Solar Energy
And Sustainable Development
Refereed, biannual scientific journal issued by:
The Libyan Center for Solar Energy Research and Studies

Comparative Study of Two ANFIS-Based MPPT Controls Under Uniform and Partial Shading Conditions

Mohamed Amine Atillah[1*], Hicham Stitou[2], Abdelghani Boudaoud[3], Mounaim Aqil[4].

[1,2,3,4]Engineering and Applied Physics Team (EAPT), Superior School of Technology, Sultan Moulay Slimane University, Beni Mellal, Morocco.

E-*mail:* [1] mohamedamine.atillah@usms.ma .

SPECIAL ISSUE ON:

The 2024 1st International Conference on Materials Sciences and Mechatronics for Sustainable Energy and the Environment
October 1-3, 2024 at Béni-Mellal, Morocco

KEYWORDS

ANFIS; MPPT techniques; PARTIAL shading; Photovoltaic energy; Renewable energy.

ABSTRACT

As the global transition to renewable energy becomes a priority, photovoltaic systems are increasingly important to ensure a sustainable and autonomous power source by exploiting the inexhaustible power of the sun. The power supplied by photovoltaic panels directly depends on climatic conditions, particularly irradiation and temperature. To maximize the energy extracted, it is essential to use a Maximum Power Point Tracking (MPPT) control. Partial shading occurs when certain sections of the photovoltaic array receive reduced irradiation.

This phenomenon causes an uneven distribution of solar energy across the panels, leading to changes in their electrical characteristics. However, the performance of MPPT controls can be disrupted by partial shading conditions, complicating optimal operation. This work aims to study two MPPT controls based on the adaptive neuro-fuzzy inference system (ANFIS), each with a different principle, and to analyze and compare their performance in extracting the maximum power available from photovoltaic panels, under uniform and partial shading conditions. The first method combines ANFIS and a fuzzy logic controller, while the second uses ANFIS alone. The comparison will focus on speed, accuracy, and stability, as well as the components required for each method. The results show that both methods perform similarly in accuracy since they can extract almost the same power. However, the second method, which excludes the use of an additional controller, is faster in extracting power with minimal oscillation and reduces the number of components in the photovoltaic system by eliminating the fuzzy controller, thus reducing the system's complexity.

*Corresponding author.

DOI: https://doi.org/10.51646/jsesd.v14iSI_MSMS2E.400

دراسة مقارنة بين طريقتين للتحكم في تتبع نقطة الطاقة القصوى باستخدام النظام العصبي الضبابي التكيفي في ظل ظروف التظليل المنتظم والجزئي

عاطي الله محمد أمين، ستيتوهشام، بوداود عبد الغاني، عاقل منعيم.

ملخص: مع تزايد أهمية التحول العالمي إلى الطاقة المتجددة كأولوية، تزداد أهمية الأنظمة الكهروضوئية لضمان مصدر طاقة مستدام ومستقل من خلال استغلال طاقة الشمس التي لا تنضب. وتعتمد الطاقة التي توفرها الألواح الكهروضوئية بشكل مباشر على الظروف المناخية، وخاصة الإشعاع ودرجة الحرارة. ولزيادة الطاقة المستخرجة إلى الحد الأقصى، من الضروري استخدام التحكم في تتبع نقطة الطاقة القصوى. ويحدث التظليل الجزئي عندما تتلقى أجزاء معينة من المصفوفة الكهروضوئية إشعاعًا منخفضًا. تتسبب هذه الظاهرة في توزيع غير متساوٍ للطاقة الشمسية عبر الألواح، مما يؤدي إلى تغيرات في خصائصها الكهربائية. ومع ذلك، يمكن أن يتعطل أداء أدوات التحكم في تتبٍع نقطة الطاقة القصوى بسبب ظروف التظليل الجزئي، مما يعقد التشغيل الأمثل. يهدف هذا العمل إلى دراسة طريقتين للتحكم في تتبع نقطة الطاقة القصوى استنادًا إلى نظام الاستدلال العصبي الضبابي التكيفي، ولكل منهما مبدأ مختلف، وتحليل ومقارنة أدائهما في استخراج الطاقة القصوى المتاحة من الألواح الكهروضوئية، في ظل ظروف التظليل المنتظم والجزئي. وتجمع الطريقة الأولى بين نظام الاستدلال العصبي الضبابي التكيفي ووحدة تحكم منطقية ضبابية، بينما تستخدم الطريقة الثانية نظام الاستدلال العصبي الضبابي التكيفي وحده. ستركز المقارنة على السرعة والدقة والاستقرار، بالإضافة إلى المكونات المطلوبة لكل طريقة. تُظهر النتائج أن أداء كلتا الطريقتين متشابه من حيث الدقة حيث يمكنهما استخراج نفس القوة تقريبًا. ومع ذلك، فإن الطريقة الثانية، التي تستبعد استخدام وحدة تحكم إضافية، أسرع في استخراج الطاقة بأقل قدر من التذبذب وتقلل من عدد المكونات في النظام الكهروضوئي عن طريق التخلص من وحدة التحكم الضبابية، وبالتالي تقليل تعقيد النظام.

الكلمات المفتاحية – النظام العصبي الضبابي التكيفي، تتبع نقطة الطاقة القصوى، التظليل الجزئي، الطاقة الكهروضوئية، الطاقة المتجددة.

1. INTRODUCTION

As renewable energy becomes a global priority, photovoltaic systems play a vital role in generating sustainable energy through solar radiation [1]. However, energy production from photovoltaic panels depends on solar irradiation and temperature. To optimize energy extraction, it is essential to use MPPT techniques [2]. The role of MPPTs is to adjust the electrical parameters of the panels in real time to ensure that they operate at optimum efficiency. However, partial shading, where certain parts of the panels receive less light, complicates this task. Partial shading causes uneven distribution of solar energy and alters the electrical characteristics of the panels, which can disrupt MPPT performance and make optimization more complex [3].

A variety of methods for MPPT is discussed in the research. It can be grouped into three main categories[3] [4]: Conventional MPPT techniques (Hill-Climbing (HC), Perturb and Observ (P&O), etc.), Soft computing methods (Fuzzy Logic (FL), Artificial Neural Network (ANN), Grey Wolf Optimiser (GWO), Particle Swarm Optimisation (PSO), etc.)), and Hybrid methods (PSO with P&O, ANN with P&O, etc.)).

Numerous studies have analyzed MPPT techniques based on ANFIS in photovoltaic systems. For example, Areola, R. I., et al [5] compared an ANFIS-based MPPT controller with the Perturb and Observe (P&O) MPPT controller under uniform shading. Esobinenwu, Chizindu Stanley [6] aimed at optimizing photovoltaic solar systems using an ANFIS controller under partial shading conditions, Revathy, S. R., et al. [7] suggest an ANFIS-based (MPPT) for optimizing the solar photovoltaic system under both uniform and partial shading conditions, Moyo, Ranganai T., et al [8] presented the design and modeling of the ANFIS-based MPPT controller.

All these works focus on the same theme, which is the analysis of the performance of ANFIS-based MPPT controls. However, they have used an additional block with the ANFIS control to ensure that the system operates at the reference point generated by the ANFIS. In addition, many studies deal only with cases of uniform irradiation. For this reason, we propose testing the control system without an additional controller, under both uniform and partial irradiation conditions. The goal of this project is to study two technique-based MPPT controls (ANFIS) with different principles and to analyze and compare their performance in extracting the maximum available power from photovoltaic panels, under uniform and partial shading conditions. The first method combines ANFIS and a fuzzy logic controller, while the second uses ANFIS alone. The comparison will focus on speed, accuracy, and stability, as well as the components required for each method. The paper is structured as follows: section 2 outlines the methodologies and materials, while section 3 analyses the results. The conclusion can be found in section 4.

2. METHODOLOGIES AND MATERIALS

To compare the two methods, we will integrate them into a photovoltaic system comprising a photovoltaic panel with MPPT control applied to a DC-DC boost converter, and a DC-AC inverter with control to regulate the DC bus voltage. In this work, the study will focus on the design and analysis of the two MPPT methods, without going into the details of the various elements of the system.
The structure of our system in MATLAB Simulink can be seen in Figure 1.

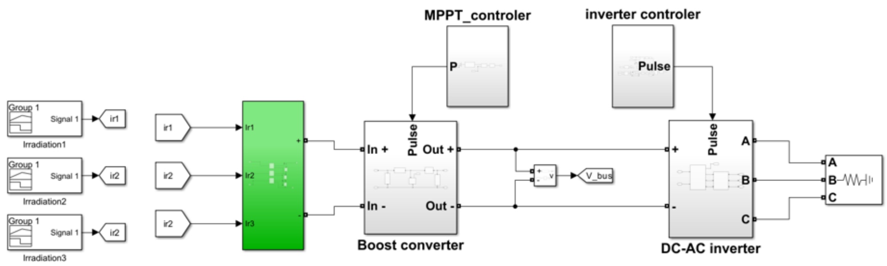

Figure 1. Simulink model of the system.

2.1. Photovoltaic array

The first element of our system is the photovoltaic array. As shown in Figure 2, it is made up of 3 groups of photovoltaic panels, with a total power of 50 kW for an irradiation of 1000 W/m².

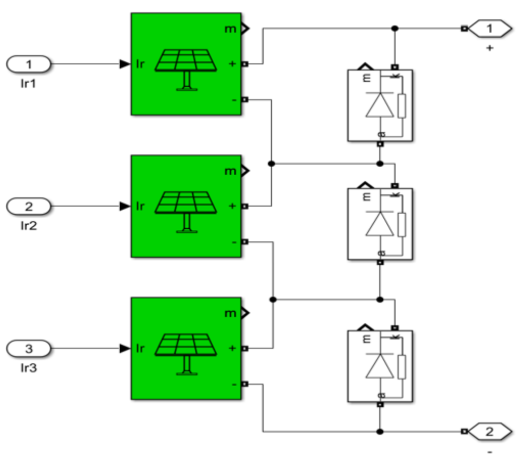

Figure 2. Photovoltaic panels chosen for the project.

Plotting the electrical characteristics of the photovoltaic panel array at a constant temperature of 25°C, we observe current and power curves as a function of voltage, as illustrated in Figure 3.

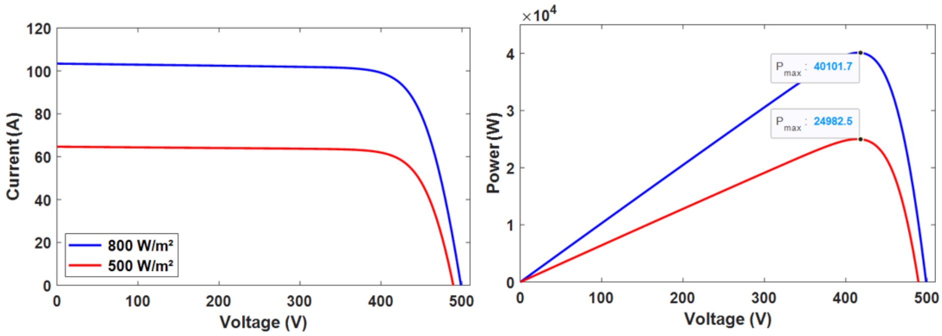

Figure 3. The electrical characteristics of the PV array at 25°C and different irradiation levels.

At 500 W/m² irradiance, the panels provide a maximum power of around 25 kW, which increases to 40 kW at 800 W/m². The power supplied by the panels depends directly on irradiation [9], increasing proportionally with it. This underlines the significant impact of climatic conditions on the performance of photovoltaic systems.

When photovoltaic panels are exposed to non-uniform irradiation, this is known as partial shading [10]. To simulate this phenomenon, each group of photovoltaic panels will be exposed to different irradiances. Then the electrical characteristics of the photovoltaic panels will be plotted to visualize the effect of partial shading on their electrical performance.

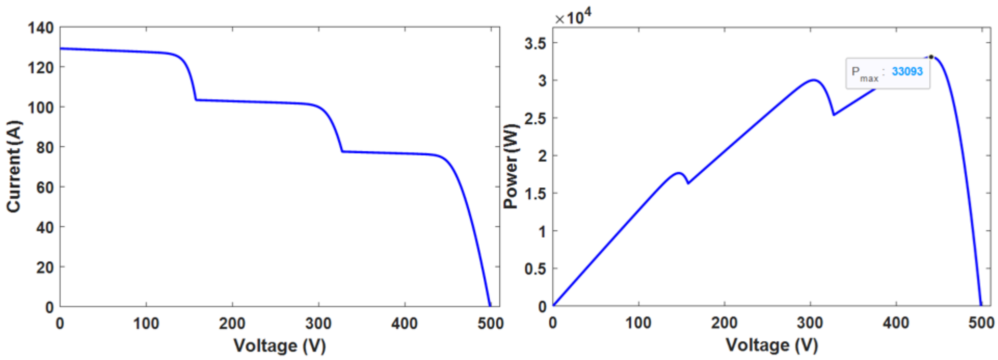

Figure 4. The electrical characteristics under partial shading of the PV array.

The clear observation from Figure 4 is that the power curve shows several peaks. This phenomenon disrupts the operation of certain MPPT controls, causing the system to operate at suboptimal power. This can be seen as a loss of available electrical power. In the case studied here, the maximum power to be followed by the control is 33 kW, corresponding to the global peak.

2.2. Mppt control techniques

As described in the earlier section, the electrical characteristics of photovoltaic panels depend on climatic conditions, and the use of MPPT control ensures that panels operate at their maximum power point, regardless of variations in these conditions [9]. Without effective MPPT control, the system could operate at power levels below its maximum potential, resulting in a loss of energy efficiency and a reduction in overall performance [11][12].

In this section, we present the methods involved in our study, detailing the operating principle of each method.

2.2.1. MPPT based on ANFIS with fuzzy logic controller

ANFIS combines artificial neural networks and fuzzy logic to optimize decision-making and modeling in complex systems [13]. ANFIS uses the ability of neural networks to learn and identify patterns from data while applying fuzzy logic principles to manage uncertainty and imprecision. This combination enables ANFIS to efficiently transform input signals into accurate outputs through an adaptive learning process, where the parameters of the fuzzy inference system are optimally tuned using machine learning algorithms [14][15].

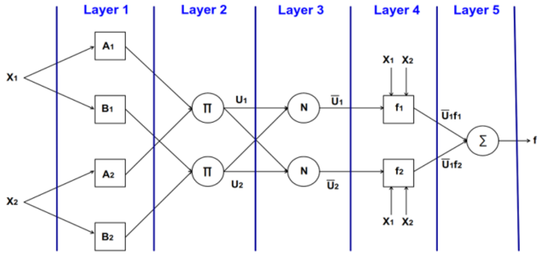

Figure 5. Simple ANFIS structure.

Figure 5. illustrates the ANFIS structure [16] [17] with two inputs, x1 and x2, and a single output f. The fuzzy rules applied to the ANFIS model being analyzed are defined as:

$$If \quad x_1 \, is \quad A_1 \quad and \quad x_2 \, is \quad B_1 \quad then: \quad f_1 = p_1 x_1 + q_1 x_2 + r_1 \qquad (1)$$

$$If \quad x_1 \, is \quad A_2 \quad and \quad x_2 \, is \quad B_2 \quad then: \quad f_2 = p_2 x_1 + q_2 x_2 + r_2 \qquad (2)$$

Where:

A_i, B_i: The fuzzy set parameters representing linguistic values.

p_i, q_i, r_i: consequent parameters.

ANFIS consists of five primary types of layers, with each layer in the neural network applying a fuzzy logic function, with weighted neural connections to transform input signals into precise outputs. The system stands out for its adaptability, rapid learning, and non-linear modeling power.

Layer 1: After receiving the input data, it must be transformed into linguistic terms to facilitate fuzzy inference. The output of node i in this layer, denoted $O_{1,i}$ is determined by the input to the membership functions of the corresponding node 1 [16] [17].

$$O_{1,i} = \mu_{Ai}(x_1) \quad for \quad i = 1,2 \qquad (3)$$

$$O_{1,i} = \mu_{Bi-2}(x_2) \quad for \quad i = 3,4 \qquad (4)$$

Where:

μ_{Ai}, μ_{Bi}: The membership grades of the inputs x_1 and x_2 in the A_i and B_i fuzzy sets, respectively.

Layer 2: In this layer, the nodes are fixed, with each node i producing an output based on its input functions. This layer operates as a multiplier and is known as the neural network layer. [16] [17].

$$O_{2,i} = U_i = \mu_{Ai}(x_1) \cdot \mu_{Bi}(x_2) \quad for \quad i = 1,2 \qquad (5)$$

Where:

U_i: The firing strength of rule *i*.

Layer 3: This layer normalizes the firing strengths of all rules to ensure that they sum up to 1 [16] [17].

$$O_{3,i} = \overline{U}_i = \frac{U_i}{U_1 + U_2} \qquad (6)$$

Where:

$\overline{U}_i$: The normalized firing strength of rule i.

Layer 4: In this layer, the nodes are adaptive, with their functions specified as [16] [17]:

$$O_{4,i} = \bar{U}_i \cdot f_i = U_i(p_i x_1 + q_i x_2 + r_i) \quad for \quad i = 1,2 \qquad (7)$$

Layer 5: This layer combines the outputs from all rules, with its output being the sum of all incoming signals [16] [17]:

$$O_{5,i} = f = \sum_i \bar{U}_i \cdot f = \frac{\sum_i U_i f_i}{\sum_i U_i} \quad for \quad i = 1,2 \qquad (8)$$

- **Principle of the proposed MPPT:**

The proposed MPPT control is based on two main elements: an ANFIS model and a fuzzy controller as shown in Figure 6. The ANFIS model takes temperature and solar irradiance as inputs and provides the fuzzy controller with the reference voltage corresponding to the maximum power point. This fuzzy controller ensures that the whole system operates at this optimal power point, thus maximizing the system's energy efficiency. In our study, we considered a constant temperature, varying only solar irradiance to assess system performance.

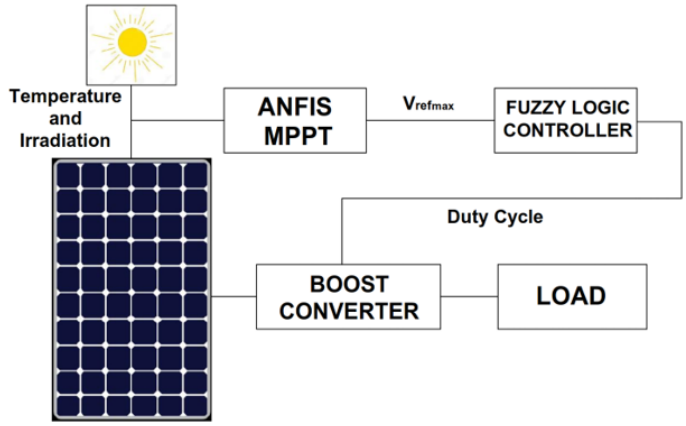

Figure 6. Principle of the proposed MPPT.

To implement the ANFIS method, the neuro-fuzzy designer in the MATLAB environment was used [18], as illustrated in Figure 7.

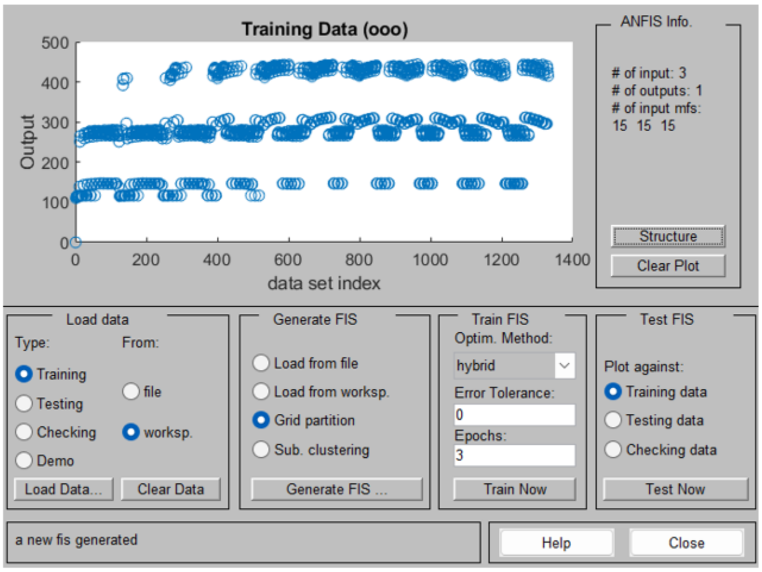

Figure 7. Data and model set up in ANFIS MATLAB designer.

The ANFIS model takes as input the irradiances of the various panels and generates the voltage corresponding to the point of maximum power. The data used to train this model are presented in Table 1.

Table 1. Selection of training data.

Irradiation Pv1	Irradiation Pv2	Irradiation Pv3	Voltage of MPP
1000	1000	1000	415.49
800	600	100	304.90
800	100	100	146.76
100	800	100	146.76
300	600	500	271.92
400	700	1000	274.70
900	400	600	441.89
600	300	400	435.41
400	800	900	269.30
200	800	800	266.48

After several simulations with different parameters such as types and number of membership functions, learning methods, etc., the configuration that generates the fewest errors is the following: the type of membership function is triangular, the number of membership functions is 15 for the three inputs, and the number of epochs is 3. The results are encouraging, showing a Root Mean Square Error (RMSE) of around $8.6\times10{-}4$.

- **Fuzzy logic controller:**

A fuzzy logic controller is used to maintain the PV system at the voltage corresponding to the maximum power point. The design process for this controller is comprehensively outlined in the sources cited in [19][20]. Once the design is complete, the controller is implemented in Simulink, as depicted in Figure 8.

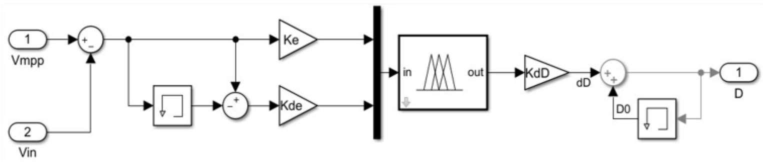

Figure 8. Design of fuzzy logic controller in Simulink.

The control was implemented using MATLAB Simulink, based on the system elements presented above. The MPPT controller simulation is shown in Figure 9.

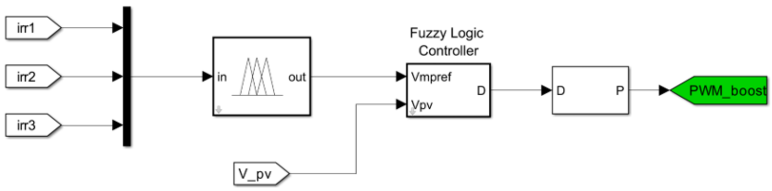

Figure 9. Design of MPPT controller in Simulink.

2.2.2. MPPT based on ANFIS and without fuzzy logic controller

The main aim of the proposed method is to simplify MPPT control by reducing the number of elements used. Unlike the control presented in the previous section, we propose to use an ANFIS-based MPPT approach without the need for an additional controller, instead of the ANFIS model providing the voltage corresponding to the maximum power point, it will directly generate the duty cycle for the boost, as shown in Figure 10.

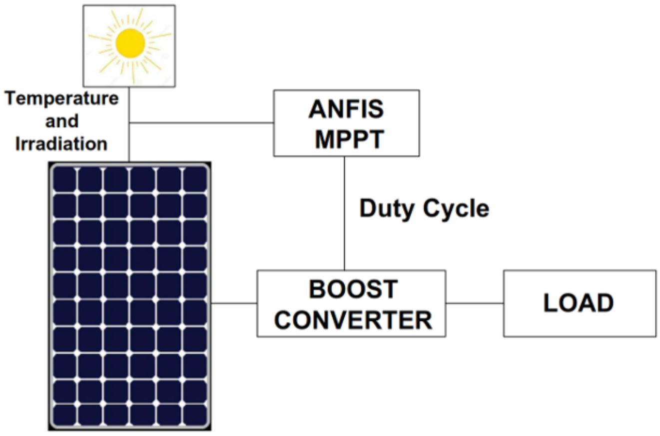

Figure 10. Improvement of the proposed MPPT control.

According to the boost converter's characteristic relations, the relationship between output voltage, input voltage, and duty cycle is expressed as follows [21]:

$$V_O = \frac{V_i}{1-D} \qquad (9)$$

Where:
V_i: The Input voltage.
V_o: The output voltage.
D: The duty cycle.

In a photovoltaic system where the DC bus voltage is not maintained constant, any change in the duty cycle results in simultaneous variations in the boost converter's input and output voltages [22]. As the output voltage depends on the load, the duty cycle required to obtain the boost input voltage corresponding to the maximum power point varies with the load, even under the same climatic conditions. In our system, we use a DC-AC inverter with a control to regulate the DC bus voltage. This maintains a constant voltage at the boost output. Therefore, when the duty cycle is modified, only the boost input voltage changes. Consequently, whatever the load, the duty cycle that gives the input voltage corresponding to the maximum power point remains the same as long as climatic conditions remain unchanged.

Following the same approach to control configuration and training presented above, and using the configuration shown in Figure 11 and data presented in Table 2, the root-mean-square error (RMSE) obtained is approximately 1.75×10^{-6}.

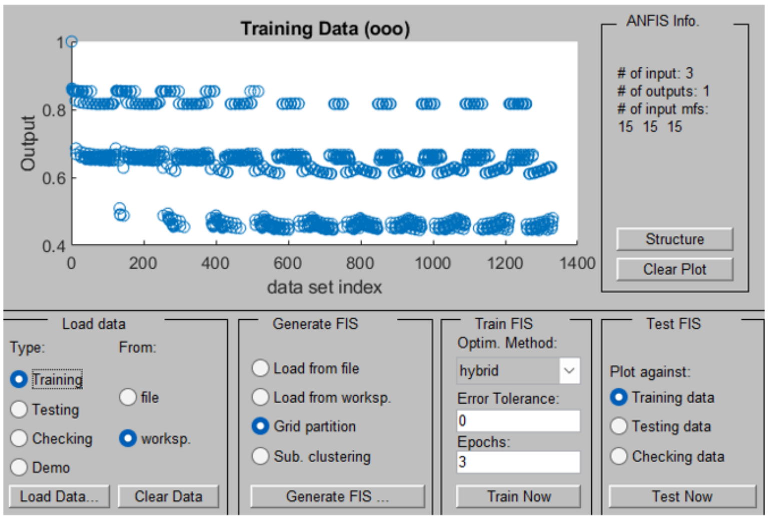

Figure 11. Data and model parameterization in ANFIS MATLAB designer.

Table 2. Selection of training data

Irradiation Pv1	Irradiation Pv2	Irradiation Pv3	Duty cycle of MPP
100	400	0	0.818
600	1000	1000	0.448
1000	400	600	0.446
300	300	400	0.480
1000	200	800	0.657
200	100	100	0.487
400	800	500	0.454
400	1000	100	0.816
500	600	400	0.456
500	800	300	0.614

The control was implemented using MATLAB Simulink, based on the system elements presented above. The MPPT controller simulation is shown in Figure 12.

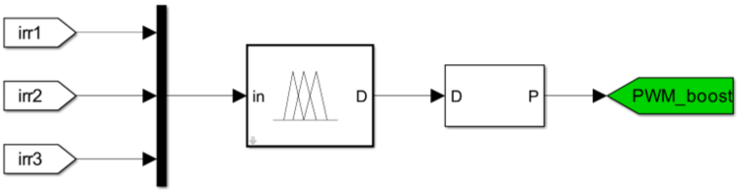

Figure 12. Design of MPPT controller in Simulink.

3. RESULTS AND DISCUSSION

3.1. Under Uniform irradiation

To evaluate the performance of the two MPPT control methods, a detailed comparison is carried out under different conditions to identify their respective strengths and weaknesses. For this purpose, an initial simulation is carried out under uniform irradiation conditions. The irradiation used varies between two values: 800 W/m² and 500 W/m², as illustrated in Figure 13. According to the panel characteristics, at an irradiation of 800 W/m², the panel should deliver around 40 kW at the maximum power point, while at 500 W/m², the maximum power should be around 25 kW.

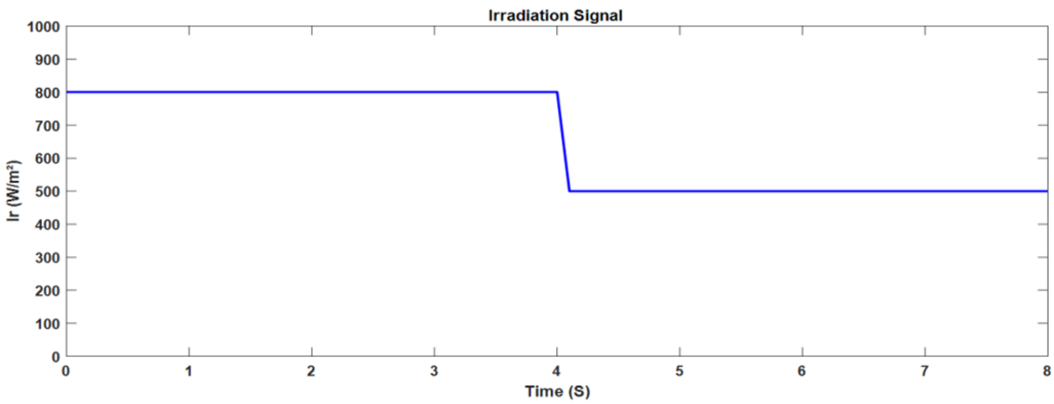

Figure 13. The irradiation signal applied to the three photovoltaic panels.

From 0 to 4 seconds, the irradiation remains stable at 800 W/m², representing constant sunlight conditions. At 4 seconds, the irradiation drops to 500 W/m², simulating cloud cover or reduced sunlight. This abrupt change is used to test the responsiveness and stability of the MPPT control methods under sudden irradiation variations, which is essential for evaluating their real-world performance.

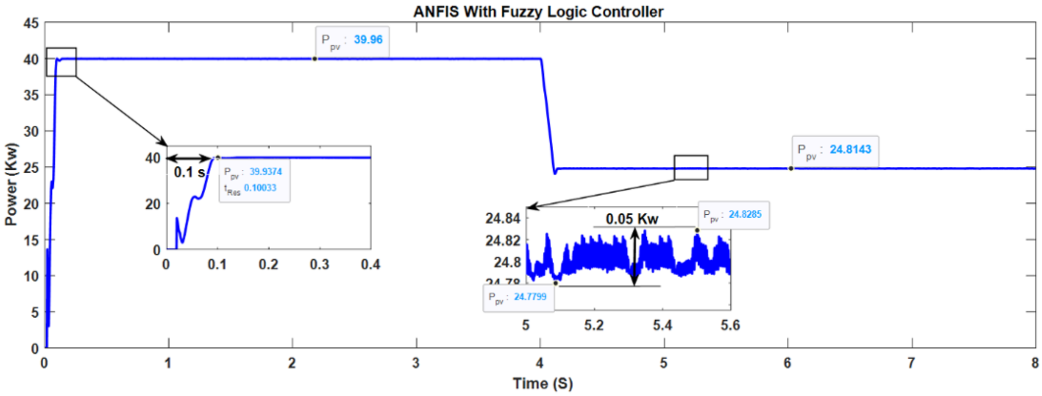

Figure 14. PV power for the ANFIS MPPT using a Fuzzy controller.

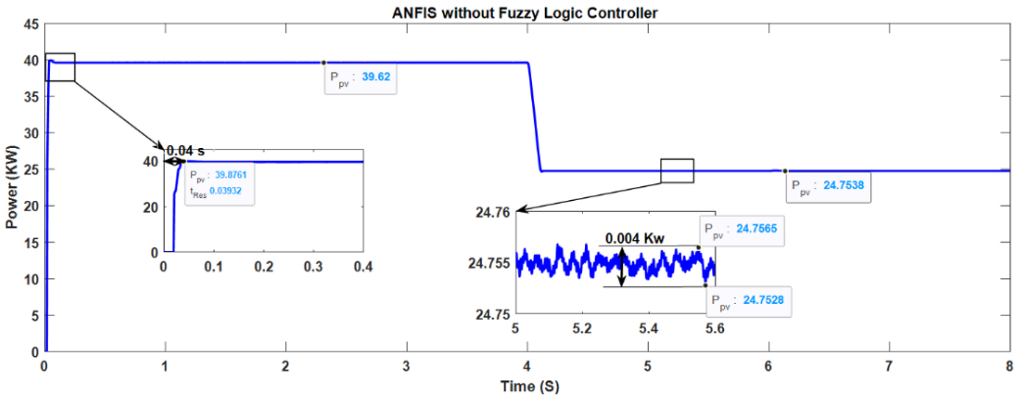

Figure 15. PV power for the ANFIS MPPT.

Table 3 summarizes the results presented in Figure 14 and Figure 15. The comparison between the two ANFIS-based MPPT control methods, one with a controller and the other simplified without, highlights differences in speed, stability, and accuracy:

• Speed: The simplified ANFIS method demonstrates a faster response time (0.04 seconds) compared to the version with a controller (0.1 seconds), allowing quicker adaptation to irradiation changes.

• Stability: The method simplified significantly reduces oscillations around the set point (0.004 compared to 0.05 using the controller), indicating enhanced system stability.
• Accuracy: While the controller-based method achieves slightly better accuracy (0.14 kW vs. 0.48 kW without), the difference is minimal and within acceptable limits.

Table 3. Response time, oscillations, and power discrepancy.

	ANFIS Using a controller	ANFIS Without a controller
Response time (s)	0.1	0.04
Oscillations (Kw)	0.05	0.004
Power discrepancy (Kw)	0.14	0.48

Overall, the ANFIS method without a controller excels in speed and stability, offering a streamlined and efficient solution by removing the need for additional components. The method using a controller, although marginally more accurate, adds complexity to the system.

3.2. Under Partial shading

To enrich the comparison and ensure an overall assessment, both methods will also be simulated under partial shading conditions. In this scenario, the three panels will experience different irradiances: 1000 W/m², 800 W/m², and 600 W/m². Under these conditions, the panels should deliver a maximum power of 33 kW.
Table 4 summarizes the results presented in Figure 16 and Figure 17. The comparison of the two ANFIS-based MPPT control methods under partial shading can be summarized as follows:
• Speed: The simplified ANFIS method responds faster (0.06 seconds) compared to the version using a controller (0.15 seconds), enabling quicker adaptation to shading variations.
• Stability: Oscillations around the set point are significantly reduced in the simplified method (0.0012 vs. 0.05), demonstrating enhanced stability with fewer fluctuations.
• Accuracy: The simplified method also shows improved accuracy, with a power disparity of 0.0079 kW compared to 0.0217 kW for the method using a controller. However, this difference is minimal and largely negligible in practical terms.
In summary, the ANFIS method without a fuzzy logic controller simplifies the system design while offering notable improvements in speed, stability, and accuracy.

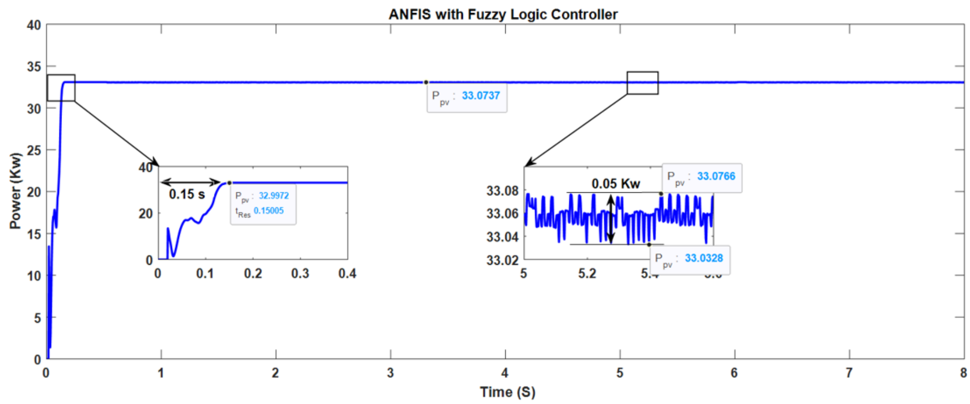

Figure 16. PV power for the ANFIS MPPT using a Fuzzy controller.

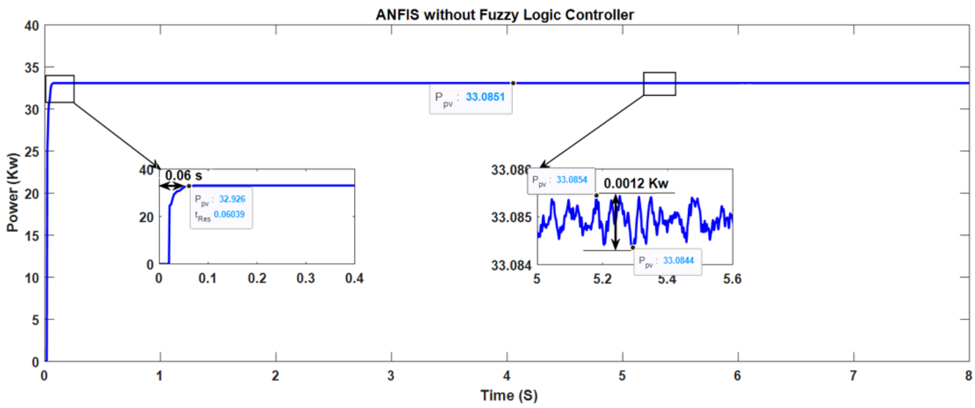

Figure 17. PV power for the ANFIS MPPT.

Table 4. Response time, oscillations, and power discrepancy.

	ANFIS Using a controller	ANFIS Without a controller
Response time (s)	0.15	0.06
Oscillations (Kw)	0.05	0.0012
Power discrepancy (Kw)	0.0217	0.0079

3.3. Comparison with prior MPPT Methods

To strengthen the contextual foundation of this study, we compare it with our previous work [23], which analyzed the performance of three MPPT methods P&O, PSO, and ANN with a fuzzy logic controller under both uniform irradiation and partial shading. This comparison highlights the advantages and limitations of each approach to the proposed ANFIS-based method. Although a precise comparison of the results would require identical test conditions and system configuration, we can identify general trends by examining the observed advantages and disadvantages of each method in both studies.

In uniform irradiation conditions, all methods demonstrated good accuracy in tracking the maximum power point. However, the P&O method exhibited notable oscillations around this point, compromising system stability. While the PSO method also successfully tracked the maximum power, it required a prolonged response time due to the high number of iterations needed to converge. The ANN method with a fuzzy logic controller offered faster and more accurate tracking but, with the added controller, introduced a slight delay in response, making it similar in speed to the ANFIS method with a controller. By contrast, the ANFIS method without a controller achieved the quickest response time, benefiting from a streamlined architecture without additional components.

Under partial shading conditions, the P&O method was limited by its tendency to lock onto local maxima, reducing tracking accuracy. Both PSO and ANN with fuzzy logic controller performed well in these conditions, with ANN offering a faster response than PSO, which again required more iteration to find the optimal point. The ANFIS method without a controller maintained the best performance, achieving a faster response with minimal oscillations, positioning it as a highly efficient solution under dynamically changing conditions without the need for a secondary controller.

3.4. Practical Benefits of the Simplified ANFIS-Based MPPT System

The proposed ANFIS-based MPPT method without a fuzzy controller provides considerable practical advantages for photovoltaic systems by reducing system complexity and enhancing efficiency. By removing the need for an additional fuzzy controller, the overall design becomes more streamlined, lowering initial setup costs by eliminating extra hardware components. This reduction in hardware not only cuts costs but also simplifies system maintenance, as there are fewer elements to monitor, troubleshoot, or replace over the system's lifetime. Moreover, eliminating the fuzzy controller reduces the likelihood of control-related failures, enhancing system reliability, particularly in demanding environments or remote locations where maintenance visits are infrequent or costly. This streamlined design does not compromise the system's ability to track the maximum power point accurately, as shown in the simulation results, making it an optimal choice for scenarios where cost-effectiveness, robust performance, and ease of maintenance are key considerations. In essence, this approach not only meets the technical requirements for efficient MPPT but also aligns well with the practical demands of real-world photovoltaic applications.

4. CONCLUSION

This study explored and compared two MPPT control methods based on the ANFIS model: one using a fuzzy logic controller and the other simplified by removing the controller. The simulation results under various irradiation conditions demonstrated that the simplified method excels in speed, stability, and accuracy while streamlining system design by eliminating the controller. This simplification not only reduces system complexity but also lowers costs and decreases the potential for component failure.

The simplified method showed superior responsiveness to irradiation variations, with a shorter response time and minimized oscillations compared to the method using a controller. Although the controller-based method achieved marginally higher accuracy in some scenarios, the difference is negligible, making the simplified method equally effective in meeting energy performance goals.

Overall, the proposed simplified ANFIS-based MPPT approach emerges as an optimal solution for photovoltaic systems, particularly where simplicity, robustness, and efficiency are key priorities. This work lays the groundwork for future research focused on further refining this method and extending its application to other areas requiring optimal energy management. For instance, integrating this technique into complex systems like Off-Grid Photovoltaic-Battery setups is highly beneficial, as efficient energy exploitation and management are critical. By streamlining MPPT control while maintaining high performance, this approach enhances overall system efficiency and reliability.

Author Contributions: All authors have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Funding: This article received no external funding.

Data Availability Statement: All the data are available in the manuscript.

Acknowledgments: The authors gratefully acknowledge the support provided by the Engineering and Applied Physics Team (EAPT) at the Higher School of Technology, Sultan Moulay Slimane University, Beni Mellal, Morocco. The authors also sincerely appreciate the editor and reviewers for their timely observations and suggestions regarding this research article.

Conflicts of Interest: The authors declare that they have no conflict of interest.

REFERENCES

[1] R. Benbba, M. Barhdadi, A. Ficarella, et al., "Solar Energy Resource and Power Generation in Morocco: Current Situation, Potential, and Future Perspective," Resources, vol. 13, no. 10, p. 140, 2024. https://doi.org/10.20944/preprints202408.1025.v1.

[2] C. Ghizlane, B. Mohcine, B. Abdenabi, and A. Abdelouahed, "Performance Analysis of MPPT Tracking Algorithm Based on Artificial Neural Network for a PV Pumping System," 2024 4th International Conference on Innovative Research in Applied Science, Engineering and Technology (IRASET), FEZ, Morocco, 2024, pp. 1-7. https://doi.org/10.1109/IRASET60544.2024.10548482.

[3] M. A. Atillah, H. Stitou, A. Boudaoud, and M. Aqil, "Performance Analysis of Three MPPT Controls Under Partial Shading: P&O, PSO, and ANN," E3S Web of Conferences, vol. 469, p. 00064. EDP Sciences, 2023. https://doi.org/10.1051/e3sconf/202346900064.

[4] S. Kim, J. A. Márquez, T. Unold, and A. Walsh, "Upper limit to the photovoltaic efficiency of imperfect crystals from first principles," Energy & Environmental Science, vol. 13, no. 5, pp. 1481-1491, 2020. https://doi.org/10.1039/D0EE00291G.

[5] R. I. Areola, O. A. Aluko, and O. I. Dare-Adeniran, "Modelling of Adaptive Neuro-fuzzy Inference

System (ANFIS)-Based Maximum Power Point Tracking (MPPT) Controller for a Solar Photovoltaic System," Journal of Engineering Research and Reports, vol. 25, no. 9, pp. 57-69, 2023. https://doi.org/10.9734/jerr/2023/v25i9981.

[6] C. S. Esobinenwu, "OPTIMIZATION OF SOLAR PV SYSTEM USING ANFIS CONTROLLER UNDER PARTIALLY SHADED CONDITION," Advance Journal of Science, Engineering and Technology, vol. 8, no. 3, 2023. https://aspjournals.org/ajset/index.php/ajset/article/view/48.

[7] S. R. Revathy, V. Kirubakaran, M. Rajeshwaran, T. Balasundaram, V. S. Chandra Sekar, S. Alghamdi, B. S. Rajab, A. O. Babalghith, and E. M. Anbese, "Design and analysis of ANFIS–based MPPT method for solar photovoltaic applications," International Journal of Photoenergy, No. 1, 2022, Art. No. 9625564, vol. 2022. https://doi.org/10.1155/2022/9625564.

[8] R. T. Moyo, P. Y. Tabakov, and S. Moyo, "Design and modeling of the ANFIS-based MPPT controller for a solar photovoltaic system," Journal of Solar Energy Engineering, vol. 143, no. 4, pp. 041002, 2021. https://doi.org/10.1115/1.4048882.

[9] C. Ghizlane, Z. Massaq, A. Abounada, and M. Mabrouki, "Speed control of induction motor driving a pump supplied by a photovoltaic array," Int. J. Renew. Energy Res., vol. 10, no. 1, pp. 237-242, 2020. https://doi.org/10.20508/ijrer.v10i1.10320.g7859.

[10] J. Teneta, W. Kreft, and M. Janowski, "Partial Shading of Photovoltaic Modules with Thin Linear Objects: Modelling in MATLAB Environment and Measurement Experiments," Energies, vol. 17, no. 14, p. 3546, 2024. https://doi.org/10.3390/en17143546.

[11] D. Mazumdar, C. Sain, P. K. Biswas, P. Sanjeevikumar, and B. Khan, "Overview of solar photovoltaic MPPT methods: a state of the art on conventional and artificial intelligence control techniques," International Transactions on Electrical Energy Systems, vol. 2024, no. 1, Art. no. 8363342, 2024. https://doi.org/10.1155/2024/8363342.

[12] M. A. Atillah, H. Stitou, A. Boudaoud, and M. Aqil, "Power Flow Management for Off-Grid Photovoltaic-Battery System Using ANN-FL Controller MPPT," International Conference on Connected Objects and Artificial Intelligence, pp. 158-164. Cham: Springer Nature Switzerland, 2024. https://doi.org/10.1007/978-3-031-70411-6_25.

[13] S. Chapala, R. L. Narasimham, and G. T. Ram Das, "Power Quality Analysis of ANFIS Based Distributed Generation System with UPQC," International Journal of Engineering and Manufacturing (IJEM), vol. 14, no. 4, pp. 1-14, 2024. https://doi.org/10.5815/ijem.2024.04.01.

[14] A. N. Mohammed, S. Umar, and S. Chatterjee, "ANFIS SYSTEMATIC ROBUSTNESS INVESTIGATION FOR AVR SYSTEM," e-Prime-Advances in Electrical Engineering, Electronics and Energy, vol. 9, Art. no. 100670, 2024. https://doi.org/10.1016/j.prime.2024.100670.

[15] H. Stitou, M. A. Atillah, A. Boudaoud, and M. Aqil, "Load forecasting using fuzzy logic, artificial neural network, and adaptive neuro-fuzzy inference system approaches: application to South-Western Morocco," International Journal of Electrical & Computer Engineering, vol. 14, no. 6, 2024. http://doi.org/10.11591/ijece.v14i6.pp7067-7079.

[16] A. M. M. AL-Qaysi, A. Bozkurt, and Y. Ates, "Load Forecasting Based on Genetic Algorithm–Artificial Neural Network-Adaptive Neuro-Fuzzy Inference Systems: A Case Study in Iraq," Energies, vol. 16, no. 6, p. 2919, 2023. https://doi.org/10.3390/en16062919.

[17] M. Ferdosian, H. Abdi, S. Karimi, and S. Kharrati, "Short-term load and spinning reserve prediction based on LSTM and ANFIS with PSO algorithm," The Journal of Engineering, vol. 2024, no. 3, Art. no. e12356, 2024. https://doi.org/10.1049/tje2.12356.

[18] L. Farah, A. Haddouche, and A. Haddouche, "Comparison between proposed fuzzy logic and ANFIS for MPPT control for photovoltaic system," International Journal of Power Electronics and Drive Systems, vol. 11, no. 2, p. 1065, 2020. http://doi.org/10.11591/ijpeds.v11.i2.pp1065-1073.

[19] J. Lorenzo, J. C. Espiritu, J. Mediavillo, S. J. Dy, and R. B. Caldo, "Development and implementation of fuzzy logic using microcontroller for buck and boost DC-to-DC converter," in IOP Conference Series: Earth and Environmental Science, vol. 69, no. 1, p. 012193. IOP Publishing, 2017. http://doi.org/10.1088/1755-1315/69/1/012193.

[20] H. Stitou, M. A. Atillah, A. Boudaoud, and M. Aqil, "Medium term load forecasting using fuzzy logic approach: A case study of Taroudannt province," in E3S Web of Conferences, vol. 469, p. 00063. EDP Sciences, 2023. https://doi.org/10.1051/e3sconf/202346900063.

[21] D. Sene, A. Sarr, M. K. Sako, A. Ouattara, M. F. Ndiaye, and V. Sambou, "Improved photovoltaic energy production under partial shading using an innovative MPPT controller based on Flying Squirrel Search Optimization algorithm," Future Energy, pp. 33-48, 2024. https://doi.org/10.55670/fpll.fuen.3.3.4.

[22] M. Chankaya, S. B. Q. Naqvi, I. Hussain, B. Singh, and A. Ahmad, "Power quality enhancement and improved dynamics of a grid-tied PV system using equilibrium optimization control based regulation of DC bus voltage," Electric Power Systems Research, vol. 226, p. 109911, 2024. https://doi.org/10.1016/j.epsr.2023.109911.

[23] M. A. Atillah, H. Stitou, A. Boudaoud, M. Aqil, and A. Hanafi, "Study and analysis of partial shading effect on power production of a photovoltaic string controlled by three different MPPT techniques: P&O, PSO and ANN," Mathematical Modeling and Computing, vol. 11, no. 3, pp. 856–869, 2024. https://doi.org/10.23939/mmc2024.03.856.