

An Accelerated Aquila Optimizer for Maximum Power Point Tracking of PV Systems under Partial Shading Conditions

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Abstract. In this work, an improved version of the recent Aquila Optimizer was designed for Maximum Power Point Tracking. The new algorithm was tested on a standalone PV system under several complex partial shading scenarios. A comparative study was conducted to evaluate efficiency, robustness, and convergence speed against the PSO, and the standard AO algorithms. The results indicate that the proposed Accelerated Aquila Optimizer (AAO) generally outperformed its competitors, particularly in terms of convergence time.

1 Introduction

In response to mounting concerns over climate change and the depletion of traditional energy sources, governments globally are advocating for the advancement and extensive integration of renewable energy technologies, specifically focusing on solar systems [1-3]. Significant reductions in the cost of photovoltaic (PV) technology and simplified installation procedures are further accelerating this transition to sustainable energy [4-5]. Solar irradiance and temperature variations play critical roles in affecting PV generator performance, resulting in fluctuating power outputs throughout the day [6]. The intersection of the load line and the IV characteristic curve determines the operational point of a photovoltaic (PV) device when it is connected directly to a load [7-8]. This frequently results in an operating point that is not at the maximum power point of the PV generator, which lowers efficiency [9-10]. PV systems use Maximum Power Point Trackers (MPPT) in conjunction with DC-DC converters to optimize the operating point and maximum power production in order to overcome this problem [11]. Golden Section approaches, Incremental Conductance, and Perturb and Observe are examples of common MPPT procedures [12-14]. However, conventional systems encounter difficulties in scenarios of partial shading, where uneven solar irradiation may generate multiple peaks in the I-V characteristic curve [15]. As a result, metaheuristic algorithms are gaining traction as replacements for traditional methods in MPPT and other engineering applications [16-19]. In

this study, we introduce an enhanced iteration of the Aquila Optimizer, known as the Accelerated Aquila Optimizer, designed for Maximum Power Point Tracking. This algorithm underwent testing under three complex partial shading scenarios, showing superior performance in tracking speed and efficiency compared to both the standard AO and Particle Swarm Optimization algorithms in all conducted experiments.

2 PV Modelling

A PV cell is a type of specifically constructed semiconductor device that is the basic part of a photovoltaic generator. The single diode model (SDM) is the most basic of the models that mimic PV cells. Its corresponding circuit is shown in Figure 1 and consists of a series resistance R_s for contact resistance, a shunt resistance R_{sh} for leakage current, and a photo-current source for the cell's output [20]. A PV array is made up of panels, whereas a PV module is made up of many linked PV cells.

The output PV current can be found using:

$$I_{pv} = I_{ph} - I_s \left[e^{\left(\frac{q(V_{pv} + R_s I_{pv})}{aKT} \right)} - 1 \right] - \frac{V_{pv} + R_s I_{pv}}{R_{sh}} \quad (1)$$

Where I_{pv} and V_{pv} are the current and voltage generated by the PV panel, and I_s is the diode's reverse saturation current. q represents the electron charge ($1.60217662 \times 10^{-19}$ C), while a is the diode ideality factor. K denotes the Boltzmann constant ($1.38064852 \times 10^{-23}$ J/K), and T signifies the temperature of the p-n junction.

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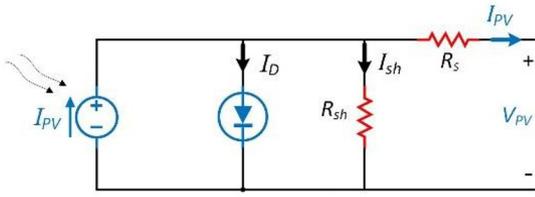


Fig. 1 The Single Diode Model [10].

3 Proposed Optimizer

3.1 Aquila Optimizer

The Aquila Optimizer (AO) derives its name and methodology from the strategic hunting behaviors observed in Aquila (eagle) species [11-13]. As a metaheuristic algorithm, the AO is intricately crafted to address intricate optimization challenges by simulating the nuanced hunting strategies of these majestic birds. Emulating nature's efficiency in pursuit, the AO unfolds through a structured, multi-phase process that systematically blends exploration and exploitation phases. These phases are strategically designed to navigate diverse and complex search spaces effectively, aiming to swiftly converge towards optimal solutions. Each stage of the AO's iterative journey is underpinned by a series of equations tailored to enhance its adaptability and precision in optimizing a wide range of parameters and constraints.

- Stage 1:

$$\overrightarrow{X}_{t+1}(i) = \overrightarrow{X}_B \left(1 - \frac{t}{T}\right) + (\overrightarrow{X}_M - rand \times \overrightarrow{X}_B) \quad (2)$$

$$\overrightarrow{X}_{t+1}(i) = \overrightarrow{X}_B \times Lv + \overrightarrow{X}_R + (y - x) \times rand \quad (3)$$

Where \overrightarrow{X}_B is the global best solution. \overrightarrow{X}_M represents the mean of the population. \overrightarrow{X}_R is a randomly chosen solution from the population. Lv represents a levy flight motion. x and y are used to generate a spiral movement as follows:

$$x = r \cos \theta \quad (4)$$

$$y = r \sin \theta \quad (5)$$

$$\theta = -0.005 + \frac{3\pi}{2} \quad (6)$$

$$r = r_1 + 0.00565 \quad (7)$$

With r_1 being an integer between 1 and 20

- Stage 2:

$$\overrightarrow{X}_{t+1}(i) = (\overrightarrow{X}_M - \overrightarrow{X}_B) \times \alpha - rand + (L + (U - L) \times rand) \times \delta \quad (8)$$

$$\overrightarrow{X}_{t+1}(i) = QF \times \overrightarrow{X}_B - G1 \times \overrightarrow{X}_t(i) \times rand - G2 \times L + rand \times G1 \quad (9)$$

Where U and L are respectively the upper bound and the lower bound of the search space. α and δ are factors both fixed at 0.01. Qf , $G1$ and $G2$ are computed as follows:

$$QF = t \frac{2rand-1}{(1-T)^2} \quad (10)$$

$$G1 = 2rand - 1 \quad (11)$$

$$G2 = 2 \left(1 - \frac{t}{T}\right) \quad (12)$$

3.2 Accelerated Aquila Optimizer

While the original Aquila Optimizer (AO) is effective for many engineering problems, it faces challenges in Maximum Power Point Tracking (MPPT) due to its online optimization nature. Some AO equations cause large perturbations, which are undesirable in the narrow MPPT search space and can lead to power losses. To address this, we improved AO's exploitation ability for smoother search operations in MPPT applications. Three modifications were made: 1- Stage 1 is now enabled only in the first third of the iterative process to reduce large perturbations. 2- Removing equation 8 to avoid solutions outside the search space and 3- Guiding the final phase with a new equation:

$$\overrightarrow{X}_{t+1}(i) = \overrightarrow{X}_B + \alpha \times G1 \times (Lv \times \overrightarrow{X}_{R1} - \overrightarrow{X}_{R2}) \quad (13)$$

Where \overrightarrow{X}_{R1} and \overrightarrow{X}_{R2} are two randomly chosen solutions from the population.

The overall flowchart of the Accelerated Aquila optimizer is shown in Fig.2:

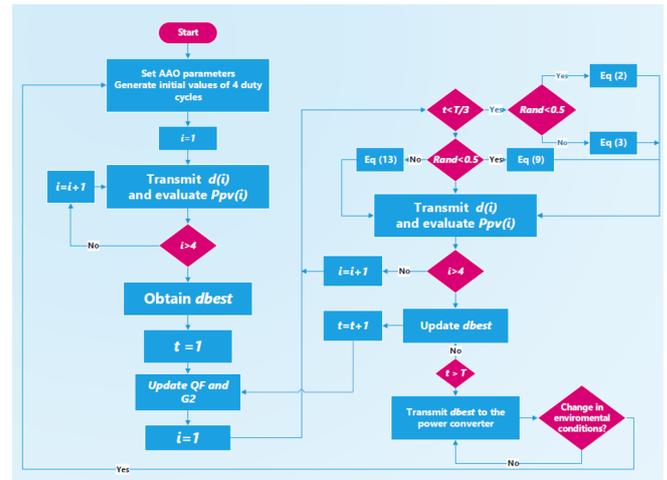


Fig. 2 Flowchart of the designed AAO

4 System Overview

A MATLAB/Simulink-based standalone PV system is developed to rigorously assess the efficacy of the proposed Accelerated Aquila Optimizer (AAO) method across three distinct and challenging partial shading scenarios. These scenarios, meticulously detailed in Table 1 and visually represented in Fig. 3, encompass varying degrees of shading conditions. The simulation setup aims to comprehensively evaluate how the AAO algorithm performs under these realistic conditions, providing insights into its robustness and efficiency in optimizing PV system performance amidst partial shading.

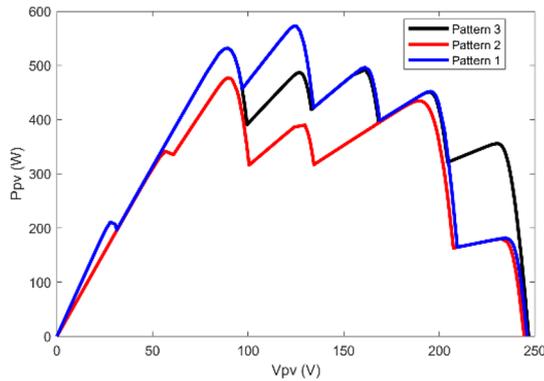


Fig. 3 PV curves of the considered Partial Shading Scenarios

Table. 1 Partial Shading Scenarios

Scenario	Irradiance levels	GMPP (W)
PSC-1	1000-800-800-600-400-300-100	573
PSC-2	700-300-800-800-400-300-100	477.4
PSC-3	1000-300-800-800-500-400-200	532.2

A thorough block diagram of the full system configuration is shown in Figure 4. It has seven 213W PV panels arranged in a sequence to effectively capture solar energy. The boost converter, which operates at a high-frequency switching rate of 50 kHz, is an essential part of the system. In order to ensure effective power distribution throughout the system, this converter is essential in optimizing the voltage output from the PV panels to meet the needs of a 40 Ω resistive load.

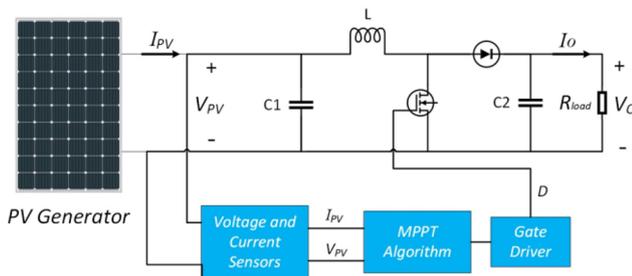


Fig. 4 Overall Schematic Diagram of the System [2].

5 Results and Discussion

Figures 5, 6, and 7 illustrate the power curves corresponding to each scenario, complemented by their respective duty cycle analyses. Notably, the power curve derived from the AAO algorithm showcases significantly smoother characteristics compared to those generated by alternative methods. This observation highlights the AAO algorithm's exceptional capability in mitigating power losses by maintaining a stable and optimal operational point. The minimal perturbations observed in its power curve underscore its superior performance in achieving consistent energy output under varying conditions. Such stability is crucial in enhancing the overall efficiency and reliability of photovoltaic systems, ensuring maximum power extraction across different environmental and operational scenarios. The quantitative outcomes in terms of efficiency and convergence time are presented

comprehensively in Table 2. Across all evaluated scenarios, the Accelerated Aquila Optimizer (AAO) algorithm consistently achieved the highest levels of efficiency compared to its counterparts, the standard AO and PSO optimizers. This signifies the algorithm's robust capability in maximizing energy extraction from photovoltaic systems across varying environmental conditions and partial shading scenarios. Moreover, the AAO algorithm demonstrated remarkable prowess in swiftly identifying and maintaining the global Maximum Power Point (MPP) in every case study. This highlights its superior exploration capabilities, crucial for ensuring optimal performance and minimizing energy losses. By efficiently adapting to changing solar irradiance and environmental factors, the AAO algorithm not only enhances energy conversion efficiency but also facilitates stable and reliable operation of PV systems.

The results underscore the algorithm's effectiveness in balancing the trade-off between exploration and exploitation phases, crucial for rapid convergence to the MPP. Specifically, the AAO algorithm's average convergence time of 0.216 seconds showcases its efficiency in swiftly adjusting to dynamic changes in solar conditions. This performance enhancement is attributed to refinements such as the exclusion of Equation 8, which historically caused significant power fluctuations in standard AO algorithms. Additionally, the integration of Equation 13 has proven beneficial in smoothing transitions between exploration and exploitation phases, contributing to a consistent and optimized energy output.

In summary, the detailed analysis presented in Table 2 confirms that the AAO algorithm not only excels in efficiency metrics but also in its ability to adapt and optimize under challenging operational conditions. These findings substantiate its role as a leading-edge solution for maximizing the performance and reliability of solar photovoltaic systems.

Table. 2 Results achieved by the considered algorithms

PSC Scenarios	Results	AAO	AO	PSO
Case-1	Tracked Power (W)	573	572.6	572.8
	Efficiency (%)	99.98	99.91	99.94
	Convergence Time (s)	0.2	0.3	0.28
Case-2	Tracked Power (W)	477.3	477.1	477.3
	Efficiency (%)	99.98	99.93	99.98
	Convergence Time (s)	0.24	0.3	0.27
Case-3	Tracked Power (W)	532.2	532.0	531
	Efficiency %	99.98	99.94	99.75
	Convergence Time (s)	0.21	0.2	0.26

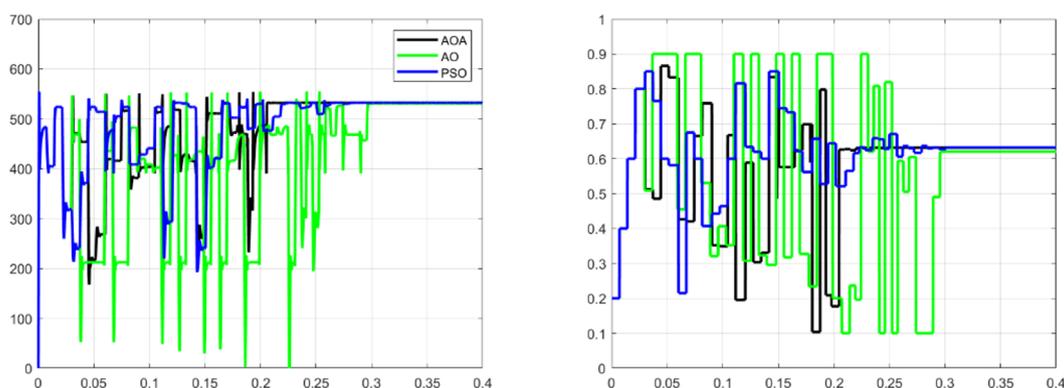


Fig. 5 Graphs depicting power usage and duty cycles in Case 1

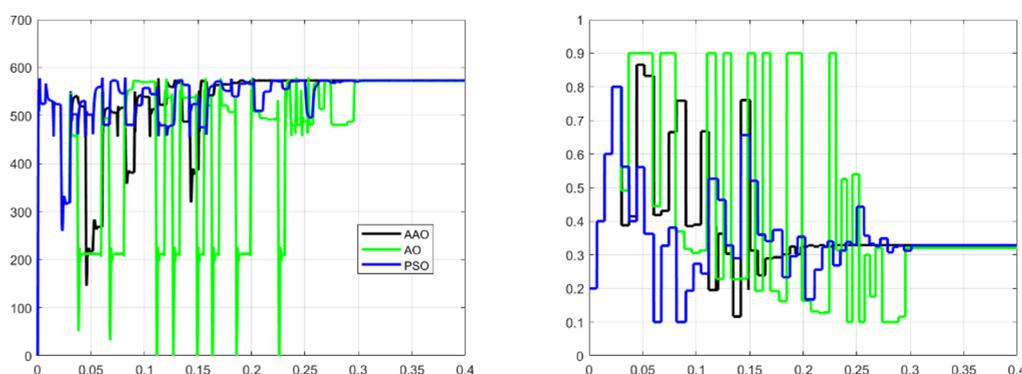


Fig. 6 Graphs depicting power usage and duty cycles in Case 2

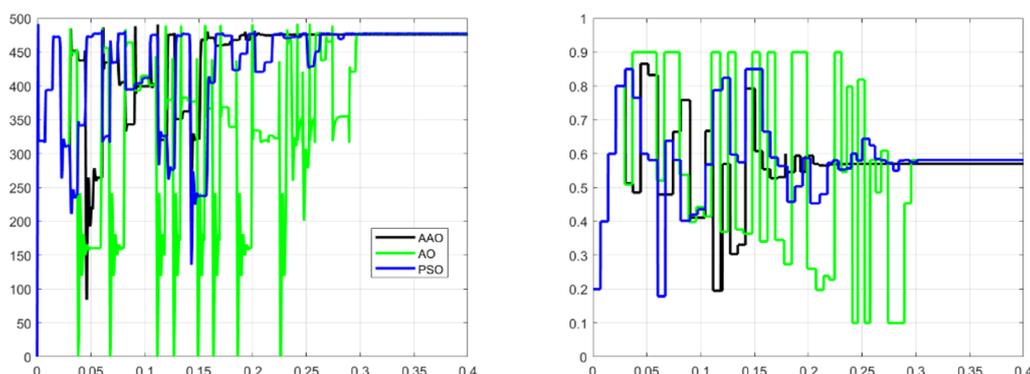


Fig. 7 Graphs depicting power usage and duty cycles in Case 3

6 Conclusion

In this work, a novel Accelerated Aquila Optimizer was designed to be an MPPT algorithm. The proposed optimizer introduces amendments to the original AO algorithm by removing an equation that causes high fluctuations, and adding a new equation for faster finer exploitation and minimal perturbations. Moreover, the first stage has been shortened into one third of the total number of iterations to further boost the tracking speed.

Consequently, the Accelerated Aquila Optimizer (AAO) exhibited exceptional performance compared to the standard Aquila Optimizer (AO) and Particle Swarm Optimization (PSO) algorithms across various critical metrics. This superior performance was rigorously demonstrated in a simulated standalone PV system that encountered several complex partial shading scenarios. Across these challenging conditions, the AAO consistently outperformed both AO and PSO in terms of efficiency, speed of convergence, and accuracy in locating the global Maximum Power Point (MPP).

These findings underscore the algorithm's robustness and efficacy in optimizing PV systems under diverse operational challenges. Future research will focus on further validating the AAO through expanded experimental trials in real-world PV installations, aiming to confirm its practical applicability and reliability across broader environmental conditions and system configurations.

For future research directions, consider validating the Accelerated Aquila Optimizer (AAO) for Maximum Power Point Tracking (MPPT) in real-world settings under varying environmental conditions and partial shading scenarios to establish its empirical reliability. Enhance the algorithm's adaptability to dynamic environmental changes by integrating real-time data and adaptive learning mechanisms. Develop hardware prototypes and integrate AAO into commercial MPPT controllers, evaluating performance through hardware-in-the-loop simulations and diverse PV system configurations. Extend optimization capabilities to multi-panel arrays, exploring hierarchical strategies and distributed control approaches. Investigate integration with energy management systems for smart grid applications and hybrid renewable energy systems, ensuring compatibility and enhancing overall system efficiency and stability. Assess the algorithm's robustness against faults and deviations, and conduct comparative studies with emerging MPPT algorithms to benchmark performance metrics. Improve PV model parameter estimation accuracy and optimize computational efficiency for scalability in large-scale installations. Finally, conduct economic and environmental impact assessments to quantify benefits in energy cost reduction and carbon emissions mitigation.

References

1. Khosravi, Nima, Rasoul Baghbanzadeh, Adel Oubelaid, Marcos Tostado-Véliz, Mohit Bajaj, Zineb Hekss, Salwa Echalih, Youcef Belkhier, Mohamad Abou Houran, and Kareem M. Aboras. "A novel control approach to improve the stability of hybrid AC/DC microgrids." *Appl. Energy* 344 (2023) : 121261.
2. Belmadani, H., Bradai, R., Kheldoun, A., Mohammed, K. K., Mekhilef, S., Belkhier, Y., & Oubelaid, A. (2024). A New Fast and Efficient MPPT Algorithm for Partially Shaded PV Systems Using a Hyperbolic Slime Mould Algorithm. *Int. J. Energy Res.*, 2024(1), 5585826.
3. Bradai, Rafik, Rachid Boukenoui, Ahmed Kheldoun, Hassen Salhi, Malek Ghanes, Jean-Pierre Barbot, and Adel Mellit. "Experimental assessment of new fast MPPT algorithm for PV systems under non-uniform irradiance conditions." *Appl. Energy* 199 (2017) : 416-429.
4. Kheldoun, A. B. R. B., Rafik Bradai, R. Boukenoui, and A. Mellit. "A new Golden Section method-based maximum power point tracking algorithm for photovoltaic systems." *Energy Convers. Manag.* 111 (2016): 125-136.
5. Belmadani, Hamza, Oussama Merabet, Adel Obelaid, Aissa Kheldoun, B. Mohit, Md Fahim Ansari, and Rafik Bradai. "Guided Seagull Optimization for Improved PV MPPT in Partial Shading." In 2023 IEEE 3rd International Conference on Applied Electromagnetics, Signal Processing, & Communication (AESPC), pp. 1-5. IEEE, (2023).
6. Sharma, Amit Kumar, Rupendra Kumar Pachauri, Sushabhan Choudhury, Ahmad Faiz Minai, Majed A. Alotaibi, Hasmat Malik, and Fausto Pedro García Márquez. "Role of metaheuristic approaches for implementation of integrated MPPT-PV systems: a comprehensive study." *Mathematics* 11, no. 2 (2023) : 269.
7. Hassan, Aakash, Octavian Bass, and Mohammad AS Masoum. "An improved genetic algorithm based fractional open circuit voltage MPPT for solar PV systems." *Energy Reports* 9 (2023): 1535-1548.
8. Sharma, P., Mishra, R.K., Bhola, P. et al. Enhancing and Optimising Solar Power Forecasting in Dhar District of India using Machine Learning. *Smart Grids and Energy* 9, 16 (2024).
9. Chtita, Smail, Aziz Derouich, Saad Motahhir, and Abdelaziz EL Ghzizal. "A new MPPT design using arithmetic optimization algorithm for PV energy storage systems operating under partial shading conditions." *Energy Convers. Manag.* 289 (2023): 117197.
10. Regaya, Chiheb Ben, Hichem Hamdi, Fethi Farhani, Afef Marai, Abderrahmen Zaafouri, and Abdelkader Chaari. "Real-time implementation of a novel MPPT control based on the improved PSO algorithm using an adaptive factor selection strategy for photovoltaic systems." *ISA transactions* 146 (2024) : 496-510. <https://doi.org/10.1016/j.isatra.2023.12.024>.
11. Belmadani, Hamza, Aissa Kheldoun, Rafik Bradai, Saad Mekhilef, and Marif Daula Siddique. "A twofold hunting trip African vultures algorithm for the optimal extraction of photovoltaic generator model parameters. *Energy Sources A: Recovery Util. Environ. Eff* 44, no. 3 (2022): 7001-7030.
12. Abualigah, Laith, Dalia Yousri, Mohamed Abd Elaziz, Ahmed A. Ewees, Mohammed AA Al-Qaness, and Amir H. Gandomi. "Aquila optimizer: a novel meta-heuristic optimization algorithm." *Comput. Ind. Eng.* 157 (2021): 107250.
13. Belkhier, Y., Oubelaid, A., & Shaw, R. N. (2024). Hybrid power management and control of fuel cells-battery energy storage system in hybrid electric vehicle under three different modes. *Energy Storage*, 6(1), e511.
14. Naoussi, S.R.D., Saatong, K.T., Molu, R.J.J. et al. Enhancing MPPT performance for partially shaded photovoltaic arrays through backstepping control with Genetic Algorithm-optimized gains. *Sci Rep* 14, 3334 (2024). <https://doi.org/10.1038/s41598-024-53721-w>.
15. Kanouni, B., Badoud, A.E., Mekhilef, S. et al. Advanced efficient energy management strategy

- based on state machine control for multi-sources PV-PEMFC-batteries system. *Sci Rep* 14, 7996 (2024). <https://doi.org/10.1038/s41598-024-58785-2>.
16. Zaghba, L., Borni, A., Benbiotur, M.K. et al. Enhancing grid-connected photovoltaic system performance with novel hybrid MPPT technique in variable atmospheric conditions. *Sci Rep* 14, 8205 (2024). <https://doi.org/10.1038/s41598-024-59024-4>.
 17. Mfetoum, I.M., Ngoh, S.K., Molu, R.J.J. et al. A multilayer perceptron neural network approach for optimizing solar irradiance forecasting in Central Africa with meteorological insights. *Sci Rep* 14, 3572 (2024). <https://doi.org/10.1038/s41598-024-54181-y>.
 18. Mohapatra, B., Sahu, B.K., Pati, S. et al. Optimizing grid-connected PV systems with novel super-twisting sliding mode controllers for real-time power management. *Sci Rep* 14, 4646 (2024). <https://doi.org/10.1038/s41598-024-55380-3>.
 19. Deghfel, N., Badoud, A.E., Merahi, F. et al. A new intelligently optimized model reference adaptive controller using GA and WOA-based MPPT techniques for photovoltaic systems. *Sci Rep* 14, 6827 (2024). <https://doi.org/10.1038/s41598-024-57610-0>.
 20. N. Kalaiarasi, A. Sivapriya, Pradeep Vishnuram, Mukesh Pushkarna, Mohit Bajaj, Hossam Kotb, Sadam Alphonse, "Performance Evaluation of Various Z-Source Inverter Topologies for PV Applications Using AI-Based MPPT Techniques", *International Transactions on Electrical Energy Systems*, vol. 2023, Article ID 1134633, 16 pages, 2023. <https://doi.org/10.1155/2023/1134633>.