**International Journal of Power Electronics and Drive Systems (IJPEDS)**
Vol. 16, No. 1, March 2025, pp. 497~508
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v16.i1.pp497-508 

# A new hybrid MPPT algorithm combining P&O and fuzzy logic techniques

**Oumaima Mrhar, Khalid Kandoussi, Mohamed Eljouad**
Science Engineer Laboratory for Energy (LabSIPE), National School of Applied Sciences, Chouaib Doukkali University, El Jadida, Morocco

**Article Info**

***Article history:***

Received May 9, 2024
Revised Sep 27, 2024
Accepted Oct 23, 2024

***Keywords:***

Fuzzy logic
Maximum power point tracking
Perturb and observe
Photovoltaic
Renewable energy

**ABSTRACT**

This study introduces an innovative approach to maximum power point tracking (MPPT) in photovoltaic systems using a hybrid algorithm that combines perturb and observe (P&O) with fuzzy logic. The novelty of this work lies in the choice of input variables for the fuzzy controller, specifically dV and dP, which addresses significant challenges such as slow response to environmental condition variations and limited responsiveness under low solar irradiation. This method of MPPT is modified to make it particularly suitable for extracting peak power from photovoltaic systems. To evaluate the effectiveness of this approach, a simulation was conducted using MATLAB/Simulink software on a system comprising a photovoltaic panel connected to the new controller. Simulation results indicate that the suggested hybrid algorithm surpasses traditional methods like perturb and observe (P&O) and fuzzy logic (FL) in several ways. It notably excels in response time and tracking efficiency, achieving a remarkable success rate of 99.7% in pinpointing the maximum power point. These outcomes could significantly boost the performance of photovoltaic systems and, consequently, further the adoption of renewable energy while lessening environmental impacts.



***Corresponding Author:***

Oumaima Mrhar
Science Engineer Laboratory for Energy (LabSIPE), National School of Applied Sciences
Chouaib Doukkali University
El Jadida 24000, Morocco
Email: oumaima.mrhar@mail.com

## 1. INTRODUCTION

The global energy context is characterized by the reliance on fossil fuels, which in 2022 accounted for 79% of the global total final energy consumption (TFEC), as can be seen in Figure 1, and more than 60% of gross global electricity production [1], [2]. This consumption of non-renewables energies has caused a potential economic disruption, major pollution problems and the release of greenhouse gases responsible for climate change [3], [4]. Today, buildings accounted for 40% of energy consumption, highlighting the necessity for renewable energy sources [5]. The demand for renewable energy is driven by these environmental degradations [3], [6], [7], which constituted around 13% of worldwide TFEC and contributed to about 29.9% of global electricity production in the year 2022 [1], [2], [8].

Photovoltaic energy is emerging as among the most interesting alternative energy sources of the future; it is clean, environmentally friendly and maintenance-free [3], [9]. Solar radiation is the primary driver of physical, biological, hydrological, and agricultural operations, and the capacity of solar energy is unlimited. This energy is available in almost all localities [10]. The performance of photovoltaic energy on temperature and irradiation, which complicates the function of tracking the maximum power point or MPP, with an energy loss of up to 25% [11], [12]. For this reason, several research have been conducted to improve the overall system effectiveness [13]-[16]. these researches focus on using electronic systems to collect and convert the maximum amount of solar energy, specifically through the use of a maximum power point tracking regulator [17]-[19].

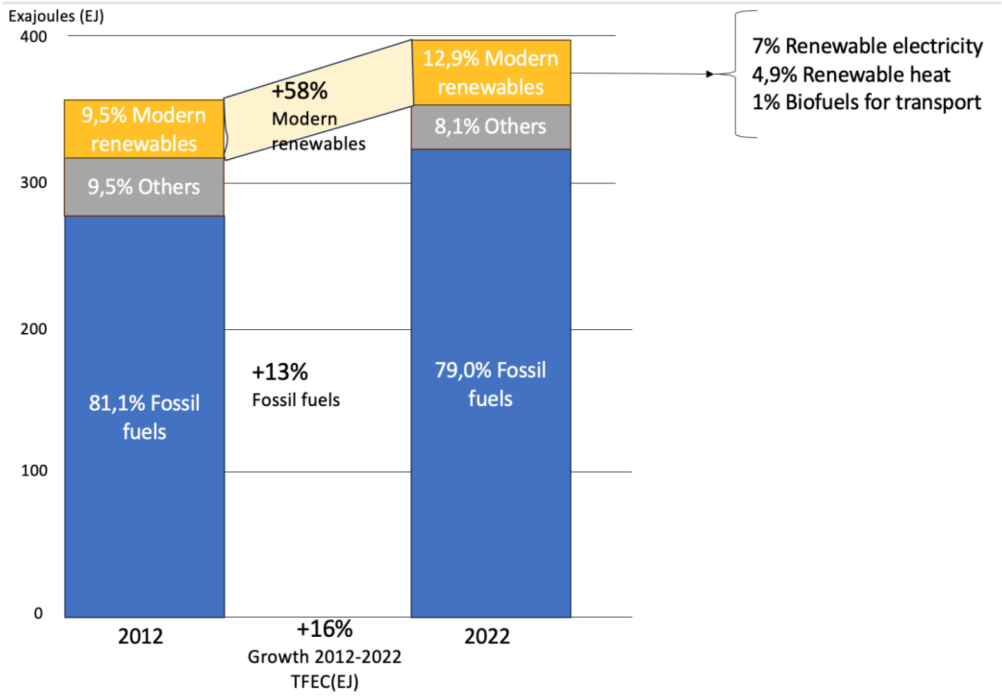


Figure 1. Total final energy consumption (TFEC) 2012-2022

In this context, a new maximum power point tracking (MPPT) algorithm is implemented incorporating an optimized duty cycle, from the fusion of two methods: fuzzy logic and the Perturb and Observe methods. This research specifically explores the influence of this combination of techniques on the efficiency of photovoltaic panels. The design of the fuzzy MPPT algorithm primarily relies on selecting input and output parameters suited to the specific module. The main output parameter is the duty cycle, which adjusts the power of the converter. For input variables, various configurations are possible, including $\frac{dP}{dV}$ and its variation, as well as combinations such as $\frac{dP}{dV}$ with dP, dP with dV, and dP with dI.

The novelty of this study lies in the selection of specific input variables for the fuzzy controller, namely dV and dP. While successful hybrid perturb & observe (P&O)-fuzzy logic (FL) techniques have achieved improved results, they have not utilized these proposed input variables. These variables, representing adjustments in power and voltage according on the P-V curve, provide a direct and rapid method to optimizing system performance. This choice was made to address key challenges associated with traditional systems, such as slow response to changes in environmental conditions and limited effectiveness under variable or low solar irradiation. To address these limitations, the fuzzy logic algorithm was combined with the conventional P&O controller, which is simple and reliable, but also it may exhibit excessive oscillations around the MPP under low irradiation [20]-[22]. By mixing these two algorithms, the aim was to leverage the advantages of both methods in developing a more effective, reactive, and stable MPPT tracking solution, capable of dynamically adapting to variable environmental conditions [23].

There are several ways to combine P&O and fuzzy logic techniques for MPPT systems, each offering unique advantages and improvements over conventional methods. According to article [24], an optimized P&O-fuzzy method for an MPPT controller significantly outperforms traditional techniques, providing a fast response time of 0.015 seconds markedly faster than the 0.04 seconds typical of P&O and 0.02 seconds for fuzzy logic (FL). Additionally, this method exhibits no overshoot and maintains low oscillation times of 0.02 seconds (compared to 0.12 seconds for P&O and 0.45 seconds for FL), ensuring greater stability even in the presence of noise within the PV module. This combination leverages the simplicity and widespread use of P&O with the responsive capabilities of fuzzy logic, resulting in a robust and efficient MPPT system. These findings are corroborated by [3], which introduced a modified MPPT perturb & observe controller that integrates a fuzzy logic controller with variable step sizes. This approach addresses the limitations of fixed step size P&O methods, such as slow convergence and considerable fluctuations around the MPP. The incorporation of fuzzy logic allows for dynamic adjustment of the step size, leading to faster response times and reduced steady-state oscillations, thus boosting the system's overall efficiency and dependability. Moreover [11], proposes a novel concept that fine-tunes the fuzzy logic controller’s membership functions based on a P&O algorithm. This method effectively combines the advantages of both techniques, leading to highly efficient results. The system demonstrated an impressive yield of approximately 99.6% under varying weather conditions, showcasing its ability to accurately track the MPP with minimal fluctuations and no divergence, even during rapid changes in irradiance. The method's ability to balance response speed, stability, and efficiency makes it a standout among MPPT techniques, particularly for grid-connected PV systems [11], [25]-[28].

The initial photovoltaic system incorporating MPPT technology was unveiled in 1968 specifically for a space application [29]-[31]. Following that, research has intensified to improve MPPT techniques, with significant progress in terms of reliability, accuracy, ease of use, tracking speed and efficiency, using search algorithms, model-based approaches, and more sophisticated electronic devices. Technological advances have contributed to the widespread adoption of MPPT in a variety of applications, from small stand-alone systems to large grid-connected solar installations. Typically, the ideal MPPT algorithm demonstrates swift response and minimal fluctuations around the maximum power point, enabling it to effectively adapt to sudden variations in output power [29], [32].

## 2. METHOD

The core focus of this work is to study the impact of combining P&O and fuzzy logic techniques on the performance of photovoltaic panels in order to optimizing the effectiveness of converting solar energy into electrical power, which is generally very low around 9 to 17% [33]. The PV module was set up by connecting the suggested photovoltaic module to a boost DC DC converter creating a unit. To assess and compare its performance the new model underwent simulation using MATLAB Simulink software, alongside the P&O and FL methods, as in Figure 2.

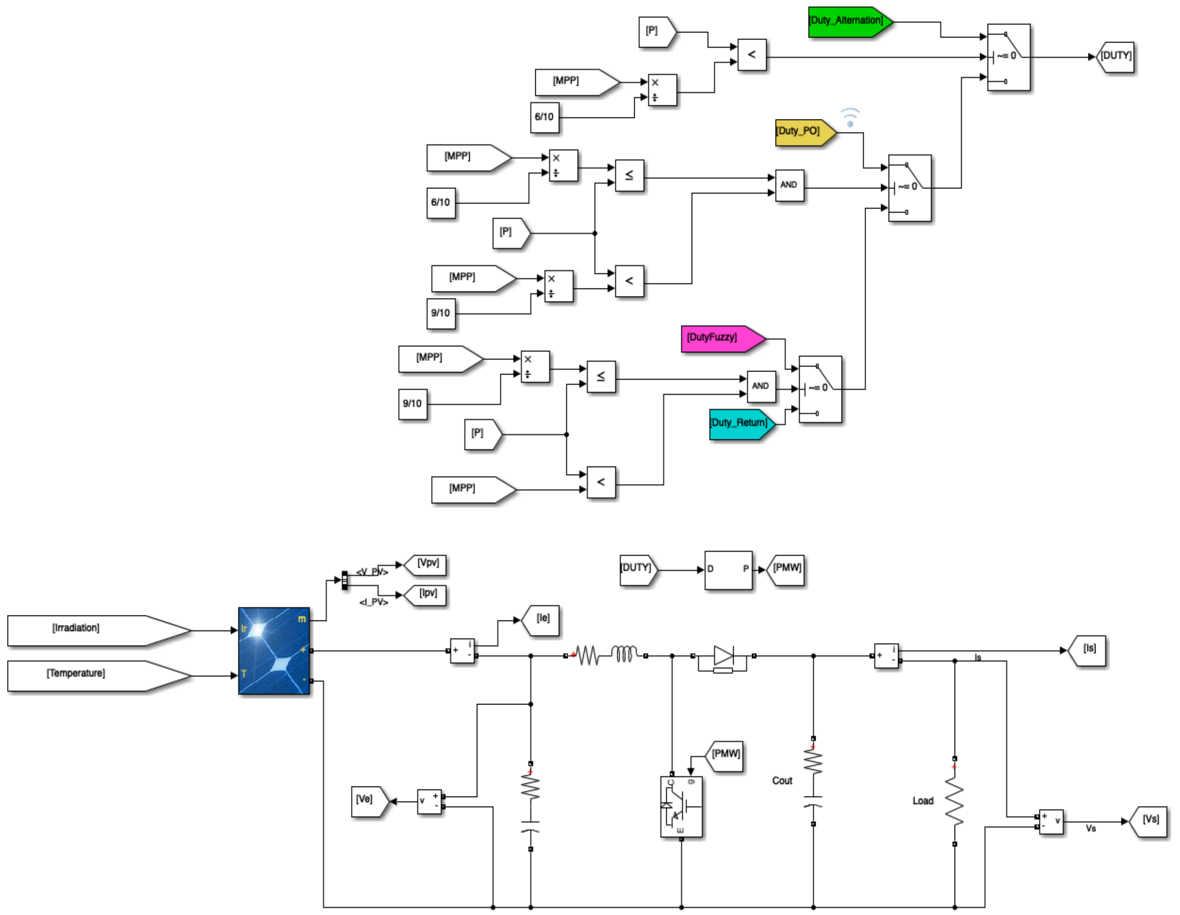


Figure 2. Proposed system modeling on MATLAB/Simulink

The fundamental operation of the new model, as presented in Figure 3, is composed of four stages:

- P< $\frac{6}{10}$ MPP: During this initial phase, the system implements an alternation of the duty cycle between the two MPPT algorithms, P&O, and FL. This alternation makes it possible to determine the best optimization method depending on the operating conditions. The MPP is calculated for the PV panel based on its specific characteristics, including the I-V curve, as well as the simulation values of temperature and irradiation.
- $\frac{6}{10}$ MPP ≤P< $\frac{9}{10}$ MPP: in this transition stage, the model favors the use of the P&O method. This decision is based on the demonstrated efficiency in calculating the maximum power point which is better than the FL method.
- $\frac{9}{10}$ MPP≤P>MPP: When the generated power is greater than or equal to 90% of the maximum power, the model switches to using the FL method. This method is chosen because it has the advantage of not exhibiting fluctuating behavior around the MPP, unlike the P&O technique.
- P=MPP: once the MPP is reached, the same duty cycle is used.

Thus, the model adapts its optimization strategy based on proximity to the MPP, using P&O for the transition and FL for optimization when the MPP is almost reached, while keeping stability when the MPP is maintained. Table 1 provides a set of parameters used in building a photovoltaic (PV) module model in MATLAB-Simulink. These parameters are essential to characterize and validate the performance of the PV module in terms of its current, voltage and power characteristics. Figures 4(a) and 4(b) shows graphs of the P-V and I-V characteristics of the selected photovoltaic system for three diverse irradiation levels. It's noted that the maximum power increases as the solar radiance increases. Similarly, the current also increases as the light intensity continues to increase [24], [34].

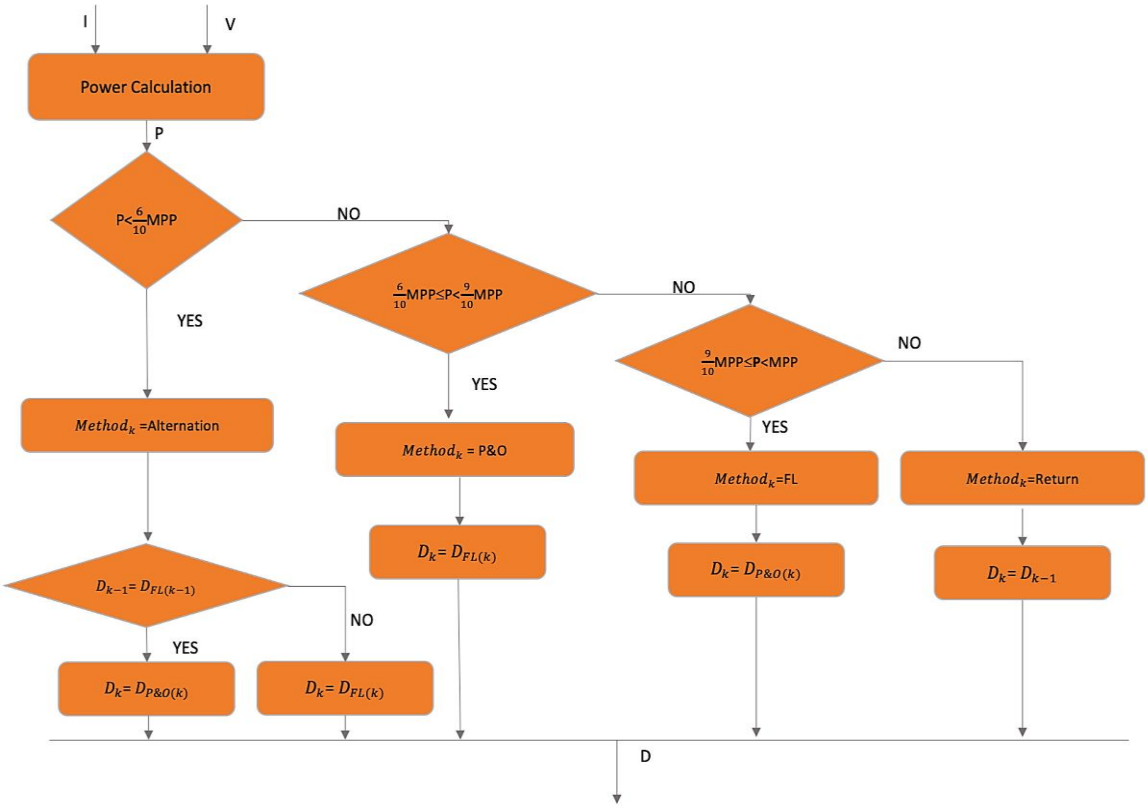


Figure 3. Workflow chart of the proposed model

Table 1. PV panel parameters

| Item | Value | Item | Value |
|---|---|---|---|
| Maximum power (Pmpp) | 213.15 W | Open-circuit voltage (Voc) | 36.3 V |
| Voltage at maximum power point Vmp | 29 V | Temperature coefficient of Voc (%/°C) | -0.36099 |
| Current at maximum power point Imp | 7.35 A | Temperature coefficient of Isc (%/°C) | 0.102 |
| Short-circuit current (Isc) | 7.84 A | | |

(a)

(b)

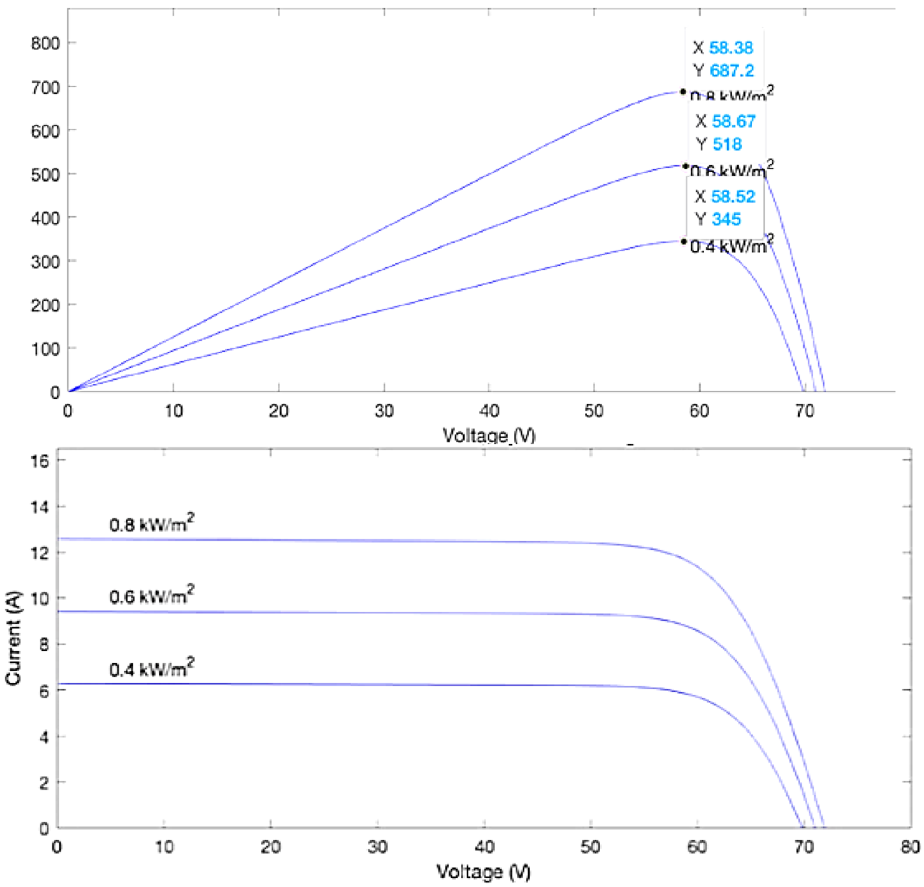


Figure 4. PV panel characteristics: (a) P-V characteristic and (b) I-V characteristics

## 2.1. Alternation stage

Since the two methods P&O and FL do not perform well under low irradiation, the approach involves maximizing the responsiveness of both methods by alternating between them. Consequently, a strategic exchange of duty cycles between the two conventional MPPT algorithms P&O and FL is applied as mentioned in Figure 5. The following sections will provide descriptions of MPPT methods applied: P&O and FL.

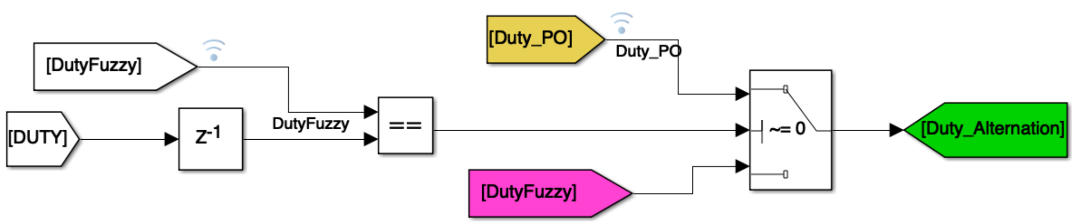


Figure 5. Alternation stage in MATLAB/Simulink

## 2.2. P&O stage

The perturb and observe or P&O technic is commonly utilized as the primary MPPT method because of its straightforward implementation. However, it has certain constraints, such as variations around the MPP and sluggish response time caused by variations in solar irradiance [35]. The P&O technic operates by continuously measuring the output power of the photovoltaic array and monitoring the changes in both PV current and voltage. Periodically, the algorithm compares the current power value with the prior value to determine whether to adjust the PV array voltage or current (based on the control strategy) in the same or opposite direction, depending on whether an augmentation or reduction in output power is observed [12], [36]-

[39]. The algorithm was simulated on MATLAB software, as displayed in Figure 6 while its flow is presented in Figure 7. However, once the MPP is attained, the system tends to oscillate around it. This problem has been corrected in this new method, by opting for the duty cycle of the fuzzy logic method only in order to minimize these oscillations.

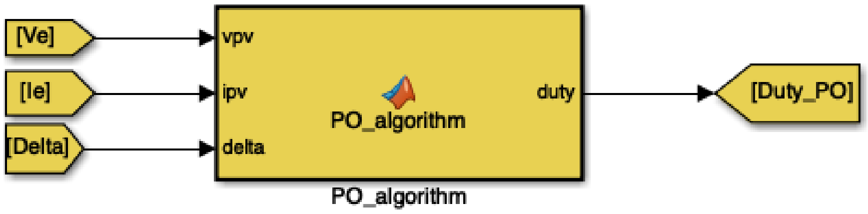


Figure 6. P&O algorithm in MATLAB/Simulink

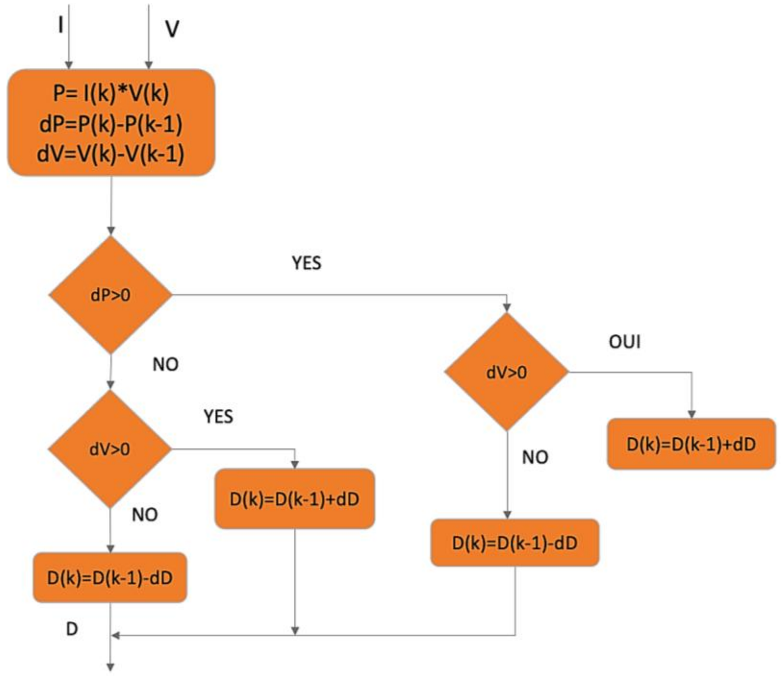


Figure 7. Characteristic of P&O method used

### 2.3. Fuzzy logic stage

The fundamental principle of a fuzzy controller is presented in Figure 8, which involves converting crisp inputs into fuzzy inputs through the application of membership functions and their respective degrees of membership (known as fuzzification). The inference engine generates a fuzzy output by taking into account the degrees of the membership functions describe in Figures 9(a)-9(c), and the rule base in Table 2, employing methods such as implication and aggregation. To obtain a precise output, the fuzzy output is transformed into a crisp output using various approaches, like the center of area method (known as defuzzification) [12]. The input variables, $dV$ and $dP$ are defined by (1) and (2), respectively:

$$dV = V(k) - V(k-1) \tag{1}$$

$$dP = P(k) - P(k-1) \tag{2}$$

The fuzzy logic control for searching the MPP was designed and tested in Simulink software, as revealed in Figure 10. This system utilizes two inputs, dP and dV at the sampling time k. The output of the fuzzy logic regulator corresponds to the duty cycle D [40], [41].

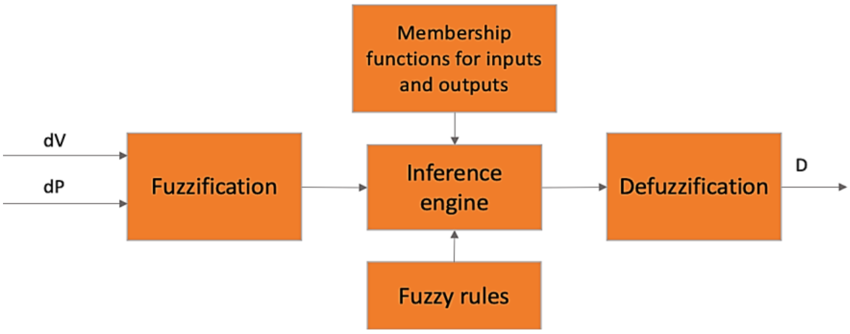


Figure 8. Block schematic of fuzzy MPPT algorithm

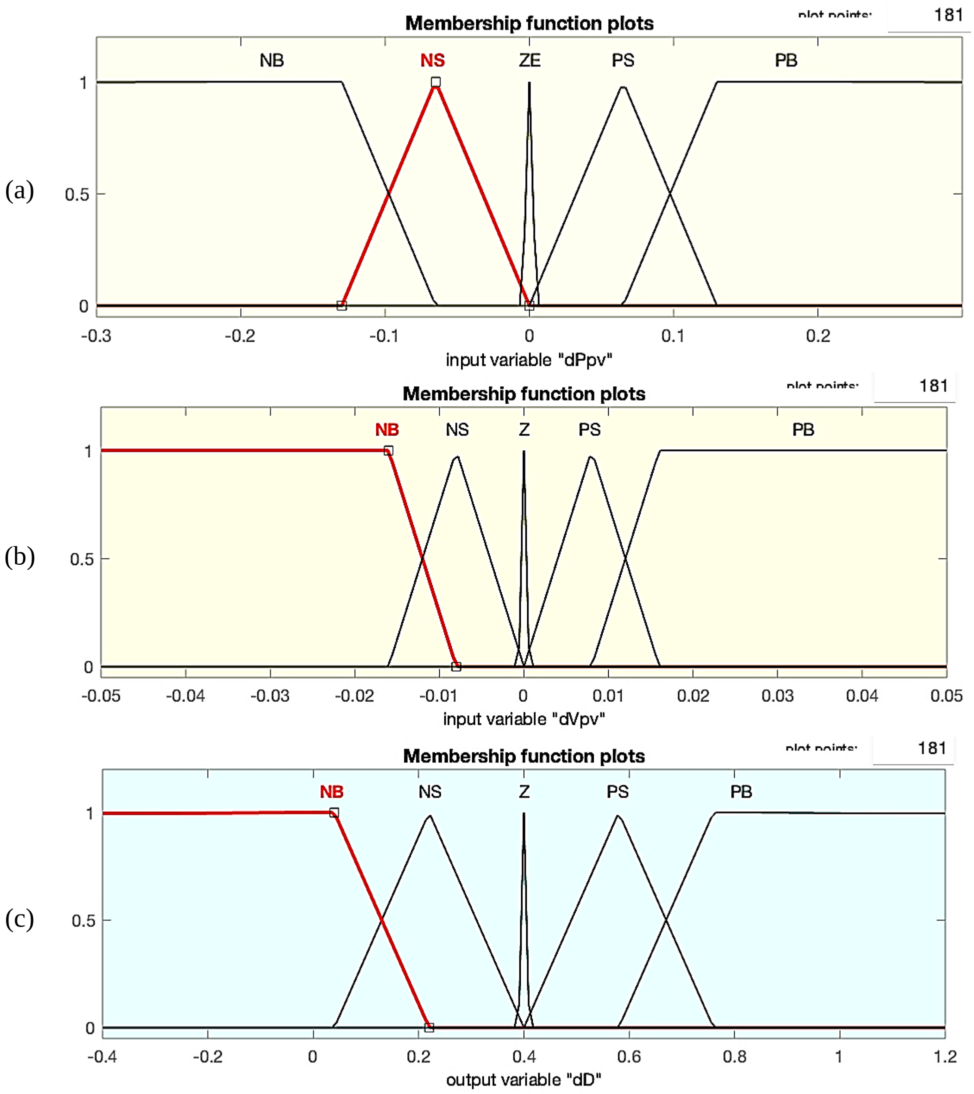


Figure 9. Membership functions for (a) input of dPpv, (b) input of dVpv, and (c) output of dD

Table 2. Fuzzy rules

| Input variable (dV) | Output Variable (dP) | | | | |
|---|---|---|---|---|---|
| | NB | NS | Z | PS | PB |
| | NB | NS | Z | PS | PB |
| | NS | NS | Z | PS | PS |
| dV | Z | Z | Z | Z | Z |
| | PS | PS | Z | NS | NS |
| | PB | PS | Z | NS | NB |

### 2.4. Return stage

After achieving the maximum power point, it is often advantageous to continue using the same duty cycle that was employed just before reaching the MPP, as revealed in Figure 11. This is because at the MPP, the PV system operates at its peak power output. Also, any significant deviation from the current operating conditions could result in a drop in power production.

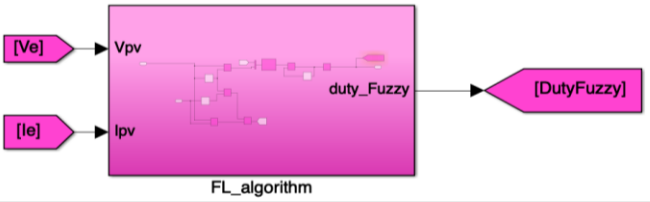


Figure 10. FL algorithm in MATLAB/Simulink

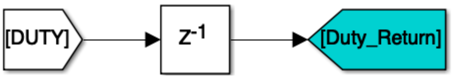


Figure 11. Return stage in MATLAB/Simulink

## 3. RESULTS AND DISCUSSION

Simulation experiments were performed using the suggested hybrid P&O-fuzzy technic, followed by conventional P&O control and fuzzy logic technics, with the aim of evaluating and comparing them. When evaluating the effectiveness of each MPPT regulator, most importance is given to time response, stability, overshot and oscillations. To assess the efficiency of the photovoltaic system, several test scenarios were simulated to compare the traditional P&O controller, the fuzzy regulator to the proposed hybrid controller. Three scenarios were created representing abrupt variations of solar radiation levels and the operational temperature of the photovoltaic module.

### 3.1. Scenario 1: Temperature of 25 °C and incremental change in solar irradiation

In this case, the performance of the regulators was evaluated at an operating temperature of 25 °C using incremental variations in solar irradiance. An irradiance signal was employed, with increases of 200 W/m², starting at 400 W/m² and reaching 800 W/m². Irradiance variations were applied every 0.02 seconds, for a total simulation time of 0.12 seconds, as in Figure 12.

Figure 13 illustrates the output power for different increases in signal irradiance. In general, the following can be observed: i) When irradiation = 400 W/m²: the hybrid controller gives the best performance, followed by the P&O controller and the fuzzy controller regarding response time and stability; this is reflected by the fact that the chosen fuzzy controller does not give good precision during low irradiation [23]; ii) When irradiation = 600 W/m²: the hybrid controller remains the most efficient, with no apparent oscillations and with remarkable speed; and iii) When irradiation = 800 W/m²: the performance of the three controllers is generally satisfactory, although there are slight fluctuations in the curve of the P&O controller and a slight response delay in the case of the FL controller.

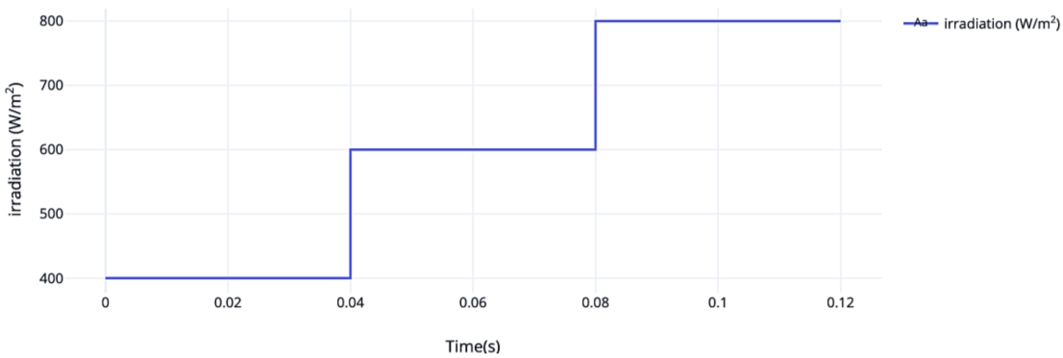


Figure 12. Incremental change in solar irradiation

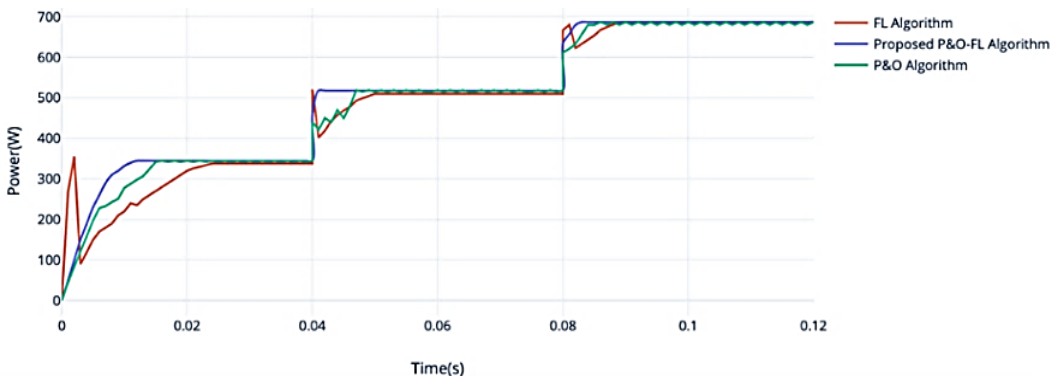


Figure 13. Output power of the PV module for incremental variation in solar irradiance

### 3.2. Scenario 2: Temperature = 25 °C decremental change in solar irradiation

This scenario deals with the behavior of MPPT controllers with a decrease in irradiation that varies between 800, 600, and 400 W/m², as seen in Figure 14, while maintaining a fixed temperature of 25 °C. The maximum power point (MPP) obtained for the irradiance levels of 800 W/m², 600 W/m², and 400 W/m² are 687.2 W, 518 W, and 345 W respectively, in accordance with the values presented in Figure 15. However, it's worth emphasizing that: i) The FL controller exhibits slow behavior and poor tracking accuracy at all irradiation levels compared to other controllers tested, with the appearance of significant fluctuations around the maximum power point for the P&O controller; ii) Regarding the P&O controller, the response time indicated in the curve is notably higher than that of the FL algorithm, the latter presents a very remarkable stability compared to the P&O; and iii) The proposed hybrid P&O-FL algorithm generates the best results.

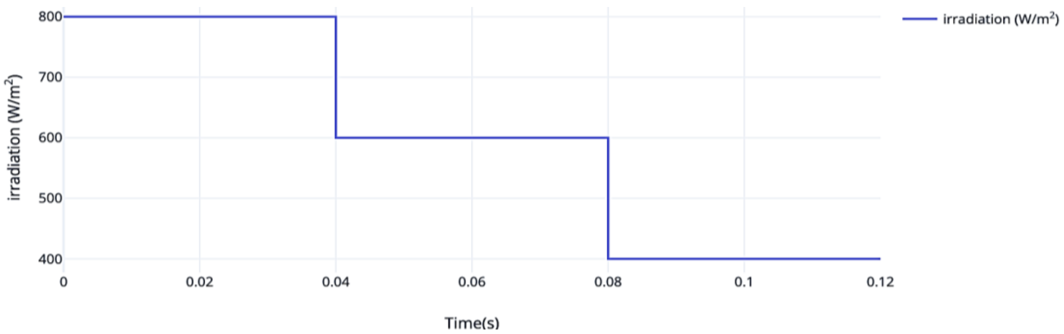


Figure 14. Decremental change in solar irradiation

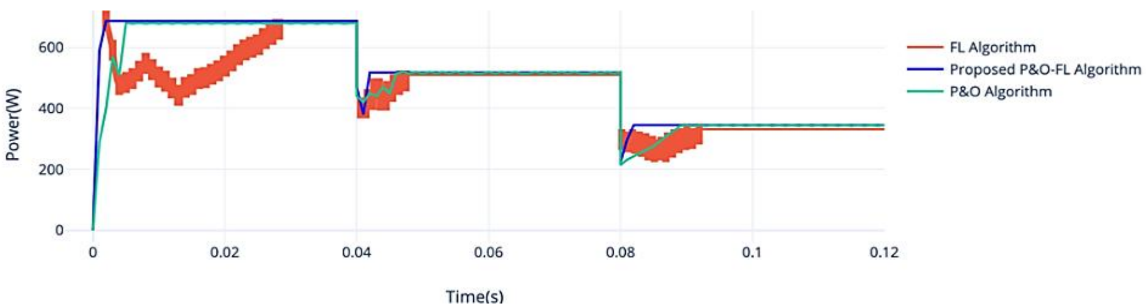


Figure 15. Output power of the PV module for decremental variation in solar irradiation

### 3.3. Scenario 3: Solar irradiation of 800 W/m² incremental change in temperature

This last scenario evaluates the effectiveness of the MPPT algorithms in the presence of a gradual temperature variation, while maintaining a fixed value of irradiation at 800 W/m². The signal shown in Figure 16 was used, with temperature increases every 0.04 seconds, covering the range from 0 °C to 50 °C, over a test period of 0.12 seconds. Figure 17 illustrates the generated power and emphasizes the power losses linked to the FL controller. Nevertheless, in this particular scenario, sudden temperature fluctuations notably affect the performance of the P&O controller. Conversely, fuzzy and hybrid regulators maintain a consistent power output that adapts to temperature changes in the operational photovoltaic module. This implies that the fuzzy regulator is not significantly impacted by temperature fluctuations but appears to be more responsive to variations in irradiation.

In summary, the findings discussed in the preceding sections provide clear evidence of the outstanding performance of the suggested hybrid approach in effectively tracking the maximum power point of the photovoltaic module achieving an impressive efficiency of 99.7%. The core objective of this hybrid method is to strategically leverage the unique advantages of both fuzzy logic and perturb and observe controllers. The choice of combining these two techniques was made with careful consideration, particularly to optimize response time and system stability.

The algorithm proposed in this paper demonstrates better performance compared to the one presented in [24]. It achieves a response time of less than 0.01 seconds (versus 0.015 seconds in [24]), eliminates overshoot, and maintains very low oscillation times; all under 0.02 seconds; as observed in [24]. When evaluating the efficacy of this approach, it becomes evident that it successfully addresses several shortcomings associated with using either the methods P&O, or FL with input variables dP and dV. By harnessing the strengths of FL and P&O while mitigating their respective weaknesses, this hybrid approach offers a well-balanced solution for maximizing the power output of the photovoltaic system. Its exceptional efficiency in following the maximum power point underscores its potential for practical applications in renewable energy systems, promising more reliable and efficient energy generation.

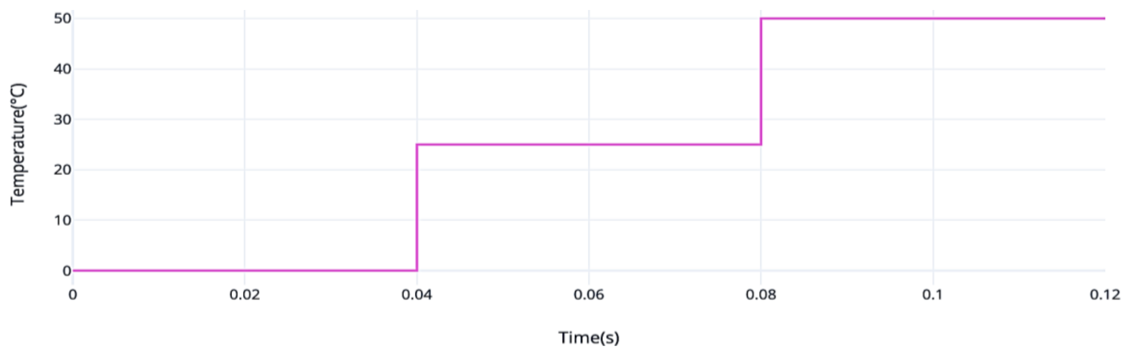


Figure 16. Incremental change in temperature

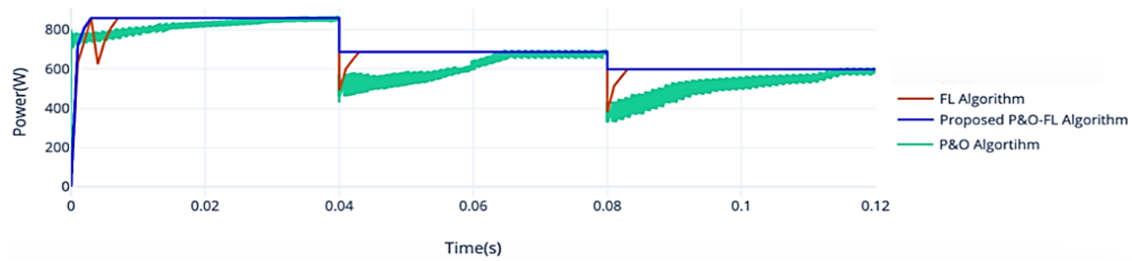


Figure 17. Output power of the PV module for incremental variation in temperature

## 4. CONCLUSION

This paper introduces a novel FL-P&O hybrid controller tailored for the precise tracking of the maximum power point in PV modules. The study conducts a comprehensive performance comparison between this hybrid controller and conventional fuzzy and P&O controllers. The entirety of the PV system, encompassing the PV module itself, the boost converter, and the newly proposed FL, P&O, and hybrid controllers, has been meticulously modeled within the MATLAB/Simulink environment. To assess the PV system's behavior under various conditions, three distinct test scenarios were carefully designed, each incorporating variations in temperature and solar irradiance.

The research findings clearly demonstrate the outstanding performance of the proposed hybrid controller, particularly when faced with sudden fluctuations in temperature and radiation impacting the PV module. Remarkably, the hybrid controller achieves an efficiency rate of 99.7%. In contrast, both the fuzzy logic and P&O controllers exhibit significant shortcomings, such as prolonged response times and considerable deviations from the MPP.

Moreover, the study highlights the robustness of the hybrid controller in responding to solar irradiance variations, consistently extracting the maximum available power based on the PV module's electrical characteristics. Conversely, the fuzzy logic controller shows a relatively slow response in these conditions, while the P&O controller displays pronounced instability, especially during abrupt irradiance changes. Finally, the study unveils the immense potential of the FL-P&O hybrid controller as a superior choice for MPP tracking in PV systems. Its exceptional performance, particularly in scenarios involving temperature fluctuations, establishes it as a promising solution for enhancing the efficiency and reliability of renewable energy generation. Future research should include experimental validation with physical hardware to confirm the practical applicability of the FL-P&O hybrid controller, as well as further investigations into its performance under a wider range of challenging environmental conditions.

## REFERENCES


[1] F. Bariloche, "Module overview policy and targets investment and finance challenges and opportunities science and academia AEE-Institute for Sustainable Technologies (AEE-INTEC) Council on Energy, Environment and Water (CEEW)", [Online]. Available: www.ren21.net/gsr-2024

[2] BP Energy Outlook, "Statistical review of world energy," BP Statistical Review of World Energy. [Online]. Available: https://www.energyinst.org/statistical-review

[3] J. Macaulay and Z. Zhou, "A fuzzy logical-based variable step size P&O MPPT algorithm for photovoltaic system," *Energies (Basel)*, vol. 11, no. 6, p. 1340, May 2018, doi: 10.3390/en11061340.

[4] R. A. Soumana, M. J. Saulo, and C. M. Muriithi, "A new control scheme for limiting the compensation current and prioritizing power injection in multifunctional grid-connected photovoltaic systems," *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, vol. 2, p. 100055, 2022, doi: 10.1016/j.prime.2022.100055.

[5] M. H. Aksoy and M. Ispir, "Techno-economic feasibility of different photovoltaic technologies," *Applied Engineering Letters: Journal of Engineering and Applied Sciences*, vol. 8, no. 1, pp. 1–9, 2023, doi: 10.18485/aeletters.2023.8.1.1.

[6] P. A. Owusu and S. Asumadu-Sarkodie, "A review of renewable energy sources, sustainability issues and climate change mitigation," *Cogent Engineering*, vol. 3, no. 1, p. 1167990, Dec. 2016, doi: 10.1080/23311916.2016.1167990.

[7] N. L. Panwar, S. C. Kaushik, and S. Kothari, "Role of renewable energy sources in environmental protection: A review," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 3, pp. 1513–1524, Apr. 2011, doi: 10.1016/j.rser.2010.11.037.

[8] L. Schernikau and W. H. Smith, "Climate impacts of fossil fuels in todays electricity systems," *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 122, no. 3, pp. 1–13, Mar. 2022, doi: 10.17159/2411-9717/1874/2022.

[9] A. A. Abdulrazzaq and A. Hussein Ali, "Efficiency performances of two MPPT algorithms for PV system with different solar panels irradiancess," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 9, no. 4, p. 1755, Dec. 2018, doi: 10.11591/ijpeds.v9.i4.pp1755-1764.

[10] A. Ašonja and V. Vuković, "The potentials of solar energy in the republic of serbia," *Applied Engineering Letters: Journal of Engineering and Applied Sciences*, vol. 3, no. 3, pp. 90–97, 2018, doi: 10.18485/aeletters.2018.3.3.2.

[11] S. D. Al-Majidi, M. F. Abbod, and H. S. Al-Raweshidy, "A novel maximum power point tracking technique based on fuzzy logic for photovoltaic systems," *International Journal of Hydrogen Energy*, vol. 43, no. 31, pp. 14158–71, 2018, doi: 10.1016/j.ijhydene.2018.06.002.

[12] E. Roman, R. Alonso, P. Ibanez, S. Elorduizapatarietxe, and D. Goitia, "Intelligent PV module for grid-connected PV systems," *IEEE Transactions on Industrial Electronics*, vol. 53, no. 4, pp. 1066–1073, Jun. 2006, doi: 10.1109/TIE.2006.878327.

[13] M. N. Ali, K. Mahmoud, M. Lehtonen, and M. M. F. Darwish, "an efficient fuzzy-logic based variable-step incremental conductance MPPT method for grid-connected PV systems," *IEEE Access*, vol. 9, pp. 26420–26430, 2021, doi: 10.1109/ACCESS.2021.3058052.

[14] A. Kumar, B. Karma, S. Sherpa, A. Kalam, and G.-S. Chae, *Green energy and technology advances in greener energy technologies*. in Green Energy and Technology. Singapore: Springer Singapore, 2020. doi: 10.1007/978-981-15-4246-6.

[15] A. S. Bayoumi, R. A. El-Sehiemy, K. Mahmoud, M. Lehtonen, and M. M. F. Darwish, "Assessment of an improved three-diode against modified two-diode patterns of MCS solar cells associated with soft parameter estimation paradigms," *Applied Sciences*, vol. 11, no. 3, p. 1055, Jan. 2021, doi: 10.3390/app11031055.

[16] C. R. Algarín, A. O. Castro, and J. C. Naranjo, "Dual-axis solar tracker for using in photovoltaic systems," *International Journal of Renewable Energy Research*, vol. 7, no. 1, pp. 137–145, 2017, doi: 10.20508/ijrer.v7i1.5147.g6973.

[17] V. Salas, E. Olías, A. Barrado, and A. Lázaro, "Review of the maximum power point tracking algorithms for stand-alone photovoltaic systems," *Solar Energy Materials and Solar Cells*, vol. 90, no. 11, pp. 1555–1578, Jul. 2006, doi: 10.1016/j.solmat.2005.10.023.

[18] S. Z. Mirbagheri, S. Mekhilef, and S. M. Mirhassani, "MPPT with Inc.Cond method using conventional interleaved boost converter," *Energy Procedia*, vol. 42, pp. 24–32, 2013, doi: 10.1016/j.egypro.2013.11.002.

[19] J. K. Sahu, B. Panda, and J. P. Patra, "Artificial neural network for maximum power point tracking used in solar photovoltaic system," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 14, no. 3, p. 1694, Sep. 2023, doi: 10.11591/ijpeds.v14.i3.pp1694-1701.

[20] S. H. Khader and A. K. K. Daud, "A novel approach to fast determining the maximum power point based on photovoltaic panel's datasheet," *Journal of Renewable Energy and Environment*, vol. 10, no. 4, pp. 44–58, 2023, doi: 10.30501/jree.2023.361697.1450.

[21] R. H. Mohammed, A. A. Abdulrazzaq, and W. K. Al-Azzawi, "Benefits of MPP tracking PV system using perturb and observe technique with boost converter," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 13, no. 4, p. 2468, Dec. 2022, doi: 10.11591/ijpeds.v13.i4.pp2468-2477.

[22] T. Hamdi, K. Elleuch, H. Abid, and A. Toumi, "Sliding mode controller with fuzzy supervisor for MPPT of photovoltaic pumping system," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 14, no. 3, pp. 1639-1650, Sep. 2023, doi: 10.11591/ijpeds.v14.i3.pp1639-1650.

[23] J.-K. Shiau, Y.-C. Wei, and B.-C. Chen, "A study on the fuzzy-logic-based solar power MPPT algorithms using different fuzzy input variables," *Algorithms*, vol. 8, no. 2, pp. 100–127, Apr. 2015, doi: 10.3390/a8020100.

[24] M. A. A. M. Zainuri, M. A. M. Radzi, A. C. Soh, and N. A. Rahim, "Adaptive P&O-fuzzy control MPPT for PV boost DC-DC converter," in *2012 IEEE International Conference on Power and Energy (PECon)*, 2012, pp. 524–529. doi: 10.1109/PECon.2012.6450270.

[25] N. S. D'Souza, L. A. C. Lopes, and X. Liu, "Comparative study of variable size perturbation and observation maximum power point trackers for PV systems," *Electric Power Systems Research*, vol. 80, no. 3, pp. 296–305, Mar. 2010, doi: 10.1016/j.epsr.2009.09.012.

[26] M. A. Elgendy, B. Zahawi, and D. J. Atkinson, "Assessment of the incremental conductance maximum power point tracking algorithm," *IEEE Trans Sustain Energy*, vol. 4, no. 1, pp. 108–117, Jan. 2013, doi: 10.1109/TSTE.2012.2202698.

[27] M. Seyedmahmoudian *et al.*, "State of the art artificial intelligence-based MPPT techniques for mitigating partial shading effects on PV systems–A review," *Renewable and Sustainable Energy Reviews*, vol. 64, pp. 435–455, Oct. 2016, doi: 10.1016/j.rser.2016.06.053.
[28] S. Duman, N. Yorukeren, and I. H. Altas, "A novel MPPT algorithm based on optimized artificial neural network by using FPSOGSA for standalone photovoltaic energy systems," *Neural Computing and Applications*, vol. 29, no. 1, pp. 257–278, Jan. 2018, doi: 10.1007/s00521-016-2447-9.
[29] A. O. Baba, G. Liu, and X. Chen, "Classification and evaluation review of maximum power point tracking methods," *Sustainable Futures*, vol. 2, p. 100020, 2020, doi: 10.1016/j.sftr.2020.100020.
[30] D. Rekioua and E. Matagne, *Optimization of photovoltaic power systems*. in Green Energy and Technology. London: Springer London, 2012. doi: 10.1007/978-1-4471-2403-0.
[31] A. Yazdani and P. P. Dash, "A control methodology and characterization of dynamics for a photovoltaic (PV) system interfaced with a distribution network," *IEEE Transactions on Power Delivery*, vol. 24, no. 3, pp. 1538–1551, 2009, doi: 10.1109/TPWRD.2009.2016632.
[32] M. Lawan, A. Aboushady, and K. H. Ahmed, "Photovoltaic MPPT techniques comparative review," in *2020 9th International Conference on Renewable Energy Research and Application (ICRERA)*, 2020, pp. 344–351. doi: 10.1109/ICRERA49962.2020.9242855.
[33] S. K. Kollimalla and M. K. Mishra, "A novel adaptive P&O MPPT algorithm considering sudden changes in the irradiance," *IEEE Transactions on Energy Conversion*, vol. 29, no. 3, pp. 602–610, Sep. 2014, doi: 10.1109/TEC.2014.2320930.
[34] H. A. Sher, A. F. Murtaza, A. Noman, K. E. Addoweesh, K. Al-Haddad, and M. Chiaberge, "A new sensorless hybrid MPPT algorithm based on fractional short-circuit current measurement and P&O MPPT," *IEEE Trans Sustain Energy*, vol. 6, no. 4, pp. 1426–1434, Oct. 2015, doi: 10.1109/TSTE.2015.2438781.
[35] A. Al-Diab and C. Sourkounis, "Variable step size P&O MPPT algorithm for PV systems," in *2010 12th International Conference on Optimization of Electrical and Electronic Equipment*, IEEE, May 2010, pp. 1097–1102. doi: 10.1109/OPTIM.2010.5510441.
[36] N. Khaehintung and P. Sirisuk, "Implementation of maximum power point tracking using fuzzy logic controller for solar-powered light-flasher applications," in *The 2004 47th Midwest Symposium on Circuits and Systems, 2004. MWSCAS '04.*, IEEE, p. III_171-III_174. doi: 10.1109/MWSCAS.2004.1354319.
[37] P. T. Krein, R. S. Balog, and X. Geng, "High-frequency link inverter for fuel cells based on multiple-carrier PWM," *IEEE Trans Power Electron*, vol. 19, no. 5, pp. 1279–1288, Sep. 2004, doi: 10.1109/TPEL.2004.833996.
[38] N. Mutoh, M. Ohno, and T. Inoue, "A method for MPPT control while searching for parameters corresponding to weather conditions for PV generation systems," *IEEE Transactions on Industrial Electronics*, vol. 53, no. 4, pp. 2006, doi: 10.1109/TIE.2006.878328.
[39] R. Boopathi and V. Indragandhi, "Comparative analysis of control techniques using a PV-based SAPF integrated grid system to enhance power quality," *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, vol. 5, 2023, doi: 10.1016/j.prime.2023.100222.
[40] S. N. Sivanandam, S. Sumathi, and S. N. Deepa, *Introduction to fuzzy logic using MATLAB*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2007. doi: 10.1007/978-3-540-35781-0.
[41] M. S. A. Cheikh, C. Larbes, G. F. T. Kebir, and A. Zerguerras, "Maximum power point tracking using a fuzzy logic control scheme," *Journal of Renewable Energies*, vol. 10, no. 3, Sep. 2007, doi: 10.54966/jreen.v10i3.771.


## BIOGRAPHIES OF AUTHORS

**Oumaima Mrhar** is currently an electric engineer at ONEE. She is a Ph.D. student at the National School of Applied Sciences of ELJADIDA. She received her engineering degree in Electronic and Automatic Systems from ENSA, Tangier, in 2018. She is a member of the Energy Engineering Laboratory (LabSIPE). Her research interests include photovoltaic systems, solar trackers, and MPPT technologies. She can be contacted at email: oumaima.mrhar@gmail.com.

**Khalid Kandoussi** is a professor at the National School of Applied Sciences, Chouaib Doukkali University, El Jadida, Morocco. Currently, he serves as the head of the Department of Sciences and Industrial Technologies (STIN) at the same institution. He is also a member of the Energy Engineering Laboratory (LabSIPE). His research has been published in over 90 international journals and conference proceedings. His areas of expertise include optimizing energy systems, power electronics, solar PV systems, MPPT, and electrical drives. He can be contacted at email: kkandouss@gmail.com.

**Mohamed Eljouad** is an assistant professor at the National School of Applied Sciences, Chouaib Doukkali University of ELJADIDA. He is also a member of the Energy Engineering Laboratory (LabSIPE). His research interests include materials for energy and photovoltaic systems. He has published more than 60 journal/conference articles on these topics. He can be contacted at email: eljouad.mohamed@gmail.com.