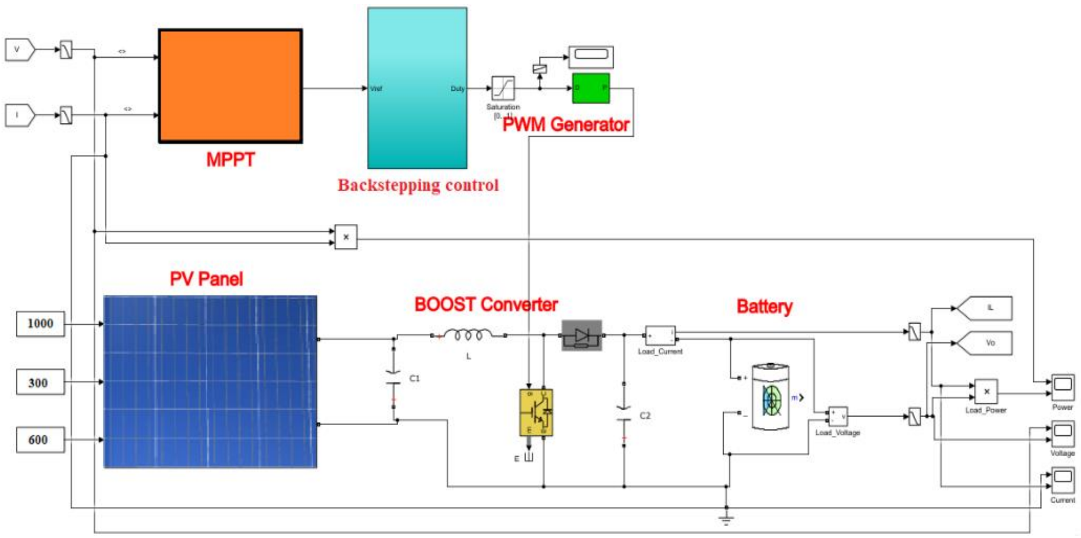


Figure 9. MATLAB/Simulink model of PV system

The indicated values in Table 2 of design parameters (K_1, K_2). Have been selected using a try –and-error search method and proved to be suitable. To get the desired output voltage and current, PV modules are connected in series and parallel to form a PV array, the configuration considered in this paper, consists of three PV modules connected in series and each model has 20 cells. In typical PSC. The corresponding PV curve is depicted in Figure 1(b), this curve has three peaks with the GMPP of 104 Watts, the specifications of single PV module used are given in Table 1. The partially shaded PV solar system has been tested with two maximum power point algorithms mentioned previously (PSO and VSP&O/GS). The simulation time has been kept short to demonstrate the response time of the algorithms and controllers under consideration.

Table 2. The DC/DC boost converter, lead acid battery and backstepping control parameters

Parameters	Nomenclature	Values
Input Capacitor	C_1	1000µF
Output capacitance	C_2	10 µF
Inductance	L	3 mH
Switching frequency	S	10 KHz
Internal resistor	R_{Bat}	68.571 mΩ
Nominal voltage	E_{Bat}	48 V
Design parameter	K_1	0,05
Design parameter	K_2	0,0001

Simulation results under partial shading conditions given by PSO and VSP&O/GS as shown in Figure 10. Figure 10(a) shows the perfect MPPT in the presence of radiation step changes while the temperature is kept constant equal to 298.15 K (25 °C). The radiation variation profile presented in this document is illustrated in Figure 10(b), the photovoltaic field is subjected to three levels of radiation Irr1: 1000 W/m², Irr2: 300 W/m², Irr3: 600 W/m². It is worth nothing that these changes are very abrupt which is not realistic in practical case. But that show a good robustness of the proposed controller to achieve the MPPT objective. It can be seen from Figure 10(a) that the power extracted from the PV panel is always maximal regardless to radiation values. Indeed, the captured PV power P achieves the values 103,4W given by the PSO algorithm and 93,84W find by the VSP&O/GS algorithm, corresponding to the associated MPP.

Figure 10(c) shows the resulting optimal voltage reference given by the two studied algorithms (PSO and VSP&O/GS) and measured photovoltaic voltage V_{pv}. It is clearly seen that the voltage reference $V_{réf}$ varies significantly in function of the radiation, V_{pv} track quickly its reference after each change in $V_{réf}$. In both scenarios it can be seen that the MPP voltage is reduced from 21V to 19V to operate the system in the GMPP region. Figure 10(d) show the Battery voltage, Figure 10(e) show the PV Current Figure 10 (f) show that the signal control d varies as a function of the simulated radiation profile and still all time between 0 and 1.

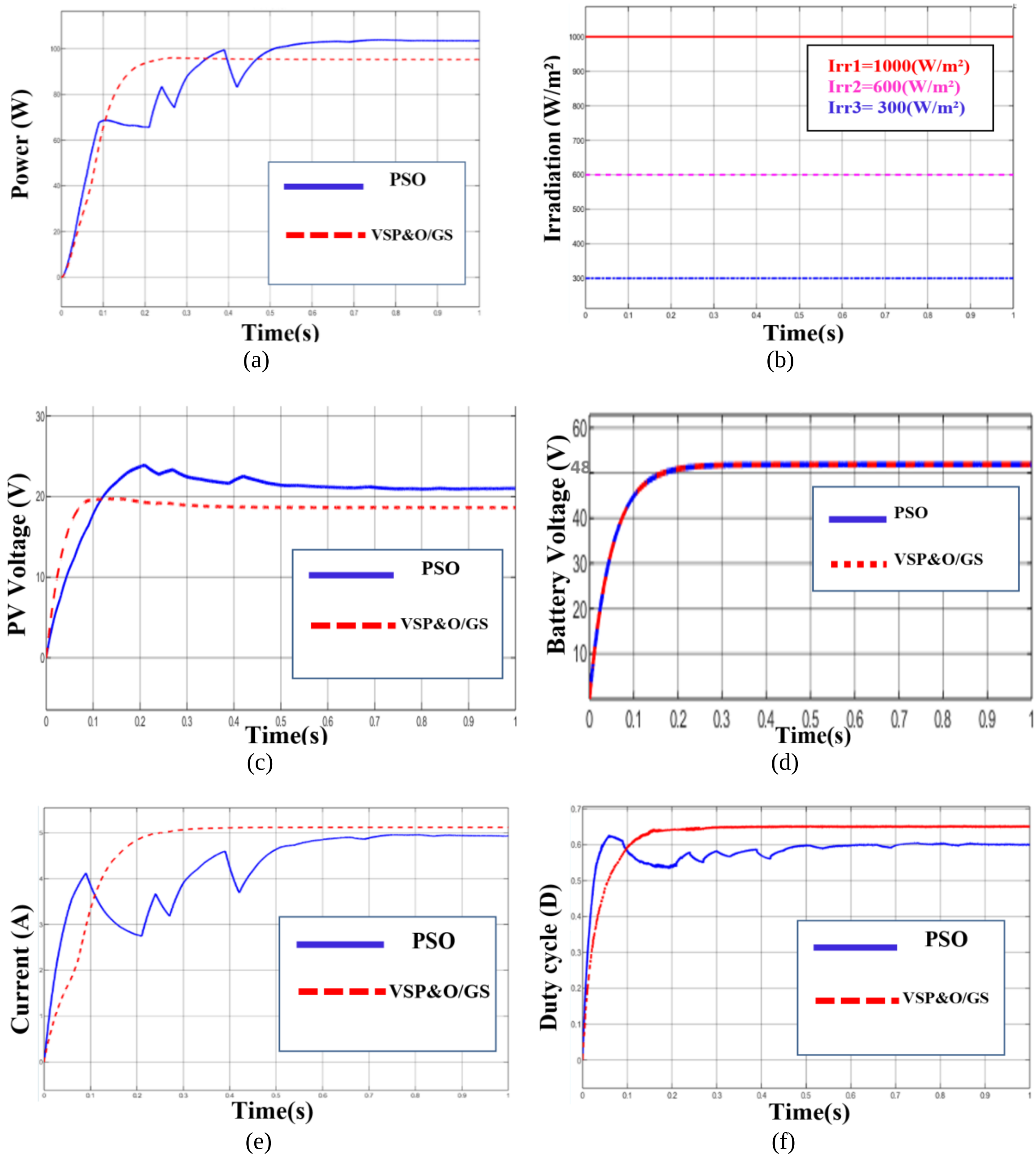


Figure 10. Simulation results under partial shading conditions given by PSO and VSP&O/GS of: (a) PV power, (b) irradiance profile, (c) PV voltage, (d) battery voltage, (e) PV current, and (f) duty cycle

7. CONCLUSION

In order to optimize PV systems with high performance, this study presents a modeling and simulation of maximum power point tracking based on a backstepping controller under partial shading weather circumstances. In a PV storage system, a comparison of the two MPPT maximum power point trackers: PSO and VSP&O/GS was conducted. The backstepping controller analysis is used to control the voltage supplied by the Boost DC/DC converter based on the reference provided by the MPPT algorithm in order to verify the PV system's global asymptotic stability. Both algorithms with the backstepping controller are efficient and robust, with the PSO algorithm showing a significant improvement. The quality of the accuracy in reaching the maximum power point, on the other hand, is the quality of the both techniques.

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