Optimizing Solar Energy Production in Partially Shaded PV Systems with PSO-INC Hybrid Control

Sarah Abboud [1], Azeddine Loulijat [2], Abdellah Boulal [3], El Alami Semma [4], Rachid Habachi [5], Hamid Chojaa [6], Alfian Ma'arif [7], Iswanto Suwarno [8], Mahmoud A. Mossa [9*]
[1, 2, 3, 4, 5] Laboratory of Engineering, Industrial Management and Innovation, Faculty of Sciences and Technology, Hassan First University, Settat, Morocco
[6] Industrial Technologies and Services Laboratory, Higher School of Technology, Sidi Mohamed Ben Abdellah University, Fez 30000, Morocco
[7] Department of Electrical Engineering, Universitas Ahmad Dahlan, Yogyakarta, Indonesia
[8] Department of Electrical Engineering, Universitas Muhammadiyah Yogyakarta, Yogyakarta, Indonesia
[9] Electrical Engineering Department, Faculty of Engineering, Minia University, Minia 61111, Egypt
Email: [1] Sarahabboud24@gmail.com, [2] rehalloulijat@gmail.com, [3] boulalabdellah@gmail.com, [4] semmaalam@yahoo.fr, [5] rachid.habachi@uhp.ac.ma, [6] hamid.chojaa@usmba.ac.ma, [7] alfianmaarif@ee.uad.ac.id, [8] iswanto_te@umy.ac.id, [9] mahmoud_a_mossa@mu.edu.eg
*Corresponding author

Abstract—**Partial shading, from obstacles such as buildings or trees, is a major challenge for photovoltaic systems, causing unpredictable fluctuations in solar energy production and underlining the need for advanced energy management strategies. In this paper, we propose an innovative approach that combines hybrid metaheuristic optimization with maximum power point tracking control (MPPT), using particle swarm optimization (PSO) in conjunction with the incremental conductance (IC) algorithm. We compare the proposed method with the conventional Perturb and Observation (P&O) algorithm. The choice of P&O as a comparison method is due to its simplicity, its familiarity with the scientific literature, its low cost of implementation. The main objective of swarm optimization combined with the IC algorithm lies in its ability to overcome the challenges posed by partial shading, ensuring accurate and efficient tracking of the point of maximum power, thanks to dynamic adaptation to variations in solar irradiation, thus enhancing the performance and resilience of the photovoltaic system. This approach is of crucial importance, offering considerable potential for solving the complex challenges associated with partial shading. Our results show that this hybrid MPPT algorithm offers superior tracking efficiency > 98% , faster convergence 500ms , better stability and increased robustness compared to traditional MPPT approaches. The system is composed of a PV and a boost converter that connects the input to the resistive load. The algorithms were implemented with MATLAB/Simulink as the simulation tool. These results not only reinforce the viability of sustainable energy solutions, but also open the way for the development of more sustainable energy solutions.The perspectives of this work are oriented towards a practical and extended integration of the proposed hybrid approach in real photovoltaic systems, with a particular emphasis on experimental validation.**

Keywords—Photovoltaic; MPPT; Partially Shaded Condition; Hybrid; Particle Swarm Optimization; Incremental Conductance; Perturb and Observe; Boost Converter; Energy Management.

I. INTRODUCTION

Photovoltaic solar energy represents one of the most promising solutions for meeting our energy needs while reducing our carbon impact. However, this renewable energy source is not immune to the challenges posed by changing environmental conditions [1]. One of the most complex and unpredictable obstacles is partial shading, which can lead to unexpected perturbations in energy production [2], [3].

The ultimate objective is to optimize energy conversion efficiency by adjusting the output voltage of photovoltaic panels in real time, even in the presence of partial shading [4], [5]. To solve this problem, specialists have focused on three main elements: the design of solar irradiation tracking systems, the integration of efficient power converters and the formulation of MPPT algorithms. While the first two elements only concern new photovoltaic systems, the third can be used in both new and existing systems [6], [7]. The central objective of our research is to maximize the efficiency of energy conversion under partial shading conditions PSC. This is part of the broader context of environmental sustainability and the global transition to renewable energies [8]. By optimizing the performance of photovoltaic systems in the face of challenges such as partial shading, our work contributes directly to promoting more sustainable solutions and advancing global renewable energy goals [9], [10].

In recent years, numerous researchers have introduced algorithms for MPPT based on optimization techniques, as detailed in the following articles [11]-[25]. One notable example is found in [11], where particle swarm optimization PSO was employed to ascertain MPPT by incorporating two additional conditions: convergence detection and detection of changes in solar insolation. Another contribution, presented in [12], involves an enhanced MPPT algorithm utilizing PSO to mitigate steady state oscillations. Furthermore, [19] proposes the PSO-based IC algorithm for MPPT, which was applied in the boost converter circuit.

The MPPT algorithm regulates the operating point of the photovoltaic system by adjusting the reference voltage, current or duty cycle of the PWM controller [26], [27].

Unlike conventional MPPT algorithms, which use fixed values to define the output voltage, the PSO allows continuous optimization of parameters to maximize energy production [28]. This flexibility means that variations in the environment can be exploited to the full, resulting in greater efficiency and a significant increase in energy output. This innovative approach maximizes solar energy production even under difficult environmental conditions, paving the way for more efficient and resilient solar systems [29]. Fig. 1 shows the path of solar energy from the sun to the final load, starting with solar irradiation from the sun. This irradiation is captured by a photovoltaic cell, where it is converted into electrical energy. The electrical flow then passes through a diode, a power conditioner, a converter and the load [30], [31].

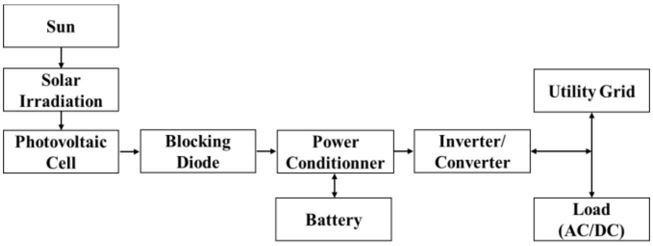

Fig. 1. Solar energy production stages

This paper examines a hybrid system that merges the principles of PSO and IC, an approach of paramount importance for PV systems faced with partial shading scenarios. We will juxtapose this method with a conventional approach, P&O control [32]. PSO dynamically adjusts system parameters to optimize energy production in the sections of the solar panel that remain exposed to sunlight. IC plays a key role in mitigating energy losses attributed to partial shading [33], [34]. The combination of PSO + IC approaches represents a promising solution for maintaining peak energy production, reducing losses and adjusting the efficiency of the photovoltaic system, even in the presence of partial shading [35]. This integration aims to offer a more robust and efficient solution, making a significant contribution to the advancement of existing solutions for the complex challenges associated with partial shading in photovoltaic systems [36], [37]. Among PSO based approaches, some have demonstrated notable efficiency in terms of MPPT, underlining the robustness of this metaheuristic under varying conditions. However, it is essential to note that these approaches can present limitations, such as slow convergence in dynamic situations or sensitivity to variations in solar irradiance [38]. therefore This hybrid approach aims to offer a more balanced and adaptive solution, overcoming the specific challenges encountered by conventional approaches in PSC, our approach seeks to make a significant contribution to the evolution of MPPT techniques in the field of photovoltaic systems [39]. We employed MATLAB/Simulink for the performance assessment of our proposed method. The findings reveal that the hybrid algorithm surpasses conventional methods in several aspects, including quicker tracking, enhanced efficiency, and heightened resilience in partial shading scenarios [40], [41].

The organization of this paper is as follows: Section 2 furnishes a system overview, Section 3 examines the P&O, IC, and PSO algorithms, Section 4 showcases the simulation results and their analysis, and the paper concludes with final remarks. Each section plays a crucial role in enhancing the comprehensive understanding of the proposed hybrid system: Section 2 establishes the foundation, Section 3 explores the employed algorithms, and Section 4 analyzes the results, collectively contributing to a holistic comprehension of the hybrid system's design and performance [42].

II. System Description

Essentially, a photovoltaic energy conversion system consists of four elements, as shown in Fig. 2: photovoltaic array, boost converter for impedance matching, integrated control algorithm and load (battery/inverter) [43], [44].

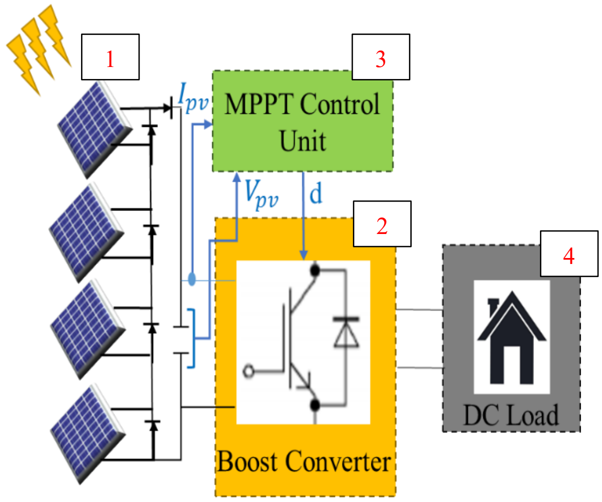

Fig. 2. Simulation of a PV system using

This system combines various components to make the most of solar energy. The photovoltaic system 1 captures solar energy using solar panels, the boost converter 2 adjusts impedance for optimum efficiency, and the control algorithm manages MPPT 3 and the load 4, such as a battery or inverter, stores or converts electricity for later use[45]. This combination of components enables the system to maximize the use of solar energy, contributing to a cleaner, more efficient power supply [46], [47].

The current-voltage (IV) and power-voltage (PV) characteristics of the photovoltaic (PV) model employed in this paper under standard test conditions [48] are depicted in Fig. 3. The (IV) and (PV) properties are detailed as follows. Additionally, Fig. 4 illustrates the impact of partial shading, considering ambient conditions such as irradiance (I_{rr} = 1000 W/m²) and temperature (T = 25 °C) [49].

III. Materials and Methods

This Section explores in detail the key algorithms used in our approach, highlighting the P&O , the IC algorithm, and the PSO . These algorithms play a central role in MPPT, providing an in-depth understanding of their operation and integration within our photovoltaic model [50].

A. Perturb and Observe Algorithm (P&O)

P&O algorithm is a prominent MPPT method, primarily employed in PV systems [51], [52]. Its principle is straight forward: the controller continually perturbs the operating point of the PV system by adjusting the voltage (or current) and observes the resulting power variation. The objective is to track the operating point that maximizes the power output from the PV module [53], [54]. It is worth noting that, despite its widespread use and simplicity, P&O algorithm may exhibit limitations, such as oscillations around the maximum power point, especially in low irradiance conditions or during rapid fluctuations in weather conditions [55]. Fig. 5 above illustrates the flowchart of the conventional P&O algorithm [56], [57].

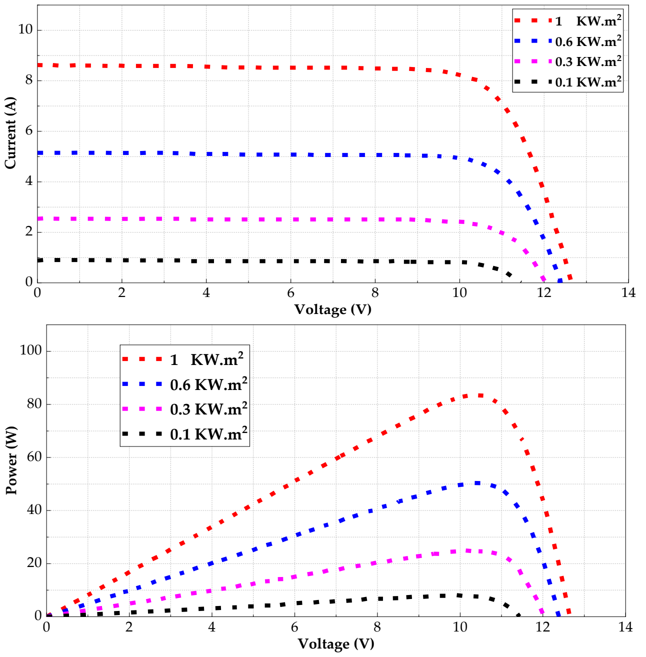

Fig. 3. I-V and P-V characteristics of a PV model under standard test conditions

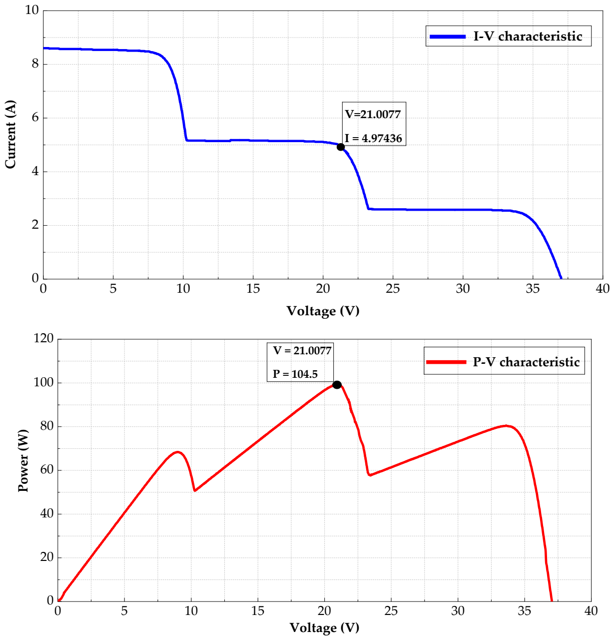

Fig. 4. I-V and P-V characteristics of the partially shaded PV model

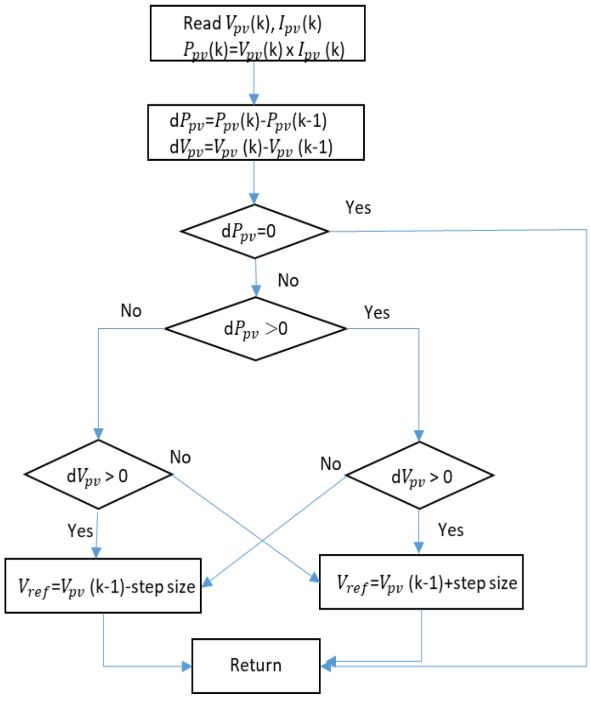

Fig. 5. Flowchart of the conventional perturb and observe algorithm

B. Incremental Conductance (IC) Algorithm

The IC algorithm is a methodology employed in photovoltaic systems to optimize energy production, especially in the face of variable conditions like partial shading or temperature fluctuations [56]. When coupled with PSO, this algorithm becomes a potent tool for dynamically adjusting the electrical conductance of PV system components, optimizing the conversion of solar energy into electricity. Fig. 6 outlines the operational process of the IC algorithm [57], [58].

In this setup, the variation in voltage and current is computed to derive the current-voltage characteristic's derivative. The conventional incremental conductance algorithm primarily relies on comparing this current derivative with the instantaneous current-voltage characteristic of the photovoltaic generator [59]. Essentially, the algorithm tracks the MPP by adjusting the reference voltage based on the current state of the photovoltaic system. Specific conditions must be satisfied at the MPP, as detailed in [60], [61].

$$\frac{dP}{dV} = 0 \tag{1}$$

$$\frac{dP}{dV} = \frac{d(V.I)}{dV} = I\frac{dV}{dV} + V\frac{dI}{dV} \tag{2}$$

$$\frac{dI}{dV} = -\frac{I}{V} \tag{3}$$

In this formulation, $\frac{\mathrm{dI}}{\mathrm{dV}}$ represents the derivative of current with respect to voltage, while $\frac{\mathrm{I}}{\mathrm{V}}$ represents the instantaneous current of the photovoltaic cell as a function of voltage [62], [63]. Furthermore, when $\frac{\mathrm{dI}}{\mathrm{dV}}$ is greater than zero, the reference voltage increases incrementally by a fixed value. Conversely, when $\frac{\mathrm{dI}}{\mathrm{dV}}$ is less than zero, the reference voltage decreases incrementally by a fixed value. It is important to note that the performance of both algorithms depends largely on the step size set by the user [64], [65].

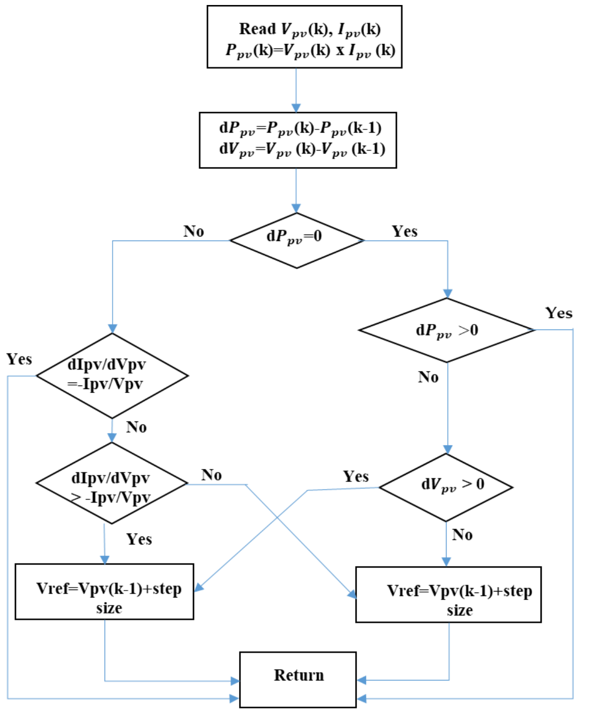

Fig. 6. Flowchart of the conventional incremental conductance algorithm

C. Particle Swarm Optimization (PSO) Algorithm

The PSO algorithm is a non-linear technique that draws its inspiration from the behaviors observed in birds, fish and bees. This approach is widely applied in various fields of engineering and science to optimize processes and design efficient systems [66], [67] PSO is based on two fundamental principles: the retention of information on past performance, and communication between the agents forming the swarm. By combining these two principles, PSO offers an elegant solution to complex optimization problems [68], [69]. The operating principle of the PSO algorithm is illustrated in Fig. 7 and Fig. 8.

The central rules that guide the behavior of swarm agents, also known as particles, are as follows: all particles aim to follow the one with the best performance, moving towards the conditions that prove optimal. Once the end criteria have been met, the speed and position of the best-performing particle are adopted as [70], [71]. This leading particle acts as a guide for the others, encouraging them to converge towards an overall optimal performance [72]. Mathematically, this dynamic is expressed by the conventional updating of velocity and position within the PSO framework [73]. And the Fig. 9 shows the system studied. PSO complements other algorithms, such as P&O and IC, bringing a more robust and global approach to system parameter optimization. Whereas P&O and IC can sometimes be sensitive to environmental conditions and variations, PSO offers a more adaptive and stable solution, helping to improve the accuracy of PV system parameter adjustment in a variety of scenarios, including those with partial shading [74].

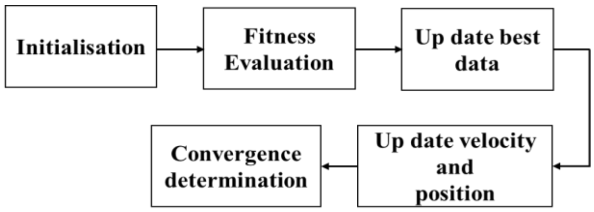

Fig. 7. The PSO operating principle

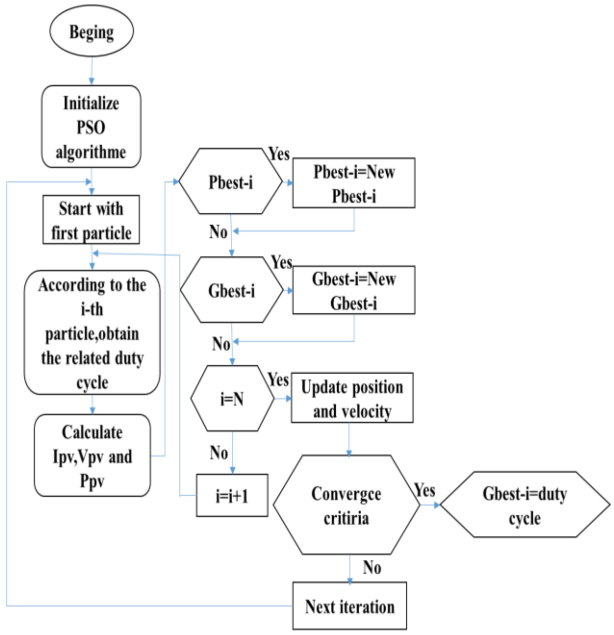

Fig. 8. Flowchart of the PSO algorithm principle

$$V_i(k+1) = wV_i(k) + C_1 r_1 (P_{best} - x_i(k)) + C_2 r_2 (G_{best} - x_i(k)) \quad (4)$$

$$x_i(k+1) = x_i(k) + v_i(k+1) \quad (5)$$

These equations describe the iterative process by which PSO particles explore the search space based on their individual experience and the knowledge shared between particles. With w : nertia weight, regulating the influence of the previous velocity. $V_i(k)$:Current velocity of particle i at iteration k. C_1 and C_2: Acceleration coefficients, controlling the impact of the best personal (Pbest) and global (Gbest) positions. r_1 and r_2 : Random numbers between 0 and 1. Pbest: Best personal position of particle i. Gbest: Best global position among all particles. $x_i(k)$: Current position of particle i at iteration k [75]. $x_i(k+1)$: New position of particle i at iteration $k+1$. $x_i(k)$: Current position of particle i at iteration k. $V_i(k+1)$: New velocity of particle i at iteration $k+1$.

The Fig. 9 shows a simplified configuration comprising photovoltaic cells generating solar energy, a boost converter that regulates the output voltage, a representation of the components of the PSO method such as w, C_1, C_2, and a load that consumes the energy produced. This visual representation illustrates how the PSO method is integrated into the system to optimize boost converter performance by dynamically adjusting parameters (w, C_1, C_2) in response to changing environmental conditions, maximizing MPPT [76].

The choice of Particle Swarm Optimization (PSO) is based on its ability to perform an efficient global exploration of the search space, enabling rapid adaptation to variations in solar irradiance, while offering rapid convergence and greater robustness than some traditional methods such as Perturb and Observe (P&O) [77].

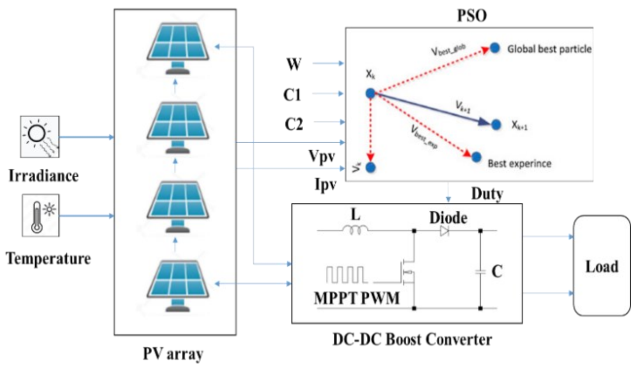

Fig. 9. Simulation circuit diagram of the designed system

IV. Simulation and Results

A partially shaded photovoltaic system was tested using the proposed hybrid maximum power point algorithm. The 60 photovoltaic cells are divided into 3 models, with 20 cells per model. Evaluate the 20-unit model using the parameters in Table I below. The three models are connected in series, each featuring a bypass diode. The aim of this work is to demonstrate the system's efficiency in terms of maximum power tracking, convergence speed, system stability and robustness to changes in solar irradiation [78] The Simulink model of the three-series photovoltaic systems is depicted in Fig. 10.

TABLE I. Electrical Characteristics Data of PV Module

Electrical characteristics data of PV module	
Voc (open-circuit voltage)	12.64 V
Vmpp (voltage at nominal power)	10.32 V
Isc (short-circuit current)	8.62 A
Impp (current at nominal power)	8.07 A
Pmpp (Nominal Power)	83.2824 W

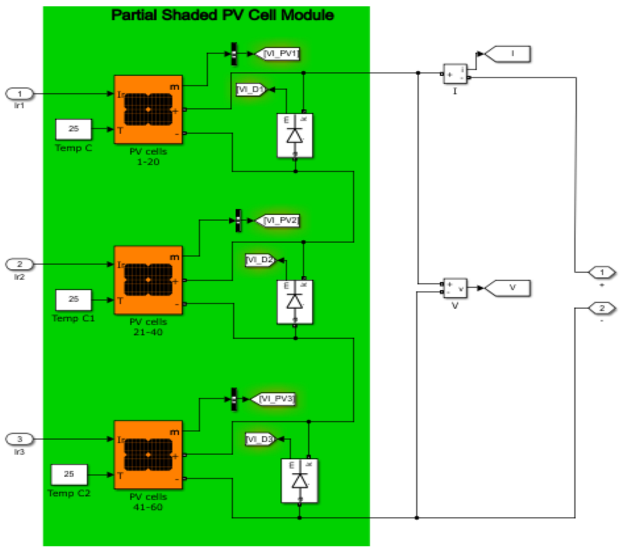

Fig. 10. Simulation of 3 PV modules in series in MATLAB/ Simulink

The Table II shows the essential components of a boost converter, a key device in photovoltaic systems, The inductor, the output capacitor ,the switching frequency and the load. These elements interact to boost the input voltage, providing a regulated output tailored to the system's needs. Table III shows the values of parameters used in the PSO command.The inertia weight parameter (w) is used to ensure a balance between the search for the global maximum and the local search. On the other hand, cognitive learning (C_1) and social learning (C_2) direct the particles' search direction. The C_1 parameter directs particles towards the P_{best} value, and the C_2 parameter directs them towards the global maximum G_{best} [79], [80]. The higher the value of the cognitive and social learning parameters, the smaller the search area of the particle, resulting in a faster convergence time.

TABLE II. Boost Converter Parameters Used

Element	Value
Inductance	3 mH
Output capacitor	100 µF
Load	30Ω
Switching frequency	10 KHZ

TABLE III. PSO Parameters Used

PSO parameters	
C_1	1.2
C_2	1.2
W	0.1

In this simulation, a signal builder was utilized to depict various irradiation levels, while maintaining a constant temperature and resistance (25 °C and 30 Ω, respectively). The maximum power point was configured at 104 watts, and to attain this, a boost converter was interposed between the photovoltaic solar panel model and the load. The simulation results presented in Fig. 12, Fig. 13, Fig. 14 and Fig. 15 showcase the experimental data for power, voltage, current, and duty cycle, respectively. These results are used to compare the proposed method with traditional Perturb and Observe (P&O) Algorithm.

The curve presented in Fig. 11 illustrates the fluctuating levels of irradiance over time t_i, as characterized by the following model:

- Consistent irradiation during the designated intervals : $(0, t_1)$, (t_1, t_2) and (t_5, t_6);
- Fluctuating irradiance within the interval: (t_2, t_3), (t_3, t_4) and (t_4, t_5);
- Irradiance experiences abrupt changes at certain points in time t_1, t_2 and t_5.

The instability in meteorological conditions within this irradiation profile provides a valuable test for evaluating the photovoltaic system performance.

During the first second of time $(0, t_1)$, with consistent irradiation of 800W/m², the power of the PV panel stabilizes at around 205W. The PSO+IC method quickly extracts this maximum power from the PV panel, requiring around 500ms to do so, whereas the P&O method couldn't follow the MPP, because at 500ms it just attained value 149 W.

The power attained 78.4V and current 2.53A. The duty cycle for PSO+IC is kept relatively constant to ensure system stability.

Concerning the second interval (t_1, t_2), the irradiation is 200 W/m², the power of the PV panel decreases to about 15 W due to this lower irradiation, and for the P&O method the power is only 10W. The voltage and current decrease in turn to 20V/0.7A respectively.

For the interval (t_2, t_3), irradiation reaches 1200 W/m², then decreases to stabilize at 900 W/m², power rises from 240W, then decreases slightly to 225W for PSO+IC, while P&O was unable to keep up with PPM, where power is around 60W.The duty cycle for PSO+IC is adjusted around 0,6 to maintain stability at this reduced irradiance level.

For the interval (t_3, t_4), irradiance increases from 900 W/m² to 1200 W/m², power continues to increase, reaching around 248 W, while P&O was unable to keep up with PPM, with a very long response time of 2.7s. The voltage and current have reached their maximum value of 85.9V/2.82A.

Similarly, in the third interval this one decreases to 600 W/m² in the interval(t_4, t_5) the power decreases to 150 W for PSO+IC and P&O.

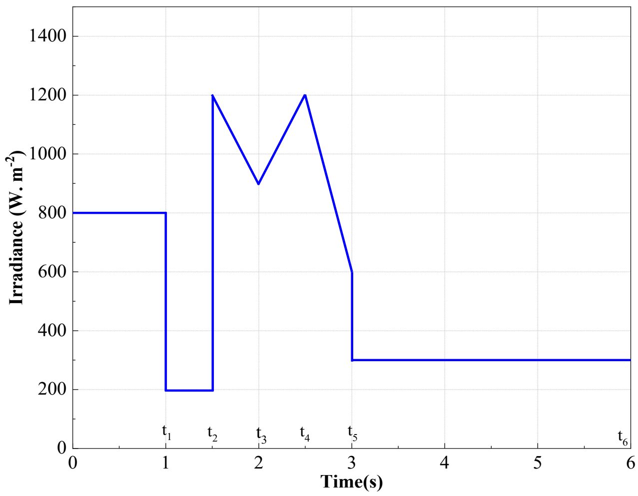

Fig. 11. An irradiance profile is employed in the simulation

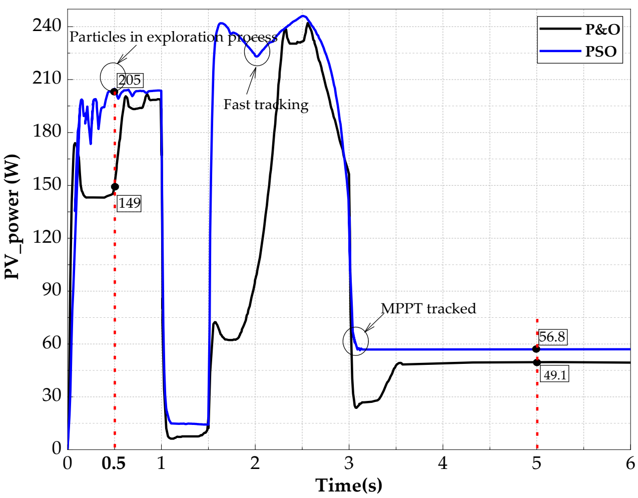

Fig. 12. PV power under partial shading conditions

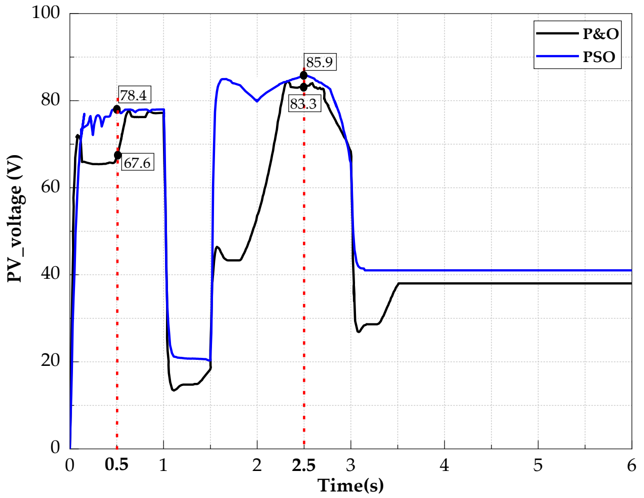

Fig. 13. PV voltage under partial shading conditions

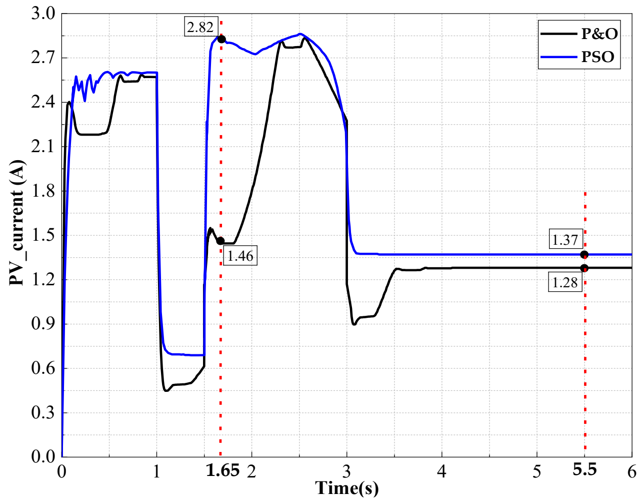

Fig. 14. PV current under partial shading conditions

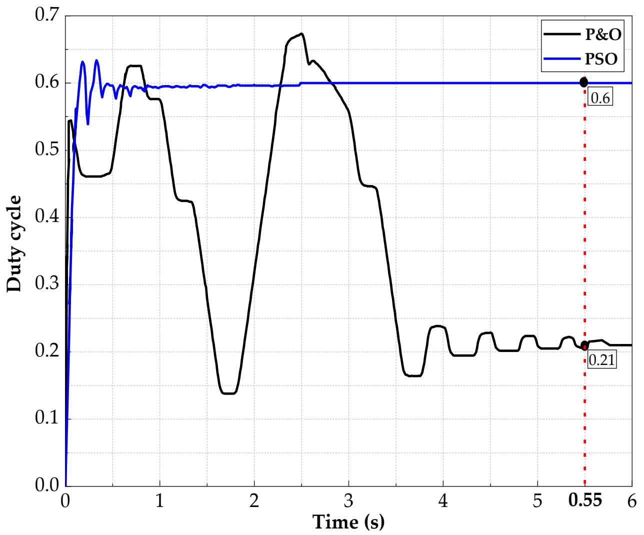

Fig. 15. Duty cycle at different irradiation and constant temperature

While irradiance had stabilized at 300 W/m² for the last few intervals, power dropped significantly to around 58.8 W for PSO+IC and 49.1W for P&O. The current is adjusted to match the available power, and the duty cycle is adapted to optimize power extraction at this low irradiance level. For the P&O method the duty cycle it changes several times, and still the MPP cannot be reached in all intervals.

Current and voltage trends are similar for the two methods compared, although they follow the respective irradiations with different follow-up times (P&O lags behind PSO+IC). In summary, these curves highlight the effectiveness of PSO++IC hybrid control, compared with P&O, in adapting to variations in solar irradiance and maintaining optimum power output with reduced tracking time.

Parameters such as voltage, current and duty cycle are adjusted accordingly to maximize the power extracted from the panel, demonstrating the system's ability to successfully manage changing conditions. A comparison of the overall performance of the different MPPT algorithms is summarized in Table IV.

TABLE IV. A COMPARISON OF THE DIFFERENT PERFORMANCES OF P&O AND PSO+IC

MPPT algorithm	Effien-Ciency %	Acc-urancy	Com-pexity	Tarcking speed	Implem-entation	Ability of tracking In partial shading
P&O	> 85%	medium	low	medium	easy	no
PSO proposed	> 98%	high	medium	fast	medium	yes

V. CONCLUSIONS

In this study, the proposed method (PSO+IC) is applied to a photovoltaic (PV) system operating under partial shading conditions (PSC) and connected to a load with a constant temperature (30 Ω at 25°C), in comparison to the Perturb and Observe (P&O) method. P&O is recognized for its simplicity and familiarity in the scientific literature, making it easily understandable and accessible.

The hybrid system presented in our work demonstrates a strong capability to identify the global optimal solution, resulting in improved system efficiency when contrasted with the P&O approach. Our solution achieves over 98% efficiency, contributing to reduced setup time (i.e., faster tracking) and Reduced variations in power output (i.e., fewer steady-state oscillations).

Future work will involve an in-depth experimental case study to further validate the proposed MPPT method's performance in a PV system connected to a load.

REFERENCES

[1] M. A. Mesbah *et al*., “Adaptive Control Approach for Accurate Current Sharing and Voltage Regulation in DC Microgrid Applications,” *Energies*, vol. 17, no. 2, p. 284, 2024, doi: 10.3390/en17020284.

[2] A. Hilali, N. El Ouanjli, S. Mahfoud, A. S. Al-Sumaiti, and M. A. Mossa, “Optimization of a Solar Water Pumping System in Varying Weather Conditions by a New Hybrid Method Based on Fuzzy Logic and Incremental Conductance,” *Energies*, vol. 15, p. 8518, 2022.

[3] A. Harrag, S. Messalti, and Y. Daili, “Innovative Single Sensor Neural Network PV MPPT,” *6th International Conference on Control, Decision and Information Technologies*, pp. 1895-1899, 2019.

[4] C. H. Hussaian Basha, and C. Rani, “Performance Analysis of MPPT Techniques for Dynamic Irradiation Condition of Solar PV,” *International Journal of Fuzzy Systems*, vol. 22, no. 8, pp. 2577-2598, 2020.

[5] N. Priyadarshi, S. Padmanaban, J. B. Holm-Nielsen, F. Blaabjerg, and M. S. Bhaskar, "An Experimental Estimation of Hybrid ANFIS–PSO-Based MPPT for PV Grid Integration Under Fluctuating Sun Irradiance," in *IEEE Systems Journal*, vol. 14, no. 1, pp. 1218-1229, March 2020, doi: 10.1109/JSYST.2019.2949083.

[6] R. B. Bollipo, S. Mikkili, and P. K. Bonthagorla, "Hybrid, optimal, intelligent and classical PV MPPT techniques: A review," in *CSEE Journal of Power and Energy Systems*, vol. 7, no. 1, pp. 9-33, Jan. 2021, doi: 10.17775/CSEEJPES.2019.02720.

[7] A. Raj, S. R. Arya, and J. Gupta, “Solar PV array-based DC–DC converter with MPPT for low power applications,” *Renewable Energy Focus*, vol. 34, pp. 109-119, 2020.

[8] R. Anand, D. Swaroop, and B. Kumar, "Global Maximum Power Point Tracking for PV Array under Partial Shading using Cuckoo Search," *2020 IEEE 9th Power India International Conference (PIICON)*, pp. 1-6, 2020, doi: 10.1109/PIICON49524.2020.9113004.

[9] H. Li, D. Yang, W. Su, J. Lü, and X. Yu, “An overall distribution particle swarm optimization MPPT algorithm for photovoltaic system under partial shading,” *IEEE Trans. Ind. Electron*., vol. 66, no. 1, pp. 265–275, Jan. 2019.

[10] N. Priyadarshi, S. Padmanaban, J. B. Holm-Nielsen, F. Blaabjerg, and M. S. Bhaskar, “An experimental estimation of hybrid ANFIS–PSO-based MPPT for PV grid integration under fluctuating sun irradiance,” *IEEE Syst. J.*, vol. 14, no. 1, pp. 1218–1229, Mar. 2020.

[11] K. Guo, L. Cui, M. Mao, L. Zhou, and Q. Zhang, “An improved gray wolf optimizer MPPT algorithm for PV system with BFBIC converter under partial shading,” *IEEE Access*, vol. 8, pp. 103476–103490, 2020.

[12] E. Mendez, A. Ortiz, P. Ponce, I. Macias, D. Balderas, and A. Molina, “Improved MPPT algorithm for photovoltaic systems based on the earthquake optimization algorithm,” *Energies*, vol. 13, no. 12, p. 3047, Jun. 2020.

[13] G. S. Chawda, O. P. Mahela, N. Gupta, M. Khosravy, and T. Senjyu, “Incremental conductance based particle swarm optimization algorithm for global maximum power tracking of solar-PV under nonuniform operating conditions,” *Appl. Sci.*, vol. 10, no. 13, p. 4575, Jul. 2020

[14] M. A. Memon, “Sizing of DC-link capacitor for a grid connected solar photovoltaic inverter,” *Indian J. Sci. Technol.*, vol. 13, no. 22, pp. 2272–2281, Jun. 2020.

[15] M. A. Mossa, O. Gam, and N. Bianchi, "Performance enhancement of a hybrid renewable energy system accompanied with energy storage unit using effective control system,” *Int. J. Robot. Control. Syst.*, vol. 2, no. 1, pp. 140-171, 2022.

[16] G. S. Chawda, O. P. Mahela, N. Gupta, M. Khosravy, and T. Senjyu, “Incremental conductance based particle swarm optimization algorithm for global maximum power tracking of solar-PV under nonuniform operating conditions,” *Appl. Sci.*, vol. 10, no. 13, p. 4575, Jul. 2020.

[17] M. A. Mossa, N. E. Ouanjli, O. Gam, and O. M. Kamel, "Performance improvement of a hybrid energy system feeding an isolated load," *2022 23rd International Middle East Power Systems Conference (MEPCON)*, pp. 1-8, 2022.

[18] M. A. Mossa, N. E. Ouanjli, O. Gam, and T. D. Do, “Enhancing the Performance of a Renewable Energy System Using a Novel Predictive Control Method,” *Electronics*, vol. 12, p. 3408, 2023.

[19] S. M. Sousa, L. S. Gusman, T. A. S. Lopes, H. A. Pereira, and J. M. S. Callegari, “MPPT algorithm in single loop current-mode control applied to dc–dc converters with input current source characteristics,” *International Journal of Electrical Power and Energy Systems*, vol. 138, 2022, doi: 10.1016/j.ijepes.2021.107909.

[20] G. M. Zhang, Y. L. Liu, and B. J. YE, “A variable step disturbance observation method in applying PV MPPT,” *Journal of xi’an engineering university*, vol. 4, pp. 433-439, 2019.

[21] H. Li, D. Yang, W. Su, J. Lü, and X. Yu, “An overall distribution particle swarm optimization MPPT algorithm for photovoltaic system under partial shading,” *IEEE Trans. Ind. Electron*., vol. 66, no. 1, pp. 265–275, Jan. 2019.

[22] K. Saidi, M. Maamoun, and M. Bounekhla, “A new high performance variable step size perturb-and-observe MPPT algorithm for

photovoltaic system," *Int. J. Power Electron. Drive Syst. (IJPEDS)*, vol. 10, no. 3, p. 1662, Sep. 2019.

[23] S. Bhattacharyya, P. D. S. Kumar, S. Samanta, and S. Mishra, "Steady output and fast tracking MPPT (SOFT-MPPT) for P&O and InC algorithms," *IEEE Trans. Sustain. Energy*, vol. 12, no. 1, pp. 293–302, Jan. 2021.

[24] E. Mendez, A. Ortiz, P. Ponce, I. Macias, D. Balderas, and A. Molina, "Improved MPPT algorithm for photovoltaic systems based on the earthquake optimization algorithm," *Energies*, vol. 13, no. 12, p. 3047, Jun. 2020.

[25] S. Abboud, R. Habachi, A. Boulal, and S. El Alami, "Maximum power point tracker using an intelligent sliding mode controller of a photovoltaic system," *International Journal of Power Electronics and Drive Systems*, vol. 14, no. 1, p. 516, 2023.

[26] M. Hebchi, A. Kouzou, and A. Choucha, "Improved incremental conductance algorithm for MPPT in photovoltaic system," in *Proc. 18th Int. Multi-Conf. Syst., Signals Devices (SSD)*, pp. 1271–1278, Mar. 2021.

[27] M. Elbar, I. Merzouk, A. Bealdel, M. M. Rezaoui, A. Iratni, and A. Hafaifa, "Power Quality Enhancement in Four-Wire Systems Under Different Distributed Energy Resource Penetration," in *Electrotehnica, Electronica, Automatica (EEA)*, vol. 69, no. 4, pp. 50-58, 2021.

[28] K. Sabri, O. El Maguiri, and A. Farchi, "Comparative Study of Different MPPT Algorithms for Photovoltaic Systems under Partial Shading Conditions," *2021 9th International Renewable and Sustainable Energy Conference (IRSEC)*, pp. 1-7, 2021, doi: 10.1109/IRSEC53969.2021.9741164.

[29] H. Li, D. Yang, W. Su, J. Lü, and X. Yu, "An overall distribution particle swarm optimization MPPT algorithm for photovoltaic system under partial shading," *IEEE Trans. Ind. Electron.*, vol. 66, no. 1, pp. 265–275, Jan. 2019.

[30] A. A. Z. Diab, M. A. Mohamed, A. Al-Sumaiti, H. Sultan, and M. A. Mossa, "Novel Hybrid Optimization Algorithm for Maximum Power Point Tracking of Partially Shaded Photovoltaic Systems. In Advanced Technologies for Solar Photovoltaics Energy Systems, pp. 201–230, 2021.

[31] M. A. Mossa, O. Gam, N. Bianchi, and N. V. Quynh, "Enhanced Control and Power Management for a Renewable Energy-Based Water Pumping System," in *IEEE Access*, vol. 10, pp. 36028-36056, 2022, doi: 10.1109/ACCESS.2022.3163530.

[32] Y. Zhang, Y.-J. Wang, and J. Q. Yu, "A Novel MPPT Algorithm for Photovoltaic Systems Based on Improved Sliding Mode Control," *Electronics*, vol. 11, no. 15, p. 2421, 2022, doi: 10.3390/electronics11152421.

[33] D. M. Djanssou, A. Dadjé, A. Tom, and N. Djongyang, "Improvement of the Dynamic Response of Robust Sliding Mode MPPT Controller-Based PSO Algorithm for PV Systems under Fast-Changing Atmospheric Conditions," *International Journal of Photoenergy*, pp. 1–13, 2021, doi: 10.1155/2021/6671133.

[34] H. Li, L. Zhao, and S. Tian, "Research on photovoltaic MPPT control Strategy based on improved sliding mode control," *Journal of Physics: Conference Series*, vol. 2310, no. 1, p. 012039, 2022, doi: 10.1088/1742-6596/2310/1/012039.

[35] A. Kihal, F. Krim, A. Laib, B. Talbi, and H. Afghoul, "An improved MPPT scheme employing adaptive integral derivative sliding mode control for photovoltaic systems under fast irradiation changes," *ISA Transactions*, vol. 87, pp. 297–306, 2019, doi: 10.1016/j.isatra.2018.11.020.

[36] F. Bodur and O. Kaplan, "Second-Order Sliding Mode Control Algorithms in DC/DC Buck Converter," *2022 10th International Conference on Smart Grid (IcSmartGrid)*, pp. 380–386, 2022, doi: 10.1109/icSmartGrid55722.2022.9848696.

[37] X. Dingyü, "Introduction to intelligent optimization methods," in *Solving Optimization Problems With MATLAB*, pp. 297–299, 2020.

[38] R. Singh, R. Yadav, L. Varshney, and S. Sharma, "Analysis and Comparison of PV Array MPPT Techniques to Increase Output Power," *2021 International Conference on Advance Computing and Innovative Technologies in Engineering (ICACITE)*, pp. 168–172, 2021, doi: 10.1109/ICACITE51222.2021.9404688.

[39] A. Aldosary, Z. M. Ali, M. M. Alhaider, M. Ghahremani, S. Dadfar, and K. Suzuki, "A modified shuffled frog algorithm to improve MPPT controller in PV System with storage batteries under variable atmospheric conditions," *Control Engineering Practice*, vol. 112, p. 104831, 2021, doi: 10.1016/j.conengprac.2021.104831.

[40] R. Rahimi, S. Habibi, P. Shamsi, and M. Ferdowsi, "A High Step-Up Z-Source DC-DC Converter for Integration of Photovoltaic Panels into DC Microgrid," *2021 IEEE Applied Power Electronics Conference and Exposition (APEC)*, pp. 1416–1420, 2021, doi: 10.1109/APEC42165.2021.9487463.

[41] M. Drif, M. Bahri, and D. Saigaa, "A novel equivalent circuit-based model for photovoltaic sources," *Optik*, vol. 242, p. 167046, 2021, doi: 10.1016/j.ijleo.2021.167046.

[42] M. A. Mossa, H. Echeikh, N. V. Quynh, and N. Bianchi, "Performance dynamics improvement of a hybrid wind/fuel cell/battery system for standalone operation," *IET Renew. Power Gener.*, vol. 17, no. 2, pp. 349-375, 2022.

[43] Z. M. S. Elbarbary and M. A. Alranini, "Review of maximum power point tracking algorithms of PV system," *Frontiers in Engineering and Built Environment*, vol. 1, no. 1, pp. 68–80, 2021, doi: 10.1108/FEBE-03-2021-0019.

[44] M. Derbeli, C. Napole, O. Barambones, J. Sanchez, I. Calvo, and P. Fernández-Bustamante, "Maximum Power Point Tracking Techniques for Photovoltaic Panel: A Review and Experimental Applications," *Energies*, vol. 14, no. 22, p. 7806, 2021, doi: 10.3390/en14227806.

[45] R. S. Inomoto, J. R. B. de A. Monteiro, and A. J. S. Filho, "Boost Converter Control of PV System Using Sliding Mode Control With Integrative Sliding Surface," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 10, no. 5, pp. 5522–5530, 2022, doi: 10.1109/JESTPE.2022.3158247.

[46] M. FatimaZohra, B. Mokhtar, and M. Benyounes, "Sliding mode performance control applied to a DFIG system for a wind energy production," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 10, no. 6, p. 6139, 2020, doi: 10.11591/ijece.v10i6.pp6139-6152.

[47] M. Jiang, M. Ghahremani, S. Dadfar, H. Chi, Y. N. Abdallah, and N. Furukawa, "A novel combinatorial hybrid SFL–PS algorithm based neural network with perturb and observe for the MPPT controller of a hybrid PV-storage system," *Control Engineering Practice*, vol. 114, p. 104880, 2021, doi: 10.1016/j.conengprac.2021.104880.

[48] S. Bhattacharyya, P. D. S. Kumar, S. Samanta, and S. Mishra, "Steady output and fast tracking MPPT (SOFT-MPPT) for P&O and InC algorithms," *IEEE Trans. Sustain. Energy*, vol. 12, no. 1, pp. 293–302, Jan. 2021.

[49] N. Swaminathan, N. Lakshminarasamma, and Y. Cao, "A Fixed Zone Perturb and Observe MPPT Technique for a Standalone Distributed PV System," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 10, no. 1, pp. 361–374, 2022, doi: 10.1109/JESTPE.2021.3065916.

[50] M. Aref, M. A. Mossa, N. K. Lan, N. V. Quynh, V. Oboskalov, and A. F. M. Ali, "Improvement of Fault Current Calculation and Static Security Risk for Droop Control of the Inverter-Interfaced DG of Grid-Connected and Isolated Microgrids," *Inventions*, vol. 7, no. 3, p. 52, 2022, doi: 10.3390/inventions7030052.

[51] S. Miqoi, A. el Ougli, and B. Tidhaf, "Adaptive fuzzy sliding mode based MPPT controller for a photovoltaic water pumping system," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 10, no. 1, p. 414, 2019, doi: 10.11591/ijpeds.v10.i1.pp414-422.

[52] T. Abderrahim, T. Abdelwahed, and M. Radouane, "Improved strategy of an MPPT based on the sliding mode control for a PV system," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 10, no. 3, p. 3074, 2020, doi: 10.11591/ijece.v10i3.pp3074-3085.

[53] C. A. Ramos-Paja, D. Gonzalez-Motoya, J. P. Villegas-Seballos, S. I. Serna-Garces, and R. Giral, "Sliding-mode controller for a photovoltaic system based on a Cuk converter," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 11, no. 3, p. 2027, 2021, doi: 10.11591/ijece.v11i3.pp2027-2044.

[54] H. Chojaa *et al*., "Robust Control of DFIG-Based WECS Integrating an Energy Storage System With Intelligent MPPT Under a Real Wind Profile," in *IEEE Access*, vol. 11, pp. 90065-90083, 2023, doi: 10.1109/ACCESS.2023.3306722.

[55] H. Attia and A. Elkhateb, “Intelligent maximum power point tracker enhanced by sliding mode control,” *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 13, no. 2, p. 1037, 2022, doi: 10.11591/ijpeds.v13.i2.pp1037-1046.

[56] A. W. Ibrahim, Z. Fang, K. Ameur, D. Min, M. B. Shafik, and G. Al-Muthanna, “Comparative study of solar pv system performance under partial shaded condition utilizing different control approaches,” *Indian J. Sci. Technol.*, vol. 14, pp. 1864-1893, 2021, doi: 10.17485/IJST/v14i22.827.

[57] M. Mohammadinodoushan, R. Abbassi, H. Jerbi, F. Waly Ahmed, H. Abdalqadir kh ahmed, and A. Rezvani, "A new MPPT design using variable step size perturb and observe method for PV system under partially shaded conditions by modified shuffled frog leaping algorithm- SMC controller," *Sustain. Energy Technol. Assessments*, vol. 45, p. 101056, 2021, doi: 10.1016/j.seta.2021.101056

[58] Z. M. Ali, N. Vu Quynh, S. Dadfar, and H. Nakamura, "Variable step size perturb and observe MPPT controller by applying θ-modified krill herd algorithm-sliding mode controller under partially shaded conditions," *J. Clean. Prod.*, vol. 271, p. 122243, 2020, doi: 10.1016/j.jclepro.2020.122243.

[59] W. Hayder, E. Ogliari, A. Dolara, A. Abid, M. B. Hamed, and L. Sbita, "Improved PSO: A comparative study in MPPT algorithm for PV system control under partial shading conditions," *Energies*, vol. 13, no. 8, 2020, doi: 10.3390/en13082035.

[60] S. Akram, L. Khalil, M. K. L. Bhatti, T. Aftab, R. Siddique, and M. Riaz, “Maximum Power Point Tracking using Direct Control with Cuckoo Search for Photovoltaic Module under Partial Shading Condition,” *Pakistan Journal of Engineering and Technology*, vol. 4, no. 2, pp. 28-31, 2021.

[61] N. Swaminathan, N. Lakshminarasamma, and Y. Cao, "A Fixed Zone Perturb and Observe MPPT Technique for a Standalone Distributed PV System," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 10, no. 1, pp. 361-374, Feb. 2022, doi: 10.1109/JESTPE.2021.3065916.

[62] G. A. Raiker, U. Loganathan, and S. Reddy B., "Current Control of Boost Converter for PV Interface With Momentum-Based Perturb and Observe MPPT," in *IEEE Transactions on Industry Applications*, vol. 57, no. 4, pp. 4071-4079, July-Aug. 2021, doi: 10.1109/TIA.2021.3081519.

[63] C. Rao, A. Hajjiah, M. A. El-Meligy, M. Sharaf, A. T. Soliman, and M. A. Mohamed, “A novel high-gain soft-switching DC DC converter with improved P&O MPPT for photovoltaic applications,” *IEEE Access*, vol. 9, pp. 58790–58806, 2021.

[64] A. I. Ali, Z. M. Alaas, M. A. Sayed, A. Almalaq, A. Farah, and M. A. Mohamed, “An efficient MPPT technique-based single stage incremental conductance for integrated PV systems con sidering flyback central-type PV inverter,” *Sustainability*, vol. 14, no. 19, p. 12105, 2022.

[65] K. Y. Yap, C. R. Sarimuthu, and J. M. Lim, “Artificial intelligence based MPPT techniques for solar power system: a review,” *Journal of Modern Power Systems and Clean Energy*, vol. 8, no. 6, pp. 1043–1059, 2020.

[66] A. M. Noman, H. Khan, H. A. Sher, S. Z. Almutairi, M. H. Alqahtani, and A. S. Aljumah, “Scaled conjugate gradient artificial neural network-based ripple current correlation MPPT algorithms for PV system,” *International Journal of Photoe nergy*, vol. 2023, 2023.

[67] M. S. Bouakkaz, A. Boukadoum, O. Boudebbouz, I. Attoui, N. Boutasseta, and A. Bouraiou, “Fuzfzy logic based adaptive step hill climbing MPPT algorithm for PV energy generation systems,” in *2020 International Conference on Computing and Information Technology (ICCIT-1441)*, pp. 1–5, 2020.

[68] H. Li, D. Yang, W. Su, J. Lü, and X. Yu, “A novel distribution particle swarm optimization MPPT algorithm for photovoltaic system under partial shading,” *IEEE Transactions on Indus trial Electronics*, vol. 66, no. 1, pp. 265–275, 2019.

[69] K. Guo, L. Cui, M. Mao, L. Zhou, and Q. Zhang, “An improved gray wolf optimizer MPPT algorithm for PV system with BFBIC converter under partial shading,” *IEEE Access*, vol. 8, pp. 103476–103490, 2020.

[70] M. Kermadi, S. Mekhilef, Z. Salam, J. Ahmed, and E. M. Ber kouk, “Assessment of maximum power point trackers perfor mance using direct and indirect control methods,” *International Transactions on Electrical Energy Systems*, vol. 30, no. 10, 2020.

[71] J. Dadkhah and M. Niroomand, “Optimization methods of MPPT parameters for PV systems: review, classification, and comparison,” *Journal of Modern Power Systems and Clean Energy*, vol. 9, no. 2, pp. 225–236, 2021.

[72] V. Kumar and M. Singh, “Derated mode of power generation in PVsystem using modified perturb andobserve MPPT Algorithm,” *Journal of Modern Power Systems and Clean Energy*, vol. 9, no. 5, pp. 1183–1192, 2021.

[73] H. Abouadane, A. Fakkar, D. Sera, A. Lashab, S. Spataru, and T. Kerekes, “Multiple-power-sample based P&O MPPT for fast-changing irradiance conditions for a simple implementa tion,” *IEEE Journal of Photovoltaics*, vol. 10, no. 5, pp. 1481 1488, 2020.

[74] P. Manoharan *et al*., "Improved Perturb and Observation Maximum Power Point Tracking Technique for Solar Photovoltaic Power Generation Systems," in *IEEE Systems Journal*, vol. 15, no. 2, pp. 3024-3035, June 2021, doi: 10.1109/JSYST.2020.3003255.

[75] J. M. Riquelme-Dominguez and S. Martinez, "Comparison of Different Photovoltaic Perturb and Observe Algorithms for Drift Avoidance in Fluctuating Irradiance Conditions," *2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, pp. 1-5, 2020, doi: 10.1109/EEEIC/ICPSEurope49358.2020.9160791.

[76] J. Dadkhah and M. Niroomand, “Real-time MPPT optimiza tion of PV systems by means of DCD-RLS based identifica tion,” *IEEE Transactions on Sustainable Energy*, vol. 10, no. 4, pp. 2114–2122, 2019.

[77] A. A. Z. Diab, H. M. Sultan, T. D. Do, O. M. Kamel, and M. A. Mossa, "Coyote Optimization Algorithm for Parameters Estimation of Various Models of Solar Cells and PV Modules," in *IEEE Access*, vol. 8, pp. 111102-111140, 2020, doi: 10.1109/ACCESS.2020.3000770.

[78] V. K. Yadav, S. K. Jha, and B. Kumar, “Comparative study of different variable step size perturb and observe based MPPT,” in *2020 International Conference on Advances in Computing, Communication & Materials (ICACCM)*, pp. 272–277, 2020.

[79] A. R. Krishnan, S. S. Mohammed, and S. Manafudeen, "Comparison of P&O MPPT Based Solar PV System with Interleaved Boost Converter," *2019 2nd International Conference on Intelligent Computing, Instrumentation and Control Technologies (ICICICT)*, 2019, pp. 1370-1376, doi: 10.1109/ICICICT46008.2019.8993209.

[80] S. Bhattacharyya, S. Samanta, and S. Mishra, “Steady output and fast tracking MPPT (SOFT-MPPT) for P&O and InC algorithms,” *IEEE Transactions on Sustainable Energy*, vol. 12, no. 1, pp. 293–302, 2021.