GLOBAL MAXIMUM POWER POINT TRACKING EXTRACTION IN PHOTOVOLTAIC SYSTEMS USING PARTICLE SWARM OPTIMIZATION UNDER PARTIAL SHADING CONDITIONS

EXTRAGEREA PUNCTULUI GLOBAL DE PUTERE MAXIMĂ ÎN SISTEME FOTOVOLTAICE UTILIZÂND OPTIMIZAREA CU ROI DE PARTICULE ÎN CONDIȚII DE UMBRIRE PARȚIALĂ

Kamal BOUJAGHAMA[1], Essadike ZAITA[2], Youssef EL BID[1], Rachid OUALAID[1], Naoufel KHALDI[2] , Rachid MARKAZI[1], and Najib EL BIAZE[6]

Abstract: *In recent years, photovoltaic (PV) energy systems have been largely expanded, thanks to advances in technology, the gradual decrease whether in installation or maintenance costs. According to the literature, Numerous maximum power point tracking (MPPT) techniques have been proposed to enable PV systems to operate at their MPP. However, under complex environmental conditions such as partial shading, PV characteristics become more complex, exhibiting multiple local maxima instead of a single global maximum. Conventional MPPT methods often fail to identify the global maximum power point (GMPP) in such scenarios. In order to improve MPPT extraction and to increase accuracy of the MPP tracking in PV systems, we*

[1]PhD student at Faculty of Science Agadir, Morocco, email: kamal.boujaghama@edu.uiz.ac.ma, *ORCID ID(0009-0004-5702-5505)*
[1]PhD student at Mohammed V University, Morocco, email: essadike_zaita@um5.ac.ma *ORCID ID (0009 0001 6058 0778)*
[2]PhD student at Faculty of Science Agadir, Morocco, email: youssef.elbid@edu.uiz.ac.ma *ORCID ID (0009 0009 8232 3148)*
[1]PhD student at Faculty of Science Agadir, Morocco, email: rachid.oulaid@edu.uiz.ac.ma *ORCID ID (0009 0006 0586 9209)*
[3]Prof., PhD., Higher School of Technology Guelmim,Morocco, email: n.khaldi@uiz.ac.ma *ORCID ID (0000 0003 1839 4434)*
[1]Prof., PhD., Higher School of Technology Guelmim,Morocco, email: r.markazi@uiz.ac.ma *ORCID ID (0009 0000 3670 0189)*
[4]Prof., PhD., Higher School of Training Agadir,Morocco, email: n.elbiaze@uiz.ac.ma *ORCID ID (0009 0006 7760 6862)*

propose in the present work two different optimization-based approaches namely, the Perturb and Observe (P&O) and Particle Swarm Optimization (PSO) technique. In this context, by assessing both approaches under various partial shading conditions, we use MATLAB/Simulink to evaluate and compare their effectiveness.

Keywords: Partial shading, MPPT, Perturb and Observe, Particle Swarm Optimization

Rezumat: *În ultimii ani, sistemele de energie fotovoltaică (PV) s-au extins considerabil datorită progreselor tehnologice și scăderii treptate a costurilor de instalare și întreținere. Conform literaturii, numeroase tehnici de urmărire a punctului de putere maximă (MPPT) au fost propuse pentru a permite sistemelor PV să funcționeze la punctul lor de putere maximă (MPP). Cu toate acestea, în condiții de mediu complexe, cum ar fi umbrirea parțială, caracteristicile PV devin mai complexe, prezentând mai multe maxime locale în loc de un singur maxim global, iar metodele convenționale MPPT eșuează adesea în identificarea punctului de putere maximă global (GMPP) în astfel de situații. Pentru a îmbunătăți extracția MPPT și a crește acuratețea urmăririi MPP în sistemele PV, propunem în această lucrare două abordări diferite bazate pe optimizare, și anume tehnica Perturb and Observe (P&O) și algoritmul Particle Swarm Optimization (PSO). În acest context, prin evaluarea ambelor abordări în diverse condiții de umbrire parțială, utilizăm MATLAB/Simulink pentru a evalua și compara eficiența acestora.*

Cuvinte cheie: Umbrire parțială, MPPT, Perturb and Observe, Optimizarea cu roi de particule

1. Introduction

Solar photovoltaic (PV) technology has become a promising renewable energy solution due to its environmental advantages, decreasing installation costs, contributing to reduce greenhouse gas emissions and dependence on fossil fuels[1], [2]. However, several challenges still limit their overall performance, including relatively low energy conversion efficiency and high initial investment costs. Consequently, efforts are focused on enhancing system efficiency, improving reliability, and optimizing energy harvesting under various operating conditions. Moreover, it is well established that the output power of PV systems is highly sensitive to environmental factors, particularly solar irradiance and temperature variations, which directly influence their electrical chcaracteristics.[3].

In order to improve the efficiency of the PV systems. The MPPT techniques was adopted to to continuously adjust the MPP of the PV generator so that it extract the maximum available power under changing environmental conditions. Under fixed irradiance, the power–voltage (P–V) characteristic typically presents a single distinct MPP. However, in real conditions, PV systems are often subjected to non-uniform conditions such as partial shading caused by clouds, nearby obstacles, or dust accumulation. Under such conditions, the P–V characteristic becomes more complex and exhibits multiple local maxima instead of a single peak [4]. This nonlinearity increases the difficulty of accurately tracking the global maximum power point and may lead to significant power losses if not properly addressed.

According to the literature, several MPPT techniques are adopted, among them Conventional methods such as Perturb and Observe and Incremental Conductance[5]. These techniques are simple to implement and have low computational requirements. Nevertheless, their performance can be limited in the presence of rapid environmental changes or multiple power peaks, where they may converge to a local maximum instead of the GMPP[6]. For this reason, more advanced approaches have been developed, including intelligent control techniques and optimization-based algorithms. Among them, Consequently, more advanced methods, including intelligent and optimization-based techniques such as fuzzy logic control[7], Artificial Neural Network[8], Particle Swarm Optimization [9] and metaheuristic algorithms, have been developed to enhance tracking accuracy and robustness under complex operating scenarios.

In this context, the objective of this work is to enhance the extraction of maximum power from PV systems operating under varying irradiance conditions, particularly in the presence of partial shading. Two MPPT strategies, namely P&O and PSO, are implemented and comparatively analyzed under different environmental scenarios using MATLAB/Simulink.

This paper is organized into 5 sections. Section II introduces the mathematical modeling of the PV system. Section III describes the MPPT techniques employed. Section IV discusses the simulation results and analyzes the performance of the proposed methods. Finally, the conclusions are drawn in the last section.

2. Modeling of the PV system

2.1. Photovoltaic cell

The PV system model developed in MATLAB/Simulink consists of a PV generator interfaced with a DC/DC SEPIC (single ended primary inductor converter). This converter is employed to implement and evaluate the performance of two MPPT controllers. Both control strategies are integrated within the SEPIC converter to ensure optimal power extraction from the PV system. The PV generator is modeled using the two-diode model, with its parameters extracted using a hybrid parameter extraction method [10] applied to define the parameters of the PV module

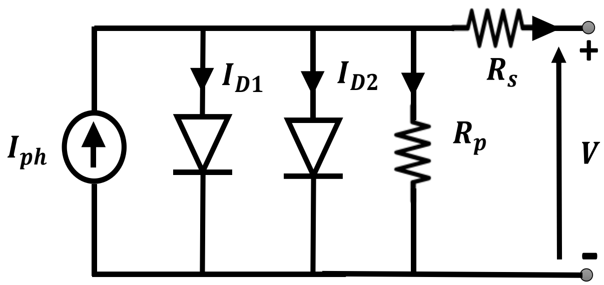

Figure 1. Equivalent circuit of a solar cell using the double diode model.

The current generated by the PV module can be expressed as:

$$I = I_{ph} - I_{D1} - I_{D2} - \frac{V + R_S I}{R_P} \tag{1}$$

V and I represent the output current and voltage of PV module, respectively, I_{ph} denotes the photocurrent generated by solar irradiation, while I_{D1} and I_{D2} correspond to the currents flowing through diode 1 and diode 2. The diode currents are given by:

$$I_{D1} = I_{01}\left(exp\left(\frac{V + R_S I}{a_1 V_{th}}\right) - 1\right) \tag{2}$$

$$I_{D2} = I_{02}\left(exp\left(\frac{V + R_S I}{a_2 V_{th}}\right) - 1\right) \tag{3}$$

Substituting Equations (2) and (3) into Equation (1) leads to :

$$I = I_{ph} - I_{01}\left(exp\left(\frac{V + R_S I}{a_1 V_{th}}\right) - 1\right) - I_{02}\left(exp\left(\frac{V + R_S I}{a_2 V_{th}}\right) - 1\right) - \frac{V + R_S I}{R_P} \quad (4)$$

In this study, the KC200GT PV module is chosen due to its suitable electrical characteristics, which make it appropriate for modeling and evaluating the performance of the proposed PV system. The module has a maximum power of 200 W, a voltage at MPP of 26.35 V, and a current of 7.59 A. The main electrical characteristics and technical specifications of the KC200GT module are presented in *Table 1*.

Table 1. **Electrical charcterististics of KC200GT module**

Maximum Power in [W]	**Current at maximum power in [V]**	**Voltage at maximum power in [V]**	**Short circuit current in [A]**	**Open circuit voltage in [V]**
200	7,59	26,35	8,21	32,9

2.2. SEPIC Converter

The electrical circuit of the SEPIC converter is presented in Figure 2.

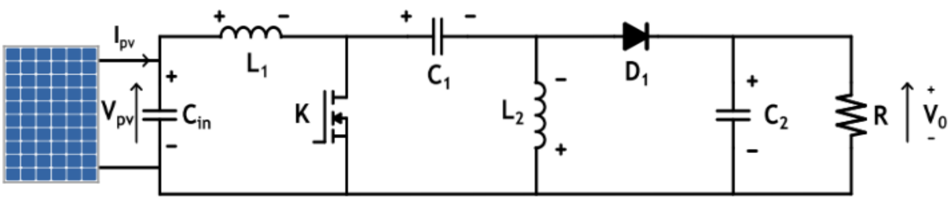

Figure 2. SEPIC converter coupled with PV system

The SEPIC converter performs DC–DC voltage conversion by transferring energy between the inductive elements L1 and L2 and the coupling capacitor C1. The amount of transferred energy is controlled by a MOSFET. According to [11], the dynamic behavior of the SEPIC converter can be described by the following mathematical equations:

$$\frac{dV_{pv}}{dt} = \frac{I_{pv}}{C_{in}} - \frac{I_{L1}}{C_{in}} \quad (5)$$

$$\frac{dV_{C1}}{dt} = \frac{(1-u)I_{L1}}{C_1} + \frac{dI_{L_1}}{C_1} \tag{6}$$

$$\frac{dV_0}{dt} = \frac{(1-u)\left(I_{L_1} + I_{L_2}\right)}{C_2} - \frac{V_0}{RC_2} \tag{7}$$

where $\boldsymbol{V_{pv}}$ and $\boldsymbol{I_{pv}}$ are the voltage and current provided by the PV generator, respectively. $\boldsymbol{C_{in}}$ is the input capacitance of the SEPIC converter, while $\boldsymbol{I_{L_1}}$ and $\boldsymbol{I_{L_2}}$ represent the currents through inductors $\boldsymbol{L_1}$ and $\boldsymbol{L_2}$, respectively. $\boldsymbol{V_{C1}}$ is the voltage across the coupling capacitor $\boldsymbol{C_1}$, and $\boldsymbol{C_2}$ denotes the output capacitance. $\boldsymbol{V_0}$ represents the output voltage of the converter, R is the load resistance, and u is the duty cycle of the MOSFET. The variable trepresents time.

3. Maximum Power Point Tracking Methods

Using MPPT techniques with DC-DC converter can allow the PV system to operate continuously at its maximal operating point, even under varying environmental conditions, including partial shading conditions. In this study, two MPPT methods are employed, namely the P&O and the PSO technique. Photovoltaic systems have nonlinear electrical characteristics, and their MPP changes continuously with variations in solar irradiance and temperature. Therefore, MPPT techniques are required to adjust the operating point of the PV generator and maximize the extracted power under different operating conditions. A DC/DC converter is generally used as an interface between the PV generator and the load, allowing the operating voltage and current to be controlled according to the MPPT algorithm.

Under uniform irradiance conditions, the PV power-voltage characteristic generally presents a single MPP. However, partial shading conditions can produce multiple local maximum power points, among which only one corresponds to the GMPP. This makes the tracking process more challenging and may lead conventional MPPT techniques to converge to a local maximum. Therefore, effective MPPT methods are needed to achieve accurate GMPP tracking with fast convergence and reduced power oscillations.

In this paper, we compare two MPPT techniques, namely the conventional Perturb and Observe method and the optimization-based Particle Swarm Optimization technique. Their flowcharts and implementation for PV systems are presented, followed by a comparative evaluation of their tracking performance under different operating conditions.

3.1. Perturb and Observe

The P&O technique [12] is based on applying a small change or perturbation to the voltage and observing the resulting variation in the output power. The current operating point is compared with the previous one to determine the effect of the applied perturbation.

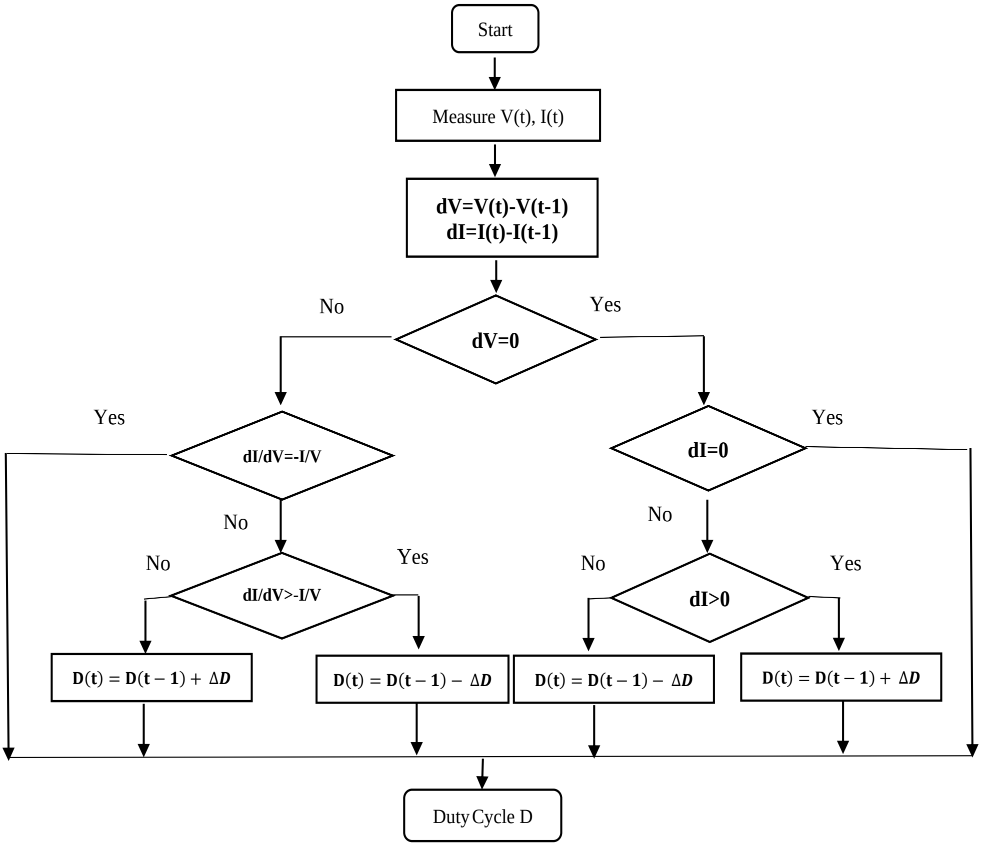

Figure 3. P&O method's flowchart

If the power increases after the voltage perturbation, the operating point is considered to be moving toward the MPP, and the voltage is perturbed further in the same direction. In contrast, a reduction in the output power indicates that the previous voltage perturbation has moved the operating point away from the optimum, and the direction of the voltage variation is therefore reversed. This adjustment is repeated to progressively bring the operating point toward the MPP. Once the optimum is reached, the operating point fluctuates slightly around it due to the continuous voltage perturbations. Therefore, the perturbation step size plays an important role in the tracking performance. A larger step enables faster convergence but results in greater power oscillations, whereas a smaller step reduces these oscillations at the expense of a slower response [13].

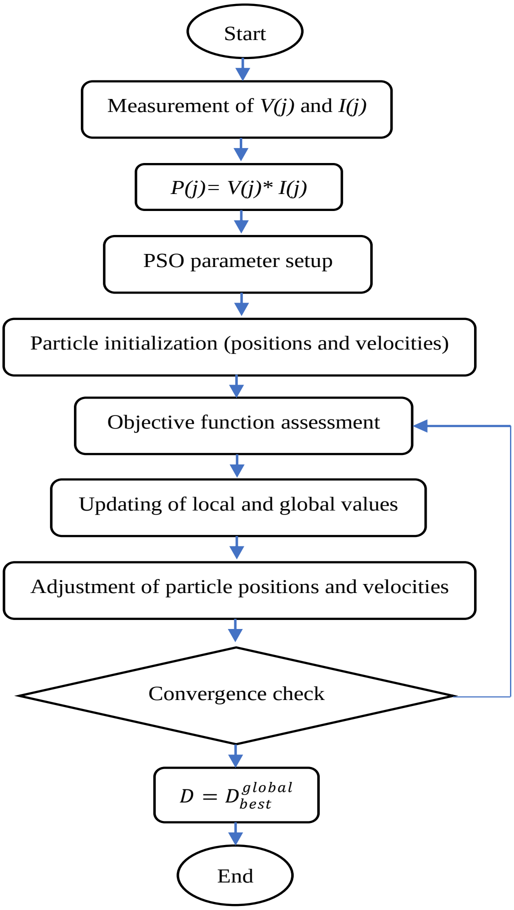

Figure 4. PSO method's flowchart

3.2. Particle Swarm Optimization

The PSO algorithm[14] presents the collective behavior observed in groups of animals such as bird flocks. The particles are randomly distributed in the search space and iteratively updates their positions to approach the optimal solution. The displacement of each particle follows simple interaction rules, leading to a progressive convergence toward the global optimum. This method is based on the concept of swarm intelligence [15].

$$V_j^{k+1} = \omega v_j^k + c_1 rand_1\left(P_{jbest} - x_j^k\right) + c_2 rand_2\left(G_{best} - x_j^k\right) \tag{8}$$

$$P_j(t+1) = P_j(t) + V_j(t+1) \tag{9}$$

where V_j^{k+1} is the speed, P_{jbest} represents the best position of the particle, G_{best} is the best global position, ω is the inertia weight, x_j^k is the particle position, c_1 and c_2 are the acceleration coefficients.

4. Results and Discussion

The proposed PV system consists of 3 modules of KC200GT, a SEPIC converter, and an MPPT control techniques, developed using MATLAB/ Simulink software. The performance of the MPPT techniques was investigated under three different partial shading profiles in order to analyze their behavior.

Under these conditions, the power-voltage characteristics reflects the effect of non-uniform irradiance on the PV output, as multiple local maxima appear along the curve as shown in the scenario 1 illustrated in Figure 5. According to the results obtained in Figure 6 and Figure 7, P&O demonstrates more stability with a better response faster than PSO method. In the other hand, PSO show the ability to achieve the GMPP, reaching a power of 257W, while P&O is limited to a local maximum of approximately 200W.

The PV module’s electrical behavior is affected by the environmental conditions, especially under varying temperature and irradiance. In Figure 6, increasing temperature leads to a reduction in open-circuit voltage and maximum power, while the current remains nearly unchanged at constant irradiance. In Figure 7, higher irradiance levels result in a significant increase in current and output power, with only a slight effect on voltage. These results highlight that temperature mainly influences voltage, whereas irradiance primarily affects current and power generation.

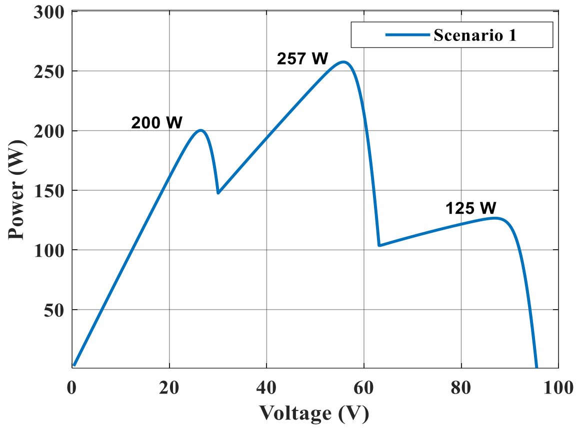

Figure 5. Proposed P-V characteristics of scenario 1 under partial shading conditions

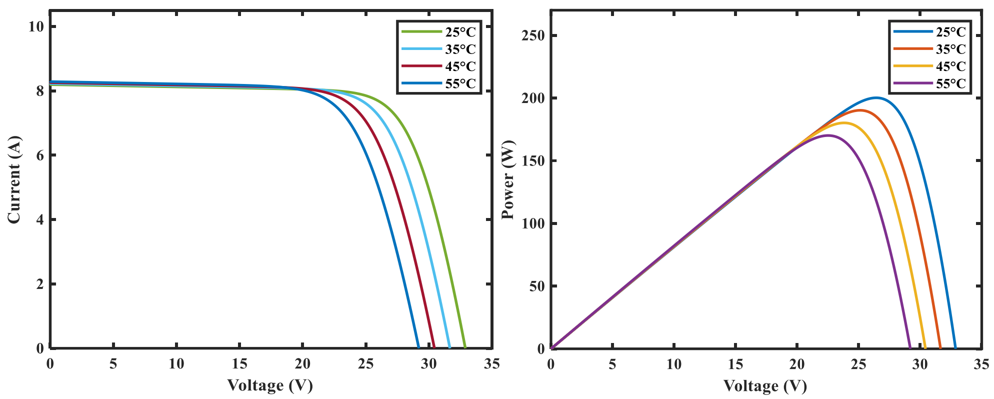

Figure 6. Influence of temperature on I–V and P–V characteristics at 1000 W/m².

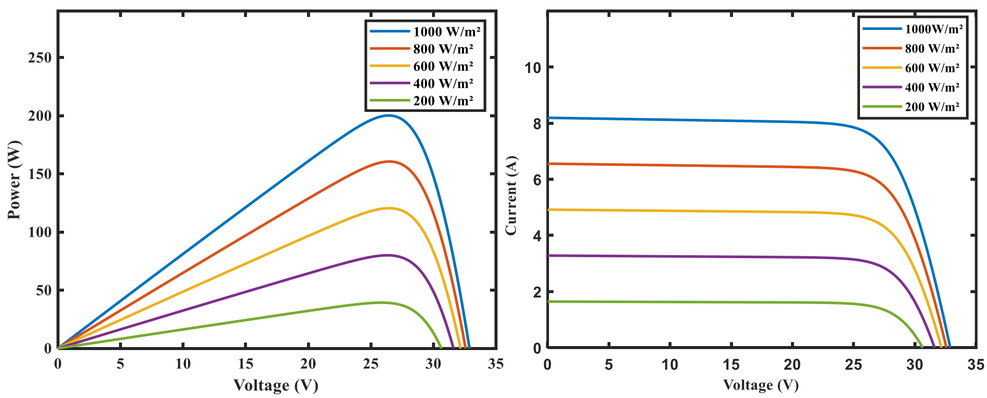

Figure 7. Influence of irradiance on P–V and I–V characteristics at 25°C

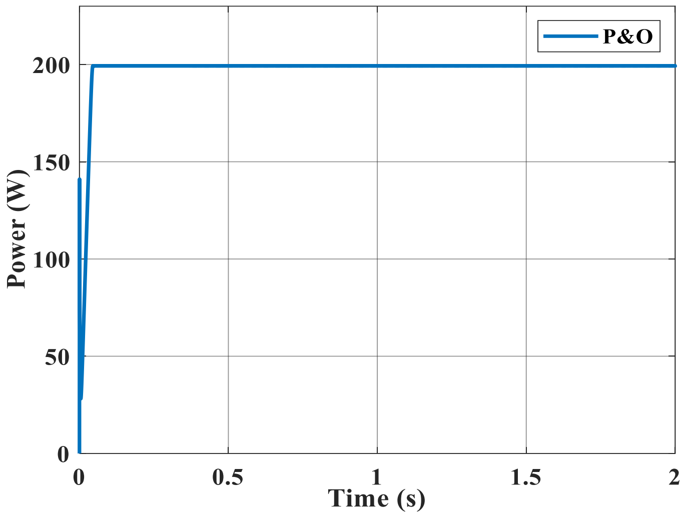

Figure 8. Power extracted by P&O in partial shading conditions of scenario 1

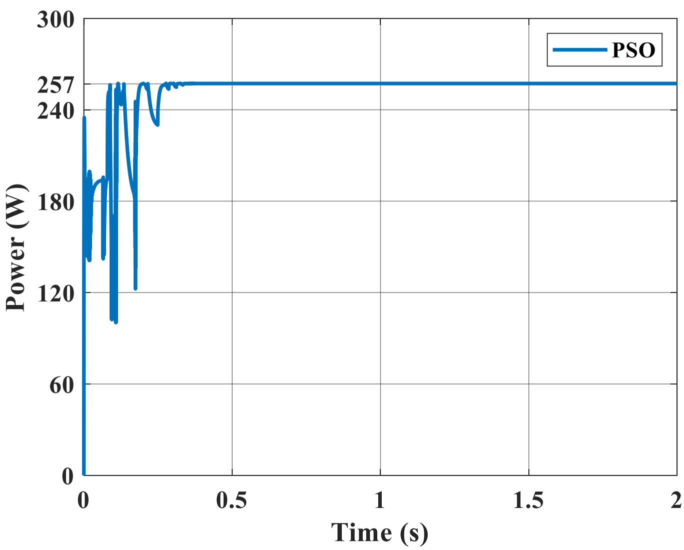

Figure 9. Power extracted by PSO in partial shading conditions of scenario 1

For Scenario 2 and scenario 3, which are shown in Figure 10 and Figure 13, different partial shading patterns are applied. The results shown in Figure 11 and Figure 14 confirm that the P&O technique tracks the first encountered peak and remains trapped at a local maximum. In contrast, the PSO method successfully identifies the GMPP, ensuring higher power extraction under these conditions.

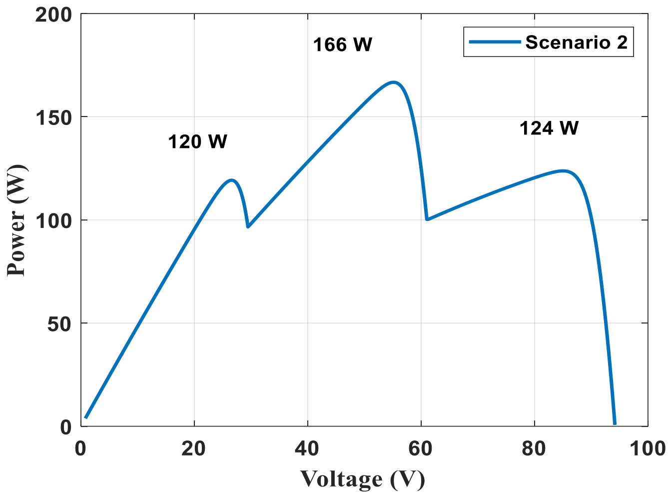

Figure 10. P-V characteristics of scenario 2 under partial shading conditions

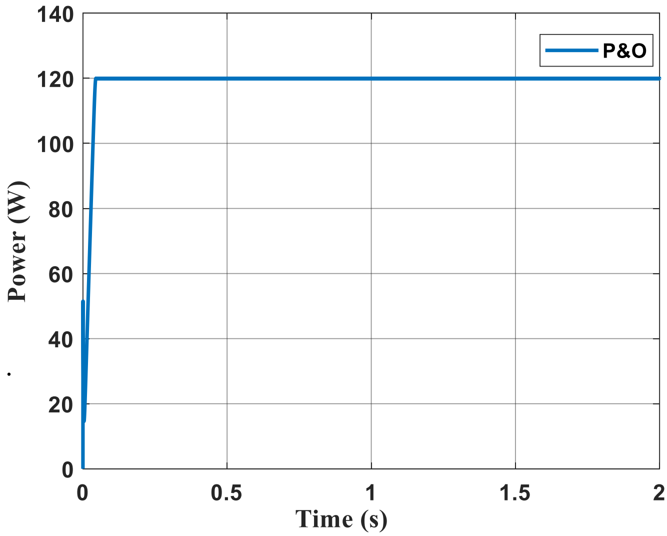

Figure 11. Power extracted by P&O in partial shading conditions of scenario 2

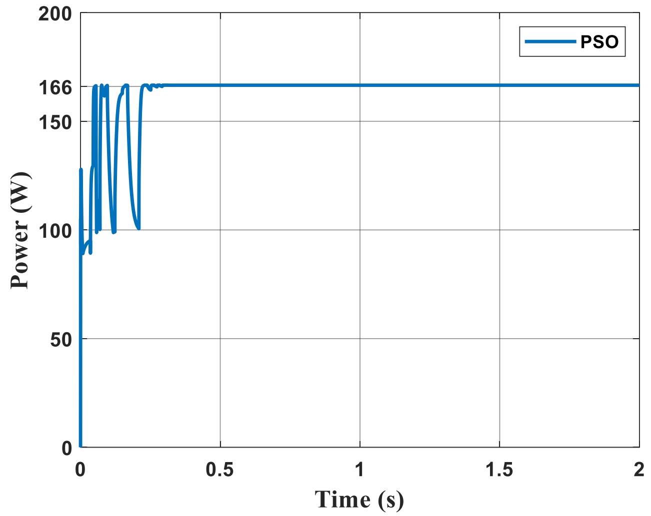

Figure 12. Power extracted by PSO in partial shading conditions of scenario 2

Overall, the results indicate that the P&O method converges to the first local maximum due to its inability to identify the GMPP. In contrast, the PSO technique successfully tracks the global maximum.

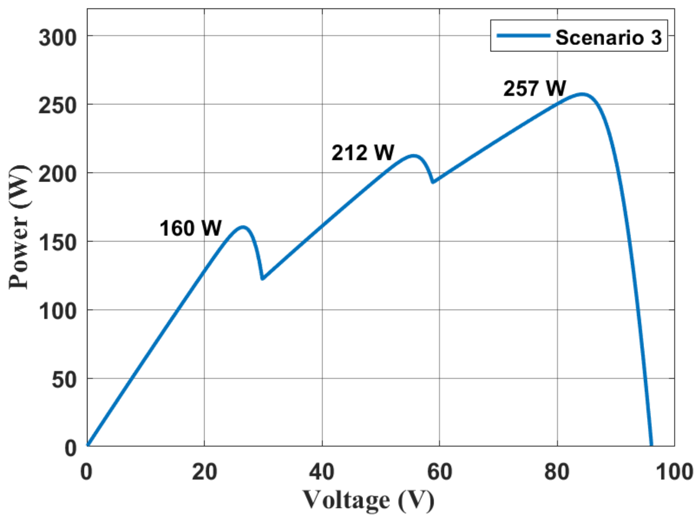

Figure 13. P-V characteristics of scenario 3 under partial shading conditions

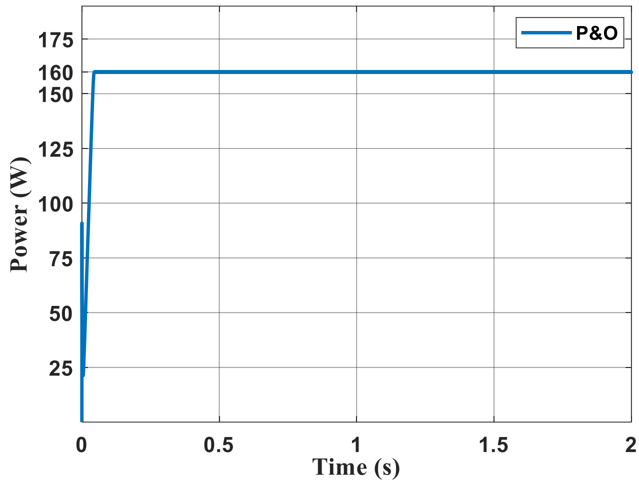

Figure 14. Power extracted by P&O in partial shading conditions of scenario 3

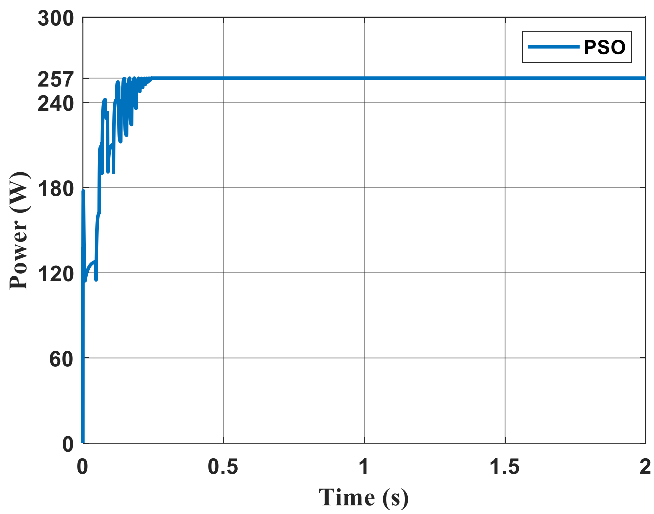

Figure 15. Power extracted by PSO in partial shading conditions of scenario 3

To further assess the tracking performance of the two MPPT techniques under partial shading conditions, the extracted power obtained in the three investigated scenarios is compared in *Table. 2*. In Scenario 1, with irradiance levels of [1000, 600, 200] W/m², the P&O and PSO methods extract 200 W and 257 W, respectively. Thus, PSO extracts 57 W more than P&O,

corresponding to an improvement of approximately 28.5%. In Scenario 2, with irradiance levels of [200, 600, 400] W/m², the extracted power increases from 120 W with P&O to 166 W with PSO, representing an improvement of approximately 38.3%. The largest improvement is observed in Scenario 3, where the irradiance levels are [400, 500, 800] W/m². In this case, PSO extracts 257 W compared with only 160 W for P&O, corresponding to an increase of 97 W, or approximately 60.6%. These results show that the advantage of PSO becomes more significant as the shading pattern becomes more challenging. Overall, the PSO-based approach achieves higher extracted power in all investigated scenarios, demonstrating its better capability to identify the GMPP under partial shading conditions compared with the conventional P&O method.

Table 2. **Extracted power of PSO and P&O**

Scenarios N°	**Irradiation (W/m²)**	**MPP and GMPP (W)**	
		P&O	**PSO**
1	[1000 600 200]	200	257
2	[200 600 400]	120	166
3	[400 500 800]	160	257

5. Conclusions

In this paper, we evaluate two MPPT techniques, namely the P&O and the PSO-based approach, under critical operating conditions characterized by partial shading, which represents a major challenge for PV systems due to the presence of multiple local maxima on the P-V characteristic. The obtained results demonstrate that the PSO algorithm provides higher tracking accuracy and improved stability compared to P&O technique, with a better ability to identify the GMPP under complex shading scenarios where traditional methods converge to local maxima. In addition, PSO achieves high efficiency in all scenarios, proving its robustness and effectiveness under variable environmental conditions.

As future work, we aim to implement the investigated MPPT strategies on a real-time experimental PV platform to validate the obtained simulation results under practical operating conditions. The experimental tests will consider different irradiance and temperature variations, as well as complex partial shading patterns, in order to further assess the tracking accuracy, stability, convergence speed, and efficiency of the different approaches. In addition, future research will focus on improving the computational efficiency of the optimization-based MPPT methods and assessing their implementation on embedded real-time control platforms. This experimental validation will provide a better assessment of the practical feasibility and robustness of the investigated MPPT strategies.

R E F E R E N C E S

[1] Y. E. Bid *et al.*, "Study of the stability, electronic and optical properties of the copper-based perovskite CuSrX3 (X = F, Cl, Br and I): DFT analysis," *Indian J Phys*, vol. 100, no. 8, pp. 3157–3169, Jul. 2026, doi: 10.1007/s12648-026-04010-x.

[2] M. Chahboun *et al.*, "Analysis of Control Strategy Development: Backstepping and Classical Regulators for Power Regulation in a Wind Turbine System," *Journal of Robotics and Control (JRC)*, vol. 7, pp. 3333–3342, Mar. 2026, doi: 10.18196/jrc.v7i1.27077.

[3] O. Bamisile, C. Acen, D. Cai, Q. Huang, and I. Staffell, "The environmental factors affecting solar photovoltaic output," *Renewable and Sustainable Energy Reviews*, vol. 208, p. 115073, Feb. 2025, doi: 10.1016/j.rser.2024.115073.

[4] S. S. Tyokighir, K. E. Ukhurebor, N. S. Achekuogene, Y. S. Itas, I. Odezuligbo, and I. Hossain, "Global maximum power point tracking in partially shaded photovoltaic systems using variable-size particle swarm optimisation," *Next Research*, vol. 2, no. 2, p. 100271, Jun. 2025, doi: 10.1016/j.nexres.2025.100271.

[5] K. Boujaghama, N. Khaldi, R. MARKAZI, Y. el Bid, and M. Chahboun, "COMPARATIVE PERFORMANCE ANALYSIS OF THE FUZZY LOGIC AND INCREMENTAL CONDUCTANCE MPPT TECHNIQUE IN RAPIDLY CHANGING IRRADIANCE CONDITIONS," *EMERG - Energy. Environment. Efficiency. Resources. Globalization*, vol. 11, pp. 131–148, Jan. 2026, doi: 10.37410//EMERG.2025.4.08.

[6] S. S. Tyokighir, K. E. Ukhurebor, N. S. Achekuogene, Y. S. Itas, I. Odezuligbo, and I. Hossain, "Global maximum power point tracking in partially shaded photovoltaic systems using variable-size particle swarm optimisation," *Next Research*, vol. 2, no. 2, p. 100271, Jun. 2025, doi: 10.1016/j.nexres.2025.100271.

[7] K. Boujaghama, N. Khaldi, R. Markazi, and L. Amhaimar, "Comparative Study of Fuzzy Logic, P&O, Incremental Conductance, and Artificial Neural Network MPPT Methods in Fluctuating Irradiance," *Rev.Int. Metodos. Numer. Calc. Disen. Ing.*, vol. 42, no. 1, 2026, doi: 10.23967/j.rimni.2025.10.71134.

[8] K. Boujaghama, N. Khaldi, R. Markazi, L. Amhaimar, M. Chahboun, and Y. El Bid, "Performance Comparison of Fuzzy-Logic, Incremental Conductance, and Artificial Neural Network MPPT Technique in Dynamic Solar Irradiance Environments," in *Proceedings of the 19th International Conference Inter-Eng 2025 Interdisciplinarity in Engineering Held During 3–4 October 2025*, L. Moldovan and A. Gligor, Eds., Cham: Springer Nature Switzerland, 2026, pp. 625–637. doi: 10.1007/978-3-032-17033-0_46.

[9] D. Sooriamoorthy, A. Manoharan, S. K. Sivanesan, K. L. Soon, A. C. H. Cheong, and S. K. S. Perumal, "Optimizing solar maximum power point tracking with adaptive PSO: A comparative analysis of inertia weight and acceleration coefficient strategies," *Results in Engineering*, vol. 27, p. 106429, Sep. 2025, doi: 10.1016/j.rineng.2025.106429.

[10] K. Boujaghama, E. Zaita, R. Oualaid, N. Khaldi, R. Markazi, and N. E. Biaze, “Accurate Parameter Extraction of Photovoltaic Modules Using A Hybrid Analytical-Genetic Algorithm Based on The Double Diode Model,” *E3S Web Conf.*, vol. 726, p. 01007, 2026, doi: 10.1051/e3sconf/202672601007.
[11] S. Biricik, T. Ngo, H. Komurcugil, and M. Basu, “Nonlinear control methods for single-ended primary-inductor power converters,” in *IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society*, Oct. 2017, pp. 1337–1340. doi: 10.1109/IECON.2017.8216227.
[12] A. Chellakhi, S. E. Beid, M. E. Marghichi, E. M. Bouabdalli, A. Harrison, and H. Abouobaida, “Implementation of a low-cost current perturbation-based improved PO MPPT approach using Arduino board for photovoltaic systems,” *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, vol. 10, p. 100807, Dec. 2024, doi: 10.1016/j.prime.2024.100807.
[13] T. Esram and P. L. Chapman, “Comparison of Photovoltaic Array Maximum Power Point Tracking Techniques,” *IEEE Transactions on Energy Conversion*, vol. 22, no. 2, pp. 439–449, Jun. 2007, doi: 10.1109/TEC.2006.874230.
[14] A. O. Baatiah, A. M. Eltamaly, and M. A. Alotaibi, “Improving Photovoltaic MPPT Performance through PSO Dynamic Swarm Size Reduction,” *Energies*, vol. 16, no. 18, p. 6433, Jan. 2023, doi: 10.3390/en16186433.
[15] H. Rezk, A. Fathy, and A. Y. Abdelaziz, “A comparison of different global MPPT techniques based on meta-heuristic algorithms for photovoltaic system subjected to partial shading conditions,” *Renewable and Sustainable Energy Reviews*, vol. 74, pp. 377–386, Jul. 2017, doi: 10.1016/j.rser.2017.02.051.

Acknowledgements

The authors would like to express their sincere appreciation to the Energy and Sustainable Development Research Team at Ibnou Zohr University for their valuable support and guidance throughout this work. Their expertise, resources, and ongoing encouragement played a key role in the successful completion of this study. The authors also acknowledge their strong dedication to the advancement of research in sustainable energy and development.