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RESEARCH ARTICLE-ELECTRICAL ENGINEERING

Metaheuristic Optimization Algorithm-Based Enhancement of Photovoltaic Energy System Performance

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Abstract

Photovoltaic panels (PVs) are solar panels that turn sunlight into electricity. Tracking the maximum power point (MPP) of PVs is especially important for economic issues. The most popular maximum power point tracking techniques are perturb and observation, hill climbing, constant voltage, parasitic capacitance, and incremental conductance (INC). However, these techniques give oscillated results about the MPP that causes low accuracy, especially in partial shading conditions. This paper is discussing the enhancement of photovoltaic energy system performance using several metaheuristic optimization algorithms. Using MATLAB SIMULINK, a comparative analysis of several algorithms for tracking MPP of PV systems under partially shadowed conditions was conducted. The metaheuristic optimization algorithms that are used in this paper are particle swarm optimization (PSO), cuckoo search algorithm (CSA), grey wolf optimization (GWO), and whale optimization algorithm (WOA). The results show that using WOA and GWO achieved the best efficiency in tracking MPP, whereas, using PSO and CSA achieved lower efficiency in tracking MPP. The MPP of the PV system was not tracked by INC under the partial shaded conditions.

Keywords Photovoltaic system · MPPT · Incremental conductance INC · Metaheuristic optimization algorithms · Particle swarm optimization PSO · Cuckoo search algorithm CSA · Grey wolf optimization GWO · Whale optimization algorithm WOA

1 Introduction

For economic reasons, it is critical to obtain the solar system's maximum power point to achieve the highest potential efficiency of use [1]. Many techniques proposed for MPPT such as curve fitting, P&O, INC, and metaheuristic optimization techniques [2]. The MPP is affected by temperature and irradiation conditions. By increasing the temperature, the PV voltage is reduced, and the current is increased. The PV features, on the other hand, depart from the usual in partially shaded situations. This is the main reason for using the metaheuristic algorithms for tracking the MPP.

Over the recent years, more scientific research discussed, under typical and partial shade conditions, the numerous MPPT approaches of solar systems [3]. Differential-based methods, numerical methods, perturbation-based, conductance-based methods, and state-space and intelligent methods are just some of the MPPT methods that have described, and their benefits and limitations discussed [4]. The MPP can easily estimate without perturbations using the incremental conductance technique. In addition, when compared to perturb and observe algorithm (P&O), the overall system efficiency improved [5]. Because irradiation and temperature have an impact on generated power, an algorithm proposed for tracking the maximum PV power when irradiation changes. To locate the MPP of the PV array under PSC with varying irradiance, a novel form of PSO is employed. The PSO algorithm has improved the solar system's maximum power point tracking efficiency [6]. The PSO and CSA approaches designed to increase the efficiency of solar systems that partially shadowed. The results show that CSA is better than PSO because the tracking time reduced by more

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than 30% when employing CSA in all the partial shading patterns studied [7]. The existence of several power peaks in the power–voltage (P–V) curve increases the likelihood of falling into local power peaks during partial shade situations. Swarm intelligence optimization control methods such as PSO and ant colony optimization (ACO) evaluated for tracking global power in solar systems under partial shading conditions [8]. An evolutionary computing approach dubbed grey wolf optimization is proposed to build a maximum power extraction algorithm for PV systems to work under PSCs. GWO is compared to P&O and improved particle swarm optimization (IPSO) methods. It is discovered that the GWO-based performs is better than using the P&O and IPSO for MPPT [9]. A swarm-based optimization technique developed, which inspired by humpback whale hunting behavior. Three operators used to replicate the hunt for prey, encircling prey, and bubble-net foraging behavior of humpback whales in the proposed technique (WOA). WOA outperformed metaheuristic optimizers and was superior to traditional approaches. The WOA algorithm currently developed in binary and multi-objective variants [10]. The WOA algorithm developed to track the global maximum power point (GMPP) of a PV system that is partially shaded. It discovered that the properties are nonlinear, making tracking GMPP in partially shadowed conditions difficult. The suggested WOA algorithm is utilized to track the GMPP for the aforesaid configurations, and it is more effective than the GWO and PSO MPPT algorithms at tracking the GMPP with high accuracy and less tracking time under dynamic partial shading situations [11]. A WOA-based proportional–integral (PI) controller is proposed to improve PV system performance by controlling the converters and making the system faster and better damped under various operating conditions such as symmetrical and unsymmetrical fault conditions, studying system responses under various irradiation and temperature conditions, and subjecting the system to a sudden load disturbance. The whale optimization algorithm (WOA) and grey wolf optimization (GWO) algorithms are used to tune the proportional–integral–derivative (PID) controller gains. They contribute to a reduction in ripple, overshoot, and response time [12, 13]. Metaheuristic swarm approaches such as the PSO, GWO, slap swarm algorithm (SSA), and bat algorithm (BA) have been used to solve the problem of trapping at the local peaks of the P–V curve. By integrating the cuckoo search (CS) and the golden section search (GSS), a new MPPT algorithm is developed to avoid being caught in a local maximum and discover the exact GMPP [14–16]. The photovoltaic module is subjected to a hybrid PSO-GWO algorithm to discover the best solution by obtaining zero error curves such as current–voltage curve (IV) and power–voltage curve (PV) [17]. For MPPT tracking, a modified butterfly optimization algorithm (MBOA) has been presented that can distinguish between partially shaded, evenly shaded, solar intensity, and load variation circumstances. Also, the algorithm implementation is simpler without the need for tedious parameter adjustment via trial and error [18]. GWO, moth flame optimization (MFO), hybrid particle swarm optimization-gravitational search algorithm (HPSO-GSA), artificial neural network (ANN), artificial bee colony algorithm (ABC), and slap swarm algorithm (SSA) are proposed for boosting the efficiency of PV systems under PSC. GWO outperformed SSA, MFO, and HPSO-GSA in terms of convergence speed and time to catch GMPP, with SSA, MFO, and HPSO-GSA following closely behind [19]. PSO and ABC algorithms need expensive controllers and software; however, the proposed ANN MPPT system can be simply implemented using a low-cost microcontroller [20, 21]. For PV systems, a fast fuzzy logic particle swarm optimization (FL-PSO) MPPT algorithm is presented to track the global MPP under various PSCs. The tracking convergence time has been enhanced because of the usage of fuzzy logic to dynamically alter the PSO key parameters [22].

The summarization of the preliminary studies in the introduction section is provided in Table 1 with references of each study.

The main contribution in this research is proposing a viable nanoparticle WOA algorithm to help overcome premature convergence, which means tracking the local peak and trapping it instead of the global peak under partial shaded conditions (PSCS). The advantages of the WOA algorithm include dealing with a nonlinear problem, tracking global peak in PSC, improved convergence speed, flexibility, less complicity, and easier to implemented. The efficacy of employing the WOA method has validated by a comparison of four significant approaches for estimating the maximum power of a series-connected PV array. INC, PSO, CSA, GWO, and WOA were the methodologies employed in this comparison.

The following is the structure of the paper: The modeling of PV system and the partial shade conditions discussed in Sect. 2. The MPPT techniques used in this paper discussed in Sect. 3. The numerical simulation and experimental results of all used methods are compared and evaluated in Sect. 4. The simulated results compared with previous studies in Sect. 5. The research conclusion presented in Sect. 6 and then the list of relevant references.

2 Modeling of PV System

The exact circuit of the photovoltaic system, as shown in Fig. 1, represented by a diode, an internal series resistance, and an internal shunt resistance. The internal series resistance (R_s) represents the voltage loss and the internal shunt resistance (R_{SH}) of the photovoltaic system represents the leakage current. As illustrated in Fig. 2, the PV's current–voltage (IV)

Table 1 Summarization of the preliminary studies

Preliminary studies	References
Tracking PV MPP is important for economic reasons	J. Smith et al., "Placeholder Text: A Study," Citation Styles, vol. 3, 2021, doi: 10.10/X
More techniques are proposed for MPPT	P. Verma et al., "Meta-heuristic optimization techniques used for maximum power point tracking in solar pv system," *Electronics (Switzerland)*, vol. 10, no. 19. MDPI, Oct. 01, 2021. https://doi.org/10.3390/electronics10192419
Under typical and partial shade conditions, the numerous MPPT approaches of solar systems have been discussed	D. Pilakkat, S. Kanthalakshmi, and S. Navaneethan, "A Comprehensive Review of Swarm Optimization Algorithms for MPPT Control of PV Systems under Partially Shaded Conditions," *Electronics (Basel)*, vol. 24, no. 1, pp. 3–14, Jun. 2020, https://doi.org/10.7251/ELS2024003P
Differential-based, numerical, perturbation-based, conductance-based, state-space and intelligent methods are some of the MPPT methods that have described with their benefits and limitations	A. Danandeh and S. M. Mousavi G., "Comparative and comprehensive review of maximum power point tracking methods for PV cells," *Renewable and Sustainable Energy Reviews*, vol. 82. Elsevier Ltd, pp. 2743–2767, Feb. 01, 2018. https://doi.org/10.1016/j.rser.2017.10.009
MPPT using INC technique is more efficient than using P&O	R. P. Kawde and S. Muley, "MPPT INCREMENTAL CONDUCTANCE TECHNIQUE FOR PV SYSTEMS," 2021. [Online]. Available: http://www.ijeast.com
Using PSO algorithm has improved MPPT efficiency under PSC with varying irradiance	K. H. Chao, "A high performance PSO-based global MPP tracker for a PV power generation system," Energies (Basel), vol. 8, no. 7, pp. 6841–6858, 2015, https://doi.org/10.3390/en8076841
Results show that CSA is better than PSO in PV MPPT in tracking time	H. Rezk, A. Fathy, and A. Y. Abdelaziz, "A comparison of different global MPPT techniques based on meta-heuristic algorithms for photovoltaic system subjected to partial shading conditions," Renewable and Sustainable Energy Reviews, vol. 74. Elsevier Ltd, pp. 377–386, 2017. https://doi.org/10.1016/j.rser.2017.02.051
Swarm intelligence optimization control methods such as PSO and ACO are evaluated for tracking GMPP in solar systems under PSCS	B. Yang et al., "Comprehensive overview of maximum power point tracking algorithms of PV systems under partial shading condition," Journal of Cleaner Production, vol. 268. Elsevier Ltd, Sep. 20, 2020. https://doi.org/10.1016/j.jclepro.2020.121983
Using GWO for MPPT of PV is more efficient than using P&O or IPSO	S. Mohanty, B. Subudhi, and P. K. Ray, "A new MPPT design using grey Wolf optimization technique for photovoltaic system under partial shading conditions," IEEE Trans Sustain Energy, vol. 7, no. 1, pp. 181–188, Jan. 2016, https://doi.org/10.1109/TSTE.2015.2482120
The WOA algorithm is developed in binary and multi-objective variants	S. Mirjalili and A. Lewis, "The Whale Optimization Algorithm," Advances in Engineering Software, vol. 95, pp. 51–67, May 2016, doi: 10. 1016/j.advengsoft.2016.01.008
The WOA algorithm is developed to track GMPP of PV under dynamic PSCS. It is more effective than GWO and PSO	C. H. Santhan Kumar and R. Srinivasa Rao, "A novel global MPP tracking of photovoltaic system based on whale optimization algorithm," International Journal of Renewable Energy Development, vol. 5, no. 3, pp. 225–232, Oct. 2016, https://doi.org/10.14710/ijred.5.3.225-232
WOA and GWO algorithms are used to tune the PID controller gains. They contribute to a reduction in ripple, overshoot, and response time	H. M. Hasanien, "Performance improvement of photovoltaic power systems using an optimal control strategy based on whale optimization algorithm," Electric Power Systems Research, vol. 157, pp. 168–176, Apr. 2018, https://doi.org/10.1016/j.epsr.2017.12.019 [13]. Z. Abderrahim, H. K. Eddine, and M. Sabir, "A new improved variable step size MPPT method for photovoltaic systems using grey wolf and whale optimization technique-based PID controller," Journal Europeen des Systems Automatises, vol. 54, no. 1, pp. 175–185, Feb. 2021, https://doi.org/10.18280/jesa.540120

Table 1 (continued)

Preliminary studies	References
By integrating CS and GSS, a new MPPT algorithm is developed to avoid being caught in a local maximum and discover the exact GMPP	A. M. Eltamaly, M. S. Al-Saud, and A. G. Abokhalil, "A novel bat algorithm strategy for maximum power point tracker of photovoltaic energy systems under dynamic partial shading," IEEE Access, vol. 8, pp. 10048–10060, 2020, https://doi.org/10.1109/ACCESS.2020.2964759 D. A. Nugraha, K. L. Lian, and S. Suwarno, "A novel mppt method based on cuckoo search algorithm and golden section search algorithm for partially shaded pv system," Canadian Journal of Electrical and Computer Engineering, vol. 42, no. 3, pp. 173–182, Jun. 2019, https://doi.org/10.1109/CJECE.2019.2914723 M. N. I. Jamaludin et al., "An Effective Salp Swarm-Based MPPT for Photovoltaic Systems under Dynamic and Partial Shading Conditions," IEEE Access, vol. 9, pp. 34,570–34,589, 2021, https://doi.org/10.1109/ACCESS.2021.3060431
PV is subjected to a hybrid PSO-GWO algorithm to discover the best solution by obtaining zero error curves such as IV PV	M. Premkumar, R. Sowmya, S. Umashankar, and P. Jangir, "Extraction of uncertain parameters of single-diode photovoltaic module using hybrid particle swarm optimization and grey wolf optimization algorithm," in Materials Today: Proceedings, 2020, vol. 46, pp. 5315–5321. https://doi.org/10.1016/j.matpr.2020.08.784
For MPPT tracking, MBOA has been presented that can distinguish between partially shaded, evenly shaded, solar intensity, and load variation circumstances	I. Shams, S. Mekhilef, and K. S. Tey, "Maximum Power Point Tracking Using Modified Butterfly Optimization Algorithm for Partial Shading, Uniform Shading, and Fast Varying Load Conditions," IEEE Trans Power Electron, vol. 36, no. 5, pp. 5569–5581, May 2021, https://doi.org/10.1109/TPEL.2020.3029607
GWO outperformed SSA, MFO, and HPSO-GSA in terms of convergence speed and time while tracking GMPP PV systems under PSCS	M. A. Mohamed, A. A. Zaki Diab, and H. Rezk, "Partial shading mitigation of PV systems via different meta-heuristic techniques," Renew Energy, vol. 130, pp. 1159–1175, Jan. 2019, https://doi.org/10.1016/j.renene.2018.08.077
PSO and ABC algorithms need expensive controllers and software, however, the proposed ANN MPPT system can be implemented using a low-cost microcontroller	V. R. Kota and M. N. Bhukya, "A novel global MPP tracking scheme based on shading pattern identification using artificial neural networks for photovoltaic power generation during partial shaded condition," IET Renewable Power Generation, vol. 13, no. 10, pp. 1647–1659, Jul. 2019, https://doi.org/10.1049/iet-rpg.2018.5142 H. M. H. Farh, A. M. Eltamaly, and M. S. Al-Saud, "Interleaved boost converter for global maximum power extraction from the photovoltaic system under partial shading," IET Renewable Power Generation, vol. 13, no. 8, pp. 1232–1238, Jun. 2019, https://doi.org/10.1049/iet-rpg.2018.5256
FL-PSO MPPT algorithm is presented to track GMPP under various PSCS	M. Merchaoui, M. Hamouda, A. Sakly, and M. F. Mimouni, "Fuzzy logic adaptive particle swarm optimization-based MPPT controller for photovoltaic systems," IET Renewable Power Generation, vol. 14, no. 15, pp. 2933–2945, Nov. 2020, https://doi.org/10.1049/iet-rpg.2019.1207

characteristics curve depicts the current–voltage relationship [23].

2.1 PV Partially Shaded Conditions PSC

Variations in open-circuit voltage and current occur when a solar system is partially shaded. As a result, both the irradiation and the temperature of the PV module affect the open-circuit voltage and current. The irradiation increases with the increment of the PV current. When the PV is partially shaded, however, the irradiance and current reduced. Equation 1 represents the PV current under PSC. In addition, Eq. 2 represents PV open-circuit voltage under PSC [24].

$$I_{\mathrm{PV}} = \left(I_{\mathrm{PV,STC}} + K_I \Delta T\right)\frac{G}{G_n} \tag{1}$$

$$V_{\mathrm{OC}} = V_{\mathrm{OC,STC}} + K_{\mathrm{V}}(T - T_{\mathrm{STC}}) + \alpha V_{\mathrm{T}} \ln \frac{G}{G_{\mathrm{STC}}} \tag{2}$$

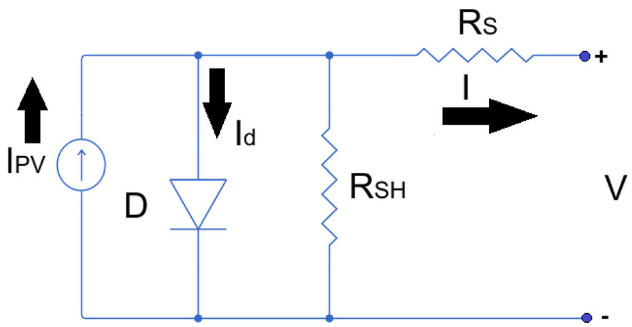


Fig. 1 Exact representation of PV equivalent circuit

where I_{PV}: PV current under PSC, $I_{PV,STC}$: current of PV under typical test conditions, K_I: temperature coefficient now, ΔT: change in temperature, G: PV irradiation, G_n: nominal PV irradiation, V_{OC}: PV open-circuit voltage under PSC, $V_{OC,STC}$: At conventional test conditions, the open-circuit voltage of a PV, K_V: voltage coefficient of temperature, T: temperature, T_{STC}: the temperature under typical test conditions, α: the diode ideality constant, V_T: voltage constant, G_{STC} : PV irradiation under typical test conditions.

As shown in the previous equations, partial shade limits the current of PV. The P–V characteristics graph of PV presented in Fig. 3 under PSC. It has the same number of peak points as the number of distinct PV panel irradiance levels. These peak points classified into local and global MPPs. The tracked point in this paper is the global MPP, which is the maximum point of the PV curve [25].

3 MPPT Techniques

For economic reasons, the maximum power point of the photovoltaic system must track to execute the highest possible power of the solar cell. Tracking the PV MPP without using any techniques is not an efficient process [26]. This, using MPPT is essential to make the tracking process more efficient with higher speed. There are many methods to track the MPP of PV. In this paper, INC, PSO, CSA, GWO, and WOA applied for MPPT to enhance the photovoltaic energy system. The block schematic of a PV equivalent circuit using the MPPT approach is shown in Fig. 4 [27].

3.1 INC Technique

One of the most widespread strategies is INC which is used as the MPPT technique of photovoltaic systems, because of its high speed and precision, as well as adaptability in rapidly changing circumstances. As shown in Eq. 3, this method is dependent on the fact that the change in power over the change in voltage of PV equals zero ($\frac{dP}{dV} = 0$) at MPP, a number greater than zero on the left of MPP and on the right, less than zero of MPP. The incremental conductance technique flowchart is shown in Fig. 5. In this flowchart, the value of voltage and current is measured and observed. Then the values of change in current (di) and the change in voltage (dv) are calculated and compared with reference values, so the duty cycle (D) changed by increasing or decreasing (dD) and stored its final value in (D_{out}) to obtain the MPP [28].

$$dV = V(k) - V(k-1)$$

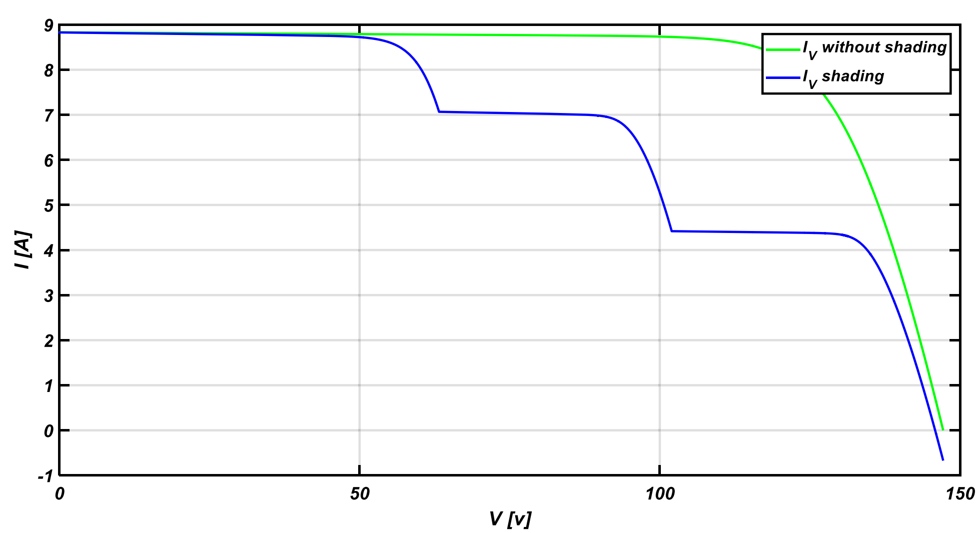
$$dI = I(k) - I(k-1)$$

$$\frac{dP}{dV} = \frac{d(VI)}{dV}$$

$$\frac{dP}{dV} = I + \frac{dI}{dV}V$$

$$\text{At MPP}: \frac{dP}{dV} = 0$$

Fig. 2 Voltage–current curve with and without shading



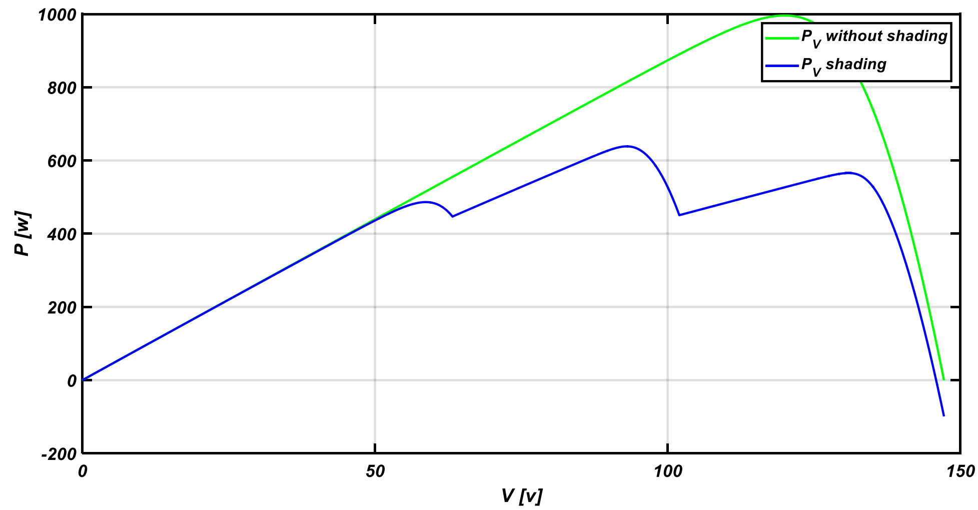


Fig. 3 PV curve with and without shading

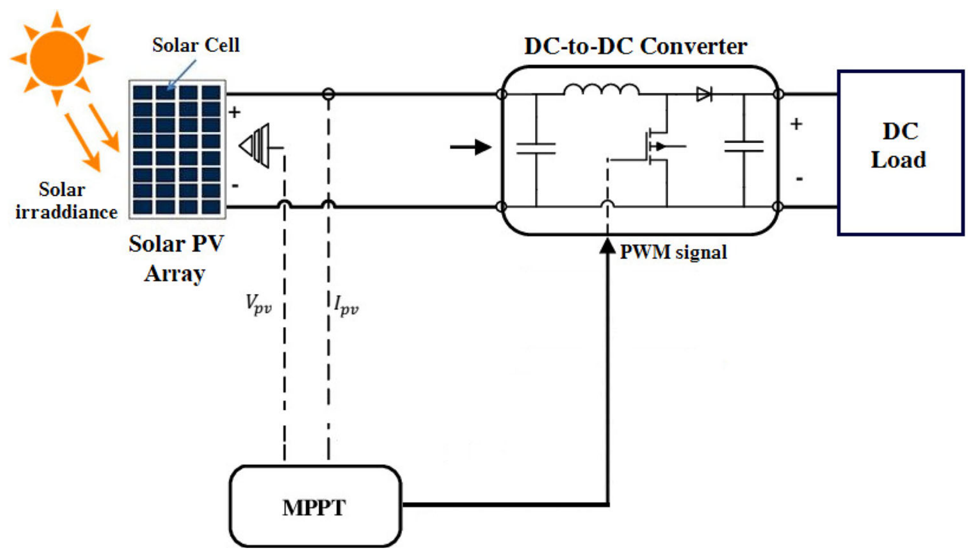


Fig. 4 The block schematic of a PV equivalent circuit using the MPPT

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

where V: voltage in PV cell, I: current in PV cell, P: power in PV cell, k: iteration number.

3.2 PSO Technique

As shown in Fig. 6, PSO is dependent on the space movements of the particle swarm. Assume that the algorithm of the swarm has i particles with a coordinate d_i which are moving with speed V_i. The particle movements in the space updated by the direction of the most advantageous circumstance of the swarm. Equation 4 shows the mathematical expression for the particle 's velocity at iteration j. In addition, Eq. 5 shows the mathematical expression for the particle 's position at iteration j [1].

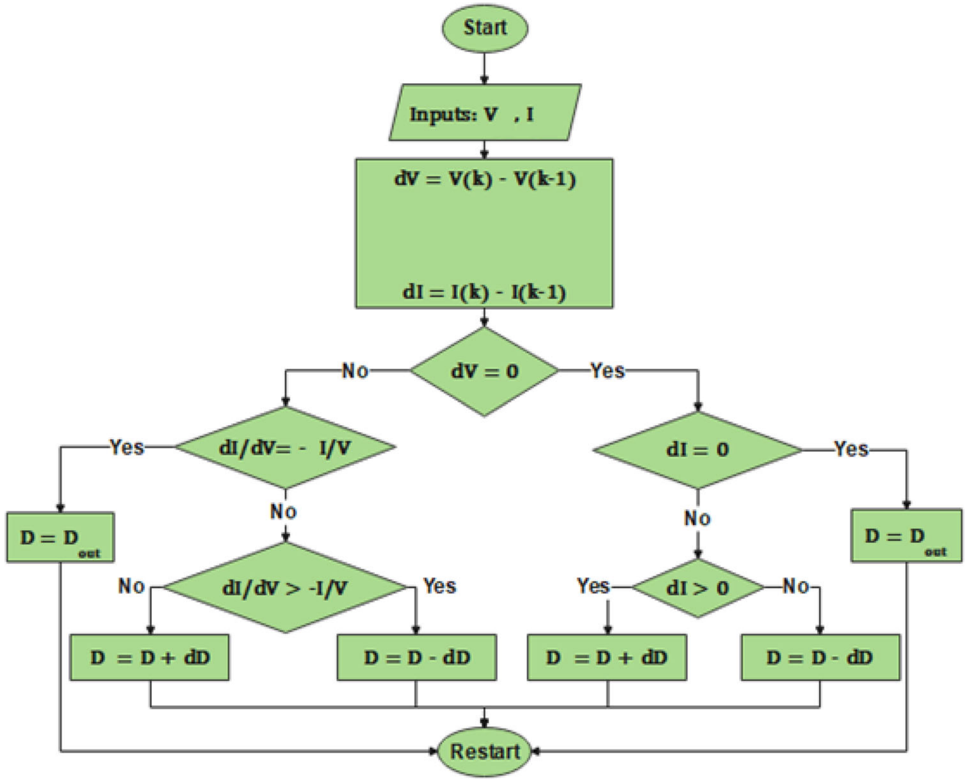
$$V_i(j+1) = W.V_i(j) + \text{rand}().C_1.(P_{\text{best}} - d_i(j)) + \text{rand}().C_2.(G_{\text{best}} - d_i(j)) \tag{4}$$

$$d_i(j+1) = d_i(j) + V_i(j+1) \tag{5}$$

where i: the optimization vectors, j: number of iterations (number of particles) ($j = 300$), $X_i(j+1)$: at iteration $j+1$, the position of i, $X_i(j)$: at iteration j, the position of i, $V_i(j+1)$: i's velocity at iteration $j+1$, $V_i(j)$: i's velocity at iteration j, W: a factor of weight ($W = 0.4$), rand(): In the range [0, 1], choose a random number, C_1 : is a particle's weight factor. ($C_1 = 1.2$), C_2:is the weight factor of all particles. ($C_2 = 2$), P_{best}: best position of particle i, G_{best}: best position in entire population.

Figure 6 shows the PSO flowchart for MPPT. a number of duty cycles randomly nominated. The PV current and voltage measured to estimate PV power. The calculated power compared with the MPP. In case of the new estimated power is

Fig. 5 INC technique flowchart



more than the old one, it is selected as the best value. Velocity and position are updated based on Eqs. 4 and 5.

3.3 CSA Technique

CSA is a method of optimization that is based on cuckoo bird behavior in their parasitic reproductive strategy. Figure 7 presents the CSA-based MPPT of PV. In this algorithm, it is important to search for a suitable host bird's nest and food. This random search can design in form of mathematical functions and algorithms. The cuckoo bird lays on its egg and places it randomly between nests. The best nest for eggs is carrying to the new iteration. The host's number of eggs detected represented as a probability. If the eggs discovered by the host bird, the cuckoo bird would construct a set number of nests. As shown in Eq. 6, the mathematical expression of the new iteration of samples (eggs) is formed. In Eq. 7, the mathematical expression of step size is formed and Levy(λ) is calculated from Eq. 8 [29].

$$d_i^{j+1} = d_i^j + \alpha \oplus \text{Levy}(\lambda) \quad (6)$$

$$\alpha = \alpha_o\left(d_j^{(j+1)} - d_i^{(j)}\right) \quad (7)$$

$$\text{Levy}(\lambda) \approx l^{-\lambda} \quad (8)$$

where ${d_i}^j$ is representative of number of duty cycles that randomly nominated at the iteration's order. (no. of iterations = 150)where d_i^{j+1} is representative of number of duty cycles that randomly nominated at the next iteration's order, i: is the duty cycle order, j: is the iteration's order, $\alpha > 0$: the step length ($\alpha = 1$), α_o: the initial step change ($\alpha_o = 0.8$), λ is between 1 and 3. ($\lambda = 1.5$), l: length of flight.

Figure 7 shows the flowchart for CSA for MPPT. Number of duty cycles randomly nominated. The PV current and voltage measured to estimate PV power. The duty cycle related to highest PV power selected as d_{best}. The duty cycle updated according to Eqs. 6, 7 and 8.

3.4 GWO Technique

GWO has considered a simulation of the grey wolf hunting algorithm. There are four wolfs: the ideal solution is Alpha. The second-best is Beta. Delta is the third best, and Omega is the fourth best. The solution is consisting of three steps: hunting, prey hunting, chasing, surrounding, and assaulting their victim. Equations 9–13 present the mathematical model of GWO prey attacking. The GWO algorithm-MPPT of PV is shown in Fig. 8 [30].

$$D = |C.x_P(t) - x_P(t)| \quad (9)$$

$$x(t+1) = x_P(t) - A.D \quad (10)$$

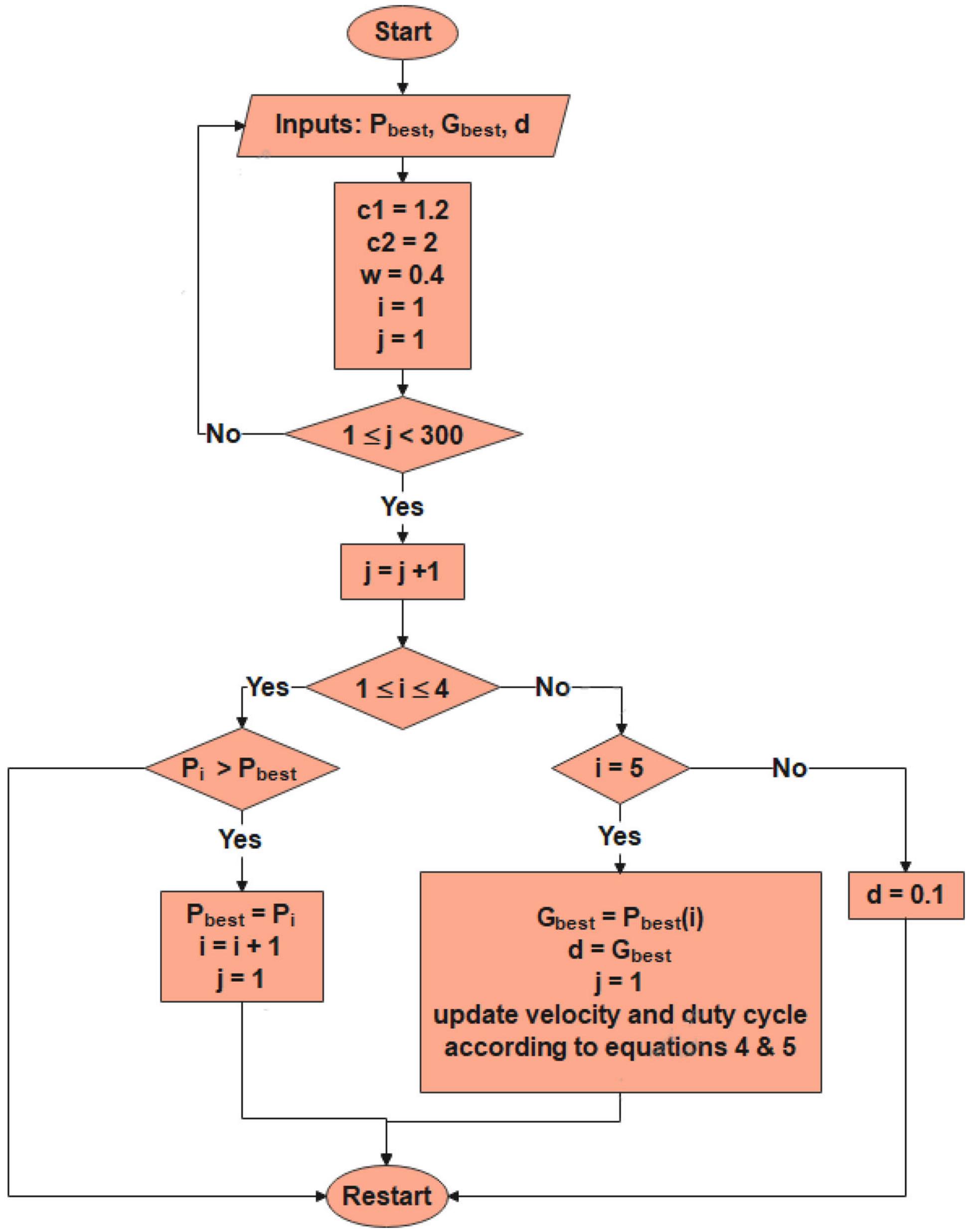


Fig. 6 PSO flowchart for MPPT

$$A = 2a.r_1 - a \tag{11}$$

$$C = 2r_2 \tag{12}$$

$$D_i(t+1) = D_i(t) - A.D \tag{13}$$

where the coefficient vectors are C, A, and D, t: the iteration's order,the prey's location vector is $x_P(t)$. The old duty cycles, the grey wolf's location vector of the next iteration is $x(t+1)$ (the updated duty cycle), a: during iterations, it decreases from 2 to 0, r_1 and r_2 are random vectors in the [0,1] range, i: the duty cycle order, D: grey wolf, $D_i(t)$: the wolf of the current iteration at the duty cycle number i, $D_i(t+1)$: the wolf of the next iteration at the duty cycle number i, No. of wolfs (no. of iterations = 100).

Figure 8 shows the flowchart for GWO for MPPT. Number of duty cycles randomly nominated. The PV current and voltage measured to estimate PV power. The duty cycle updated according to Eqs. 9–13.

3.5 WOA Technique

The main difference between (GWO) and (WOA) is the hunting behavior. The GWO is using a random search factor or best factor to hunt prey; however, WOA is using vortex to model the attack mechanism of humpback whales on bubble networks additional. Humpback whales generate bubbles

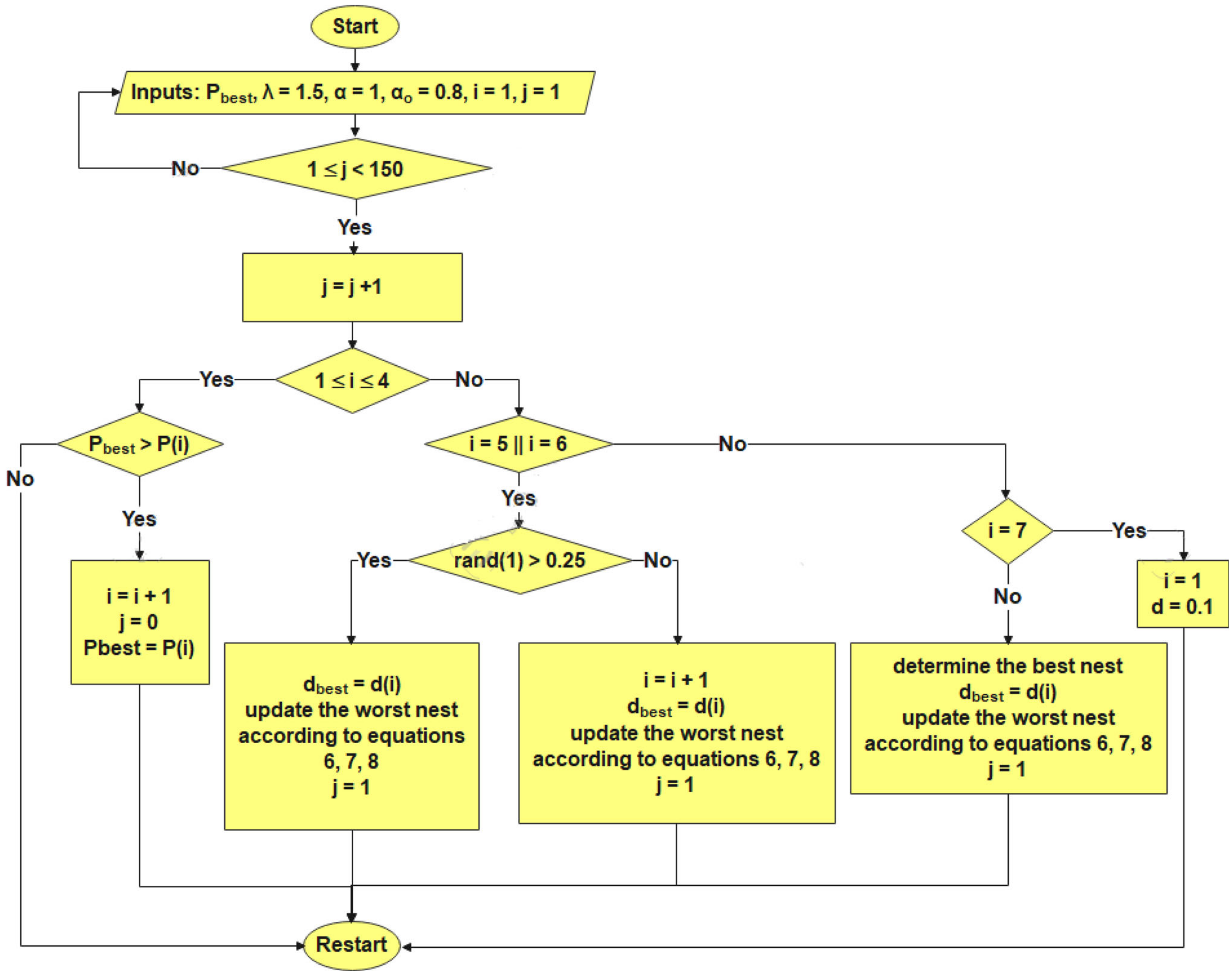


Fig. 7 CSA flowchart for MPP

spiraling around the prey and go to the surface to attack it. This algorithm divided into two parts mathematically, encircling prey shown in Fig. 9, and bubble-net attacking shown in Fig. 10. The mathematical model of encircling prey obtained in Eqs. 14: 17. The mathematical model of bubble-net attacking is obtained in Eq. 18. The flowchart of WOA-based MPPT is shown in Fig. 11 [31, 32].

$$D = |CX_B(t) - X(t)| \tag{14}$$

$$X(t+1) = X_B(t) - AD \tag{15}$$

$$A = 2ar - a \tag{16}$$

$$C = 2r \tag{17}$$

$$X(t+1) = D'.e^{bl}.\cos(2\pi l) + X_p(t) \quad P \geq 0.5 \tag{18}$$

where ***D***: distance between whales and prey, t: iteration's order, ***X(t)***: the position of the whale. (The old duty cycle of the encircling prey), *A, C:* coefficients, $X_B(t)$: the current best solution's position, *a:* drops from 2 to 0 as the number of iterations increases, *r, l:* random vectors in the [0,1] range, $X(t+1)$: the whale position vector of the next iteration. (The updated duty cycle), *b:* constant, $X_p(t)$:the position of the whale.(The old duty cycle of the bubble-net attacking), No. of whales (no. of iterations = 100).

Figure 11 shows the flowchart for WOA for MPPT. Number of duty cycles randomly nominated. The PV current and voltage measured to estimate PV power. This algorithm divided into two parts mathematically, encircling prey with probability which is higher than 0.5, and bubble-net attacking with probability which is lower than 0.5. If the probability is higher than 0.5, the duty cycle updated according to Eqs. 14–17. If not, the duty cycle updated according to Eqs. 14 and 16–18.

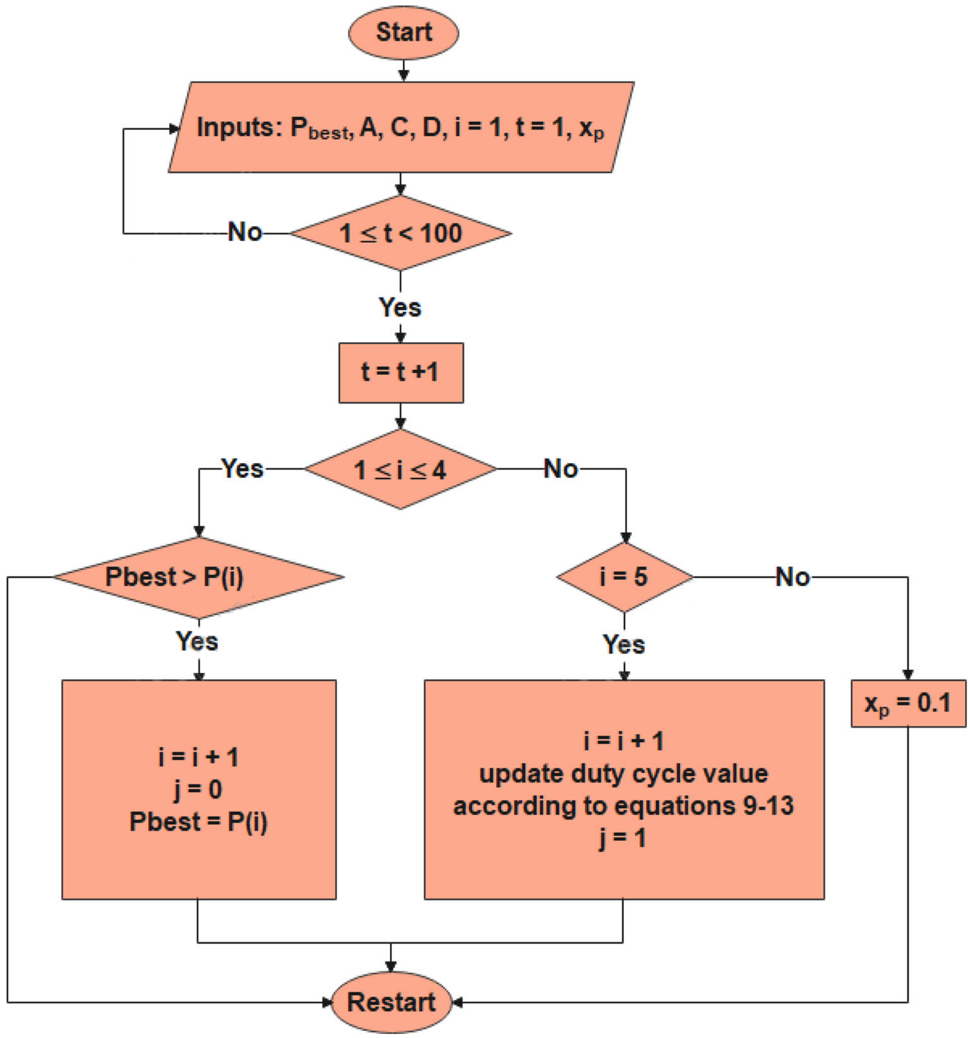


Fig. 8 GWO MPPT flowchart

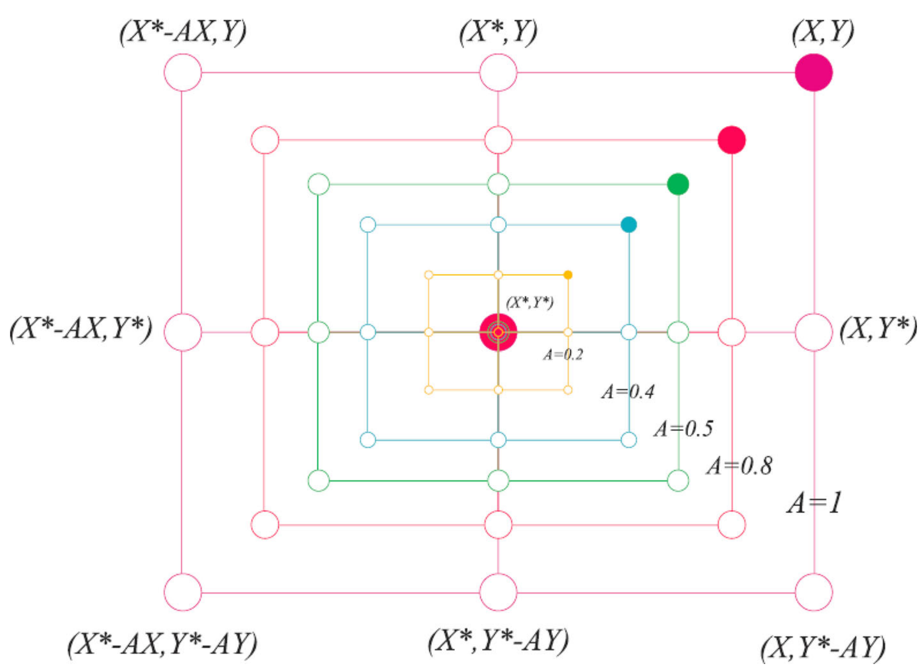


Fig. 9 Encircling prey of WOA in 2D motion [32]

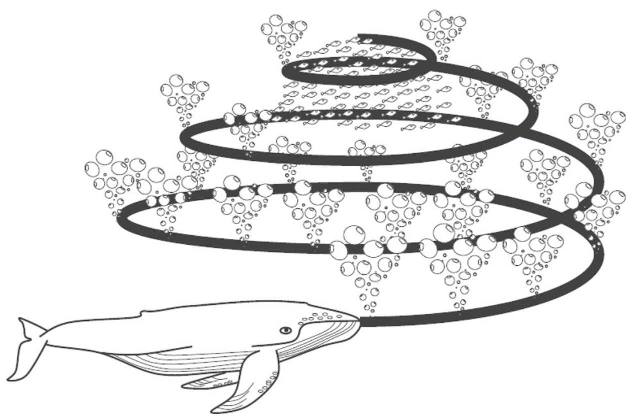


Fig. 10 Bubble-net attacking of WOA [32]

3.6 The Differences, Similarities, Advantages and Disadvantages Between the Techniques Mentioned

As shown in Table 2, the differences, similarities, advantages and disadvantages between the techniques INC, PSO, CSA, GWO and WOA are illustrated.

4 Numerical Simulation and Experimental Results

The MATLAB Software Package has been used to simulate a solar power plant consisting of four solar cells, 250W each. Practically, an experiment has been conducted using two solar cells, 5W each. The simulated results have been illustrated in Sect. 4.1; however, the experimental results have been illustrated in Sect. 4.2.

4.1 Simulated Results Using Numerical Simulation Method

Figure 12 presents the design of the PV equivalent circuit with MPPT techniques. As shown in Fig. 13, solar irradiances of 0.5 kw/m^2, 1 kw/m^2, 0.8 kw/m^2, and 1 kw/m^2 provided by four PV modules connected in series. The temperature is 25 °C for each cell. The PV module used in the system is Tata Power Solar Systems TP250MBZ. Open-circuit voltage is 36.8 v, short-circuit current is 8.83 A, voltage at maximum power point is 30 v, and current at the maximum power point is 8.3 A. The boost converter used in the design has the elements $L = 1.478$ mH, the input capacitor is 10 µf, the output capacitor is 0.4676 mf, and the load resistance is 53 ohms.

Fig. 11 WOA-based MPPT

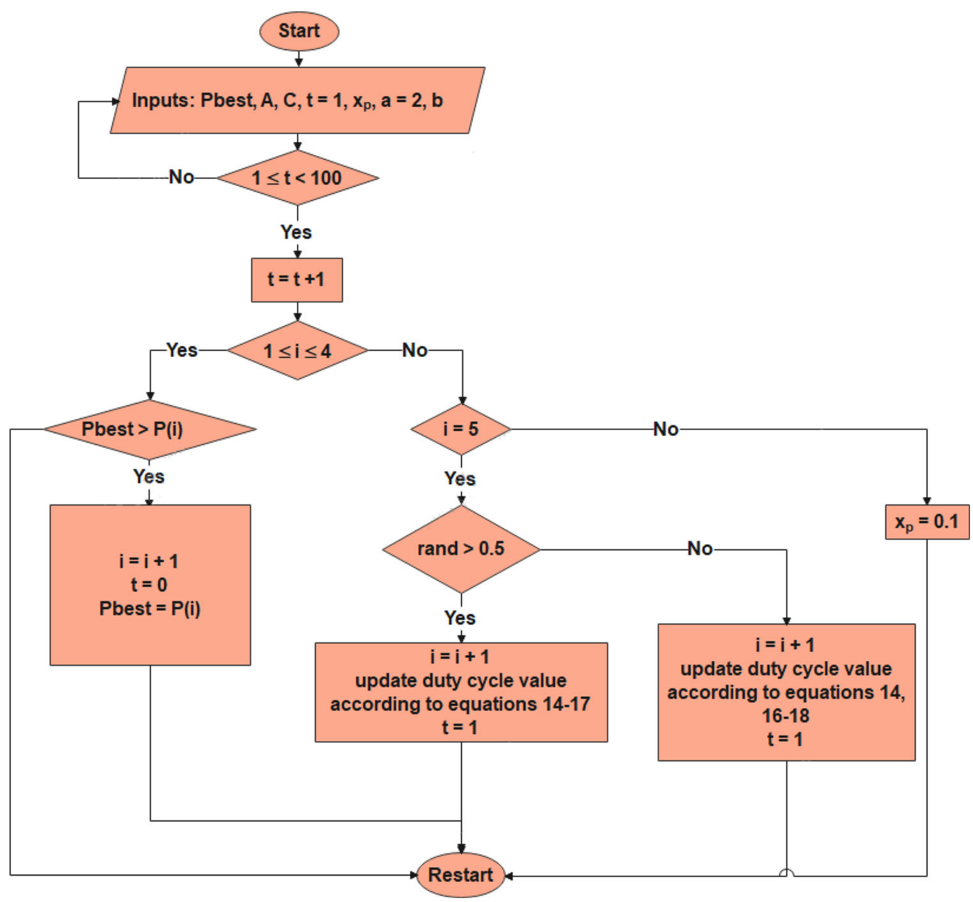


Table 2 The differences, similarities, advantages, and disadvantages between the techniques INC, PSO, CSA, GWO, and WOA are illustrated

Techniques	INC	PSO	CSA	GWO	WOA
Differences	It is not a metaheuristic method	Different from CSA in implementation	Different from PSO in implementation	Different from WOA in implementation	Different from GWO in implementation
Similarities	It is not depending on particles, as the same of GWO and WOA	Depends on particles, as the same in CSA	Depends on particles, as the same in PSO	It is not depending on particles, as the same of INC and WOA	It is not depending on particles, as the same of GWO and INC
Advantages	Design is easier compared with metaheuristic techniques, lower implementation cost	Moderate implementation cost, moderate design complexity	Moderate implementation cost, moderate design complexity. High efficiency in locating the MPP of PV	High tracking speed and efficiency of MPP of PV	Avoid premature convergence by tracking the local peak and trapping it instead of the global peak in PSCs Dealing with a nonlinear problem, tracking global peak in PSC, better convergence speed, flexibility, less involvement
Disadvantages	Low efficiency in tracking MPP of PV	High oscillations about MPP of PV during tracking	High oscillations about MPP of PV during tracking	Complex design, high implementation cost. High oscillations about MPP of PV during tracking in PSCS	Complex design, high implementation cost

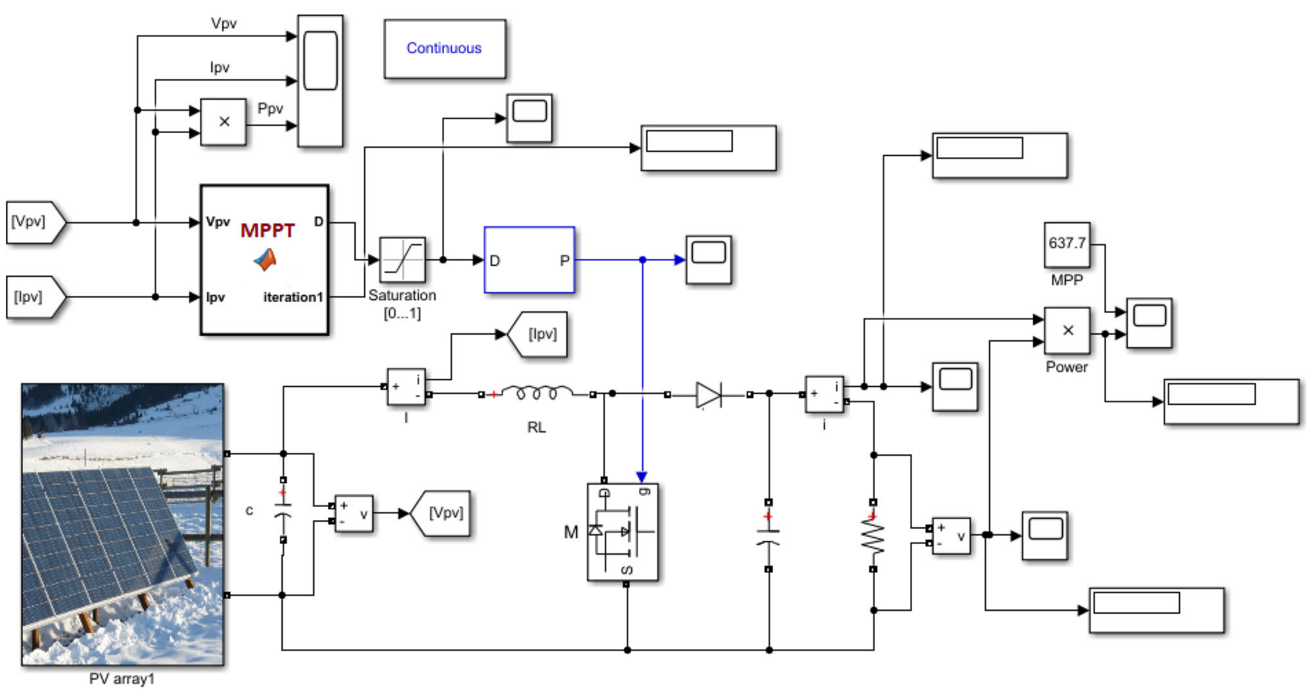


Fig. 12 The design of the PV equivalent circuit with MPPT techniques

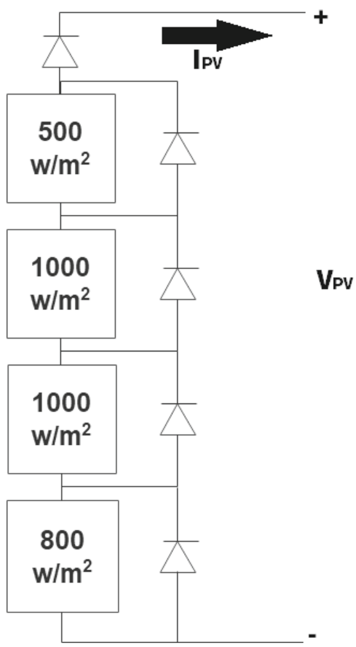


Fig. 13 PV modules with different irradiances

The sampling time of DC to DC PWM generator is zero and the switching frequency is 50 KHZ.

Figure 14 depicts PV output power without the use of MPPT techniques, indicating that it failed to follow the MPP. Table 3 shows the photovoltaic system's voltage, current, and power experiment results using INC, PSO, CSA, GWO and WOA. The measurements taken at 2 secs.

As shown in Table 3, the current and the voltage of PV are measured using virtual ammeter and voltameter from the measurement library in the MATLAB software package. So, the power is calculated by multiplying the current with the voltage. The efficiency is calculating by dividing the calculated power by the MPP computed from Simulation. Tracking speed, accuracy and steady-state oscillations are obtained from the signals shown on the MATLAB virtual scope. For, the incremental conductance has the minimum efficiency in tracking the maximum PowerPoint of the photovoltaic system. Form simulated results, the advantages of the INC method are simple and does not need prohibitive cost in implementation compared with other techniques. However, it has a disadvantage in that it oscillates lot around the maximum power point and has lot of power tracking inaccuracy when changing quickly under partially shadowed situations. The output PV power using INC compared with MPP is shown in Fig. 15. For PSO, despite the high tracking efficiency of using it in tracking MPP is that it has high oscillation and needs much more time to rest around the MPP of the PV. The output PV power using PSO compared with MPP is shown in Fig. 16. For CSA, it considered an improvement of PSO. Thus, when compared to the, PSO tracking time was reduced by 60% with usage of CSA, but it failed to recover the steady-state oscillation problem. The output PV power using CSA compared with MPP is shown in Fig. 17. For GWO, the tracking time improved by 75% compared with CSA, also the oscillation about of PV MPP improved. The output PV power using GWO compared with MPP is shown in Fig. 18. For WOA, it is slightly more accurate than GWO. The output PV power using WOA compared with MPP is shown in Fig. 19. The main difference between GWO and WOA is the hunting method. The drawbacks of GWO and WOA are needing prohibitive costs for implementation, and they considered complicated optimization methods.

4.2 Experimental Results and Evaluation

For the implementation, an ARDUINO UNO has been used as a microcontroller, two (ACS712) sensors are used for measuring input and output PV currents and input and output PV voltages. So, the input and output PV powers can be calculated by multiplying the voltage measurement with the current measurement. The MATLAB software is interfaced with ARDUINO using ARDUINO package to store the power signals and present them using MATLAB virtual scope. The PV module power used in the system is 5 watts. Open-circuit voltage is 21.6 v, short-circuit current is 0.36 A, voltage at maximum power point is 17.5 v, and current at the maximum power point is 0.29 A. The boost converter used in the design has the elements $L = 1$ mH, the input capacitor is 10 μf, the output capacitor is 470 μf, and the load resistance is 47 ohms. The sampling time of DC to DC PWM generator is zero and the switching frequency is 50KHZ. The prototype of the PV system and boost converter circuit has been designed as shown in Fig. 20. The system connection is shown in Fig. 21.

As shown in Table 4, under partially shaded conditions, the PV system is composed of two series solar cells with irradiances of 750–500 W/m^2. The temperature is 25 Celsius degrees for each cell. Using PSO for tacking the MPP, the power executed is 6.24 W at 0.35 s. Therefore, the efficiency achieved 98.365% as shown in Fig. 22. Using CSA for tacking the MPP, the power executed is 6.32 W at 0.72 s. Therefore, the efficiency achieved is 99.626% as shown in Fig. 23. Using GWO for tacking the MPP, the power executed is 6.332 W at 0.43 s. Therefore, the efficiency achieved is 99.815% as shown in Fig. 24. Using WOA for tacking the MPP, the power executed is 6.343 W at 0.323 s. Therefore, the efficiency achieved is 99.988% as shown in Fig. 25.

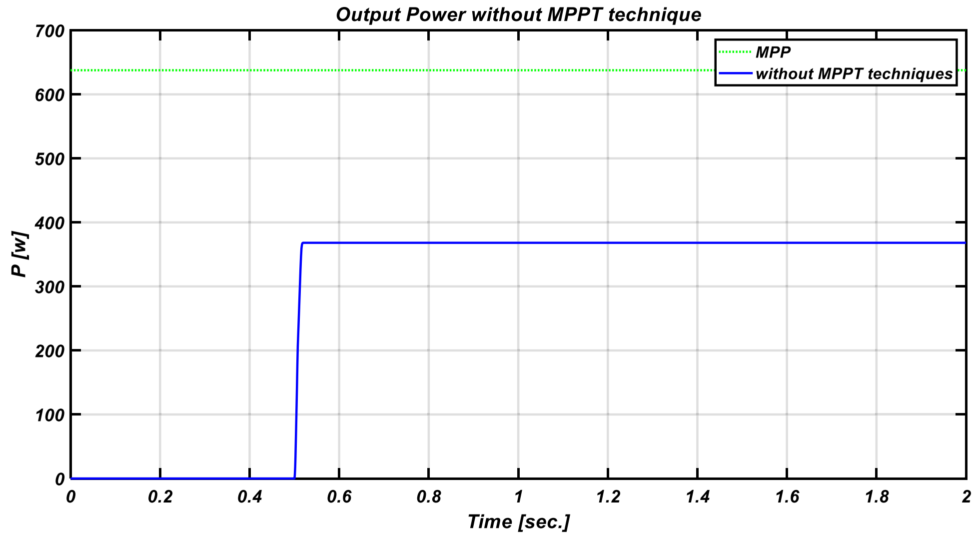


Fig. 14 Pout without using MPPT techniques

Table 3 Comparative results of PV using different techniques (INC, PSO, CSA, GWO, and WOA)

Techniques	INC	PSO	CSA	GWO	WOA
I (A)	3.093	3.469	3.467	3.465	3.466
V (v)	163.9	183.8	183.8	183.6	183.7
P (w)	507.1	636.2	636.6	636.8	636.9
Efficiency %	79.42	99.64	99.7	99.73	99.75
Tracking time (sec.)	Inf	1.8	0.7	0.17	0.15
Tracking speed	Zero	LOW	LOW	HIGH	HIGH
Tracking accuracy	LOW	HIGH	HIGH	HIGH	HIGH
Steady-state oscillations	HIGH	HIGH	HIGH	LOW	LOW

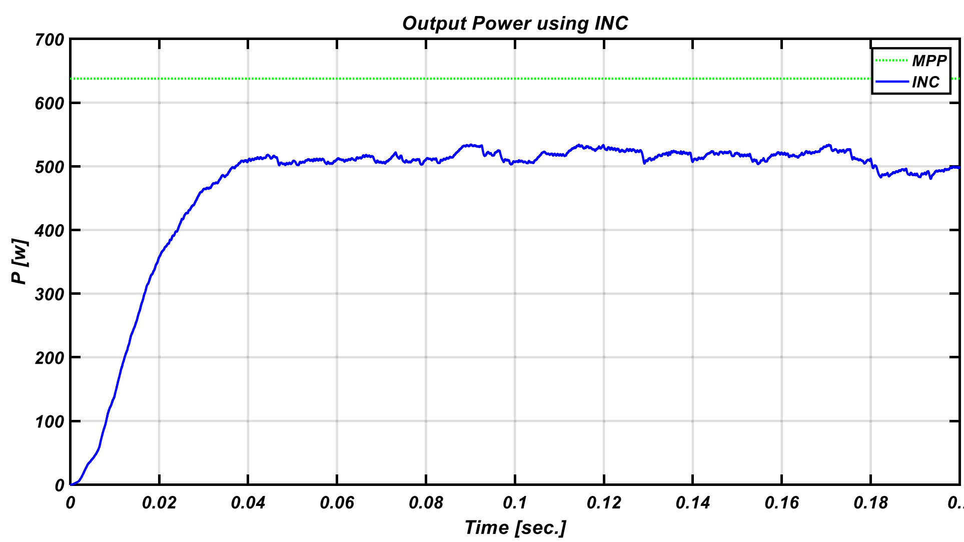


Fig. 15 Pout using INC technique

Fig. 16 Pout using PSO algorithm

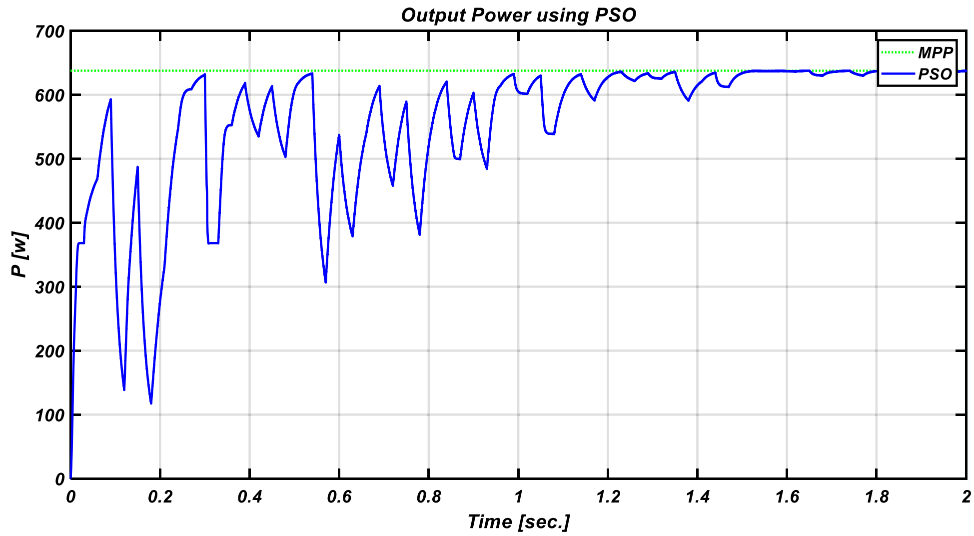


Fig. 17 Pout using CSA

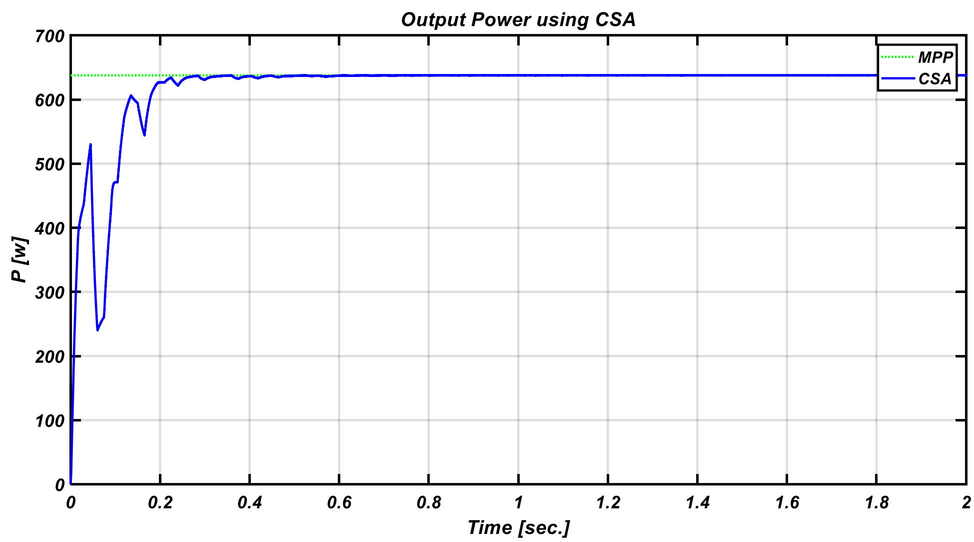


Fig. 18 Pout using GWO

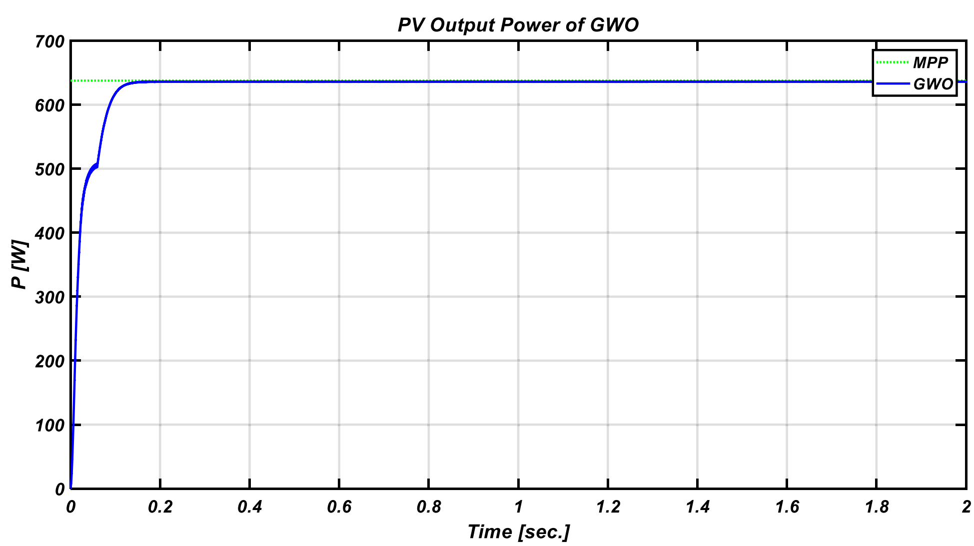
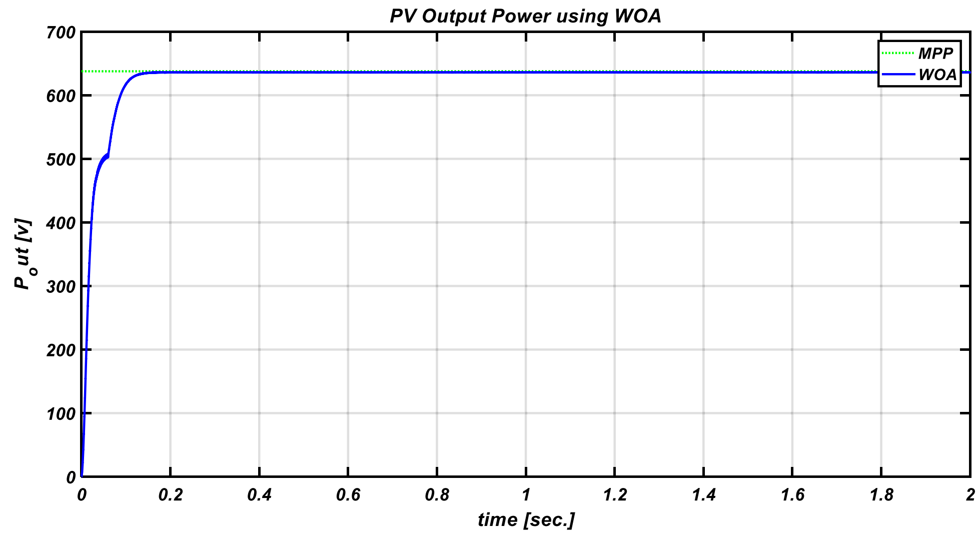


Fig. 19 Pout using WOA



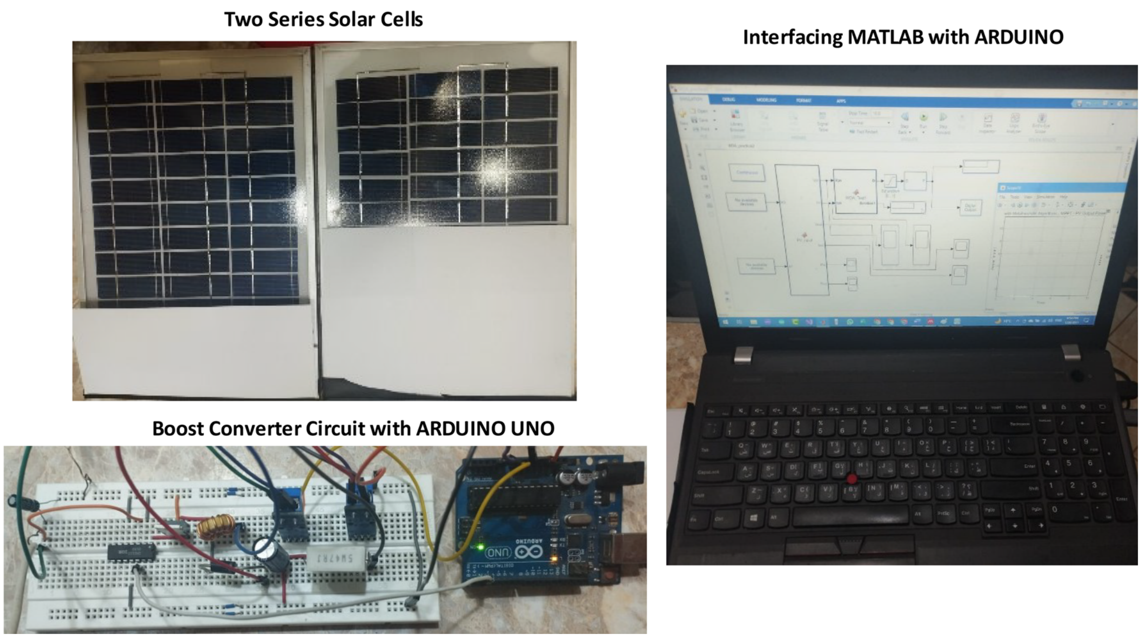


Fig. 20 Experimental setup for the developed PV system

5 Comparing Simulated Results with Previous Studies

In the literature review [33], WOA used for tracking PV systems under typical and partial shaded situations. Under normal conditions, the PV system is composed of four series solar arrays with irradiances of 1000–1000–1000–1000 W/m^2. Figure 26 shows the global point of MPP is 982.7 W. Using WOA for tacking the MPP, the power executed is 982 W at 0.135 s. Therefore, the efficiency achieved 99.926% and improved by 0.026%, and the tracking speed improved 32.5% over the results of the literature review [33]. Under partially shaded conditions, the PV system is composed of four series solar arrays with irradiances of 500–1000–1000–1000 W/m^2. Figure 27 shows the global point of MPP is 696.95 W. Using WOA for tacking the MPP, the power executed is 696.6 W at 0.09 s. Therefore, the efficiency achieved 99.926% and improved by 0.25%, and the tracking speed improved 50% over the results of the literature review [33]. The PV module used in the simulation experiment is VIKRAM SOLAR ELDORA VSP.60.250. Open-circuit voltage is 37.8 v, short-circuit current is 8.8 A, voltage at maximum power point is 30.6 v,

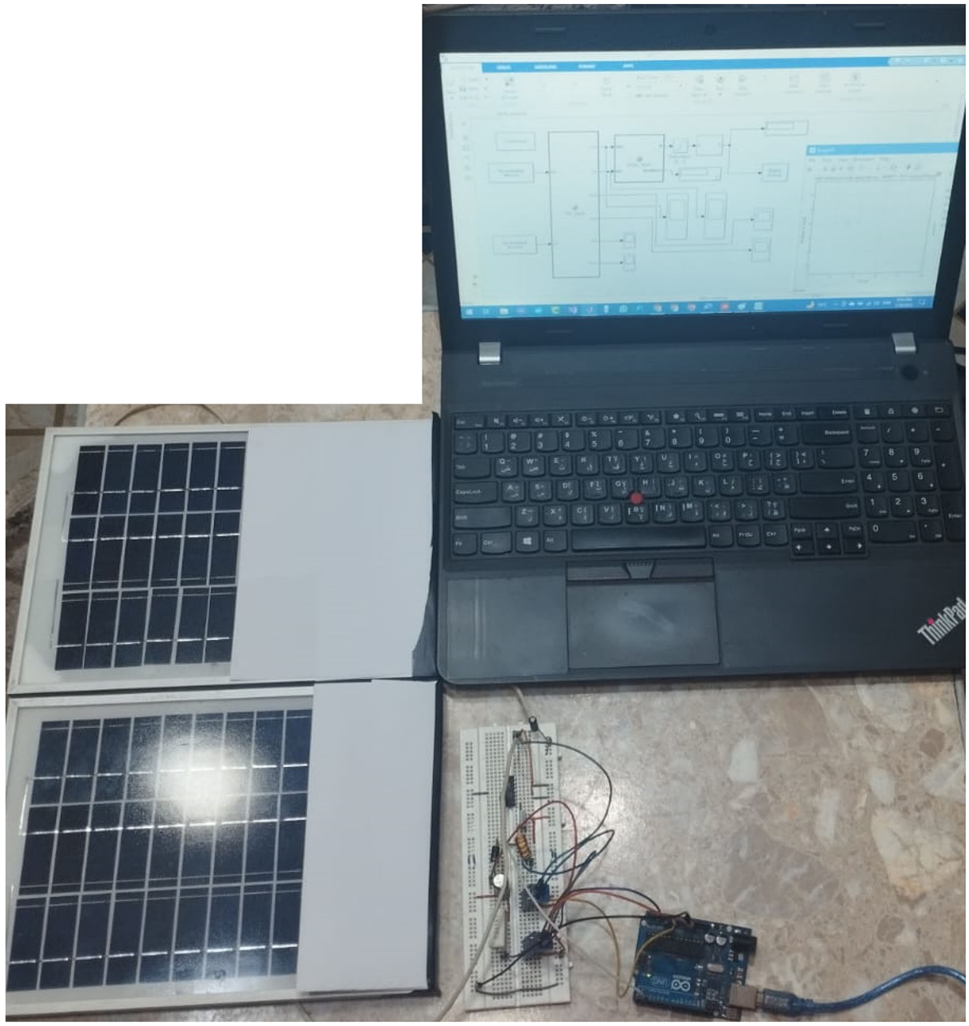


Fig. 21 The system connection

Table 4 Experimental results of PV using different techniques (PSO, CSA, GWO, WOA)

Techniques	PSO	CSA	GWO	WOA
P (w)	6.24	6.32	6.332	6.343
Efficiency %	98.365%	99.626%	99.815%	99.988%
Tracking time (s)	0.35	0.72	0.43	0.323
Tracking speed	Moderate	LOW	Moderate	HIGH
Maximum overshot	LOW	LOW	HIGH	LOW
Transient oscillations	Moderate	HIGH	Moderate	LOW

and current at the maximum power point is 8.2 A. The boost converter used in the design has the elements $L = 1.478$ mH, the input capacitor is 10 μf, the output capacitor is 0.4676 mf, and the load resistance is 53 ohms. Table 5 illustrates the comparison between the literature review [33]and the current study on the efficiency and tracking speed of MPPT using WOA.

6 Conclusion

The paper's strategy focused on proposing a revolutionary nanoparticle WOA algorithm to help avoid premature convergence by tracking the local peak and trapping it instead of the global peak in PSCs. Dealing with a nonlinear problem, tracking global peak in PSC, better convergence speed, flexibility, less involvement, and ease of implementation are all

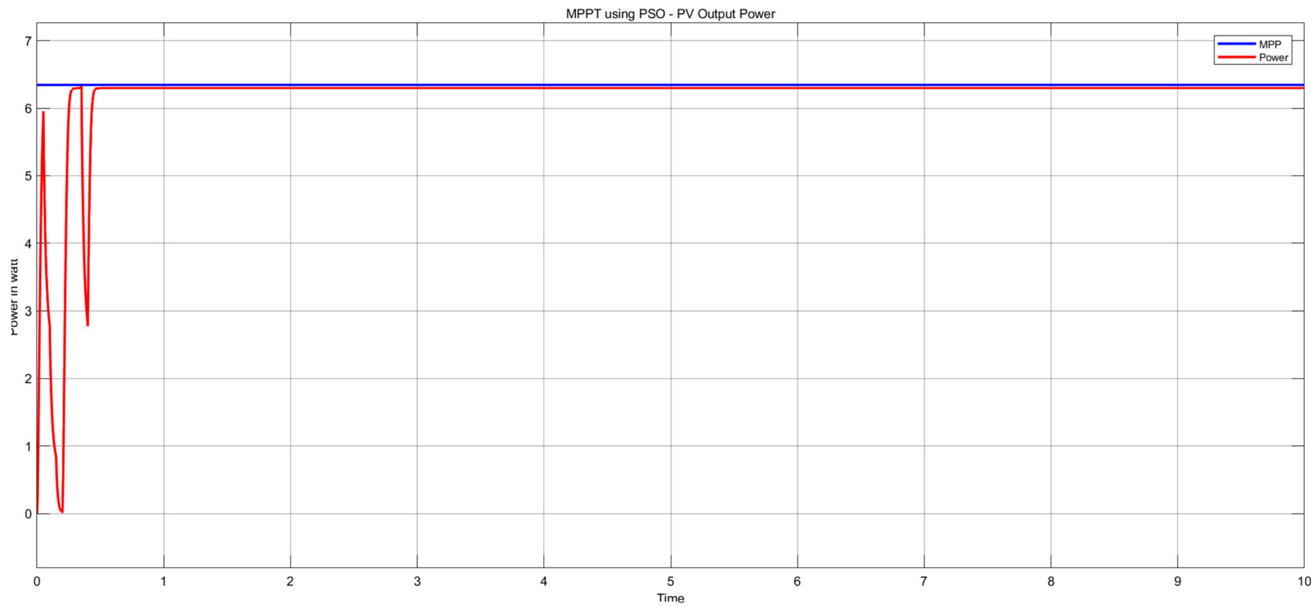


Fig. 22 MPPT using PSO—output power compared to MPP

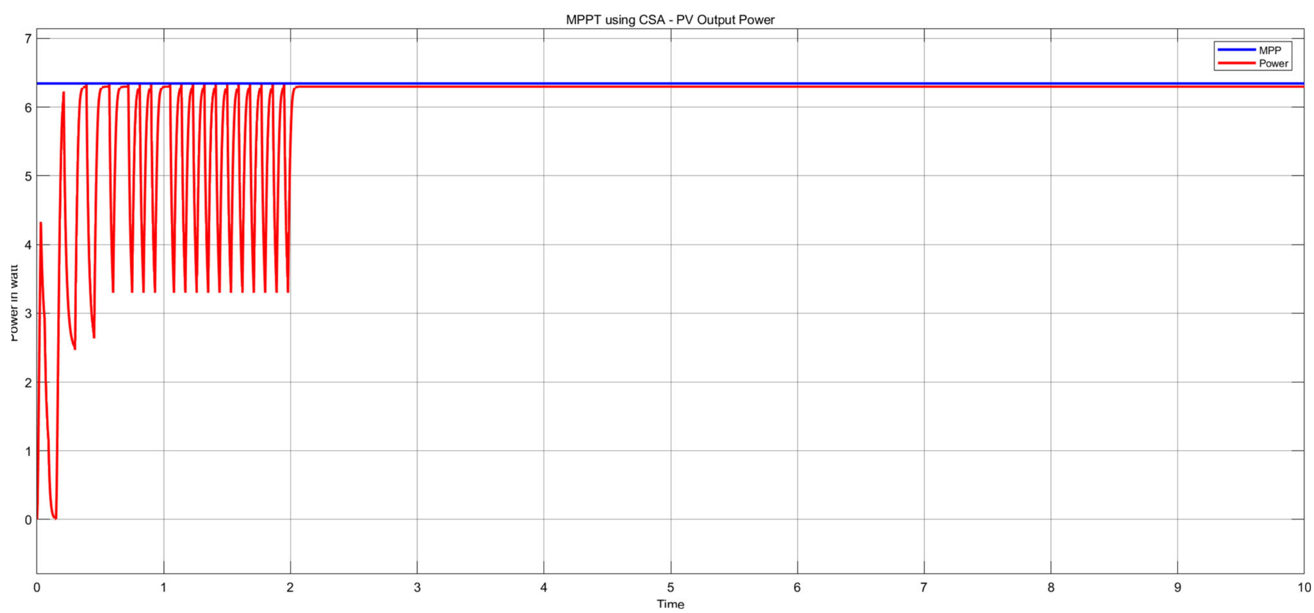


Fig. 23 MPPT using CSA—output power compared to MPP

advantages of the WOA method. A comparison of four significant methodologies for determining the maximum power of a series-connected PV array verified the efficiency of using the WOA method. The techniques used in this comparison are INC, PSO, CSA, GWO, and WOA using a vast number of iterations (one hundred iterations). The findings of the experiments showed that using metaheuristics approaches to track the MPP of a PV system is more efficient than using conventional methods such as INC, which tracked the MPP with a low efficiency (79.42%) when compared to metaheuristic algorithms. Despite its excellent tracking efficiency (99.64%) when used to track MPP, PSO has a significant oscillation and requires much more time (1.8 s) to rest around the PV's MPP. It deemed a PSO improvement by CSA. When compared to PSO, CSA improves tracking efficiency (99.7%) and reduces

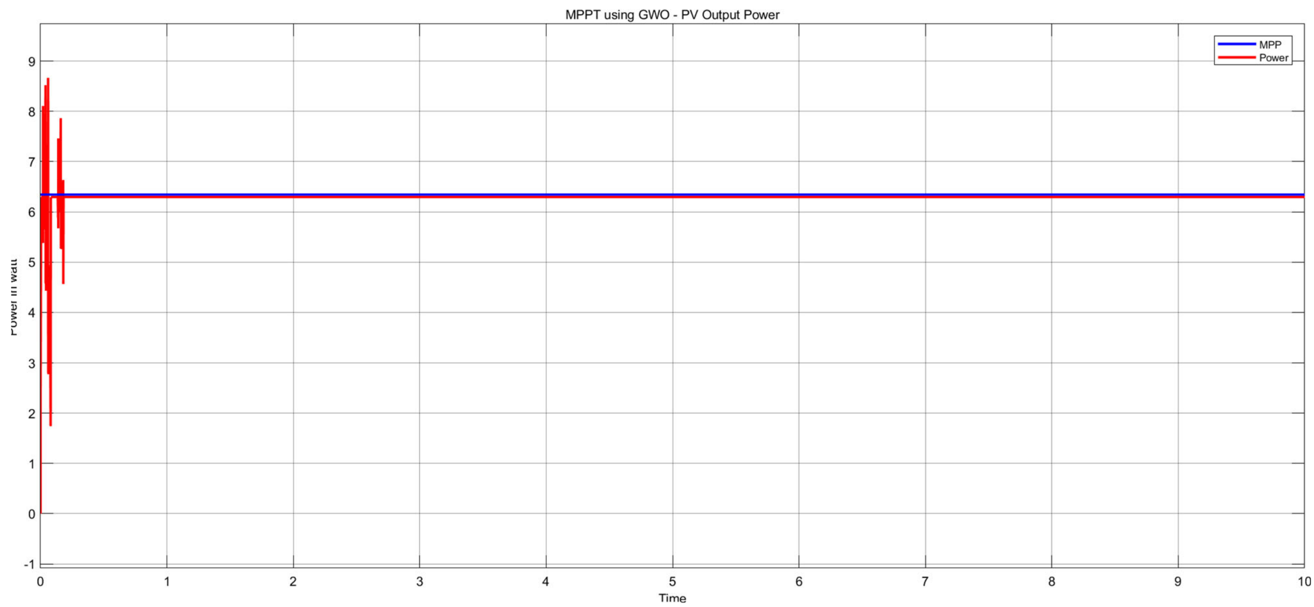


Fig. 24 MPPT using GWO—output power compared to MPP

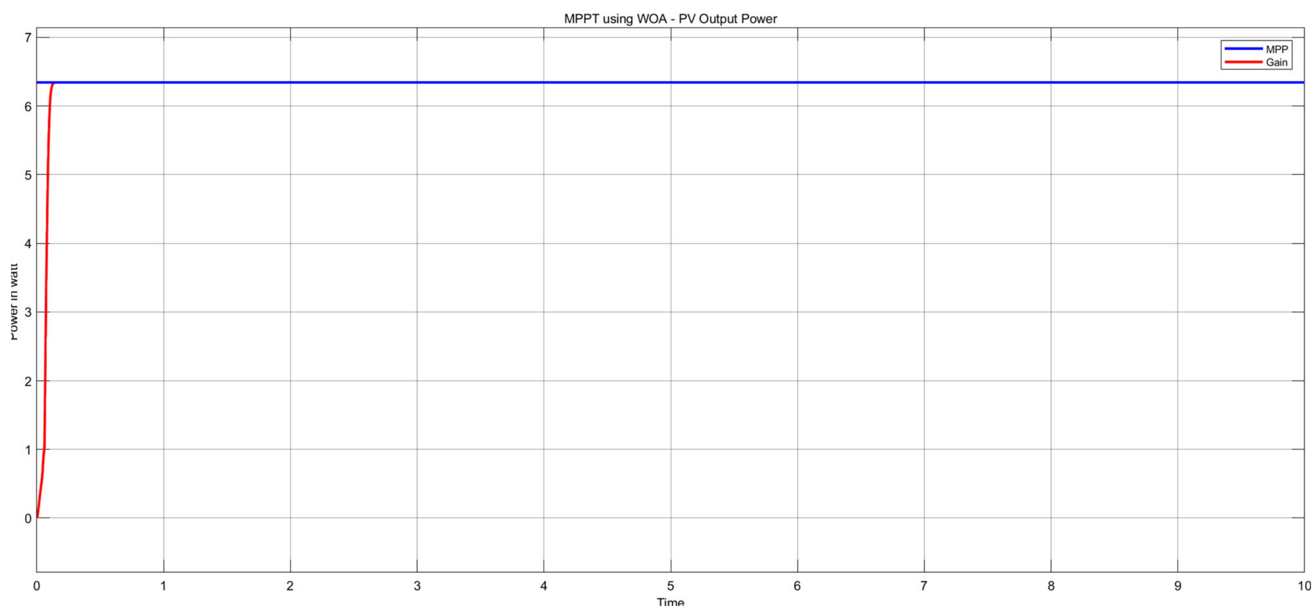


Fig. 25 MPPT using WOA—output power compared to MPP

tracking time (0.7 s) by 60%, but it fails to recover the steady-state oscillation problem. When compared to CSA, GWO has a tracking efficiency of 99.73% and a tracking time of 0.17 s, which is 75% faster. When compared to GWO, WOA is slightly more accurate. The tracking efficiency (99.75%) and tracking time (0.15 s) are both enhanced by 11%. The fundamental distinction between GWO and WOA is the way of hunting. The main disadvantages of utilizing WOA to track MPP are the high implementation costs and the fact that it is a sophisticated optimization method. As a result, future work will focus on proposing a hybrid technique (GWO-WOA) for MPPT and examining the reaction of the proposed algorithm in an abrupt and gradual change in solar irradiances and shading patterns with time.

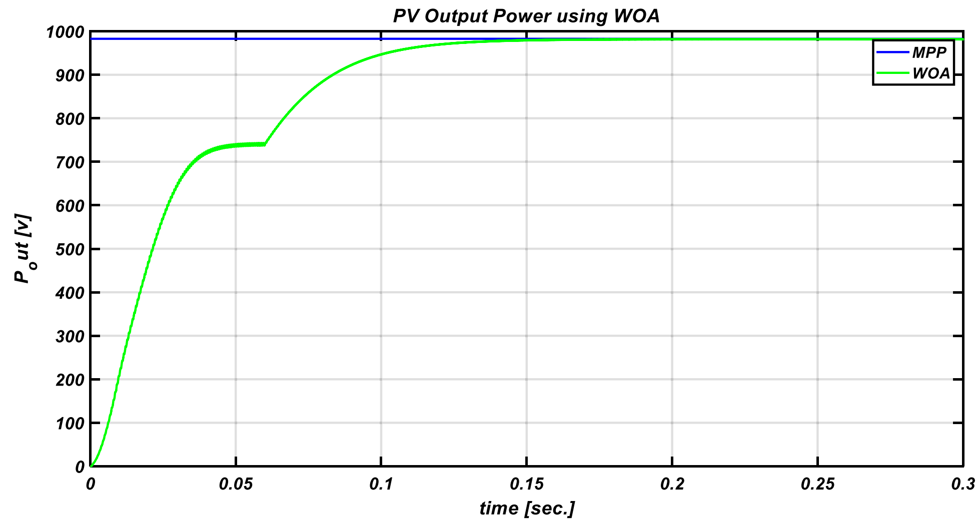


Fig. 26 Output PV power of literature review [33] using WOA

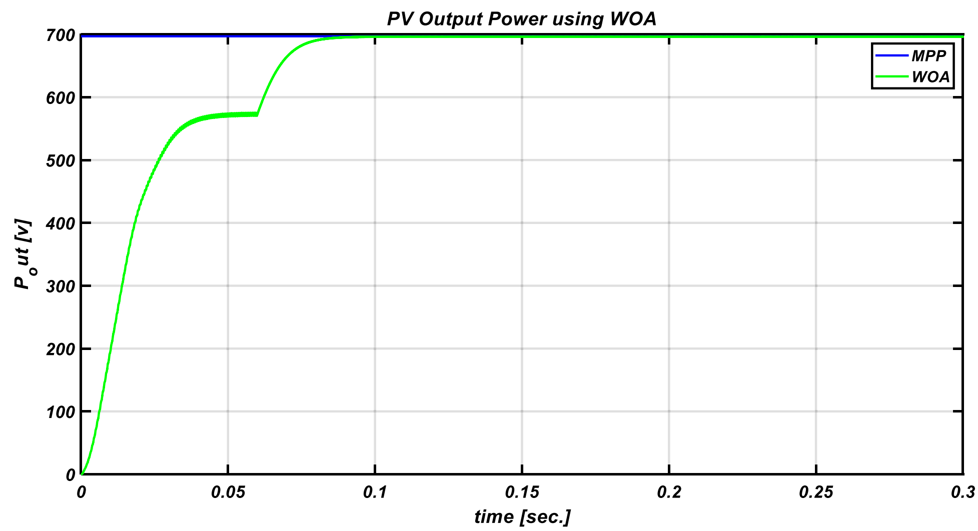


Fig. 27 Output PV power of current study using WOA under partially shaded conditions

Table 5 Compare simulated results with previous studies using WOA

Factors	Literature review [33]	Current study
Efficiency % Under normal condition	99.9	99.926
Tracking Time (s) Under normal condition	0.2	0.135
Efficiency % Under the partially shaded condition	99.7	99.95
Tracking time (s) Under the partially shaded condition	0.2	0.09

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Declarations

Conflict of interest The authors report no conflicts of interest. The authors alone are responsible for the content and writing of this research.

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