New Hybrid HRA MPPT Strategy for Stand-Alone PV Energy Conversion Systems

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A R T I C L E I N F O

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A B S T R A C T

This study proposes a hybrid maximum power point tracking (MPPT) approach designed for photovoltaic systems operating under partial shading conditions. The method integrates a horse-racing-inspired algorithm with an improved incremental conductance (IInC) technique, enabling precise tracking of the global maximum power point and quick adaptation to changes in weather conditions. Simulation results demonstrate superior performance compared to conventional techniques. The hybrid solution reaches the global MPP within 0.68 seconds with 100 percent accuracy. In contrast, the traditional incremental conductance approach fails to reach the global point, requiring 0.48 seconds and delivering an efficiency between 80.28 and 96.80 percent. The grey wolf algorithm (GWA) needs 1.00 second to achieve 99.44 percent accuracy. Furthermore, steady-state oscillations are effectively eliminated by the proposed approach. These outcomes indicate strong applicability under dynamic environmental conditions and potential for real-world implementation.

1. INTRODUCTION

Renewable energy sources are increasingly receiving attention from investors as well as scientists. Among them, wind energy and solar energy are the two main energy sources that receive the most attention. Wind turbines with a capacity of megawatts (MW) are installed in favorable areas [1]. However, the cost of installing and operating wind turbines is very high, not suitable for households and small businesses. In recent years, there has been a significant rise in the popularity of solar energy as one of the leading renewable resources, emerging as a prominent energy source among renewable energy sources. Its widespread adoption can be attributed to a number of attractive advantages, especially free and abundant solar energy, coupled with ease of installation and low maintenance costs. Solar energy fields are being built everywhere, from urban to rural areas, especially in areas with low agricultural productivity, where agricultural production has difficult terrain and unfavorable weather conditions. Typically, author Thanh Ba Nguyen et al evaluated the feasibility of grid-connected residential solar power projects in 7 regions of Vietnam [2]. The convenience of solar energy has motivated researchers to focus on finding solutions to effectively harvest this energy source [3, 4].

To make the most of solar energy, many solutions have been proposed. Authors T. M. Yunus Khan et al. and M.A.A. Mamun et al. [5, 6] researched the optimal configuration to extract the highest possible energy output from solar-based systems. However, this system only applies to small-scale production and business households. When this solution is applied to large PV power systems, installation and operating costs are very expensive. To reduce installation and operating costs, researchers focus on software solutions to find the MPP for photovoltaic (PV) power systems. Salah Necaibia et al. proposed a novel control approach was introduced to divide the system into two distinct operational zones [7]. I where each zone applies a unique step size for improved responsiveness. Due to this strategy, some disadvantages of the conventional InC method are eliminated. This solution is very effective in reducing the oscillation amplitude around the MPP, but it still takes a lot of searching time. Besides, other method for optimizing the MPP of PV system using improved InC method operating under different dynamic weather effects was proposed by M. Elzein et al [8]. The tracking system can deliver high overall energy efficiency along with a minimal oscillation around the MPP. However, this solution is only considered at the optimal assessment level when the radiation intensity is uniform on the solar PV panel system. Furthermore, Sy Ngo et al [9] proposed a new MPPT approach grounded in the InC method, tailored specifically for scenarios involving partial shading. This algorithm demonstrated significant advantages over existing methods, including high precision for global MPP tracking and a significant reduction in oscillation amplitude around the MPP. However, as the

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number of participating groups rises, the time required for this method to identify the global MPP remains considerably lengthy. Some other traditional methods have been improved to quickly find the MPP. Nevertheless, the method continues to exhibit substantial oscillations in the vicinity of the maximum power point [10, 11]. Besides, many metaheuristics methods have been proposed to exploit PV power systems effectively. However, if the methods converge quickly, they are limited by the oscillation amplitude around the MPP and vice versa [12-18]. A new trend in research to find global MPP is to use hybrid methods that combine metaheuristics methods with traditional methods or two metaheuristics methods together [19, 20]. There, metaheuristic algorithms are employed to explore the global maximum power region, whereas conventional techniques tend to follow the most dominant peak within that region [21-23]. However, these algorithms are not adaptable to the real environment when the convergence speed is still slow. Several other solutions have been mentioned in [24-29], which effectively address the performance as well as convergence speed in the global MPP search. However, they still have some limitations such as complex calculations, high memory consumption, etc.

Taking into account both the strengths and the unresolved issues of previous approaches, this research introduces a hybrid MPPT method that blends horse-racing-inspired competition with the precision of the traditional InC technique. The new hybrid method, called new hybrid HRA MPPT strategy for stand-alone PV energy conversion systems, is inspired by the competitive nature of horse racing, in which each individual "horse" (or candidate) tries to achieve the leading position. In an MPP tracking situation, this competitive spirit is leveraged to rapidly and precisely pinpoint the global maximum power zone, while simultaneously minimizing both tracking time and output fluctuations. By incorporating the horse racing algorithm (HRA) into the improved InC method, the proposed hybrid method significantly enhances MPPT capabilities. The HRA rapidly identifies the global neighborhood of the MPP, while the InC method precisely pinpoints the MPP within this area. This synergistic approach markedly boosts the efficiency and performance of solar power systems, as demonstrated through simulation outcomes. To evaluate the practicality of this MPPT technique, a standalone solar power system was implemented for testing purposes, comprising solar panels, a boost converter, a standalone DC load, and an Arduino board for controlling pulse width modulation (PWM).

2. PROPOSED HYBRID METHOD

2.1. HRA method

The horse racing algorithm (HRA), initially introduced by S Ngo et al. [30], was designed to emulate the principles of competitive horse racing in order to locate the global maximum power point (MPP) in solar energy systems. This method operates in two main phases. The first phase, termed "qualifying," focuses on scanning and identifying the global power region. Upon completing this phase, the most effective candidates (racehorses) are selected for the second phase of evaluation, called the final ranking stage. In this proposed method, the qualifying phase is applied to explore the global power region. Following this, the enhanced InC technique is applied to efficiently extract the global maximum power point from the PV system. The earlier qualifying stage of the horse racing algorithm is utilized to determine the most suitable racehorses, as outlined below.

First, the racehorse is positioned as described in Equation 1.

$$L_{hr(g,i)} = \left[(L_{\min} + (hr-1)(L_{\max} - L_{\min}) / Hr) \quad \dots \quad (L_{\min} + hr(L_{\max} - L_{\min}) / Hr) \right] \tag{1}$$

In this equation, both $L_{\min}$ and $L_{\max}$ correspond to multiples of 100 derived from the minimum and maximum duty ratios, $D_{\min}$ and $D_{\max}$, respectively. The parameter hr (where $hr = 1, 2, ..., Hr$) denotes the number of horses within a group, while $gr = 1, 2, ..., Gr$ represents the grouping count. The iteration index $i = 1, 2, ..., I$ stands for the number of laps. Once the initial area is divided, each racehorse is allowed to move randomly within its designated region. This randomized movement is described by Equation 2.

$$d_{hr(gr,i)} = randi(L_{hr(gr,i)}) / 100 \tag{2}$$

Once each lap concludes, Inequality 3 is applied as a filtering criterion to remove the racehorses with lower power outputs, thereby shortening the duration needed to locate the global MPP. This inequality reflects empirical tuning in selecting the most suitable η value for advancing racehorses to subsequent laps.

$$P_{hr(gr,i)} > \eta * P_{b\_1} \tag{3}$$

where, $P_{b\_1} = \max(P_{hr(gr,i)})$ denotes the highest power output among all racehorses. A subsequent lap is triggered if Inequality 4 is violated, indicating that the top three racehorses have yet to converge within a single global maximum power region. Once the condition specified by Inequality 4 is fulfilled, the race concludes, as expressed below:

$$\left| d_{hr(gb\_\beta)} - d_{hr(gb\_1)} \right| \le \varepsilon \cdot \partial d_{hr} \tag{4}$$

The value of ε is empirically determined through simulation and is inversely proportional to the number of racehorses per group. The term $\partial d_{hr} = (D_{\max} - D_{\min}) / Hr$ specifies the span of the track assigned to each horse. If Inequality 4 is not met, it indicates that the leading racehorses are dispersed across separate local maxima regions, meaning the global power area remains unresolved.

To continue refining the search, racehorses advancing to the next lap are relocated to new randomized positions near their previous starting points, enabling a focused search around potential optima. This concept is executed by shifting the position of the top three contenders to the left and right, allowing the algorithm to pinpoint the best location before the next lap begins. The procedure is formalized in Equation 5.

$$d_{b\_\alpha} = d_{b\_\alpha} + (-1)^k \cdot k \cdot randi(L_s)/(2\cdot 100) \quad (5)$$

The value of L_s is determined using the following expression: $L_s = 100[D_{\min}, D_{\max}]/Hr$, where $k = 1$ corresponds to a shift to the right and $k = 2$ to a shift to the left. The index $\alpha = 1$ to 3 denotes the top three performing racehorses in each lap. These movements form the basis for the subsequent search adjustments. Following these movements, the top-performing racehorses are reassessed to identify new optimal positions. This strategy gathers the leading racehorses, directing them to converge toward a position that meets the condition outlined in Inequality 4. Simultaneously, to avoid stagnation in local optima, the algorithm revises the positions of the remaining qualified candidates for the next iterations using the principle formulated in Equation 6:

$$d_{b\_1(gr,i+1)} = d_{b\_1(gr,i)} + \lambda \cdot randi(L_s)/100 \quad (6.a)$$

$$d_{hr(gr,i+1)} = \begin{cases} d_{hr(gr,i)} - \partial d_{plus}/2; \text{ for } d_{hr(gr,i)} > d_{b\_1} \\ d_{hr(gr,i)} + \partial d_{plus}/2; \text{ for } d_{hr(gr,i)} < d_{b\_1} \end{cases} \quad (6.b)$$

In the above equation, d_{b_1} is the first best racehorse; ∂d_{plus} is is defined as the distance between the best and worst racehorses: $\partial d_{plus} = |d_{b\_1} - d_{worst}|$; λ is the adjustment coefficient and this value is less than 0.5. A schematic overview of the proposed hybrid strategy is presented in Figure 1 to highlight its operational process.

2.2. IInC algorithm

Not derived from the initial duty ratio position like the traditional InC method, the proposed hybrid method receives a duty ratio value from the HRA algorithm, which means that the estimated MPP is at or close to the global MPP. This results in a shorter global MPP search time. Moreover, refining the coefficient V after each step (S) leads to a significant reduction in oscillation amplitude. The step size (V) decreases by 25% with every step (S).

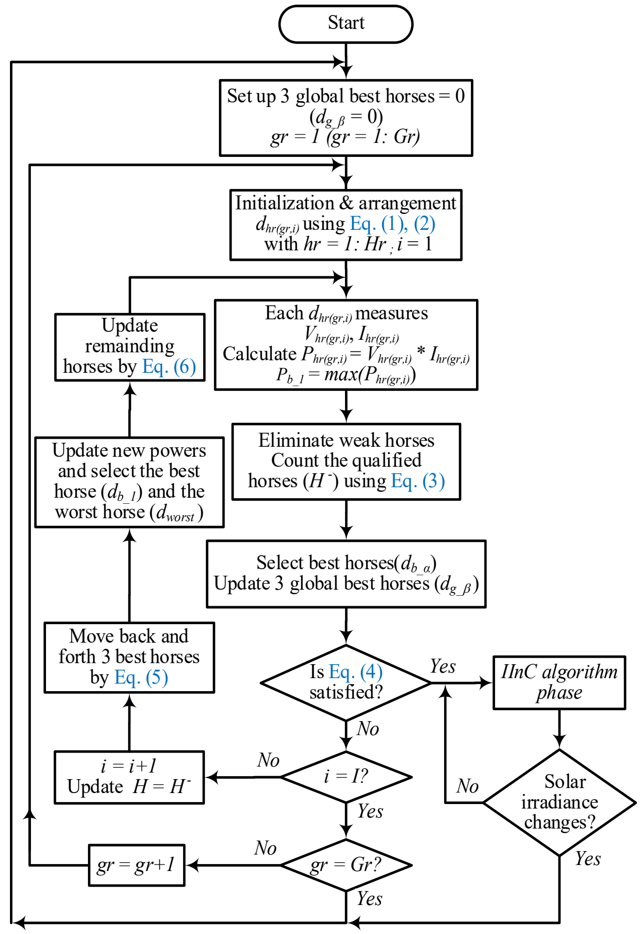

Fig. 1. Block diagram illustrating the structure of the hybrid MPPT algorithm.

Beginning with an initial step size Δd, the value gradually decreases and reaches approximately 0.017* Δd by the 14th iteration. A step reduction formula, constructed using Microsoft Excel, is presented in Figure 2 and defined as:

$$V = 1.3333^{e^{-0.288*S}} \quad (7)$$

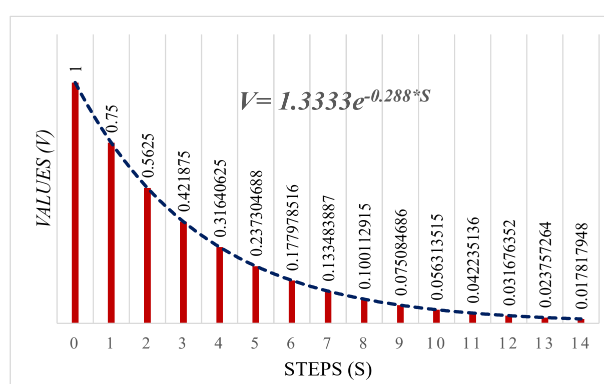

Fig. 2. The proposed decreasing step size.

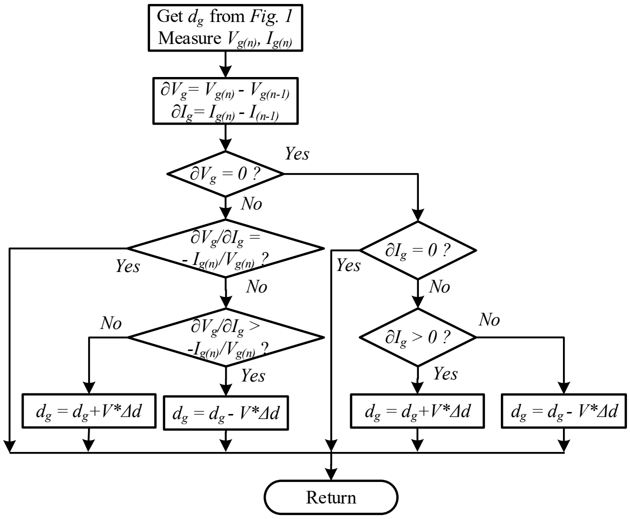

Fig. 3. Flowchart of IInC algorithm.

Unlike the conventional InC approach, where the step size remains fixed throughout the tracking process, this concept introduces dynamic step size adjustment. A visual representation of the improved IInC algorithm can be found in Figure 3.

3. SIMULATION RESULTS AND DISCUSSION

A simulation model representing the power conversion system is established to validate both the efficiency and applicability of the proposed hybrid method, as shown in Figure 4. This model is composed of four main sections: the PV panel module, the control unit, the boost converter, and the load component. The PV section comprises several solar panels arranged in series. By applying the developed algorithm, the control unit determines an appropriate duty cycle to operate the boost converter. The boost converter is built using an inductor, a switching MOSFET, and a fast-recovery diode.

As for the load, it is modeled as an isolated resistive element. The specifications of the PV panels are provided in Table 1.

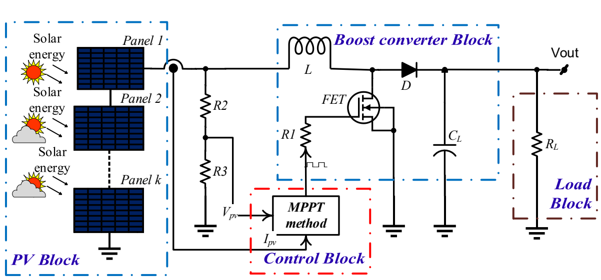

Fig. 4. Power conversion model for stand-alone PV energy system.

Table 1. Parameters of the Photovoltaic panel 165.34 W

PV Data	Value
Maximum output power (P_{max})	165.54W
Maximum operating current (I_{max})	4.65A
Maximum operating voltage (V_{max})	35.6V
Open circuit voltage (V_{oc})	43.2V
Short circuit current (I_{sc})	5.2A
PV cell in series (N_s)	72
PV cell in parallel (N_p)	1

3.1. Case of three serial PV panels for the power systems

In this situation, three distinct power peaks are observed on the P–V characteristic curves. The presence of multiple local maxima complicates the process of identifying the global maximum power point (MPP). To validate the performance of the proposed hybrid approach, two partial shading test cases with varying intensities are established. 100/60/35 mW/cm^2 are the irradiation intensities set for scenario 1. Scenario 2 is simulated with irradiation intensities of 100/85/50 mW/cm^2. The P-V curves showing the results of these radiation intensities are shown in Figure 5. In the plotted curves, the top three initial racehorses are indicated by green squares in the first scenario and pink squares in the second scenario. The search results for the three best updated racehorses are labeled blue circles for scenarios 1 and 2. With the assistance of the IInC method, the global MPP is found with a red star symbol. As illustrated in Figure 5, the three updated leading racehorses have successfully converged toward the global maximum power region, despite starting from distinct initial locations. However, they have not yet occupied the top of this global region. The global peak is achieved with the help of the IInC method which takes advantage of the fast convergence rate of the traditional InC method and reduces the oscillation amplitude around the MPP from the proposed IInC method. The global MPP exploration and exploitation process of the hybrid method, the grey wolf algorithm (GWA)[12], and the traditional InC method are shown in detail in Figures 6, 7, 8, respectively.

As presented in Figures 6 through 8, the proposed hybrid method successfully located the global MPP, achieving output powers of 212.3 W and 294.1 W, with corresponding convergence times of 0.64 s and 0.68 s for scenarios 1 and 2, respectively. Meanwhile, the traditional InC method falls into the local power peak and reaches power 191.9W, 277.0W and time 0.60, 0.38 seconds respectively for scenarios 1, 2. The GWA method also has the same power as the proposed hybrid method but is more time consuming. For scenarios 1 and 2, the GWA method required 0.98 s and 1.00 s, respectively, to reach the corresponding power levels. Moreover, the proposed hybrid approach demonstrated a notable reduction in oscillation amplitude around the MPP when compared to the conventional InC technique. Figures 6d,e and 8d,e present the visual representation of these findings, while Table 2 offers a comprehensive comparison of the evaluated techniques.

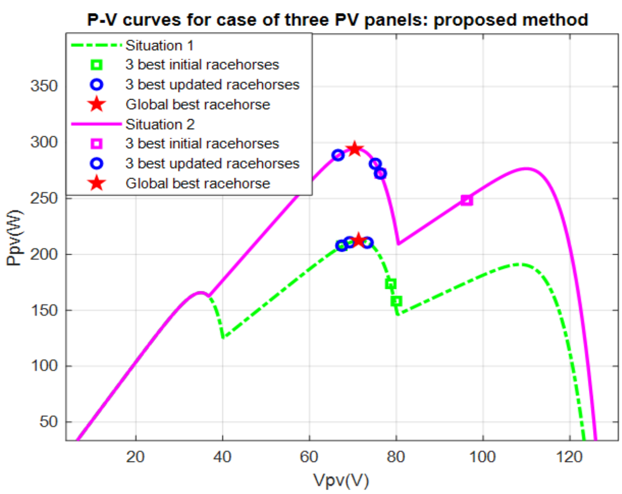

Fig 5. P-V curves for case of three PV panels.

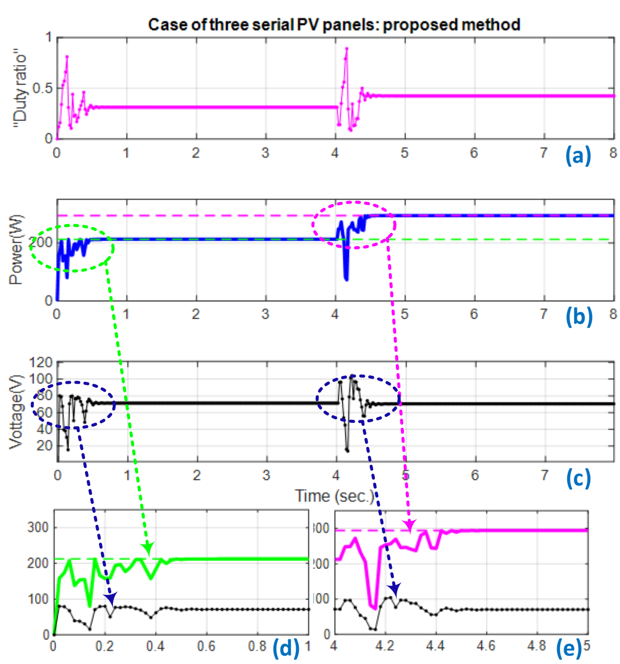

Fig 6. Simulation results for case 1 using the hybrid MPPT method: (a) duty ratio, (b) photovoltaic power, (c) PV voltage, and (d), (e) transient responses under scenarios 1 and 2, respectively.

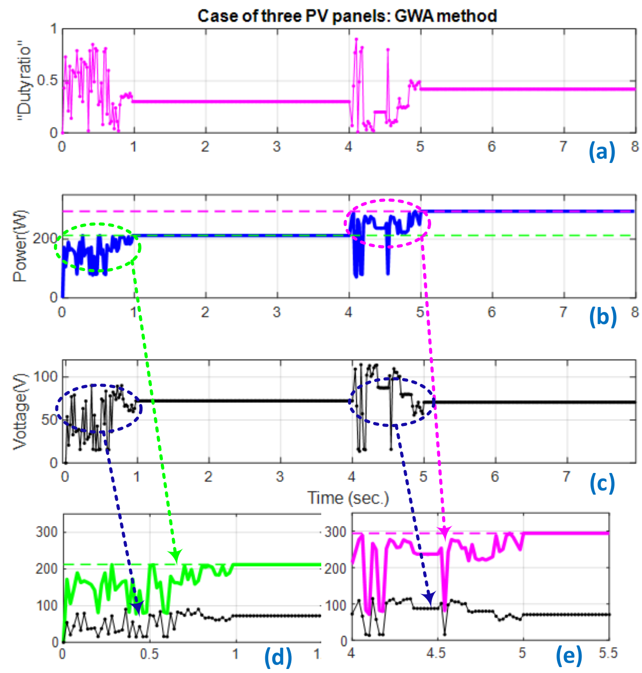

Fig 7. Simulation results for case 1 using the GWA MPPT method: (a) duty ratio, (b) photovoltaic power, (c) PV voltage, and (d), (e) transient responses under scenarios 1 and 2, respectively.

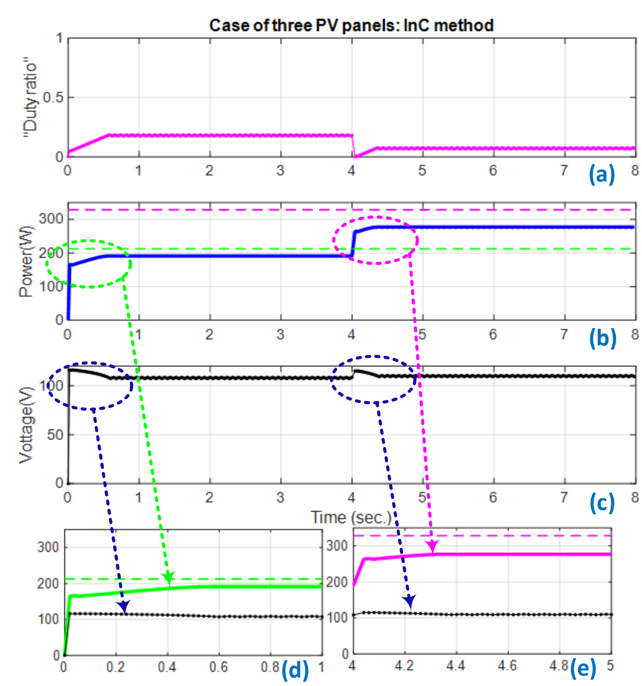

Fig. 8. Simulation results for case 1 using the traditional InC MPPT method: (a) duty ratio, (b) photovoltaic power, (c) PV voltage, and (d), (e) transient responses under scenarios 1 and 2, respectively.

Table 2. Comparison of MPPT methods for case 1

Case 1		Case of three serial PV panels	
		Situation 1	Situation 2
Illuminance intensity (mW / cm^2)		100/60/35	100/85/50
Ideal power at global MPP (W)		212.3	294.1
Proposed method	Harvested Power (W) (Efficiency %)	212.3 (100 %)	294.1 (100 %)
	Convergence time (s)	0.64	0.68
GWA method	Harvested Power (W) (Efficiency %)	212.3 (100 %)	294.1 (100 %)
	Convergence time (s)	0.98	1.00
InC method	Harvested Power (W) (Efficiency %)	191.9 (90.39 %)	277.0 (94.17 %)
	Convergence time (s)	0.60	0.38

3.2. Case of four serial PV panels for the power systems

When partially shaded, PV panels will receive different irradiation intensities. As a result, many local power peaks are generated. In this case, four different irradiation intensities are set on the PV system such that the global power peak and the nearest local power peak do not deviate by more than 5% of the global power peak. This is a challenge for MPPT methods in the process of searching for the MPP. The set values of the illuminance intensity are 100/85/60/35 mW / cm^2 , 100/95/80/55 mW / cm^2 for situations 1, 2, respectively, and the resulting power are shown in Figure 9. The symbols on the P-V curves are explained as in the above case.

As observed in Figure 9, similarly to what was illustrated in Figure 3, although the top three initial racehorses were positioned in separate regions under scenario 1, the application of the HRA technique led to their convergence within the global maximum power zone, even though their updated locations had not yet reached the absolute peak within that region. The IInC algorithm will capture the best location and execute the proposed IInC method to reach the top of this global region. Search results are marked with red stars on the P-V curves. The exploration process using the improved HRA method to reach the global power takes about 0.42 to 0.46 seconds, then using the proposed IInC method takes about 0.22 to 0.26 seconds to exploit the maximum peak of the global region. This combination has brought about the effect of fast speed as well as reduced oscillation amplitude as mentioned in the above case.

As illustrated in Figures 10–12, the hybrid technique demonstrates superior capability in locating the global MPP with minimal fluctuation, outperforming both GWA and InC methods. In contrast, the conventional InC method struggles with local power peaks and exhibits significant oscillation around the MPP. Detailed simulation results for the proposed method, GWA, and traditional InC methods are presented in Table 3. Furthermore, A detailed comparison in Table 4 highlights the differences in convergence speed and global MPP tracking efficiency among the proposed method and other contemporary algorithms.

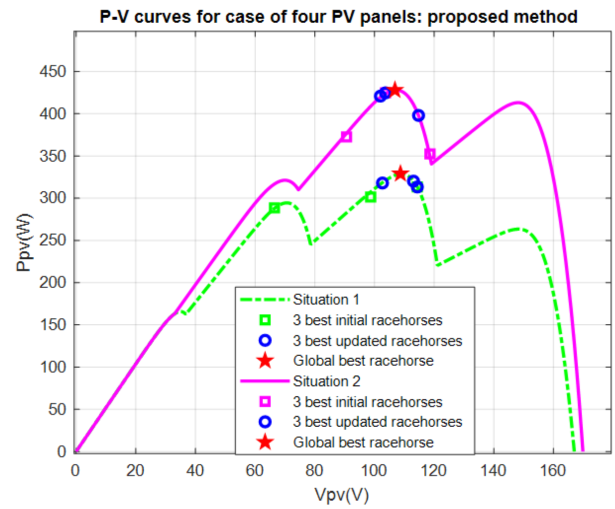

Fig. 9. P-V curves for case of four PV panels.

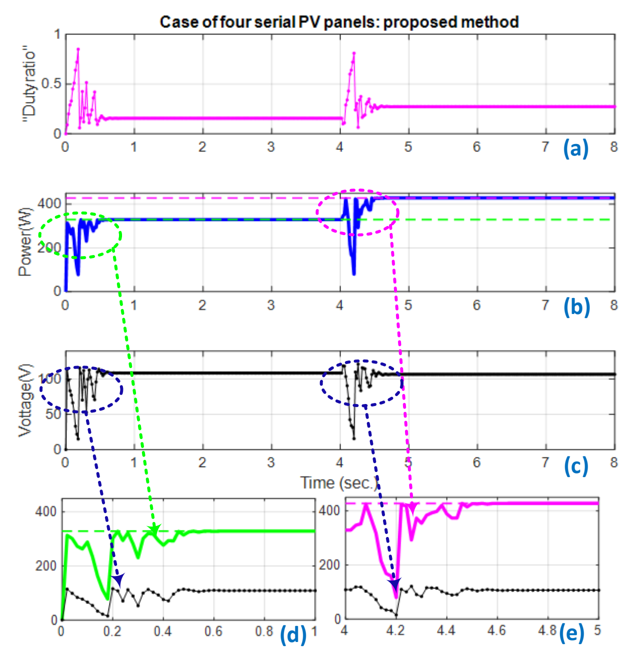

Fig 10. Simulation results for case 2 using the hybrid MPPT method: (a) duty ratio, (b) photovoltaic power, (c) PV voltage, and (d), (e) transient responses under scenarios 1 and 2, respectively.

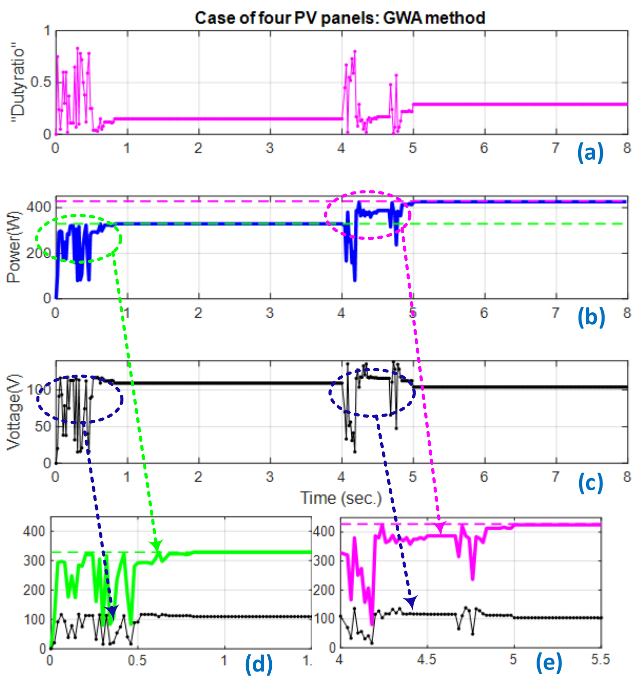

Fig 11. Simulation results for case 2 using the GWA MPPT method: (a) duty ratio, (b) photovoltaic power, (c) PV voltage, and (d), (e) transient responses under scenarios 1 and 2, respectively.

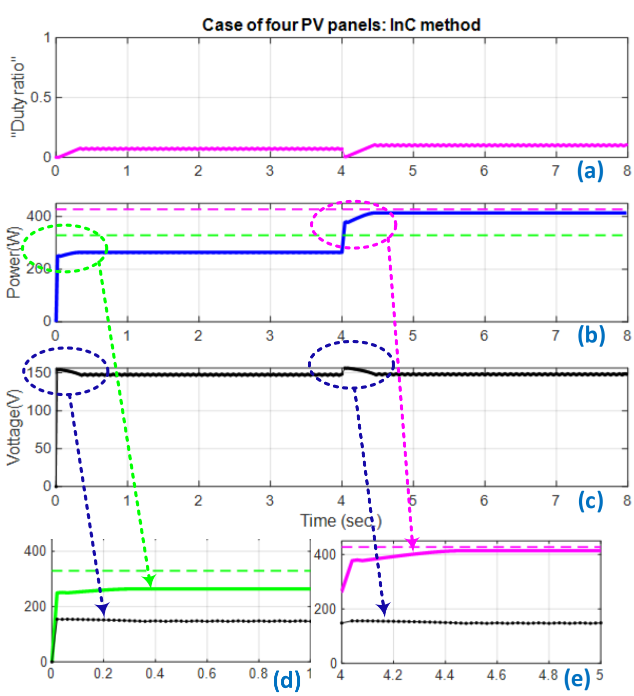

Fig 12. Simulation results for case 2 using the traditional InC MPPT method: (a) duty ratio, (b) photovoltaic power, (c) PV voltage, and (d), (e) transient responses under scenarios 1 and 2, respectively.

Table 3. Comparison of MPPT methods for case 2

Case 2		Case of four serial PV panels	
		Situation 1	Situation 2
Illuminance intensity (mW / cm^2)		100/85/60/35	100/95/80/55
Ideal power at global MPP (W)		328.9	427.7
Proposed method	Harvested Power (W) (Efficiency %)	328.9 (100 %)	427.7 (100 %)
	Convergence time (s)	0.68	0.68
GWA method	Harvested Power (W) (Efficiency %)	328.9 (100 %)	425.3 (99.44 %)
	Convergence time (s)	0.82	1.00
InC method	Harvested Power (W) (Efficiency %)	264.0 (80.28 %)	414.0 (96.80 %)
	Convergence time (s)	0.36	0.48

Table 4. Comparison of different methods

Method	Convergence time (s)		Steady state oscillation
CS in reference [31]	0.42 – 0.65		Low
MBO in ref. [32]	4.00 – 4.50		High
Hybrid SFLA in reference [22]	0.68 – 0.72		Low
Improved GWA in reference [33]	3.40 – 5.80		Zero
ELPSO-P&O in reference [34]	0.50 – 0.68		Moderate
Proposed hybrid method	0.64 – 0.68		Zero

4. CONCLUSIONS

Under partially shaded conditions, the horse-racing-inspired hybrid InC algorithm efficiently locates the global MPP, delivering faster convergence and better performance compared to standard InC and GWA techniques. Simulations indicate that the proposed method reduces search time to just 68% to 78% of that required by the GWA technique. Furthermore, the oscillation amplitude in the hybrid method is significantly lower than in the traditional InC approach. This reduction is crucial for experimental models, as excessive oscillations can damage electronic components operating under high power and frequency. The efficiency of method would be further validated through experimental testing. This is also a limitation that we will implement in the future.

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