A novel hybrid method based MPP tracking design using boost converter for solar power systems

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Article Info

ABSTRACT

The convergence time is one of the key parameters for evaluating the energy conversion efficiency of PV power systems in the experimental process of tracking the maximum power point (MPP) in real-time. When the PV system is partially shaded, for example, MPP tracking easily slips into the local MPP and takes a long time. To overcome this drawback, a new solution for a stand-alone PV power system has been proposed that combines the incremental conductance (In-Cond) algorithm and the improved grey wolf optimization (GWO) approach. The improved GWO technique changed the methodology is used to find the global power area in this proposed method, and it is integrated with the In-Cond algorithm to fast obtain the global MPP. To demonstrate the efficacy of the suggested strategy, MATLAB/ Simulation and experiment results of the PV system are provided. The proposed hybrid method has a quick response time of 0.18 to 0.42 seconds for good transient oscillation and global power tracking, whereas the classic GWO and particle swarm optimization (PSO) methods take 0.82 to 2.1 seconds and 0.68 to 2.2 seconds, respectively. The global MPP was obtained not only with uniform irradiance intensity, but also with partial shade.

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1. INTRODUCTION

It is the fact that there is a host of renewable energy sources, encompassing solar, wind, hydrogen, and tidal energy, and all of which are widely acknowledged as being synonymous with clean energy sources. Solar energy distinguishes itself as a significantly utilized energy source due to its universally prevalent availability, minimal emissions of pollutants, and inherent renewability. Numerous scholars have proposed concepts aimed at enhancing the effectiveness of solar energy conversion through the utilization of the perturbation and observation (P&O) technique to discern the global maximum power point (MPP) [1], [2], the In-Cond method [3], [4] and analogous approaches. Due to their inherent simplicity, ease of implementation, and rapid attainment of the MPP, the P&O and In-Cond methodologies are commonly utilized for tracking the MPP. Nevertheless, the easy oscillation around the MPP reduces the performance of the PV systems, which also represents a drawback of the P&O method. Additionally, these conventional methodologies are readily integrated into the local MPPs under conditions of partial shading. In response to these limitations, scholars

have endeavored to resolve these issues through various inventive alterations [5], [6]. Nevertheless, a comprehensive solution enabling the efficient operation of photovoltaic systems within authentic environmental contexts remains elusive; if these inventive solutions perform proficiently in a uniform environment, they may encounter challenges when faced with intricate environmental occurrences, and vice versa. Despite some solutions exhibiting a degree of effectiveness, there are still some technological and computational restrictions caused by cheaply constructed processors.

The P-V characteristic curve displays a singular peak under conditions of uniform photovoltaic irradiance distribution, thereby enabling the aforementioned approaches to readily identify this apex. Nevertheless, the influence of environmental factors, such as clouds and obstacles, upon photovoltaic panels engenders numerous local MPPs in conjunction with the global MPP. In contexts of this nature, the conventional algorithms alluded to earlier prove insufficient in ascertaining the global MPP throughout the entirety of the operational spectrum. Consequently, the imperative arises for an inventive methodology to ascertain the optimal region of global maximum power, especially considering the variability of environmental conditions. A comprehensive array of sophisticated methodologies has been cataloged [7], classified into two categories: those reliant on hardware-based implementation and those predicated on soft computing principles for the pursuit of maximum power tracking. The subset of soft computing-based MPP tracking approaches encompasses metaheuristic strategies [8]–[11], refined metaheuristic variations [8], [12]–[14], and hybrid methods [15]–[19]. In contrast, hardware-based techniques encompass measures such as the reconfiguration of photovoltaic power systems [20], [21] and similar methodologies. Each of these methodologies showcases distinct advantages. The overarching objective of these strategies is to effectively explore the global MPP domain while minimizing power oscillations and necessitating fundamental computations. In a particular study [13] scholars have introduced the SDRA-MPPT technique, demonstrating its competence in tracking the global MPP across diverse weather scenarios. Nonetheless, the pursuit of the MPP encounters extended tracking times, primarily attributed to the substantial iterations requisite for pinpointing the global region. In [16], the use of hybrid method has brought high efficiency and accuracy. However, updating all the locations in the shuffled frogs took a long time to reach the global MPP.

The paper has successfully developed a PV maximum power controller that meets the desired outcomes by incorporating the findings from previous studies. Drawing inspiration from the grey wolf optimization [22] and the hybrid method combining the P&O and GWO techniques [23], a new hybrid approach was suggested to efficiently explore the global MPP. This pioneering approach entails the initial application of the enhanced grey wolf optimization (GWO) technique to swiftly survey the worldwide area, succeeded by the deployment of the In-Cond algorithm to precisely identify the MPP within that specific sector. This methodology not only curtails computational time and manipulation but also mitigates the magnitude of ripples in power output. A self-contained photovoltaic (PV) power conversion setup, encompassing an MPP tracking controller, a DC boost converter, and a load, has been put into operation [2], [24]. Varied duty ratio values result in diverse power inputs received by the system from the PV modules. The refined GWO method leverages these duty ratio values to ascertain the global power zone, even when confronted with scenarios of partial shading and uniform irradiances.

2. MPP TRACKING CONTROL OF THE SOLAR POWER SYSTEM
2.1. Circuit design for the stand-alone solar power system

Figure 1(a) depicts a stand-alone PV energy conversion system for efficient PV panel utilization. PV power panels, the MPPT method, a control circuit, a DC boost converter, and a DC load are all part of this system. The experimental configuration for this system is depicted in Figure 1(b). PV power panels generate current and voltage when they collect solar irradiation energy. The proposed hybrid approach is harnessed to determine the global maximum power point (MPP). Upon obtaining the resultant value, the control circuit adjusts the duty ratio of the boost converter, thus facilitating the transfer of the globally optimal power value to the load. During system operation, the initial duty ratio (D) is chosen under the presumption that operational power surpasses or equals 80% of the maximum PV power. The solar irradiance intensity on the PV power panels is assessed by utilizing both the measured current and voltage. The processed measured current is integrated into the control circuit. Similarly, the measured voltage, after undergoing suitable voltage division utilizing a resistor bridge, is linked to the control circuit for processing. The control circuit employs these two signals in conjunction with the suggested hybrid technique to determine the optimal MPP. The duty ratio has replaced the position of the grey wolf in this proposed technique, and the fitness F_i has also been replaced by the output power (P_{pv}) of the PV panels.
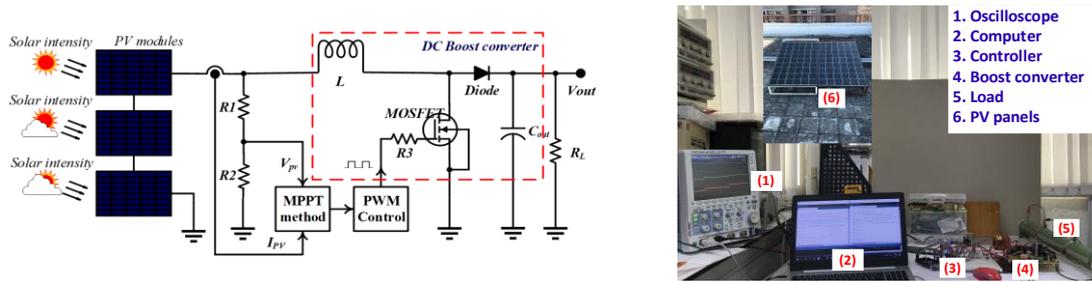
Figure 1. Basic controller: (a) and experimental model of two serial PV panels and
(b) for the PV system circuit design for the stand-alone solar power system

2.2. Proposed MPP tracking method for solar power systems

The traditional MPPT tracking techniques are susceptible to becoming readily ensnared within localized MPPs, as previously discussed. When environmental circumstances lead to the shading of PV power panels, numerous power peaks emerge. The efficacy in converting PV power energy will decline. This research therefore offered a combination solution, which is a hybrid approach between the In-Cond algorithm and the improved GWO method. In addition to locating the global maximum energy area fast, the improved GWO approach is employed to avoid local areas. It will transition to the In-Cond approach to obtain the global MPP after the global area has been located. This hybrid approach, which can effectively prevent a localized trapped area, is divided into two phases.

2.2.1. Phase 1. Improved grey wolf optimization technique

The application of the grey wolf optimization (GWO) technique is employed to address optimization challenges encountered in the exploration of global domains. Acknowledged as one of the latest heuristic optimization algorithms, the GWO method was originally introduced in [25]. This algorithm draws its inspiration from the behavioral patterns of grey wolves as they navigate their existence and engage in hunting activities in their natural habitat. Grey wolves typically exhibit a tendency to form groups comprising an average of 5 to 10 individuals. Within the hierarchical framework governing the social dominance among grey wolves, a meticulously structured arrangement is present, which classifies their leadership into a four-tier hierarchy that escalates in dominance from the uppermost to the lowermost echelons [22]. The conduct of grey wolves has been replicated within the context of optimization through the formulation of the grey wolf algorithm [25]. The hierarchical structure of leadership within grey wolf packs is emulated through the assignment of distinct leader levels, delineated as follows: primary leaders are designated as level 1 ($L1$), subleaders are identified as level 2 ($L2$), wolves of lower rank are categorized under level 3 ($L3$), while those with the lowest rank are ascribed to leader level 4 ($L4$). During their pursuit of prey, grey wolves employ an encircling tactic as an integral component of their hunting methodology. This encircling behavior has been translated into a mathematical model employing equations [22]. In the preliminary stage of the hybrid approach, an advanced GWO strategy was introduced to provide a fresh vantage point by partitioning areas using incremental values ranging from Dw_{min} to Dw_{max}. Each individual wolf operates randomly within its designated range. Through this procedural framework, the enhanced GWO method expeditiously identifies the global domain, in contrast to the utilization of randomly moving wolves without a specific configuration.

Each grey wolf navigates its allocated territory through stochastic movements, as (1)-(2):

$$Dw_n = [(Dw_{min} + (n-1) \times \Delta Dw) \ (Dw_{min} + n \times \Delta Dw)] \qquad (1)$$

$$\Delta Dw = (D\,w_{max} - D\,w_{min})/Nw \qquad (2)$$

where Nw denotes the number of grey wolves in the herd. A fitness value ($Pw_n = P(Dw_n)$) will be assigned to each Dw_n location. Among these Nw sites, the best fitness position is termed Dw_{best} (or Dw_{L1}) and corresponds to wolf $L1$, one place is called Dw_{L2} and corresponds to wolf $L2$, and one location is labeled Dw_{L3} and corresponds to wolf $L3$. The three best grey wolves will continue to hunt in their respective territories after being chosen. The following equations are used to update the location of these grey wolves.

$$Dw_{Lk(i+1)} = Dw_{Lk(i)} \pm \Delta Dw/i; \ \text{with } k = 1,2,3 \qquad (3)$$

where i denotes the iteration count. Given that the three optimal values are employed for recalibrating the fresh positions, this methodology substantially diminishes the count of test samples undertaken at non-essential locales. Consequently, this innovative technique significantly abbreviates the time required for discerning the global domain.

The wolves will conclude their hunting endeavor upon the fulfillment of (4). This event indicates the successful determination of the global area.

$$\left| Dw_{best} - Dw_{Lk(i+1)} \right| \leq \eta \times \Delta Dw; \tag{4}$$

where η is a adjusting number, its value is lower than 1. The magnitude of this value exhibits an inverse relationship with the quantity of grey wolves, diminishing as the number of grey wolves increases, and conversely, increasing as their number decreases.

2.2.2. Phase 2. Incremental conductance (In-Cond) algorithm

When the criterion outlined in (4) is fulfilled with respect to the separation between the grey wolves and their prey, it signifies the successful hunting or approach of the prey by the grey wolves, thereby concluding the first phase of the enhanced GWO approach. Put differently, the enhanced GWO method has either achieved the global maximum power value or closely approximated it. To attain the optimal resolution that ensures consistent attainment of the global maximum power value across all scenarios, the In-Cond method is integrated. This method employs the dP_{pv}/dV_{pv} slope to determine the direction of voltage regulation [4]. The essential condition for achieving the MPP is governed by the subsequent (5).

$$\frac{dP_{pv}}{dV_{pv}} = \frac{d(V_{pv} \times I_{pv})}{dV_{pv}} = I_{pv} + V_{pv} \times \frac{dI_{pv}}{dV_{pv}} = 0 \tag{5}$$

After completing the above equation, the following equation is obtained:

$$\frac{dI_{pv}}{dV_{pv}} = -\frac{I_{pv}}{V_{pv}} \tag{6}$$

In this context, dV_{pv}, dI_{pv} symbolize the disparities in measurements of voltage and current taken prior to and subsequent to the alteration. Through the comparison between the instantaneous conductance value (I_{pv}/V_{pv}) and the progressive conductance value (dI_{pv}/dV_{pv}), this methodology discerns the operational juncture characterized by the highest power output. When the condition stipulated in (6) is fulfilled, the In-Cond method will circumvent the procedure of modifying the duty ratio. The flow chart depiction of the proposed hybrid approach can be observed in Figure 2 (see Appendix), delineating each individual step encompassed within the procedure of identifying and attaining a global MPP. As the system commences its operation, the initial value Dw is established, grounded in the assumption that the operational power equals 80% of the maximum power value. This criterion is met in instances where the irradiance intensity impinging upon the panels is both uniform and maximal. To expedite the tracking of the MPP, the In-Cond method is implemented, thereby circumventing the need to sequentially progress through phases 1 and 2. The selection of this initial value Dw is informed by practical expertise and substantiated by the simulated P-V output curve of the PV power system.

3.   RESULTS AND DISCUSSION
3.1. Simulation results

The outcomes of the various strategies were visualized using MATLAB simulations. PV power panel specifications are $P_{max} = 200\ W$, $N_s = 54$pcs, $N_p = 1$, $V_{oc} = 32.9\ V$, $V_{max} = 26.3\ V$, $I_{sc} = 8.21\ A$, $I_{max} = 7.61\ A$. In the case of the enhanced GWO approach, the quantity of grey wolves is set at 8. Subsequently, upon the fulfillment of condition (4), the hybrid approach transitions to the utilization of the In-Cond method.

The distinctions between the In-Cond method, the conventional GWO method, the PSO, and the novel hybrid method were subjected to simulation under conditions involving partial shading, as depicted in Figures 3(a) and 3(b). The GWO method, referred to as "conventional GWO" employed the equation sourced from [23] to adjust the positions of the wolves. These methodologies were simulated across all three scenarios, with each scenario being executed within a time frame of 6.0 seconds.

3.1.1. Case of two panels connected in series

in this case, situation 1 (P-V curve #1) which is set up irradiance intensities to (85, 57) mW/cm^2 is displayed by the red line. Situation 2 (P-V curve #2) that is irradiated to (85, 85) mW/cm^2 is shown by the green line. Situation 3 (P-V curve #3) is seen in the black line with irradiance intensities of (85, 35) mW/cm^2, respectively (Figure 3(a) for this case and Figure 3(b) for the case below). The simulation results are displayed in Figures 4 and 5. In each figure, the magenta line named "Voltage(V)-magenta" is used to show the working voltage values and the blue line named "Power(W)-blue" is called to display the working power values of the methods. The specifications and the initial database are set up the same in the methods.

Under circumstances involving partial shading, the In-Cond method becomes entrapped within the local MPP domains, as illustrated in Figure 4(a) for situation 1 and 3. The PSO (Figure 4(b)) and the conventional GWO (Figure 5(a)) method achieve the global MPP in all 3 situations (200.5 W, 280 W, 140 W, respectively), however, these methods request a long time, complex calculations. The proposed hybrid technique is quickly to get the global MPP in all 3 situations (Figure 5(b)). The points on the "Voltage(V)-Magenta" line shown in the small figures are the number of samples when the system is operating. The outcomes of the simulation are presented in Table 1. The suggested approach demonstrates swifter performance compared to the PSO and GWO techniques for the pursuit of global MPPs.
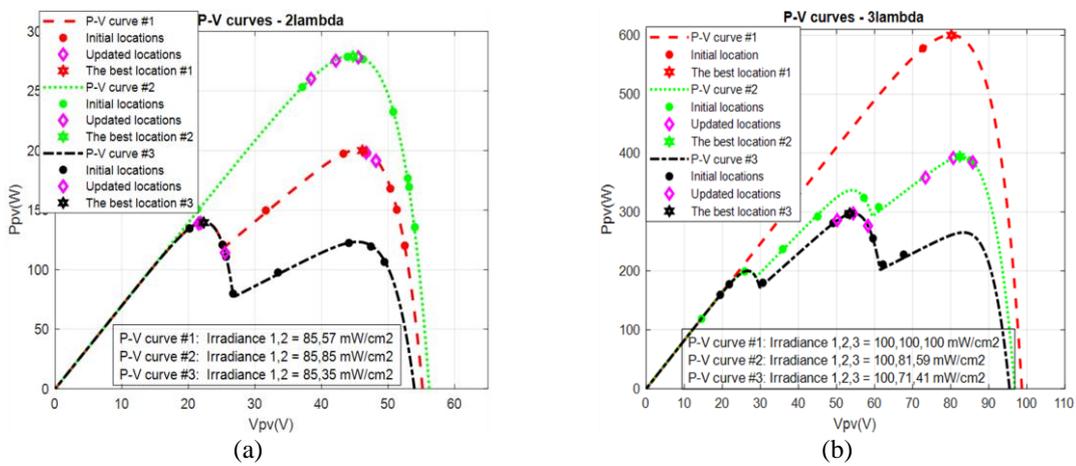
Figure 3. P-V curves under PSCs of (a) two serial panels and (b) three serial panels
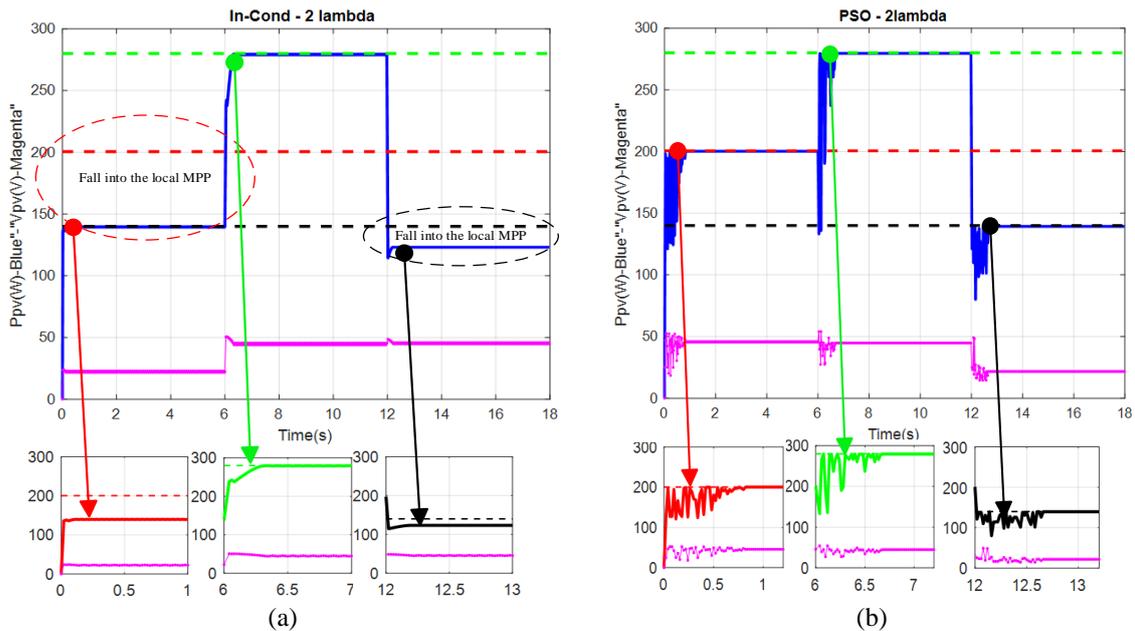
Figure 4. Simulation results under PSCs of (a) In-Cond method and (b) PSO method

3.1.2. Three panels connected in series

The linkage of the PV power system is illustrated in Figure 1(a). This configuration is likewise implemented across the three scenarios, each characterized by varying levels of irradiance intensities denoted as $(100, 100, 100)\ mW/cm^2$, $(100, 81, 59)\ mW/cm^2$, and $(100, 71, 41)\ mW/cm^2$, respectively (see Figure 3(b)). The simulation results are displayed in Figures 6 and 7. Amid conditions of partial shading, the In-Cond method also converges towards local maximum power points (MPPs) (situations 2 and 3), as depicted in Figure 6(a). Analogously, the particle swarm optimization (PSO) method necessitates more time compared to the hybrid method to attain the global MPP (Figure 6(b)) [11].
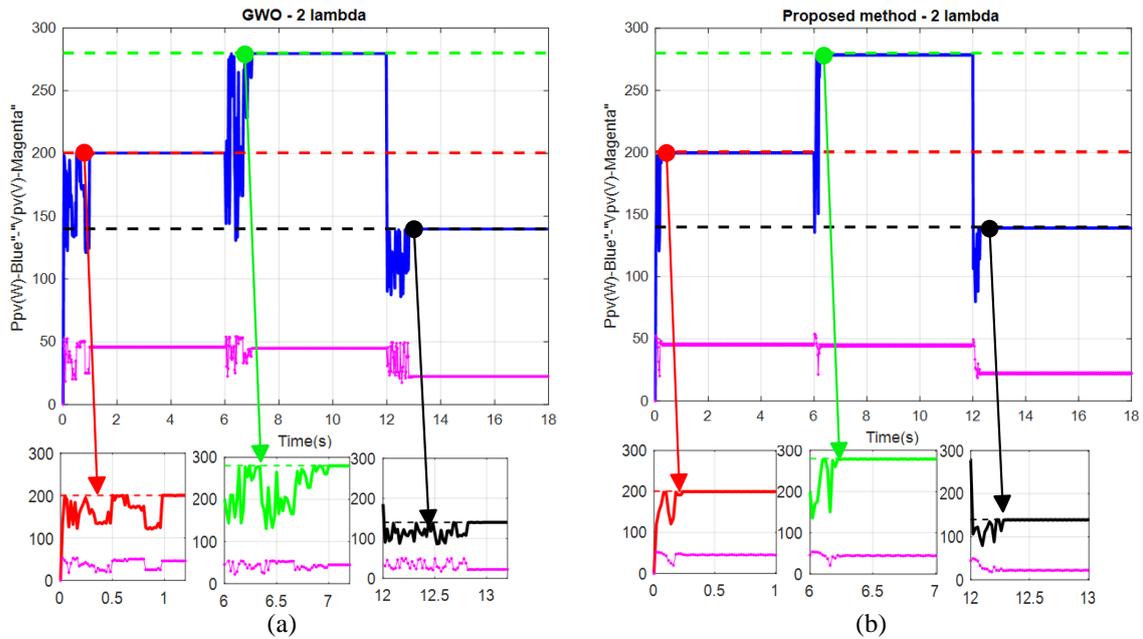
Figure 4. Simulation results under PSCs of (a) conventional GWO method and (b) proposed hybrid method
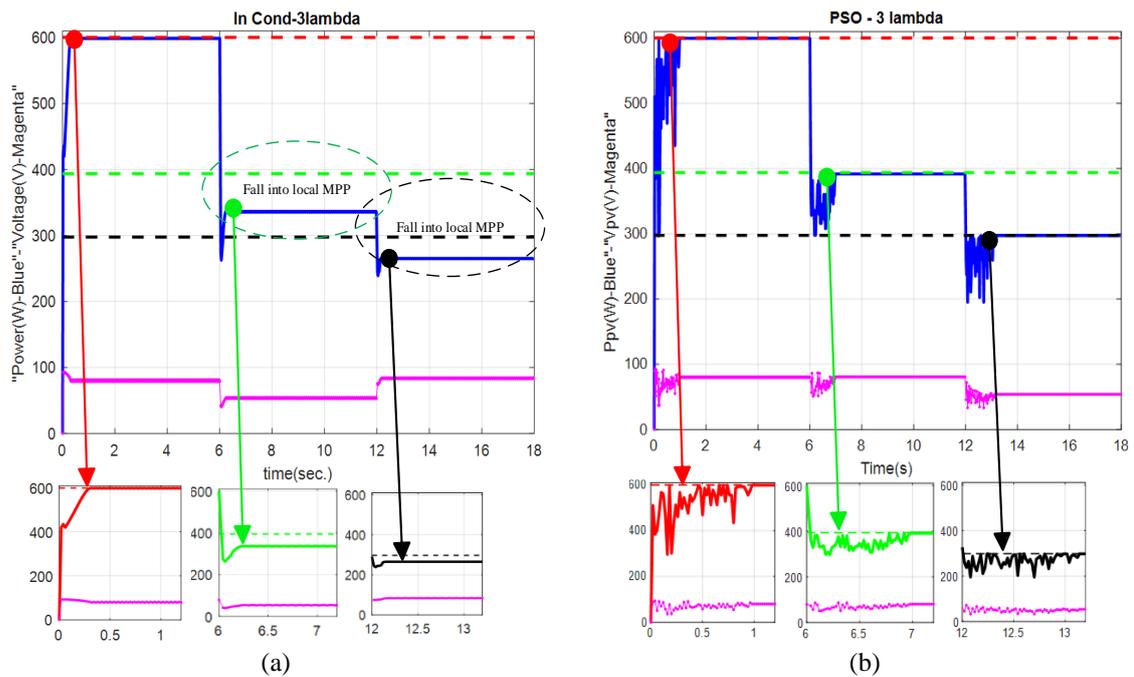
Figure 5. Simulation results under PSCs of (a) in-cond method and (b) PSO method

Conversely, the conventional grey wolf optimization (GWO) method not only demands considerable time to identify the global MPP but occasionally encounters challenges in reaching this global MPP (Figure 7(a)). By amalgamating the enhanced GWO method with the In-Cond method, achieving the global MPP is facilitated. This study demonstrates the swift global area identification through the enhanced GWO method. As a result, the proposed hybrid method excels in effectively exploring and tracking the global MPP across all three scenarios. The simulation findings are also presented in Table 1. Utilizing the optimal positions of the three superior grey wolves for location updates contributes to a reduction in execution time for the proposed hybrid method, as mentioned earlier. Additionally, the convergence of this approach surpasses that of alternative GWO and PSO methods [22], [26]. The power values progressively approach the maximum power value, as depicted in Figure 7(b).

The comparison of convergence times for the aforementioned and corresponding cases is outlined in Table 1, revealing that the proposed maximum power point tracking (MPPT) method demonstrates reduced transient response times. Notably, the updated positions resulting from the hybrid MPP search process are graphically depicted in Figure 7(b). The positions identified in the proposed method consistently tend to approximate the global MPP after each cycle. Consequently, diminished computations are required in the proposed MPPT method, leading to an expedited response. Furthermore, the achievements of the proposed method are benchmarked against other approaches in terms of convergence speed, both under uniform radiation and partial shading conditions. The corroborative evidence for this assertion is presented in the comparison results of Table 2.
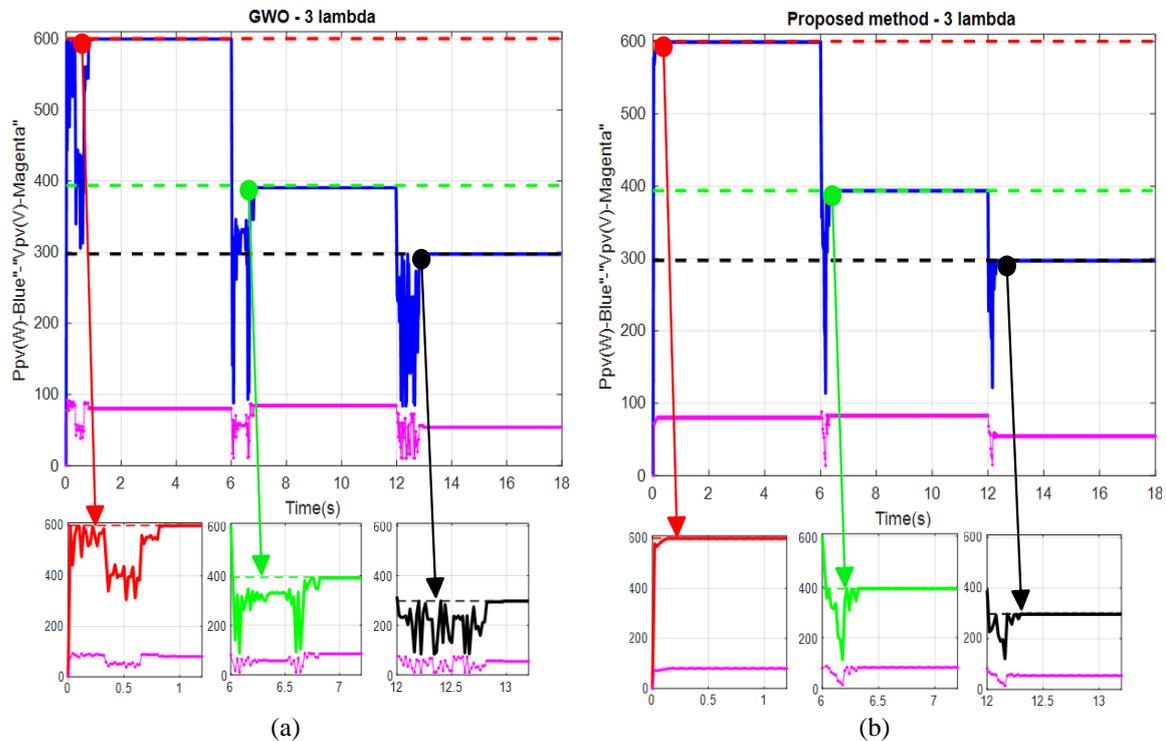
Figure 7. Simulation results under PSCs of (a) conventional GWO method and (b) proposed hybrid method

Table 1. Comparison of simulation results of four MPPT methods for two cases

Case	Irradiance intensity (mW/cm^2)	Ideal MPP (W)	Power (W)/Convergence time (sec.)			
			In-Cond	PSO	GWO	Proposed method
Two panels	[85, 57]	200.5	139.8/0.14	200.5/0.82	200.5/1.00	200.5/0.26
	[85, 85]	280.0	280.0/0.38	280.0/0.68	280.0/1.00	280.0/0.28
	[85, 35]	140.0	123.1/0.26	140.0/0.68	140.0/0.82	140.0/0.32
3 panels	[100, 100, 100]	600.2	600.2/0.28	600.2/0.98	600.2/0.92	600.2/0.18
	[100, 81, 59]	393.8	336.8/0.24	393.8/0.98	393.8/0.82	393.8/0.32
	[100, 71, 41]	297.5	265.2/0.15	297.5/1.14	297.5/0.98	297.5/0.30

Table 2. Comparison of the simulation results of different methods

MPPT method	Enhanced GWO in Reference [22]	GWO-GSO in Reference [27]	Improved In-Cond in Reference [5]	Improved CS in Reference [28]	Adjustment PSO in Reference [26]	Proposed method
Convergence time of simulation results (s)	2.63 – 2.85	0.42 - 0.64	0.46 – 0.60	0.52 - 0.75	0.89 – 1.5	0.18 - 0.32

3.2. Experimental results

The experimental configuration is depicted in Figure 1(b). The elements comprising the boost converter are fabricated with the ensuing parameters: inductor with a value of $L = 1.2\ mH$, output capacitor with values $C_{out} = 470\ \mu F/450\ V$, high-frequency switching diode represented by $D = MBR30200\ PT$, electronic power switch MOSFET denoted as $Q = IRFP250\ N$, and resistive load designated as $R_L = 35\ \Omega$. The constructed boost converter is engineered to accommodate an output voltage of $200\ V$ and an output power of $500\ W$. The experimentation was conducted utilizing an ARDUINO Mega2560 board-controlled DC/DC boost converter to evaluate the feasibility and effectiveness of the MPP search approach employing the proposed hybrid method. This ARDUINO Mega 2560 board boasts an easily navigable I/O interface, a high clock speed ($16\ MHz$), and a streamlined design. The Mega 2560 microcontroller features 16 analog inputs, each equipped with 10 bits of resolution, and 54 digital I/O pins (of which 14 offer PWM output) for measurement and signal control. Each duty ratio value operates for a duration of 30 milliseconds to capture the PV current and PV voltage values of the power system, utilizing the current sensor and the voltage divider generated by resistors R_1 and R_2. The specifications of the PV power panel employed for experimental implementation have been delineated above. In this experiment, two panels are arranged in series and irradiated with angles of 85-57 mW/cm^2 and 85-85 mW/cm^2 for two distinct scenarios, respectively. The MPPs corresponding to these situations are 200.5 W for situation 1 and 280 W for situation 2, as observed in Figure 3(a) (situations 1 and 2). Results from the conventional GWO method are depicted in Figure 8, illustrating values of 44 V, 4.5 A, and 198 W (from top to bottom) for situation 1, and 43.5 V, 6.4 A, and 278.4 W for situation 2. Elaborated details of the experimental outcome of the PSO method are presented in Figure 9.

Both the PSO and proposed hybrid methods yield identical values to the conventional GWO, however, the proposed method rapidly attains the global MPP. Experimental findings are illustrated in Figure 10. The time taken for the proposed method to reach the global MPP is approximately 0.4 seconds. After this duration, the proposed method autonomously updates the current and voltage values of the PV system to ascertain new maximum values in response to any changes. When the PV system power undergoes a 20% alteration from its prior value, the new maximum power point is automatically identified. The results showcased in Figure 10 affirm that the proposed method not only exhibits the swiftest global MPP attainment time but also demonstrates minimal oscillation amplitude. The amplitude of oscillation is mitigated due to the subsequent loop power values gradually converging toward the global MPP. These notable merits underscore the superiority of the proposed method when compared to the PSO and GWO methods [11], [26] and other methods [5], [7], [27], [28]. These results are displayed in Table 3.
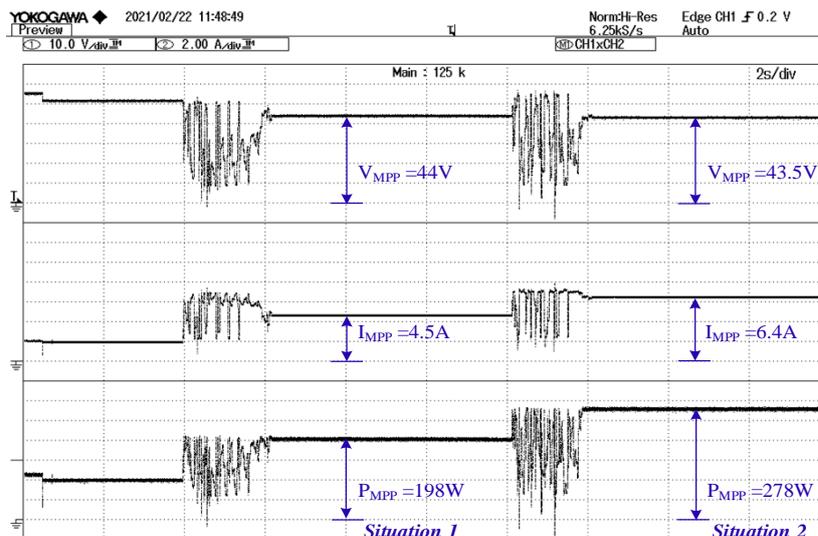
Figure 8. Conventional GWO method under PSCs
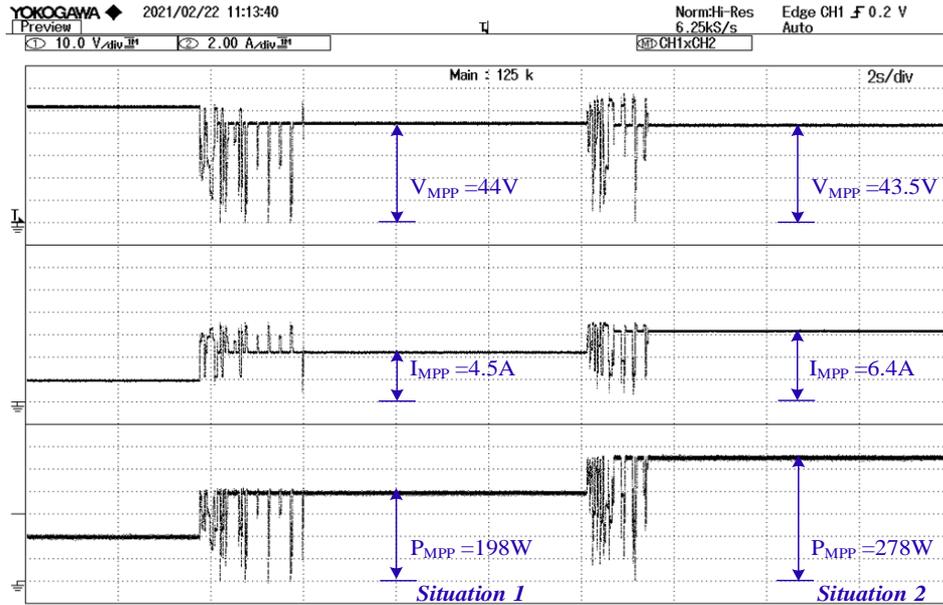
Figure 9. Conventional PSO method under PSCs
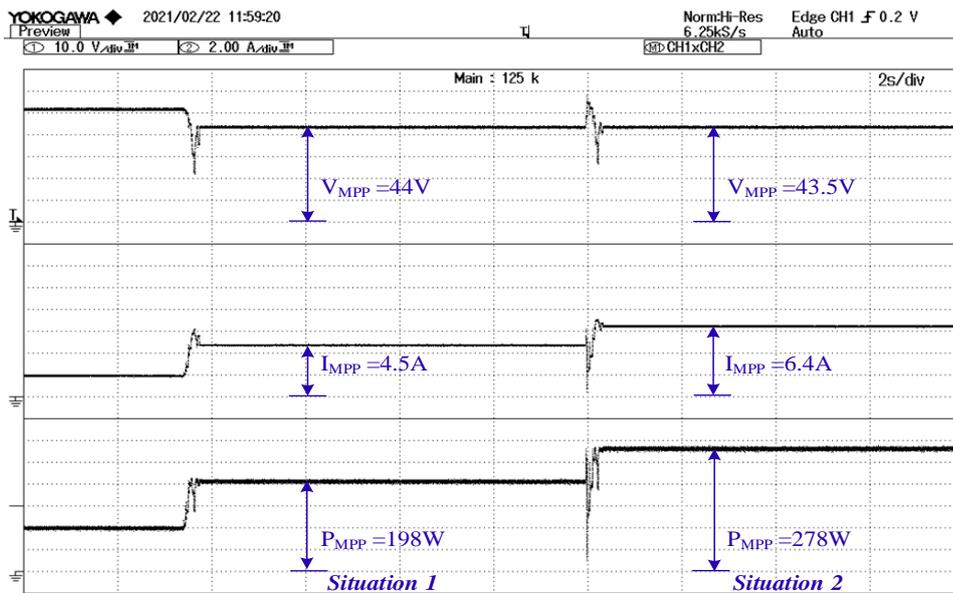
Figure 10. Proposed hybrid method under PSCs

Table 3. Comparison of the experimental results of different algorithms

MPPT method	Enhanced GWO in [11]	GWO-GSO [27]	Improved In-Cond in [5]	Improved CS in [28]	Adjustment PSO in [26]	Proposed method
Convergence time of simulation results (s)	2.63 – 2.85	0.54 – 1.24	0.70 – 0.85	0.35 - 0.48	1.51 – 1.93	0.35 - 0.42

4. CONCLUSION

In this paper, a self-contained PV power system was employed in conjunction with the proposed integrated methodology. By organizing and segmenting the operational domain, the initial-stage duty ratio values have been strategically managed to prevent susceptibility to the limitations encountered in conventional

methods. In addition, the selection of several high-ranking GWO locations to update the new location significantly reduced the search time for the global maximum power zone. The combination with the IC method is also a new idea to quickly find the global MPP and always pursue to this MPP when the illuminance intensity has a small change. This hybrid methodology addresses the drawbacks inherent in conventional MPP tracking techniques within partially shaded conditions. The outcomes garnered from both simulation and experimental trials affirm that the proposed approach not only proficiently circumvents local MPP challenges but also expeditiously attains optimal PV energy conversion capabilities. Furthermore, the swiftness of convergence and the straightforward nature of value updates stand out as salient features of this novel method, distinguishing it from conventional GWO, PSO, and In-Cond methods.

APPENDIX
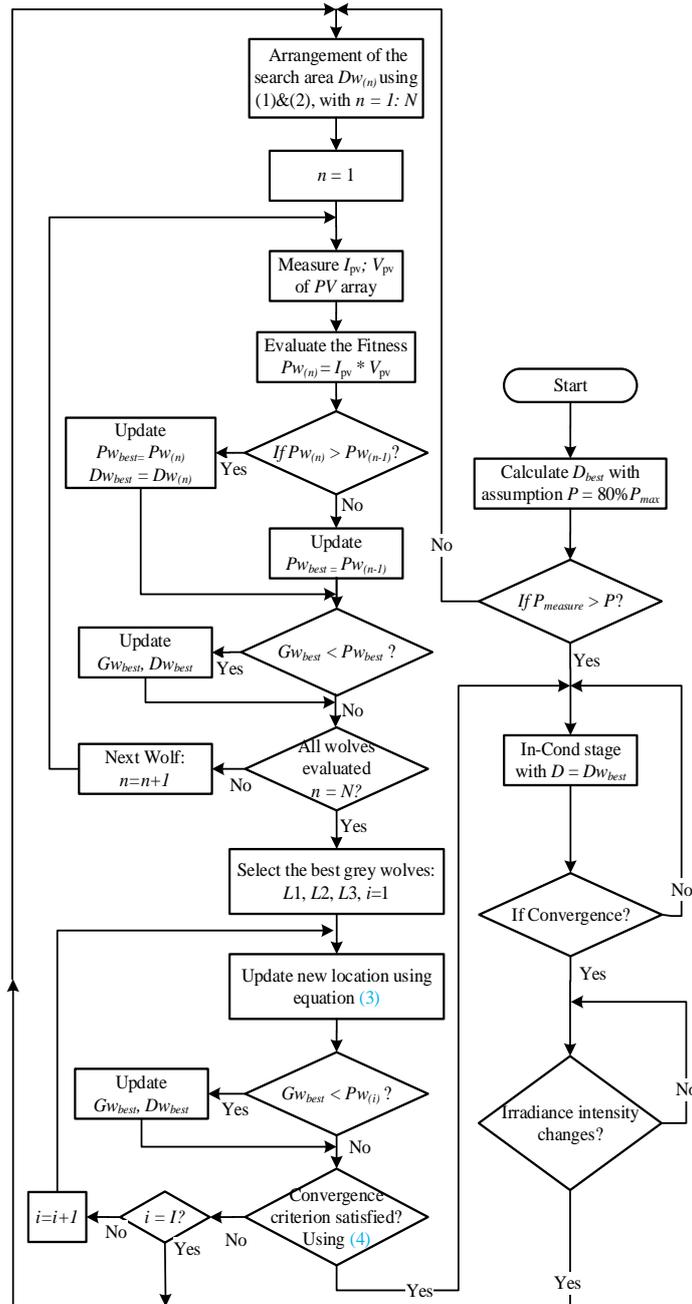
Figure 2. Flow chart of the proposed hybrid method

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