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RESEARCH ARTICLE - ENGINEERING

Maximizing Energy Output of Photovoltaic Systems: Hybrid PSO-GWO-CS Optimization Approach

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Abstract

Photovoltaic (PV) systems suffer from partial shade and nonuniform irradiance conditions. Meanwhile, each PV module has a bypass shunt diode (BSD) to prevent hotspots. BSD also causes a series of a peak in the power-voltage characteristics of the PV array, trapping traditional maximum Power Point Tracking (MPPT) methods in local peaks. This study aims to address these challenges by combining cuckoo search (CS), gray wolf optimization (GWO), and particle swarm optimization (PSO) to enhance MPPT performance. The results compared the yield power by Tracking the MPP using only GWO, CS, or PSO MPPT techniques and combining them. Results show that in four cases: in case 1) Uniform Irradiation in three patterns (High, Medium, and Low), In case 2) Fixed Nonuniform Irradiation, While In case 3) Slow Dynamic Nonuniform Irradiation and case 4)) Fast Dynamic nonuniform irradiation. The efficiency (PSO + CS) 97.86%, (PSO + GWO) 97.74%, and (GWO + CS) 98.55% were the highest performers in the case 1 results in (high, medium, and low), respectively. In Case 2, the efficiency (GWO + CS) is 98.62%, and it operates more effectively under fixed nonuniform irradiance. It has the highest efficiency in both Cases 3 and 4, even though its respective PSO + GWO efficiencies are 97.45% and 97.26%. Based on these results, a hybrid mode of merging algorithms based on weather radiation conditions is proposed.

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Keywords: Hybrid Optimization; Maximum Power Point Tracking; Photovoltaic System; Partial Shading Condition; Cuckoo Search; Grey Wolf Optimization.

1. Introduction

Electricity generation does have the potential to provide the necessary electricity needs using both traditional and unconventional sources. Coal, oil, fossil fuels, and natural gas are traditional resources. Nonetheless, the total cost of power is fast increasing due to a scarcity of supplies and rising transportation costs [1]. On the other side, the global environment has suffered due to the use of fossil fuels. Several researchers are turning to unconventional resources such as solar, wind, tidal, and ocean energy to mitigate difficulties and lower system costs. For example, solar photovoltaic (PV) energy is critical in incorporating the power needed. The cost of a photovoltaic (PV) system is continually dropping as improved technology advances [2]. The PV system generates power by tracking solar energy. However, because of passing clouds, building shadows, and partial shading conditions (PSC), the PV system confronts several obstacles in tracking the maximum power [3].

Hill-Climbing(HC) [4], Incremental Conductance(INC) [5], and Perturb & Observe (P&O) [6] are examples of conventional algorithms [7]. Under uniform conditions, these approaches can track the maximum power. However, the maximum peak power (MPP) under PSC exhibits some oscillations. In this case, multiple peak power points (MPPP) are formed under PSC, with only one peak for a uniform state [8].

Many articles proposed MPPT algorithms and other solutions to find fundamental global MPP points among other local MPPs [9, 10]. As a complement to typical approaches for partial shading photovoltaic (PV) systems, soft computing (SC) techniques have gained popularity due to their capacity to resolve challenging non-linearity issues. As a result, numerous optimization algorithms have been put forth, including Artificial Bee Colony (ABC) [11], Ant Colony Optimization (ACO) [12], Glow-Worm Swarm Optimization (GSO) [13], Whale Optimization Algorithm (WOA) [14], etc. The multi-peak GMPPT problem can be solved using these algorithms, which also offer high efficiency, but each algorithm's performance can be improved further. Recent hybrid approaches combine traditional and intelligent algorithms, i.e., P&O with Neural Network (P&O-ANN) [15], Grey Wolf with P&O (GWO-P&O) [16], Particle Swarm Optimization with P&O (PSO-P&O) [17], or

Nomenclature & Symbols

MPPT	Maximum PowerPoint Tracking	A	Algorithm
MPP	Maximum Peak Power	P_{max}	Maximum Power (W)
MPPP	Multiple Peak PowerPoints	T_r	Rise Time (ms)
PV	Photovoltaic	OS	Overshoot (%)
PSO	Particle Swarm Optimization	η	Efficiency (%)
GWO	Grey Wolf Optimization	US	Undershoot (%)
CS	Cuckoo Search	PS	Pre-Shoot (%)
GMPP	Global Maximum PowerPoint	r_1, r_2	Random Variables
PSC	Partial Shading Condition	v_i	Speed of a Particle
INC	Incremental Conductance	K	Iteration Number
HC	Hill-Climbing	w	Inertia Weight
P&O	Perturb & Observe	c_1	Cognitive Coefficient
SC	Soft Computing	c_2	Asocial Coefficient
ABC	Artificial Bee Colony	$P_{best,i}$	Best Position
ACO	Ant Colony Optimization	$G_{best,i}$	Best Particles Stored
GSO	Glow-Worm Swarm Optimization	A, and C	The Same Coefficient Vectors
WOA	Whale Optimization Algorithm	$\vec{a}$	Elements are Linearly Lowered
P&O-ANN	P&O with Neural Network	SNFI	Slow Dynamic Nonuniform Irradiance
GWO-P&O	Grey Wolf with P&O	FDNI	Fast Dynamic Nonuniform Irradiance
PSO-P&O	Particle Swarm Optimization with P&O		
SA-PSO	Simulated Annealing with Particle Swarm Optimization		

mixing two or more intelligence algorithms such as Simulated Annealing with Particle Swarm Optimization (SA-PSO) [18], Fish Swarm with PSO [19], PSO – I GWO [20], GWO–PSO [21]. As a result, the current work proposes a comparison of hybrid methods (PSO+GWO), (GWO+CS), and (PSO+CS) by evaluating the PV power efficiency and, maximum power, Over Shoot, undershoot, pre-shoot and rise time of such approaches under uniform and nonuniform-irradiance-where-the-average-is taken for all method used of such approaches under uniform and nonuniform irradiance. The selection of these methods was based on the results obtained in the [22] where the best method for high irradiance was PSO, the best method for medium irradiance was GWO, and the best method for low irradiance was CS. MATLAB/SIMULINK is used to simulate and assess performance by estimating each technique's efficiency while considering different shading patterns (SPs). The principal findings of this study are 1) a comparison of three different hybrid methods (PSO+GWO, GWO+CS, and PSO+CS) for improving algorithm efficiency under PSC; and (2) further analysis of the algorithms PSO, GWO, and CS for PV systems providing different results for future studies and the development of physical models. Part 2 describes the strategy, while Section 3 describes the proposed hybrid model. Part 4 presents the hybrid model's results, description, and comparison with competing techniques. Section 5 finally provides the conclusion.

2. Methodology

This article employs the Particle Swarm Algorithm, Grey Wolf Algorithm, and Cuckoo Search Algorithm to obtain hybrid methods. These hybrid methods (PSO-GWO), (PSO-CS), and (GWO-CS) are compared to the three trend bioinspired methods to address three crucial concerns. The first question is which approach performs best in low, medium, and high irradiation conditions. Then, the second question is which approach adjusts to rapid changes in uniform irradiance, and the last question is which method extracts the most power under rapid nonuniform irradiance changes. To answer these questions, three bio-inspired algorithms will be compared to hybrid approaches under uniform and nonuniform irradiance conditions.

Fig. 1 research approach summarizes the research methodology. In uniform irradiance matter, three levels of irradiance, 300, 500, and 900 W/m^3, will be applied consistently to three panels in a string. In the following steps, each panel will have a varied irradiance level applied to generate multi-maximum points. Finally, a changing irradiance level will be used to investigate the irradiance effect and response time.

3. Modeling Hybrid Optimization

Algorithms proposed by the bio-inspired algorithms PSO, CS, and GWO are based on social interaction patterns. Nature-inspired algorithms are another name for these techniques.

3.1. Particle swarm optimization

Eberhart and Kennedy created the algorithm for particle swarm optimization (PSO). The concept was generated in 1995 due to observations of fish schooling and bird flocking [23, 24]. PSO is a technique for finding the optimal answer for a point or area in an n-dimensional environment. When employing the PSO approach, fewer particles or agents were used during the search step. During their search process, these particles or agents can potentially communicate information with one another. Each particle in the search process must abide by two principles. First, each particle must follow the best-performing particle, which is determined. Second, each particle aims for the best particle position in the following search and direction. These two rules are followed for every particle in the search process until an optimal or close solution is identified. Eq (1) and Eq (2) describe the PSO approach, respectively. The velocity should be updated using Eq (1), while the location is updated using Eq (2).

$$v_i(k+1) = wv_i(k) + c_1r_1(P_{best,i} - x_i(k)) + c_2r_2(G_{best,i} - x_i(k)) \quad (1)$$

$$x_i(k+1) = x_i(k) + v_i(k+1) \quad (2)$$

Where r_1 and r_2 are random variables evenly distributed between (0,1), v_i is the speed of a particle of i, x_i is its posit, location,K marks the iteration number, w is the inertia weight, c_1 is the cognitive coefficient and $c_2$is the asocial coefficient. The best position saved by n particles was denoted by $P_{best,i}$, and the best particles stored were denoted by $G_{best,i}$.The MPPT application technique based on the PSO algorithm is depicted in Fig. 2a.

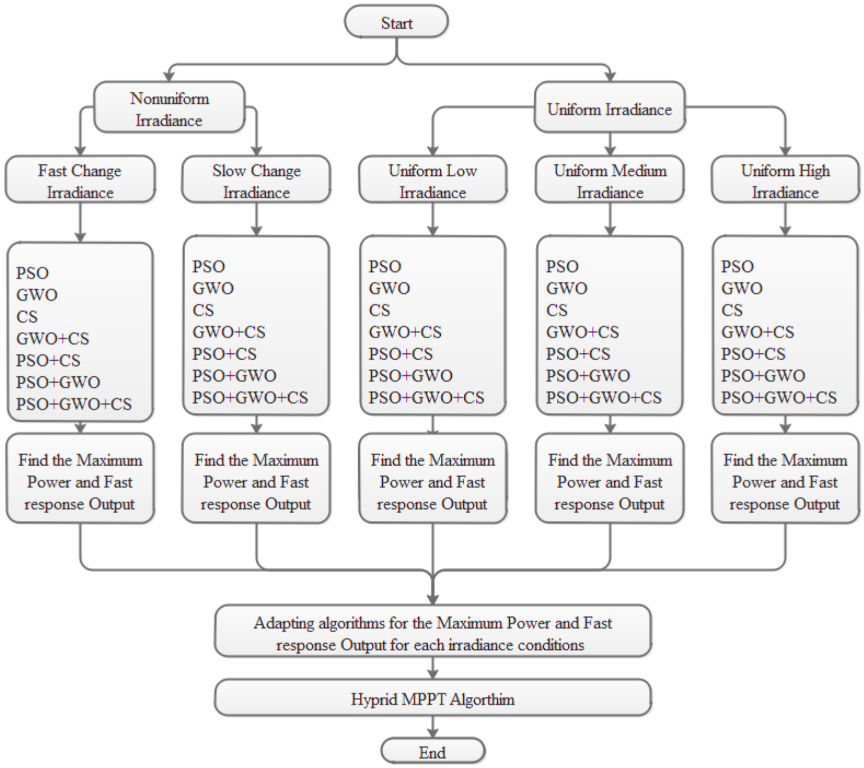


Fig. 1. Research Methodology

3.2. Grey wolf optimization

In 2014, a new algorithm called GWO was added to the family of swarm intelligence-based optimization methods [25]. The GWO algorithm takes its cues from how grey wolves pursue their prey. Grey wolves pursue their prey in packs using a four-level hierarchy. Alphas (α), the group's leaders, are in charge of making all decisions about the hunt. In this hierarchy, the sub-leaders who assist the leaders in making choices are referred to as beta (β). The third-level grey wolves in this hierarchy are known as deltas (δ), which are submissive to alphas and betas but possess superiority over the omegas (ω). The group's lowest rank, Omega, is deferential to all other dominant wolves. The candidate solutions are divided into four groups using the GWO approach, with alpha being the best, beta being the second best, and delta being the third best, to imitate the leadership hierarchy. Omega refers to the leftover solutions. When hunting, grey wolves surround their prey, and this action can be predicted using Eq (3) and Eq (4):

$$\vec{D} = |\vec{C}.\ \vec{x}_P(t) - \vec{x}(t)| \tag{3}$$

$$\vec{x}(t+1) = |\vec{x}_P(t) - \vec{A}\cdot\vec{D}| \tag{4}$$

where t marks the latest iteration, D, A, and C the same coefficient vectors, x_P the prey's position direction, and X the grey wolf's coordinates Calculations for the vectors A and C are shown in Eq (5) and Eq (6):

$$\vec{A} = 2\vec{a}\cdot\vec{r_1} - \vec{a} \tag{5}$$

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

where $\vec{r}_1$, $\vec{r_2}$ are random numbers in the range (0, 1), and $\vec{a}$'s elements are linearly lowered from 2 to 0 across iterations. Beta and Delta may occasionally join the hunt, but Alpha, often known as the leader, usually controls it. The pack's injured wolves are treated by Delta and Omega. As a result, we consider alpha to be the candidate solution with the best information about the location of the prey. When the target stops moving, the grey wolves conclude the hunt by attacking it. Finally, the MPPT application is subjected to the following procedure. The flowchart proposed by GWO is shown in Fig. 2b.

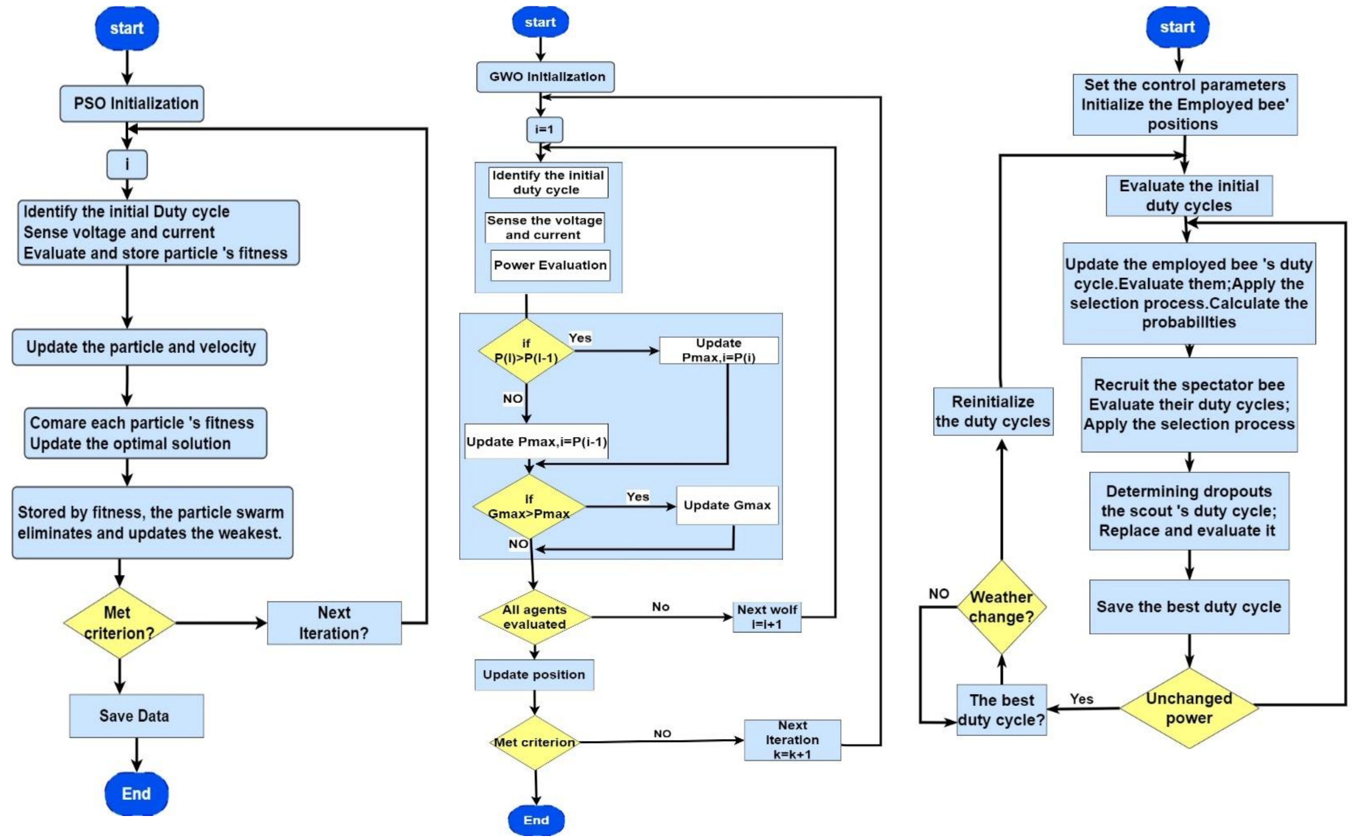
3.3. Cuckoo search optimization

The CS method was first introduced by Yang and Deb in 2009[26], which was inspired by The breeding habits of the cuckoo species. When CS is used, there are three basic standards. In each iteration, each cuckoo first lays a single egg before picking a nest at random to place it in. Second, the best nest and best solution would be transmitted to the successive layer. Third, a host bird finds the alien egg with a probability of P_a∈ (0,1) utilizing the constant number of host nests. the following Lévy flight Eq (7) is

$$x_i^{t+1} = x_i^t + \alpha \oplus \text{Levy}(\lambda) \tag{7}$$

To where $X_i = [x_1, x_2, x_3, \dots x_D]$, D is the problem dimension, α > 0 is the step size, ⊕ the product, λ > 0 is the problem's scale, as represented by the step size, and sequence number represented by t. Multiplication by entries is represented by the symbol in the product and Lévy (λ) generates a random walk with step lengths that are chosen at random from a Lévy range, as demonstrated in Eq (8). Fig. 2c displays the CS flowchart procedures for the MPPT applied.

$$Levy(\lambda) \approx t^{-\lambda}, (1 < \lambda \leq 3) \quad (8)$$



(a) (b) (c)

Fig. 2. Flowchart for the MPPT application; a) The PSO algorithm, b) The GWO algorithm, and c) The CS algorithm

4. Results and Discussion

The presented hybrid model was created using the MATLAB/Simulink environment and a series of tests were carried out on both individual and hybrid methods, as shown in Table 1, to determine the most effective approach depending on the level of partial shading and the different types of shading. The selection of the best method was based on many factors including maximum power, rise time, efficiency, and others. where the average is taken for all methods used Eq (9). Three panels were connected in series in the photovoltaic model, as shown in Fig. 3. Variable irradiance levels across the PV modules highlighted the mismatch effect and caused numerous peaks to emerge on the P-V curve. Each PV module's terminal has a bypass diode added to ensure the safe passage of high currents. The uniform and nonuniform model circuits in MATLAB Simulink are shown in Fig. 4.

G1, G2, and G3 describe changing irradiance at random intervals every second. Table 2 shows the technical specifications of the Photovoltaic panel and the DC-to-DC boost converter. The final output is divided into four scenarios, each showcasing a different MPPT algorithm and its distinct characteristics.

$$\text{Duty Cycle}_{\text{Hybrid}} = \text{Average } (\text{Duty Cycle}_i) \quad (9)$$

Where $i = 1$ *to Number of Algorthims*, $(\text{Duty Cycle}_1 = \text{Duty Cycle}_{\text{PSO}}), (\text{Duty Cycle}_2 = \text{Duty Cycle}_{\text{GWO}})$, and $(\text{Duty Cycle}_3 = \text{Duty Cycle}_{\text{CS}})$

4.1. Case1: uniform irradiance

A uniform irradiance was applied to all three PV panels in this case. Three irradiance levels (High, Medium, and Low) as illustrated in Table 3. Fig. 5a shows the P-V curve with a single maximum power point due to that uniform irradiance. The output power, in this case, is depicted in Fig. 5b, where the (PSO+CS) hybrid method reaches efficiency higher than another method at the high irradiance levels. In contrast, in Fig. 5c, the (PSO+GWO) hybrid method performs better at medium irradiance levels.

Moreover, in Fig. 5d, the (GWO+CS) hybrid method has higher efficiency at low irradiance levels. Table 4Fig. 5. Case 1; a) P-V curve, b) the output power at high irradiance, c) the output power at medium irradiance, and d) the output power at low irradiance summarizes the system response in high, medium, and low irradiance levels based on crucial performance, Rise time, efficiency, and Maximum power. Where A is the used Algorithm, P _max is the maximum power, T_r is the Rise Time in (ms), OS is the OverShoot (%), US (%) is the Under Shoot (%), PS (%) is the Pre shoot (%), and η (%) is the power efficiency (%).

Table 1. Difference algorithms' efficiency

$G_1(W/m^2)$	$G_2(W/m^2)$	$G_3(W/m^2)$	η_{CS}	η_{PSO}	η_{GWO}	$\eta_{PSO+GWO}$	η_{PSO+CS}	η_{GWO+CS}	$\eta_{GPSO+GWO+CS}$
300	300	300	93.30	98.03	96.36	98.55	98.51	98.55	98.51
500	500	500	97.50	97.50	97.39	97.74	97.23	94.39	97.17
900	900	900	93.46	97.78	97.78	97.86	97.86	97.86	97.52
(300, 300, 600)	(300,600, 300)	(600, 300, 300)	93.03	97.17	93.38	98.52	98.62	98.62	97.66
(300, 300, 1000)	(300, 1000, 300)	(1000,300,300)	92.15	91.57	85.008	97.43	96.91	90.96	97.20
(300, 600, 600)	(600, 600, 300)	(600,300, 600)	93.05	97.17	93.38	98.52	98.62	98.62	97.90
(300, 300, 600, 600, 1000, 000)	(1000, 600, 1000, 300, 300, 600)	(600,1000,300, 1000, 600, 300)	58.12	95.93	89.61	97.45	74.91	81.03	73.94
(300, 1000, 1000)	(1000, 300, 1000)	(1000, 1000, 300)	47.81	47.45	98.14	98.39	47.81	92.25	95.50
(600, 600, 1000)	(600, 1000, 600)	(1000, 600, 600)	97.36	97.26	97.23	97.49	97.70	97.28	97.002
(600, 1000, 1000)	(1000, 600, 1000)	(1000, 1000, 600)	97.51	86.51	97.17	66.70	97.73	83.97	89.48
(800, 500, 300, 1000)	(500, 300, 800, 600)	(200,600, 900, 300)	91.33	90.32	91.33	97.26	90.32	91.33	90.32

Table 2. Specifications of the implemented PV system

System Parameters	Values	System Parameters	Values
PV module		*DC-DC Boost converter*	
Maximum power	320.399 w	Cin	72 μF
Open-circuit voltage	49.5 V	Cout	133 μF
Short circuit current	8.6 A	L	5.5 mH
Maximum power voltage	40.1 V	R_{load}	60 Ω
Maximum power current	7.99 A	F_{sw}	5 kHz

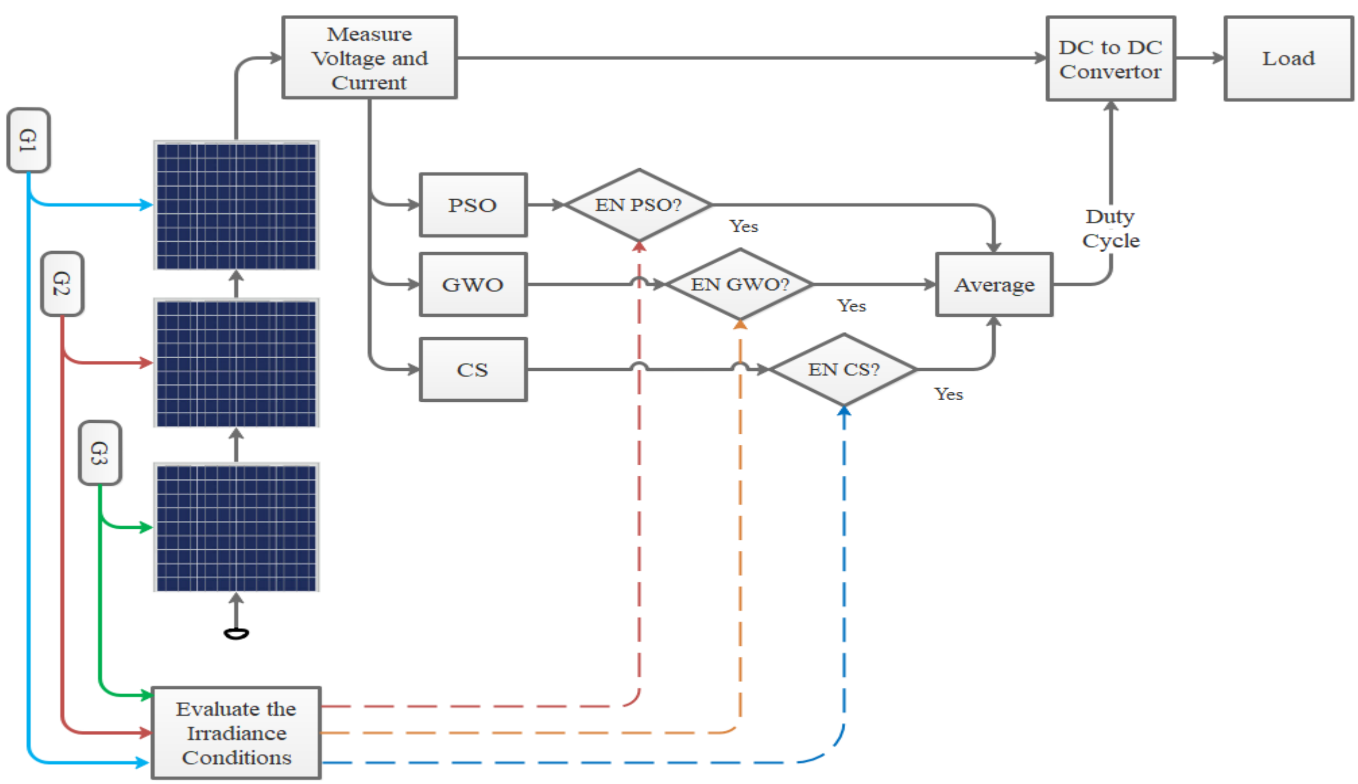


Fig. 3. The Proposed system block diagram

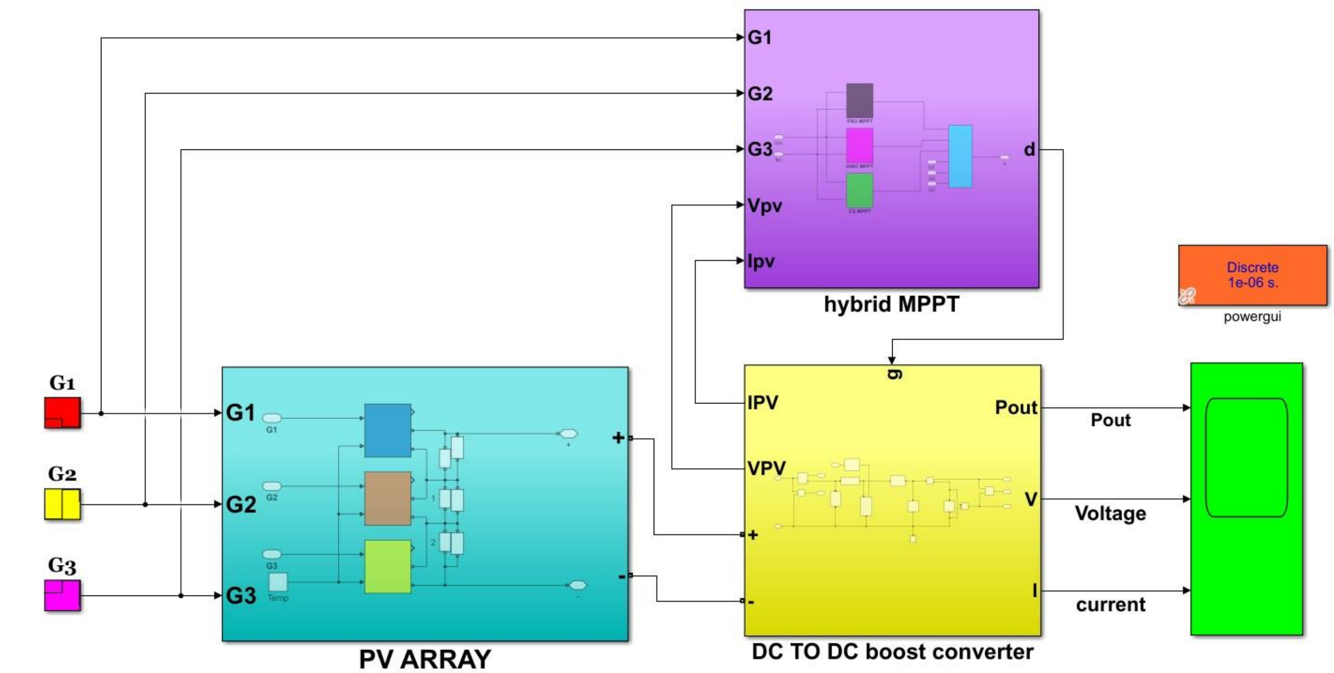


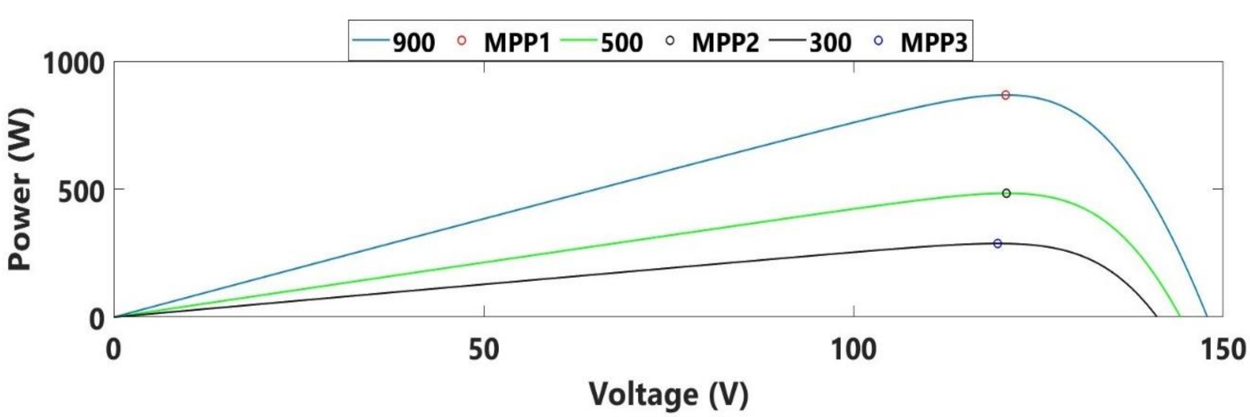
Fig. 4. MATLAB Simulink

Table 3. Case 1: Pattern of the irradiance conditions

	Pattern 1	Pattern 2	Pattern 3
G1 in (W/m^2)	900	500	300
G2 in (W/m^2)	900	500	300
G3 in (W/m^2)	900	500	300

Table 4. Summarized results for Case 1

A	P_{max}	T_r(ms)	OS(%)	US(%)	PS(%)	η(%)
			High Irradiance $900(kW/m^2)$			
PSO+CS	849.1	21.889	3.289	21.975	6.274	97.86
PSO	848.4	27.840	2.185	16.567	34.511	97.78
CS	810.9	17.056	6.618	26.611	25.593	93.46
			Medium Irradiance $500(kW/m^2)$			
PSO+GWO	472.8	31.152	10.458	29.144	69.108	97.74
PSO	471.6	123.890	4.131	16.783	19.424	97.50
GWO	471.1	16.535	6.210	43.317	18.476	97.39
			Low Irradiance $300(kW/m^2)$			
GWO+CS	283.4	19.937	15.267	68.105	5.761	98.55
GWO	277.1	13.608	22.876	42.534	10.643	96.36
CS	268.3	13.168	42.982	66.000	27.031	93.30



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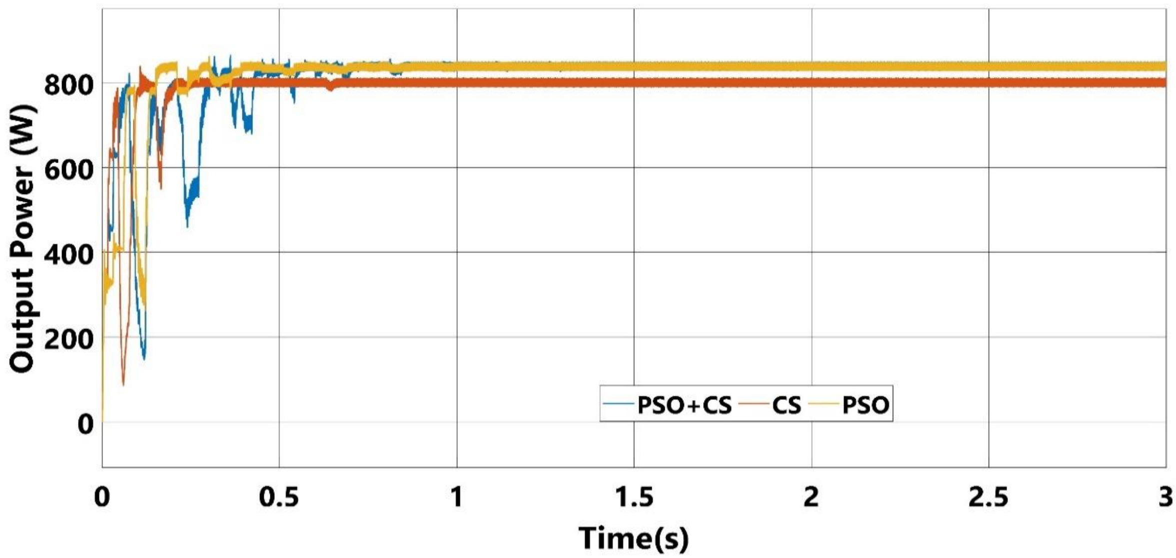

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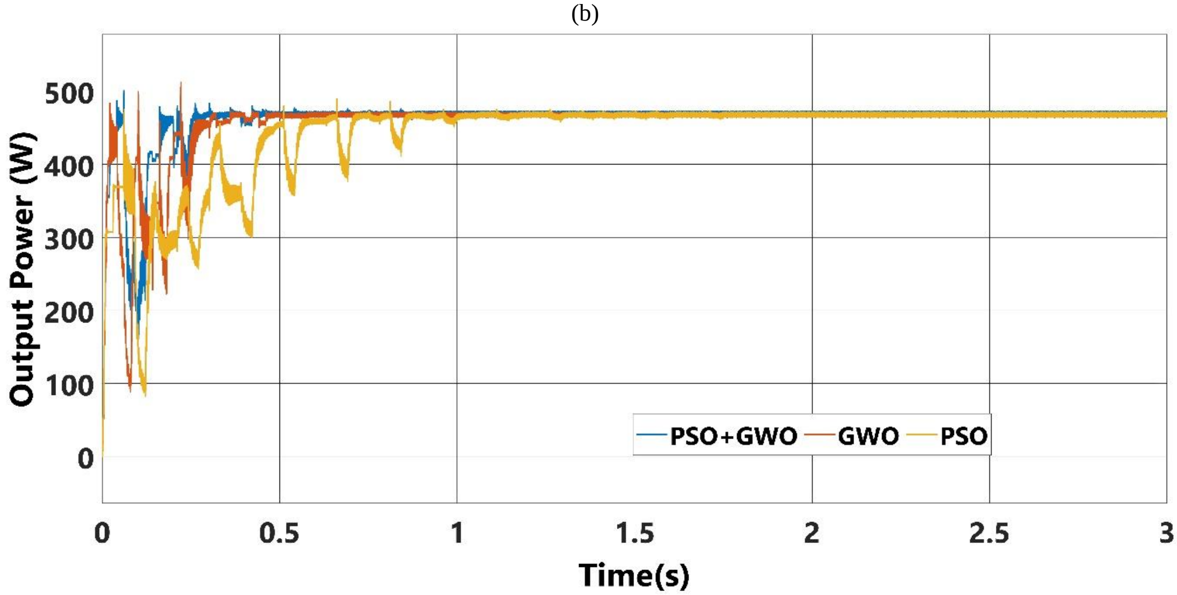

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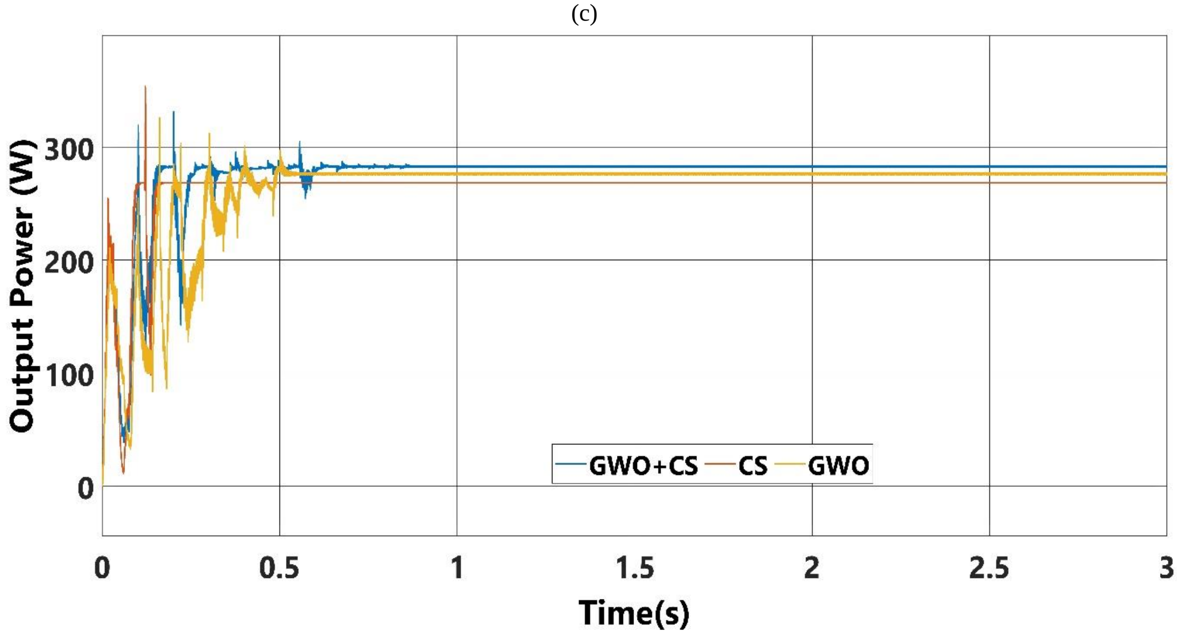


(d)

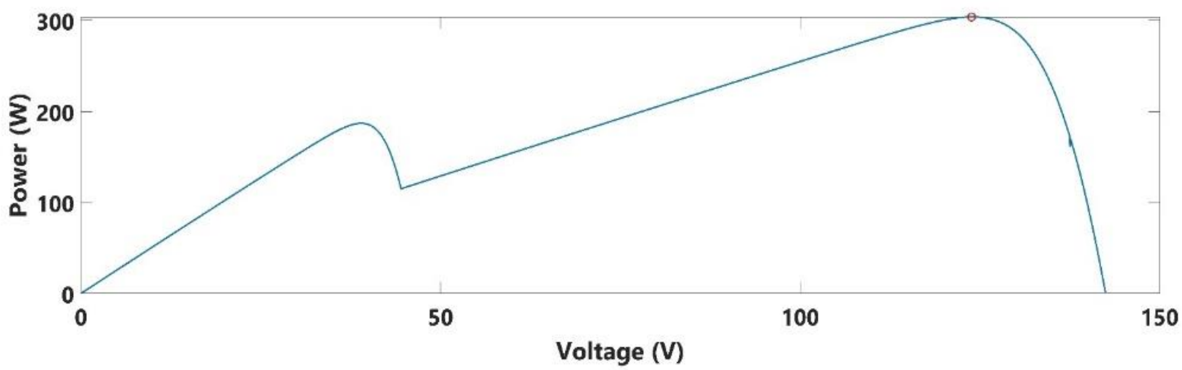
Fig. 5. Case 1; a) P-V curve, b) the output power at high irradiance, c) the output power at medium irradiance, and d) the output power at low irradiance

4.2. Case2: fixed nonuniform irradiance

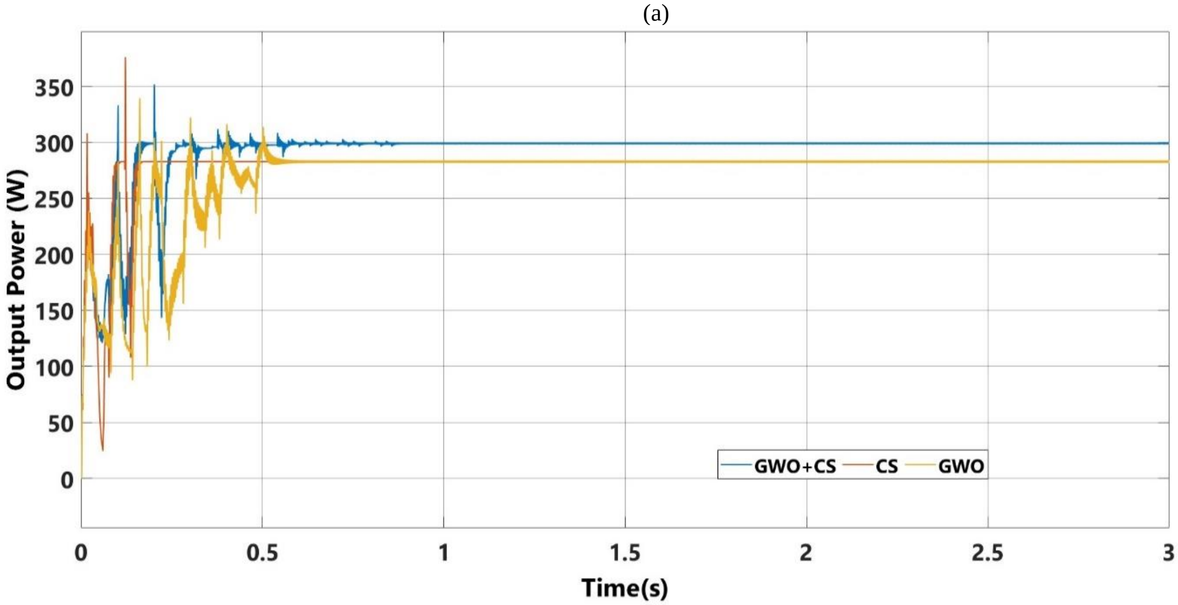
A fixed nonuniform irradiance is applied in case 2, as listed in Table 5. The P-V curve in Fig. 6a shows two maximum power points, one of them is local, and the other is global. In this case, the (GWO+CS) is adopted, and the results are compared to both GWO and CS algorithms, as shown in Fig. 6b. Table 6 summarizes the MPPT methods based on key performance Rise time, efficiency, and Maximum power.

Table 5. Case 2: Pattern of the irradiance conditions

	Pattern 1	**Pattern 2**	**Pattern 3**
G1 in (W/m^2)	300	300	600
G2 in (W/m^2)	300	600	300
G3 in (W/m^2)	600	300	300



(a)



(b)

Fig. 6. Case 2; a) P-V curve, and b) The output power

Table 6. Summarized results for Case 2

A	P_{max}	T_r(ms)	OS(%)	US(%)	PS(%)	η(%)
GWO+CS	299.6	13.031	12.152	12.318	34.217	98.62
GWO	283.7	19.090	19.290	21.916	22.073	93.39
CS	282.7	8.526	4.527	3.903	48.362	93.06

4.3. Case 3: slow dynamic nonuniform irradiance

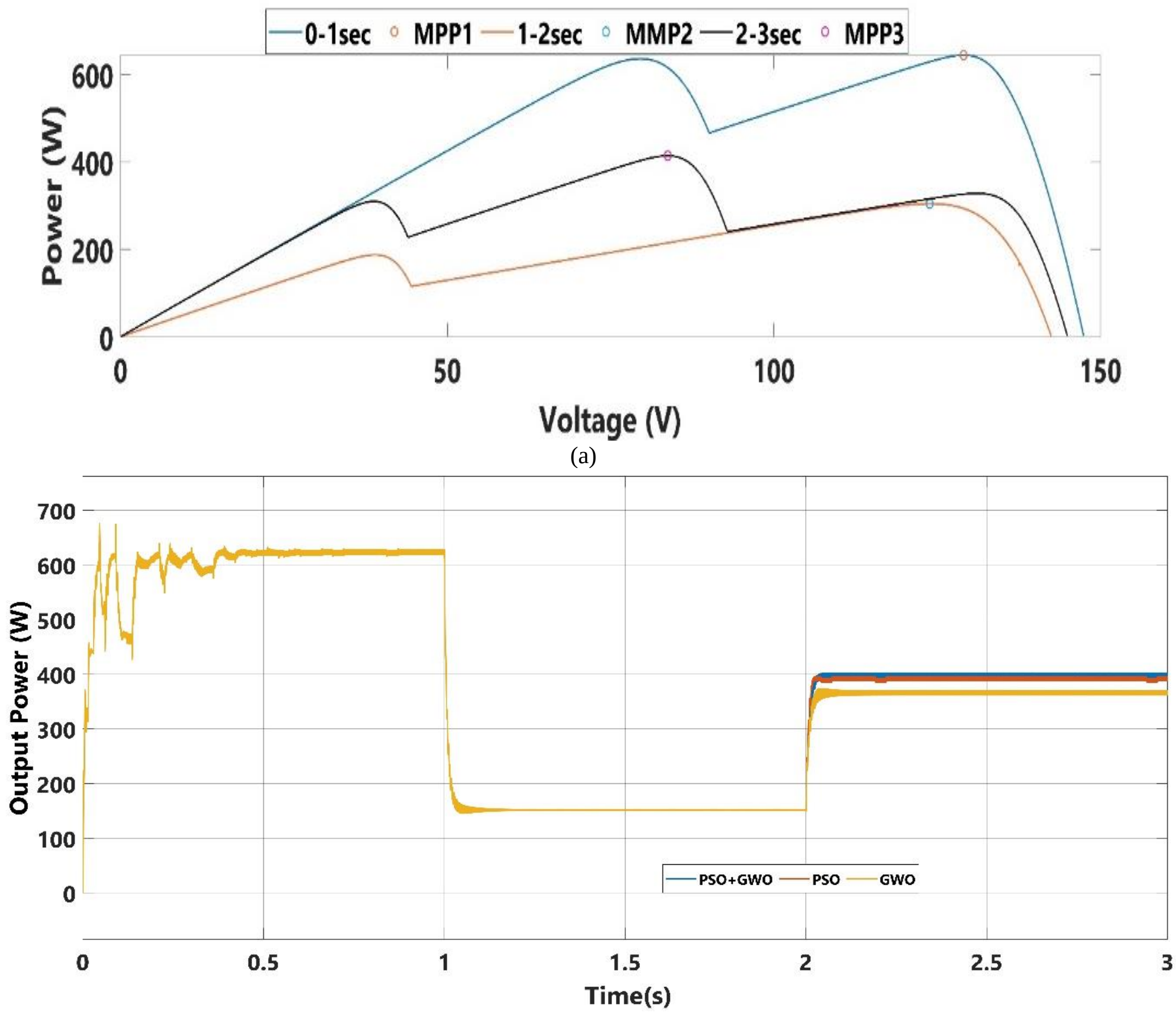
In the Slow Dynamic Nonuniform Irradiance (SNFI), the irradiance changed slowly in nonuniform patterns, as in Table 7. The irradiance levels are different for each panel and change every second as planned. The P-V curve in Fig. 7a. shows every global and local maximum power point change. For case 3, the (PSO+GWO) hybrid method is adopted, and the results are compared to both PSO and GWO MPPT algorithms, as shown in Fig. 7b. Table 7 summarizes the MPPT methods based on key performance Rise time, Settling Time, Efficiency, and the maximum power output.

Table 7. Case 3: Pattern of the irradiance conditions

	0-1(sec)	**1-2(sec)**	**2-3(sec)**
G1 in (W/m^2)	600	300	1000
G2 in (W/m^2)	1000	300	600
G3 in (W/m^2)	1000	600	300

Table 8. Summarized results for Case 3

A	P_{max}	T_r(ms)	OS(%)	US(%)	PS(%)	ɳ(%)
PSO+GWO	402.9	10.130	14.320	4.270	31.976	97.45
PSO	396.6	8.019	16.289	4.235	32.802	95.93
GWO	370.5	9.979	10.650	23.589	36.074	89.61



(a)

(b)

Fig. 7. Case 3; a) P-V curve, and b) The output power

4.4. Case 4: fast dynamic nonuniform irradiance

In the Fast Dynamic Nonuniform Irradiance (FDNI), the irradiance changed fast in nonuniform patterns. Table 9 illustrates the irradiance level changes for each panel per second. The P-V curve in Fig. 8 shows three maximum power points, one global and two local maximum power points. For case 4, the (PSO+GWO) hybrid method is also adopted, and the results are compared to both PSO and GWO MPPT algorithms, as shown in Fig. 8b. Table 10. Summarized results for Case 4.

A	P_{max}	T_r(ms)	OS(%)	US(%)	PS(%)	ɳ(%)
PSO+GWO	402.1	5.052	16.667	3.664	1.665	97.26
GWO	377.6	4.975	32.881	15.195	27.803	91.33
PSO	373.4	1.435	38.239	12.223	4.661	90.32

summarizes the MPPT methods based on key performance Rise time, Settling Time, Efficiency, and the maximum power output.

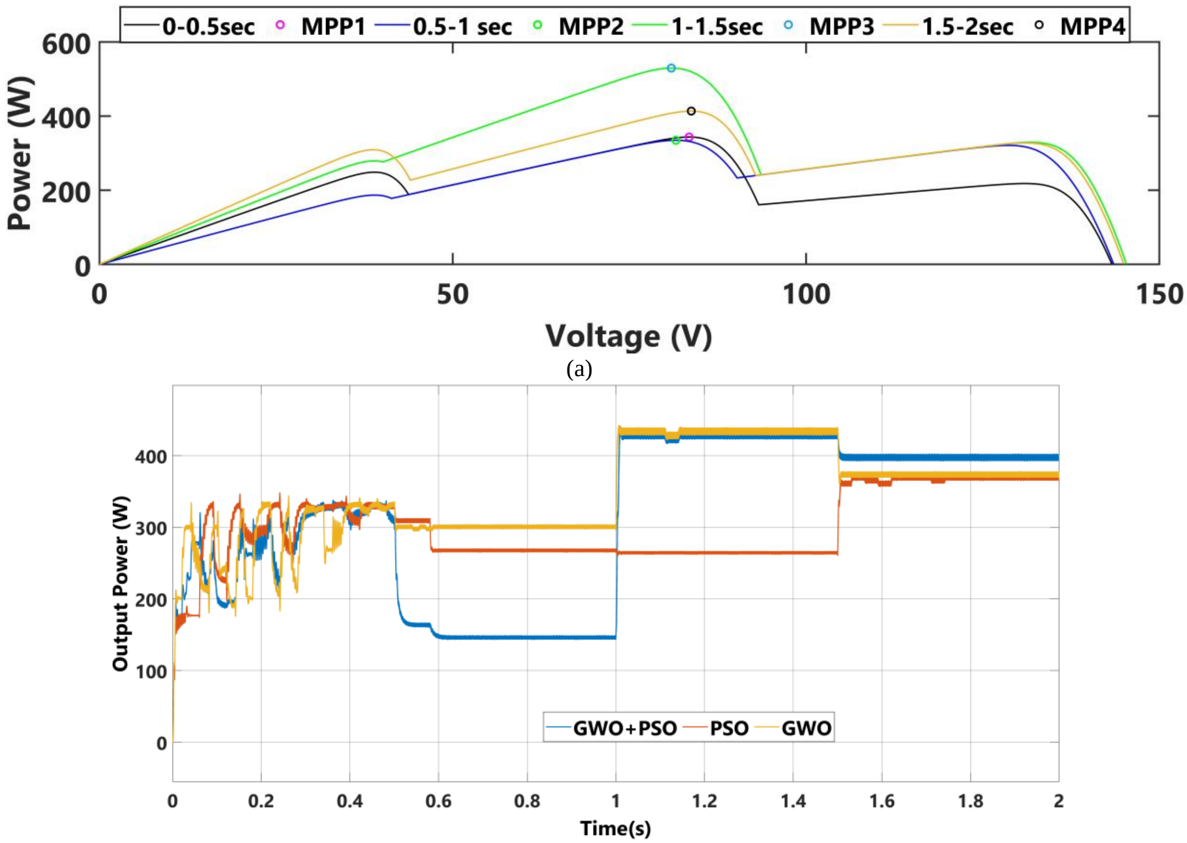
Table 9. Case 4: Pattern of the irradiance conditions

	0-0.5 sec	0.5-1 sec	1-1.5 sec	1.5-2 sec
G1 in (W/m^2)	800	500	300	1000
G2 in (W/m^2)	500	300	800	600
G3 in (W/m^2)	200	600	900	300

Table 10. Summarized results for Case 4.

A	P_{max}	T_r(ms)	OS(%)	US(%)	PS(%)	ɳ(%)

PSO+GWO	402.1	5.052	16.667	3.664	1.665	97.26
GWO	377.6	4.975	32.881	15.195	27.803	91.33
PSO	373.4	1.435	38.239	12.223	4.661	90.32



(a)

(b)

Fig. 8. Case 4; a) P-V curve, and b) The output power

5. Conclusion

This article discusses and compares the mismatching effect and MPPT performance of PSO, GWO, and CS algorithms under uniform and nonuniform solar irradiance conditions. The article proposes a new hybrid MPPT algorithm that combines the individual performance of these algorithms. The bio-inspired methods can track the global maximum power point (GMPP) while the PV system is under partial shading conditions (PSC), resulting in the best power yield. The proposed hybrid system offers an efficiency of 98.55%, 97.86%, and 97.76% under uniform irradiance levels of High, Medium, and Low, respectively. However, under fixed nonuniform irradiance, the efficiency is 98.62%. The system's performance efficiency under slow and fast dynamic nonuniform irradiance is 97.45% and 97.26%, respectively. The proposed technique has limitations, such as not reducing the effect of local maximum points and only tracking the GMPP. In future work, it is recommended to combine the PV reconfiguration technique with this hybrid method.

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