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Hybrid GW-PSO Algorithm for Enhanced Maximum Power Point Tracking under Various Conditions

N. Douifi [1]*, A. Abbadi [2,3], F. Hamidia [2,3], N. Rai [1] and A. Tlemçani [2,3]

[1] *Laboratory of Advanced Electronic Systems -LAES, Electrical Engineering Department, Faculty of Technology, University of Medea, Medea, Algeria.*
[2] *Research Laboratory of Electrical Engineering and Automation-RLEA, Electrical Engineering Department, Faculty of Technology. University of Medea, Medea, Algeria.*
[3] *Renewable Energy and Materials Laboratory-LERM, Electrical Engineering Department, Faculty of Technology. University of Medea, Medea, Algeria.*

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Abstract: Photovoltaic (PV) systems face challenges in maximizing their output potential due to non-uniform sunlight distribution and unpredictable weather conditions, known as partial shading. To address these challenges, hybrid control algorithms have emerged as a promising solution. This paper presents a novel hybrid algorithm called HGW-PSO, which combines the strengths of Particle Swarm Optimization (PSO) and Grey Wolf Optimization (GWO). The hybrid approach utilizes the exploration capabilities of GWO and the convergence capabilities of PSO to achieve faster convergence, reduced oscillations, and improved implementation efficiency. The performance of the proposed HGW-PSO algorithm was evaluated under various scenarios of uniform and non-uniform shading. The results showed that HGW-PSO outperformed PSO, GWO, and Peafowl Optimization Algorithm (POA) in terms of tracking accuracy and convergence speed. Specifically, HGW-PSO achieved an average efficiency of 99.96% and a convergence time of less than 40 milliseconds, compared to 99.51% for GWO, 99.28% for POA, and 99.11% for PSO. These results demonstrate the effectiveness of the HGW-PSO algorithm in maximizing power tracking outcomes under challenging shading conditions.

Keywords: *global maximum power point; Grey Wolf Optimization; maximum power point tracker; partial shading conditions; Particle Swarm Optimization; Peafowl Optimization algorithm; photovoltaic.*

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* Corresponding author: mailto:douifi.nadia@univ-medea.dz

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1 Introduction

In the last decade, the world has seen an increase in demand for energy due to the rapid growth of industrial technology and urbanization, which in turn increases the use of fossil fuels and traditional sources of energy [1], [2]. Therefore, it became essential to search for new clean energy sources to replace traditional ones and reduce their serious negative effects on the environment. Photovoltaic (PV) energy, in particular, has become the most attractive among all renewable energy sources.

The performance of PV panels is mainly impacted by several factors such as solar irradiation, temperature, and load values [3]. Moreover, in large-scale PV systems installed in urban areas, the PV system commonly faces a major problem known as partial shading (PS), which occurs when the PV array receives non-uniform irradiance levels [4]. Solar radiation is distributed unequally on the PV array because of obstacles in the surrounding installation sector such as clouds, trees, and buildings. The power-voltage characteristics of a photovoltaic array under partially shaded conditions (PSCs) are highly nonlinear, exhibiting multiple local peaks and a global peak denoted as GMPP [5], [6].

The maximum power is harvested from the photovoltaic panel only when the global peak is tracked. Therefore, a maximum power point tracking (MPPT) controller with proper technique becomes an essential component in any PV system to locate and track the specific maximum power point (MPP) regardless of the operating conditions of the PV system [7]. MPPT's main function is to control the duty cycle of the boost converter with the help of meta-heuristic algorithms to match the output power of the PV array to the load, guaranteeing power optimization and improving system efficiency.

Among all the MPPT techniques existing in the literature, Artificial Intelligence techniques (AI) including Artificial Fuzzy Logic (FL) [8], Ant Colony Optimization (ACO) [9], and Whale Optimization Algorithm (WOA) [10] are the most popular and widely used because of their accuracy and capabilities in dealing with MPP tracking, especially under PSC. Despite the merits of these MPPT techniques, they still have some demerits in relation to each other. Furthermore, no technique can assure the best result in all terms and under all circumstances [11]. Hence, hybrid algorithms have been presented in research papers to overcome the drawbacks of the original algorithms and merge their strength features.

In this paper, a new intelligent hybrid algorithm is proposed as an MPPT technique. The exploration potential of the GWO algorithm is combined with the exploitation potential of the PSO algorithm to develop the suggested Hybrid Grey Wolf-Particle Swarm Optimization (HGW-PSO) algorithm. The performance of the proposed HGW-PSO was evaluated under various weather conditions, including the Standard Test Conditions (STC), uniform fast-varying irradiance conditions as well as three different non-uniform (partial shading) scenarios.

A comprehensive comparison was conducted between HGW-PSO and three of the most commonly used MPPT techniques including GWO [12], Peafowl Optimization Algorithm (POA) [13], and PSO [14]. By testing the system under different scenarios, the study aimed to assess its ability to effectively track the maximum power output in dynamic and challenging conditions and to achieve a balance between response time, energy efficiency, and stability.

2 Proposed MPPT Algorithm

2.1 PSO

Particle Swarm Optimization algorithm is one of the most used and well-known population-based optimization techniques. It was first developed in 1995 by Kennedy [15], inspired by the intelligent swarm behaviour of birds. Initially, in the PSO technique, particles are distributed randomly in the search area with a unique position x_i and velocity v_i.

During the search process for the optimum solution, a particle's position is updated based on the best solution found by the particle in the neighbourhood P_{best_i} and the global best solution suggested by the whole population G_{best}. Accordingly, the position of the particle x_i is modified by using the relations [16]

$$x_i^{k+1} = x_i^k + v_i^{k+1}, \tag{1}$$

$$v_i^{k+1} = \omega v_i^k + c_1 r_1 (P_{best_i} - x_i^k) + c_2 r_2 (G_{best} - x_i^k), \tag{2}$$

where ω is the inertia weight, c_1, c_2 are the acceleration coefficients, r_1, r_2 denote the random values within the interval [0, 1] and k is the current iteration number.

2.2 GWO

Grey Wolf Optimizion (GWO) is a bio-inspired meta-heuristic algorithm introduced by Mirjalili et al. [17] in 2014, based on the hunting behavior and hierarchical structure of grey wolves. Wolves are categorized into alpha (α), beta (β), delta (δ), and omega (ω). In GWO, α represents the best solution, followed by β and δ. The hunting process updates wolves' positions through encircling, hunting, and attacking prey [18].

The encircling behaviour of grey wolves is mathematically modelled as follows [19]:

$$\vec{D} = |\vec{C}.\vec{X}_P^k - \vec{X}^k|, \tag{3}$$

$$\vec{X}^{k+1} = \vec{X}_P^k - \vec{A}.\vec{D}, \tag{4}$$

$\vec{D}$, $\vec{A}$ and $\vec{C}$ are the coefficient vectors, while k is the current iteration. $\vec{X}$ and $\vec{X}_P$ denote the position vector of the search agent and the optimum solution (prey position), respectively. The vectors $\vec{A}$ and $\vec{C}$ are calculated as

$$\vec{A} = 2.\vec{a}.\vec{r}_1 - \vec{a}, \tag{5}$$

$$\vec{C} = 2.\vec{r}_2, \tag{6}$$

r_1, and r_2 are the random vectors in the range [0,1]. The value a linearly decreases from 2 to 0 over the iterations.

In Grey Wolf Optimization, Alpha leads the hunt, assuming the best solution (prey location), with Beta and Delta as the next best. Other wolves, including Omega, update their positions to follow the best candidate. The search agent's position is updated using the formulas [20]

$$\vec{D}_\alpha = |\vec{C}_1.\vec{X}_\alpha^k - \vec{X}^k|, \quad \vec{D}_\beta = |\vec{C}_2.\vec{X}_\beta^k - \vec{X}^k|, \quad \vec{D}_\delta = |\vec{C}_3.\vec{X}_\delta^k - \vec{X}^k|, \tag{7}$$

$$\vec{X}_1 = \vec{X}_\alpha - \vec{A}_1.\vec{D}_\alpha, \quad \vec{X}_2 = \vec{X}_\beta - \vec{A}_2.\vec{D}_\beta, \quad \vec{X}_3 = \vec{X}_\delta - \vec{A}_3.\vec{D}_\delta, \tag{8}$$

$$\vec{X}^{k+1} = (\frac{\vec{X}_1 + \vec{X}_2 + \vec{X}_3}{3}). \tag{9}$$

2.3 HGW-PSO

This algorithm was developed by Narinder Singh et al. [21] in 2017. The main hybridization principle of the HGW-PSO algorithm is to merge the exploration ability of GWO with the exploitation ability of the PSO algorithm. In other words, the PSO algorithm mechanism is used to replace the updating function of GWO represented in (9). This hybridization is done to obtain the advantages and strengths of the individual algorithms and reduce their limitations. In the suggested HGW-PSO algorithm, the effect of delta wolves δ is eliminated to enhance its convergence time and efficiency. P_{best_i} and G_{best} in the velocity equation of the PSO algorithm are replaced with the Alpha solution X_1 and the agent's updated position is calculated using (9). In the HGW-PSO algorithm, the position of search agents is then updated using the mathematical expressions

$$v_i^{k+1} = \omega v_i^k + c_1 r_1 (X_1 - x_i^k) + c_2 r_2 (X - x_i^k), \tag{10}$$

$$x_i^{k+1} = x_i^k + v_i^{k+1}. \tag{11}$$

To apply the proposed HGW-PSO algorithm for MPPT in a PV system, each grey wolf position is set as the duty cycle (D_c) of the boost converter and (11) is modified as presented in the equations

$$\vec{D}_\alpha = |\vec{C}_1.\vec{D}^k_{c_\alpha} - \vec{D}^k_c|, \quad \vec{D}_\beta = |\vec{C}_2.\vec{D}^k_{c_\beta} - \vec{D}^k_c|, \tag{12}$$

$$\vec{D}_{c_1} = \vec{D}_{c_\alpha} - \vec{A}_1.\vec{D}_\alpha, \quad \vec{D}_{c_2} = \vec{D}_{c_\beta} - \vec{A}_2.\vec{D}_\beta, \tag{13}$$

$$D_c^{k+1} = \frac{D_{c_1} + D_{c_2}}{2}, \tag{14}$$

$$\Delta D^{k+1}_{c_i} = \omega.\Delta D^k_{c_i} + c_1 r_1 (D_{c_1} - D^k_{c_i}) + c_2 r_2 (D_c - D^k_{c_i}), \tag{15}$$

$$D^{k+1}_{c_i} = D^k_{c_i} + \Delta D^{k+1}_{c_i}. \tag{16}$$

3 Simulation Results and Analysis

To verify the abilities of the proposed MPPT HGW-PSO algorithm, a PV system illustrated in the block diagram shown in Figure 1a is modelled and simulated with MATLAB-Simulink. The PV array used as a PV source in the aforementioned system consists of three series-connected sub-arrays with a total power of 100.37 kW in standard test conditions (STC). The first and second-row sub-arrays contain 2*66 sub-modules, and the third-row sub-array consists of 1*66 sub-modules.

The suggested MPPT algorithm is tested for various scenarios of uniform (fast varying irradiance) and non-uniform shading (PSC) to validate its capabilities in tracking GMPP. The simulated operating conditions are summarized in Table 1, and their corresponding PV characteristic curves are shown in Figure 1b. The performance of the HGW-PSO is also compared to the performance of the GWO, PSO, and POA algorithms to prove its efficacy.

Figures 2 and 3 show the output power performance of the tested MPPT algorithms under the studied scenarios of shading and fast varying irradiance. For a fair comparison, all the obtained results are summarized in Table 2.

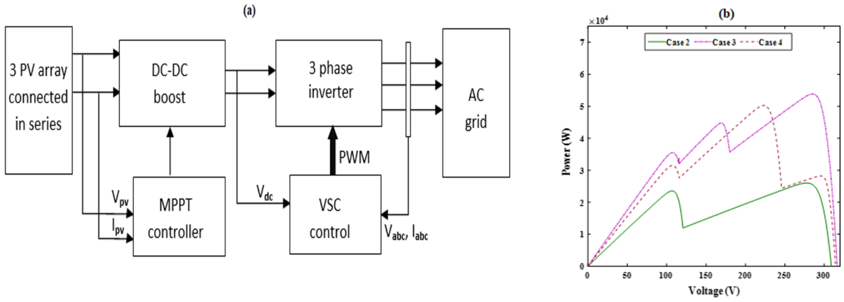

Figure 1: a. Block diagram of the simulated PV system.-b. PV characteristic curves of the studied PSC scenarios.

Case	PV1 (KW/m^2)	PV2 (KW/m^2)	PV3 (KW/m^2)	P_{MPP} (kW)
1	1, 0.3, 0.8, 0.5, 1	1, 0.3, 0.8, 0.5, 1	1, 0.3, 0.8, 0.5, 1	100.37, 29.418, 80.16, 49.704
2	0.6	0.25	0.6	26.016
3	0.5	0.9	0.7	53.85
4	0.8	0.6	0.25	50.29

Table 1: Irradiance levels for Cases 1 to 4.

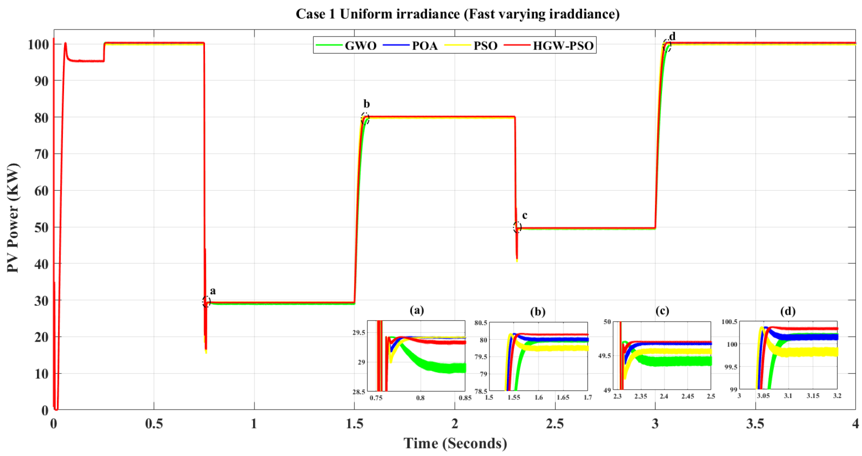

Figure 2: Output power performance of MPPT GWO, POA, PSO and HGW-PSO for uniform fast varying irradiance (Case 1).

3.1 Uniform irradiance

3.1.1 Case 1

This case study involves uniform irradiance levels that undergo an abrupt change from 1 KW/m^2 to 0.3 KW/m^2, as detailed in Table 1. In response to the rapid changes in irradiance, all techniques exhibit rapid changes in output power. This can be observed from Figure 2 and Table 2. While all techniques achieve stable output, the suggested technique stands out by attaining a steady output power with minimal oscillation and the highest efficiency of 99.96%. The POA technique follows closely with an efficiency of 99.88%, followed by PSO with 99.65% and GWO with 99.40%. Furthermore, the proposed HGW-PS technique exhibits desirable tracking speeds of around 30 ms in the fast-varying irradiance condition.

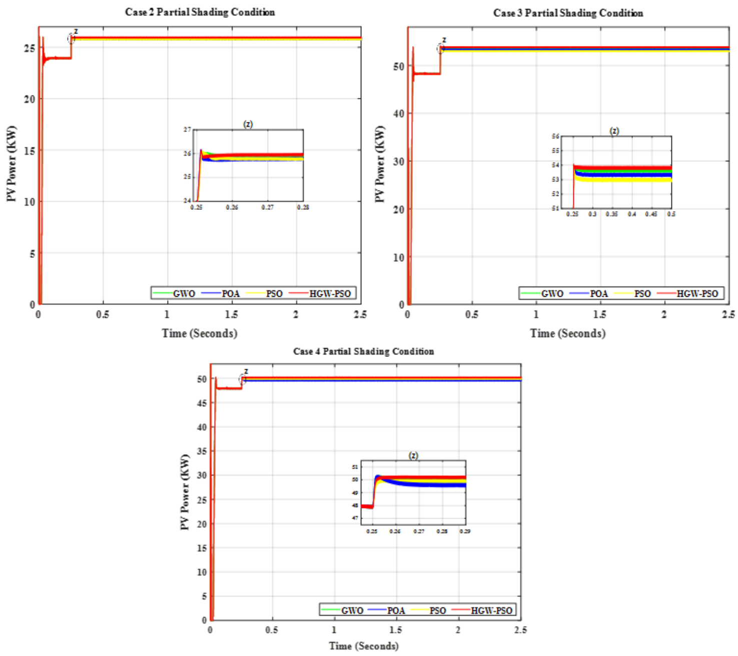

Figure 3: Output power performance of MPPT GWO, POA, PSO and HGW-PSO for partial shading Cases 2,3 and 4.

3.2 Non uniform irradiance

3.2.1 Case 2

In this scenario, as illustrated in Figure 1b, the PV curve depicts the response of the photovoltaic system under partial shading conditions. The shading induces two closely spaced operating points on the curve: LMPP at 23.542 kW and GMPP at 26.016 kW. The proposed technique effectively avoids the local peak and stabilises at the GMPP in under 35 ms, outperforming other techniques. The HGW-PSO algorithm achieves the highest efficiency of 99.98%, followed by GWO with 99.55%, POA with 99.36%, and PSO with 99.13%.

3.2.2 Case 3

Under this scenario of partial shading conditions, the three PV sub-arrays receive different irradiance levels, resulting in a characteristic curve with three multiple peaks, including two closely spaced LMPPs and one global peak at 50.87 kW. The proposed HGW-PSO algorithm demonstrates robustness against local peaks and efficiently reaches the GMPP with minimal power loss. HGW-PSO achieves the highest efficiency of 99.96%, outperforming GWO, POA, and PSO, which achieve efficiencies of 99.61%, 99.02%, and 98.40%, respectively. These results highlight the superior power output, faster convergence, and superior tracking capabilities of the suggested algorithm under partial shading conditions.

3.2.3 Case 4

To enhance the comprehensiveness of the comparative study, an additional partial shading case is included in Figure 1b, along with its corresponding PV curve. The maximum output power achieved by HGW-PSO, GWO, POA, and PSO is 50.26 kW, 50.02 kW, 49.72 kW, and 49.92 kW, respectively. Particularly, HGW-PSO achieves the highest efficiency of 99.94% among the considered techniques. In contrast, GWO, POA, and PSO achieve lower efficiencies of less than 99.46%. Moreover, HGW-PSO reaches the GMPP faster, within 25 ms.

Technique	Case	MPP tracked (kW)	Tc (s)	Efficiency(%)
GWO	1	100.15,28.90,79.97,49.40,100.15	0.284	99.40 (avg)
	2	25.90	0.275	99.55
	3	53.66	0.30	99.61
	4	50.02	0.272	99.46
POA	1	100.19,29.415,80.03,49.68,100.19	0.28	99.88 (avg)
	2	25.85	0.285	99.36
	3	53.34	0.29	99.02
	4	49.72	0.276	98.87
PSO	1	99.87,29.405,79.78,49.57,99.87	0.285	99.65 (avg)
	2	25.79	0.285	99.13
	3	53.01	0.282	98.40
	4	49.92	0.275	99.26
HGW-PSO	1	100.36,29.37,80.16,49.70,100.36	0.285	99.96 (avg)
	2	26.01	0.262	99.98
	3	53.85	0.286	99.96
	4	50.26	0.265	99.94

Table 2: Comparative analysis of MPPT GWO, POA, PSO and HGW-PSO.

When analyzing the results presented in Table 2, it becomes apparent that the proposed MPPT HGW-PSO algorithm exhibits a remarkable performance compared to the other tested algorithms, particularly in terms of MPP tracking efficiency and convergence time. Across all examined cases, HGW-PSO consistently achieves the highest efficiency, boasting an average efficiency of 99.96%. This surpasses the performance of GWO, POA, and PSO, which achieve average efficiencies of 99.40%, 99.88%, and 99.65%, respectively. Moreover, HGW-PSO demonstrates quicker convergence times across most cases, further underlining its effectiveness in optimizing power generation within photovoltaic systems across a spectrum of operating conditions.

4 Conclusion

In conclusion, this paper introduces and investigates a novel HGW-PSO MPPT-based algorithm designed to optimize power harvesting within the proposed PV system across various operating conditions. A 100 kW PV system was meticulously modeled and simulated using MATLAB-Simulink software to assess the performance of the HGW-PSO algorithm under various shading scenarios, including uniform and partial shading conditions (PSC). Through comparative analysis with existing MPPT techniques, namely GWO, POA, and PSO algorithms, the capabilities of the proposed MPPT method were rigorously validated. The results obtained across the four operating scenarios demonstrate the superior performance of the HGW-PSO algorithm in terms of GMPP tracking efficiency and convergence time.

Importantly, the nonlinear dynamics underlying the PV system behavior plays a crucial role in the performance of the proposed HGW-PSO MPPT algorithm. The existence of multiple local maxima and the complex interactions between environmental factors such as shading patterns, result in highly nonlinear power-voltage characteristics in the PV array. The HGW-PSO method's ability to rapidly converge to the global maximum power point, even under partial shading, indicates its strong capacity to navigate these nonlinear landscapes. By incorporating both global and local search strategies, the HGW-PSO algorithm effectively overcomes the challenges posed by the inherent nonlinearities in the PV system. This highlights the significance of the obtained results for advancing nonlinear optimization techniques applied to renewable energy systems.The insights gained from this work have important implications for enhancing the power generation efficiency of photovoltaic installations in real-world, dynamically changing operating conditions.

References

[1] A. K. Bilhan. Integrated solar-based PEMWEs for green electricity production. *International Journal of Hydrogen Energy* **75** (2024) 415–427.

[2] A. Medjber, A. Moualdia and A. Morsli. PI-Fuzzy Control Applied to the Hybrid PV / Wind Pumping System with Energy Storage. *Nonlinear Dynamics and Systems Theory* **22** (3) (2022) 319–329.

[3] A. Morsli, A. Tlemcani and H. Nouri. Control of a Shunt Active Power Filter by the Synchronous Referential Method Connected with a Photovoltaic Solar Energy. *Nonlinear Dynamics and Systems Theory* **22** (4) (2022) 424–431.

[4] M. Neethu and R. Senthilkumar. Soft Computing Based MPPT Controller for Solar Powered Battery Charger Under Partial Shading Conditions. In: *2019 Fifth International Conference on Electrical Energy Systems (ICEES)*. IEEE, Chennai, India, 2019, 1–6.

[5] F. Hamidia, A. Abbadi, M. R. Skender, A. Morsli, F. Bettache, A. Medjber and A. Tlemcani. Maximum Power Point Tracking Based on Remora Algorithm under PSC. *Nonlinear Dynamics and Systems Theory* **23** (4) (2023) 381–389.

[6] C. B. Oguz, E. Avci and S. B. Ozturk. Analysis of PV power plant performance considering combination of different MPPT algorithms, shading patterns and connection types. *Engineering Science and Technology, an International Journal* **48** (2023) 101559.

[7] M. A. Ebrahim, A. Osama, K. M. Kotb and F. Bendary. Whale inspired algorithm based MPPT controllers for grid-connected solar photovoltaic system. *Energy Procedia* **162** (2019) 77–86.

[8] T. Hai, J. Zhou and K. Muranaka. An efficient fuzzy-logic based MPPT controller for grid-connected PV systems by farmland fertility optimization algorithm. *Optik* **267** Elsevier, (2022) 169636.

[9] G. S. Krishnan, S. Kinattingal, S. P. Simon and P. S. R. Nayak. MPPT in PV systems using ant colony optimisation with dwindling population. *IET Renewable Power Generation* **14** (7) 1105–1112. Wiley Online Library, 2020.

[10] D. E. Zabia, H. Afghoul and O. Kraa. Maximum power point tracking of a photovoltaic system under partial shading condition using whale optimization algorithm. *Artificial Intelligence and Heuristics for Smart Energy Efficiency in Smart Cities: Case Study: Tipasa, Algeria*. Springer, 2022, 121–132.

[11] S. Sarwar, M. Y. Javed, M. H. Jaffery, J. Arshad, A. Ur Rehman, M. Shafiq and J.G. Choi. A novel hybrid MPPT technique to maximize power harvesting from pv system under partial and complex partial shading. *Applied Sciences.* **12** (2) (2022) 587.

[12] D. K Kishore, M. R. Mohamed, K. Sudhakar and K. Peddakapu. An improved grey wolf optimization based MPPT algorithm for photovoltaic systems under diverse partial shading conditions. *Journal of Physics: Conference Series* **2312** (1) (2022) 012063.

[13] D. Li, J. Li and N. Wang. A Novel Technique Based on Peafowl Optimization Algorithm for Maximum Power Point Tracking of PV Systems Under Partial Shading Condition. *Frontiers in Energy Research* **9** (2021) 801571.

[14] A. I. Nusaif and A. L. Mahmood. MPPT algorithms (PSO, FA, and MFA) for PV system under partial shading condition, case study: BTS in Algazalia, Baghdad. *International Journal of Smart Grid-ijSmartGrid* **4** (3) (2020) 100–110.

[15] A. Khernane. Numerical Approximation of the Exact Control for the Vibrating Rod with Improvement of the Final Error by Particle Swarm Optimization. *Nonlinear Dynamics and Systems Theory* **20** (2) (2020) 179–190.

[16] C. B. Regaya, H. Hamdi, F. Farhani, A. Marai, A. Zaafouri and A. 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.

[17] S. Mirjalili, S. M. Mirjalili and A. Lewis. *Grey Wolf Optimizer. Advances in Engineering Software* **69** (2014) 46–61.

[18] J. A. Salim, B. M. Albaker, M. S. Alwan and M. Hasanuzzaman. Hybrid MPPT approach using Cuckoo Search and Grey Wolf Optimizer for PV systems under variant operating conditions. *Global Energy Interconnection* **5** (6) (2022) 627–644.

[19] K. Atici, I. Sefa and N. Altin Grey wolf optimization based MPPT algorithm for solar PV system with sepic converter. In: *2019 4th International Conference on Power Electronics and their Applications (ICPEA)*. IEEE, Elazig, Turkey, 2019, 1–6.

[20] B. Laxman, A. Annamraju and N. V. A. Srikanth. A grey wolf optimized fuzzy logic based MPPT for shaded solar photovoltaic systems in microgrids. *International Journal of Hydrogen Energy* **46** (18) (2021) 10653–10665.

[21] N. Singh and S. B. Singh. Hybrid algorithm of particle swarm optimization and grey wolf optimizer for improving convergence performance. *Journal of Applied Mathematics* **2017** (2017) 15 pages.