UDC 621.3 https://doi.org/10.20998/2074-272X.2025.5.03

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Maximum power point tracking improving of photovoltaic systems based on hybrid triangulation topology aggregation optimizer and incremental conductance algorithm

Introduction. *Maximum power point tracking (MPPT) in photovoltaic (PV) systems has been a key research focus in recent years. While numerous techniques have been proposed to optimize power extraction, each suffers from inherent limitations that hinder their effectiveness.* ***Problem.*** *Environmental factors such as shading, partial shading, and low irradiance levels significantly impact PV system performance, with partial shading being the most critical and complex challenge due to its creation of multiple local power maxima.* ***Goal.*** *This study aims to improve MPPT in PV systems under partial shading conditions by developing a hybrid approach that integrates a Triangulation Topology Aggregation Optimizer (TTAO) with the Incremental Conductance (IC) algorithm.* ***Methodology.*** *Simulations were conducted in MATLAB/Simulink under four static partial shading scenarios, comparing the hybrid TTAO-IC algorithm against traditional methods like Perturb and Observe (P&O), IC and metaheuristic algorithms.* ***Scientific novelty*** *of this work lies in the hybrid TTAO-IC algorithm, which combines the global optimization strength of TTAO with the precision of IC, addressing the shortcomings of conventional methods.* ***Practical value****. The results show that the hybrid TTAO-IC algorithm achieves tracking efficiencies exceeding 99 %, outperforming existing methods and demonstrating robust adaptability to varying environmental conditions.* References 31, tables 5, figures 15.

Key words: **solar photovoltaic system, triangulation topology aggregation optimizer, maximum power point tracking, global maximum power point, partial shading conditions.**

Вступ*. Відстеження точки максимальної потужності (MPPT) у фотоелектричних (PV) системах є ключовим напрямком досліджень в останні роки. Хоча було запропоновано численні методи оптимізації отримання енергії, кожен з них має певні обмеження, що зменшують їх ефективність.* ***Проблема****. Фактори навколишнього середовища, такі як затінення, часткове затінення та низький рівень опромінення, суттєво впливають на продуктивність PV системи, причому часткове затінення є найбільш критичною та складною проблемою через створення кількох локальних максимумів потужності.* ***Мета****. Це дослідження спрямоване на покращення MPPT у PV системах в умовах часткового затінення шляхом розробки гібридного підходу, який інтегрує оптимізатор агрегації топології триангуляції (TTAO) з алгоритмом інкрементальної провідності (IC).* ***Методологія****. Моделювання проводилося в MATLAB/Simulink за чотирма статичними сценаріями часткового затінення, порівнюючи гібридний алгоритм TTAO-IC з традиційними методами, такими як метод збурень та спостережень (P&O), IC та метаевристичними алгоритмами.* ***Наукова новизна*** *роботи полягає в гібридному алгоритмі TTAO-IC, який поєднує глобальну оптимізаційну силу TTAO з точністю IC, усуваючи недоліки традиційних методів.* ***Практична цінність****. Результати показують, що гібридний алгоритм TTAO-IC досягає ефективності відстеження, що перевищує 99 %, перевершуючи існуючі методи та демонструючи надійну адаптивність до різних умов навколишнього середовища.* Бібл. 31, табл. 5, рис. 15.

Ключові слова: **сонячна фотоелектрична система, оптимізатор агрегації топології тріангуляції, відстеження точки максимальної потужності, глобальна точка максимальної потужності, умови часткового затінення.**

Introduction. Photovoltaic (PV) systems play a key role in the global energy transition by harnessing solar energy to generate electricity. Using semiconductor devices, these systems directly convert solar energy into electricity. However, the conversion efficiency typically ranges from 10 % to 25 % of the total incident solar power, highlighting the importance of optimizing power extraction to maximize energy efficiency. In this context, Maximum Power Point Tracking (MPPT) algorithms have become essential tools for achieving this goal. Since their inception in the 1950s, MPPT strategies have continuously evolved to address growing challenges, such as irradiance fluctuations, temperature variations, and partial shading effects [1]. Traditional approaches, particularly the Perturb and Observe (P&O) and Incremental Conductance (IC) methods, dominated early generations of MPPT systems due to their simplicity and effectiveness under stable conditions. However, these methods have significant limitations when applied to dynamic or complex environments. These limitations include slow convergence, inadequate tracking accuracy, and an inability to effectively manage partial shading scenarios [2–4]. To overcome these challenges, innovative approaches based on metaheuristic and hybrid algorithms have been developed. Methods such as Particle Swarm Optimization (PSO), Cuckoo Search (CS) [5] and Grey Wolf Optimization (GWO) [6] have proven to be particularly promising. These algorithms allow for a more accurate localization of the Global Maximum Power Point (GMPP), while improving convergence speed and reducing steady-state oscillations [7, 8]. Additionally, advanced variants, such as modified PSO, Plant Propagation Algorithm (PPA), and hybrid solutions like Radial Basis Function Neural Network based on PSO (PSO-RBFNN), have demonstrated their ability to achieve energy yields above 99 %, even in variable and complex weather conditions [9–12]. The emergence of artificial intelligence in MPPT strategies has marked the beginning of a new era of innovation. Algorithms based on artificial neural networks, combined with hybrid techniques like PSO-RBFNN, help address complex challenges while enhancing the reliability and speed of systems [13, 14]. Previous work, such as the study by [15], introduced improvements to traditional methods. For instance, an optimized version of the P&O algorithm achieved an energy efficiency of 96 % under uniform atmospheric conditions, but it did not account for the effects of non-uniform conditions. Simultaneously, advancements in DC-DC converter design, such as high-voltage gain converters with soft switching, have significantly contributed to improving the energy efficiency of grid-connected PV systems [16].

Moreover, advanced control strategies, such as Terminal Sliding Mode Controllers (TSMC), hybrid PSO-TSMC algorithms, and approaches utilizing fuzzy logic and fractional-order controllers, offer enhanced robustness. These solutions stand out for their ability to reduce oscillations, improve system stability, and provide a quick response to environmental changes [17–20]. Given the variety of available methods and the rapid advancements in the field, it is crucial to evaluate and compare these approaches to determine the most suitable solutions for current challenges. A detailed analysis of existing MPPT techniques is provided, highlighting innovative strategies that integrate metaheuristic algorithms, artificial intelligence, and innovations in converter design, as evidenced by [21–23]. Other efforts, such as those by [24], have proposed variants of the IC algorithm adapted to changing irradiance profiles. Although these approaches have demonstrated promising performance, they remain limited by the lack of experimental validation or their inability to effectively address partial shading scenarios and rapid irradiance variations. A hybrid algorithm combining a wavelet neural network and a cuckoo search algorithm has demonstrated superior performance in predicting PV production, better capturing the chaotic variations of solar radiation [25]. Furthermore, optimizations of the flower pollination algorithm for MPPT under partial shading have led to reduced tracking time and increased efficiency [26]. Another hybrid control approach abbreviated as ACO-ANN, based on a neural network and ant colony optimization, has enhanced MPPT and energy quality in industrial applications [27]. Strategies such as the improved grey wolf optimizer and the super-twisting sliding mode controller have also contributed to significant improvements in robustness and response time under shading conditions [28, 29]. Additionally, a strategy for quickly locating the global peak in PV systems under partial shading conditions, without particle reset, has been introduced, reducing convergence time by 650 % compared to traditional PSO reset methods and avoiding premature convergence [30]. However, despite the progress made, a major limitation remains for many MPPT techniques: their inefficiency in the face of slow or sudden changes in ambient temperature and solar irradiance. This highlights the need for even more robust and adaptive algorithms.

Goal. This study aims to improve MPPT in PV systems under partial shading conditions by developing a hybrid approach that integrates a Triangulation Topology Aggregation Optimizer (TTAO) with the IC algorithm. By integrating the global optimization capabilities of TTAO with the precision of the IC method, the proposed TTAO-IC algorithm addresses the limitations of traditional MPPT techniques, such as P&O and standalone IC, which often struggle with local optima, oscillations, and slow convergence under non-uniform irradiance. The goal is to provide a robust, efficient, and reliable solution for improving energy extraction in PV systems, particularly in large-scale deployments where partial shading is a common challenge. Simulation results demonstrate the superior performance of TTAO-IC, particularly in cases where conventional methods fail to converge to GMPP. The algorithm achieves tracking efficiencies exceeding 99 % across diverse partial shading conditions, highlighting its robustness and reliability. Key advantages of the TTAO-IC algorithm include:

- Rapid convergence to the GMPP, ensuring minimal energy loss during the tracking process.
- Significant reduction in oscillations around the MPP, even under dynamic and non-uniform irradiance conditions.
- Consistently high tracking efficiency, leading to enhanced energy yield and improved overall system performance.

The results from simulations demonstrate the effectiveness of this hybrid algorithm, which combines precision, speed, and robustness. This advancement opens new perspectives for optimizing solar systems, ensuring optimal and reliable energy exploitation.

1. Modelling and analysis.

1.1. PV conversion chain. The MPP is achieved by controlling a DC-DC converter with an MPPT controller (Fig. 1). The MPPT controller optimizes power transfer from the PV system to the load, adapting to varying weather conditions to ensure maximum efficiency.

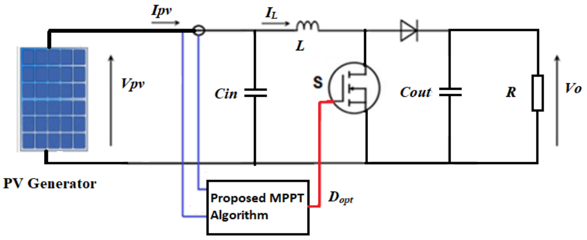

Fig. 1. DC-DC boost converter

PV system is made up of two identical solar panels connected in series, with their electrical specifications (Table 1). Connecting panels in series combines their voltages while maintaining the same current, enabling the system to achieve a higher output voltage. This configuration is particularly useful for applications requiring higher voltage levels, as it reduces the need for voltage amplification by the DC-DC converter.

Table 1

PV panel specifications

Parameter	PV module	PV installation
Maximum power output $P_{\max}$ under standard test conditions (STC), W	213.15	426.3
Open-circuit voltage V_{oc} under STC, V	36.3	72.6
Short-circuit current I_{sc} under STC, A	7.84	7.84
Voltage at the MPP V_{mp} under STC, V	29	58
Current at the MPP I_{mp} under STC, A	7.35	7.35

The electrical parameters of the DC-DC boost converter used in the simulation are provided in Table 2.

Table 2

Boost converter component specifications

Parameter	Value
Inductance L, mH	1.1478
Input capacitor C_{in}, μF	6800
Output capacitor C_{out}, μF	3300
PWM frequency f, kHz	10
Resistive load R, Ω	100

The components of the boost converter are essential to the system's operation and have a direct impact on the performance of the TTAO-IC algorithm. The inductor (L) reduces current ripple, providing a stable power supply, while the input (C_{in}) and output (C_{out}) capacitors ensure smooth voltage levels on both sides of the converter, minimizing disturbances during MPPT. The load resistance (R) simulates power consumption and is crucial for evaluating the converter's energy efficiency. Additionally, the switching frequency (f) influences system responsiveness a higher frequency allows for faster MPPT adjustments but can increase switching losses. Optimizing these parameters is essential for stable converter operation, which in turn improves the accuracy and convergence speed of the TTAO-IC algorithm. This is particularly valuable under challenging conditions, such as partial shading and rapid changes in irradiance.

1.2. PV panel model. A PV cell is represented by the single-diode model. This model can be extended to a PV module by treating it as a group of identical cells connected in series and/or parallel. The model of an individual cell is developed using the widely adopted equivalent electrical circuit (Fig. 2).

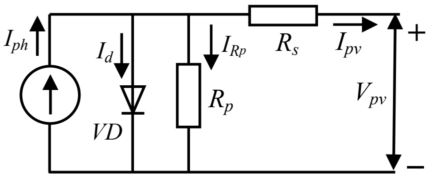

Fig. 2. Equivalent circuit diagram of a single-diode solar cell model

A PV system consists of multiple PV modules that are connected in series and parallel configurations to increase overall power output. The series connection of modules helps increase the system's voltage, while the parallel connection raises the current output [23]. The mathematical model of a PV system is described by a set of equations that represent the electrical behavior and characteristics of the modules under different conditions. These equations consider factors such as the irradiance, temperature, internal resistances, and electrical parameters of the PV cells:

$$I_{pv} = I_{ph}N_p - I_d N_p \times$$
$$\times[\exp(\frac{q(V_{pv}+\frac{I_{pv}R_sN_s}{N_p})}{nN_sk_bT})-1]-\frac{V_{pv}+\frac{I_{pv}R_sN_s}{N_p}}{R_p\frac{N_s}{N_p}} \qquad (1)$$

with
$$V_t = k_bT/q\,; \qquad (2)$$

$$I_{ph} = (I_{sc}+k_i(T-270))\frac{G}{1000}\,; \qquad (3)$$

$$I_d = (I_{dr}(\frac{T}{298})^3\exp[\frac{q.E_q}{N_sk_bV_t}(\frac{1}{298}-\frac{1}{T})]\,, \qquad (4)$$

where I_{ph} is the photocurrent; I_{sc} is the short-circuit current; I_{dr} is the dark saturation current; N_s is the number of series cells; N_p is the number of parallel cells; R_s is the series resistance; R_p is the shunt resistance; V_t is the thermal voltage; q is the electron charge; E_q is the photon energy; k_i is the short-circuit coefficient; k_b is the Boltzmann constant; T is the temperature; G is the irradiance.

1.3. Boost converter. In PV systems, the DC-DC converter is essential for implementing MPPT, ensuring maximum energy capture and enhancing system efficiency, especially in fluctuating environmental conditions. MPPT algorithms work in conjunction with DC-DC converters to fine-tune the system's electrical parameters for optimal power conversion. A widely used DC-DC converter for this purpose is the boost converter, which steps up the output voltage in comparison to the input voltage. The power produced by the PV panel is fed to this boost converter, which is regulated using a PWM signal generated by the MPPT controller. To ensure maximum power extraction from the PV system, the duty cycle (D) of the boost converter is continuously adjusted based on changes in solar irradiation, temperature, and other environmental factors [17]. This dynamic adjustment enables the PV system to maintain operation at or near its MPP. An input capacitor is typically placed on the PV panel side to filter out high-frequency variations and stabilize the current. The optimal duty cycle for the boost converter, which allows maximum power extraction from the PV generator, is determined using specific mathematical relationships and control strategies, based on system parameters and environmental inputs:

$$D_{opt} = 1 - V_{mpp}\Big/\sqrt{P_{mpp}R}\,, \qquad (5)$$

where P_{mpp} is the peak power a PV system can generate while functioning at its MPP; V_{mpp} is the voltage level at which the PV panel operates to achieve maximum power output at the MPP; R is the load's equivalent resistance at the output of the DC-DC boost converter plays a crucial role in determining the efficiency of power transfer; D_{opt} is the ideal duty cycle configuration for the boost converter is essential for efficient MPPT, enabling the PV system to achieve maximum power output.

The MPPT block produces a duty cycle signal to regulate the switching element of the boost converter, which typically functions at an operating frequency of 10 kHz. A boost converter is employed in PV systems to increase the output voltage to a higher level, meeting system requirements. Its straightforward design and ease of control further contribute to its widespread use, as highlighted in [22]. In continuous conduction mode the inductor current and capacitor voltage are typically chosen as state variables. These variables are utilized to derive the averaged model of the boost converter, which can be represented by a set of equations, as illustrated in Fig. 1:

$$\frac{\mathrm{d}I_L(t)}{\mathrm{d}t} = -(1-D)\frac{1}{L}V_0(t)+\frac{1}{L}V_{pv}(t)\,; \qquad (6)$$

$$\frac{\mathrm{d}V_0(t)}{\mathrm{d}t} = (1-D)\frac{1}{C_{out}}I_L(t)+\frac{1}{RC_{out}}V_0(t)\,, \qquad (7)$$

where I_L is the current through the inductor; V_0 is the output voltage across the capacitor C_{out}; V_{pv} is the supply voltage; D is the duty cycle ($\in$ [0, 1]). In the boost converter circuit, the parameters R, L, C_{out} are the load resistance, the input circuit inductance, and the output filter capacitance, respectively.

1.4. Configuration of PV modules under static partial shading conditions. In non-uniform irradiance scenarios, such as shading caused by obstacles like trees, buildings, or passing clouds, PV generator systems may experience partial shading. As illustrated in Fig. 3, this phenomenon leads to a power-voltage (P-V) curve with multiple peaks, representing different maximum power points (MPPs). Among these, one is the GMPP, while the others are classified as local maximum power points (LMPPs). To replicate partial shading conditions, PV panels are exposed to varying irradiance levels, resulting in P-V curves with multiple peaks. To validate our method, a case study under static partial shading conditions is provided, including 4 practical test scenarios for simulation:

1. Scenario 1: a test under STC (1000 W/m^2 at 25 °C).
2. Scenario 2: G_1 = 1000 W/m^2, G_2 = 400 W/m^2 at 25 °C.
3. Scenario 3: G_1 = 800 W/m^2, G_2 = 400 W/m^2 at 25 °C.
4. Scenario 4: G_1 = 600 W/m^2, G_2 = 400 W/m^2 at 25 °C.

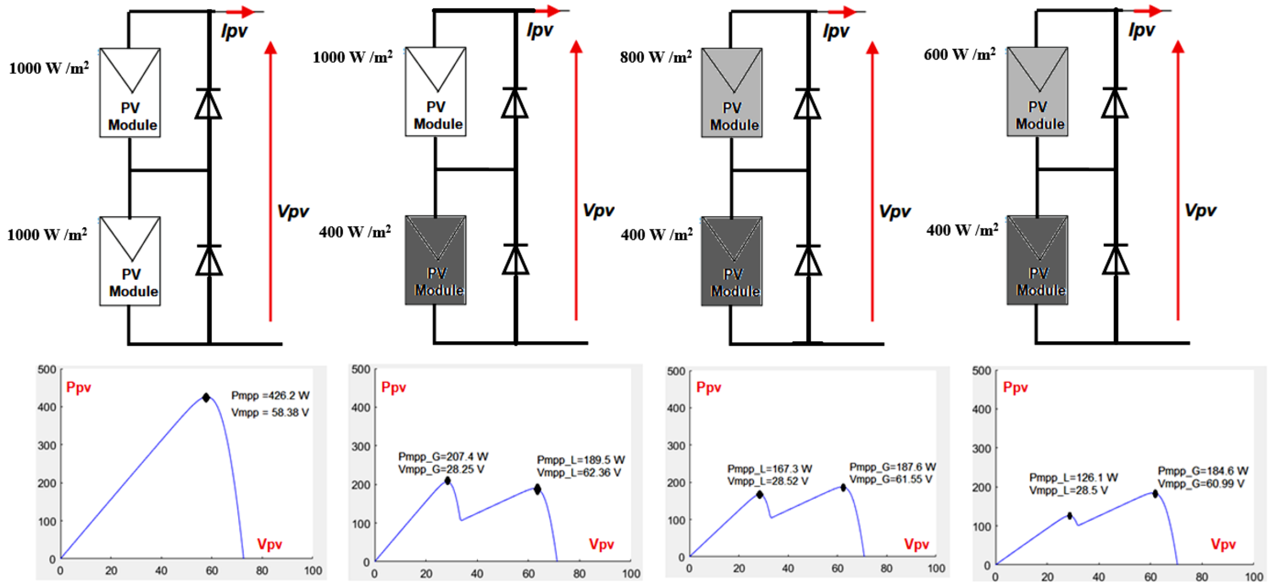

Fig. 3. Arrangement of PV modules across various static partial shading scenarios: *a*) scenario 1 (STC); *b*) scenario 2; *c*) scenario 3; *d*) scenario 4

The optimal duty cycles for each scenario, as determined by (5), are provided in Table 3.

Table 3

Optimal duty cycle calculated for each scenario

Scenario	P_{mpp}, W	D_{opt}
Scenario 1	$P_{mpp} = 426.3$	$D_{opt\_G} = 0.71721425$
Scenario 2	$P_{mpp\_G} = 207.4$ $P_{mpp\_L} = 189.5$	$D_{opt\_G} = 0.80383836$ $D_{opt\_L} = 0.54699656$
Scenario 3	$P_{mpp\_G} = 187.6$ $P_{mpp\_L} = 167.3$	$D_{opt\_G} = 0.55062217$ $D_{opt\_L} = 0.77950357$
Scenario 4	$P_{mpp\_G} = 184.6$ $P_{mpp\_L} = 126.1$	$D_{opt\_G} = 0.55110705$ $D_{opt\_L} = 0.74620251$

*Note. P_{mpp_G} is the output power at the GMPP; P_{mpp_L} is the output power at LMPP; D_{opt_G} is the optimal duty cycle corresponding to the GMPP; D_{opt_L}: is the optimal duty cycle corresponding to the LMPP.

MATLAB/Simulink simulations were carried out to evaluate the performance of the hybrid TTAO-IC algorithm under defined static partial shading conditions. The outcomes were benchmarked against those of two conventional MPPT techniques: P&O and IC.

2. Enhanced MPPT based on hybrid TTAO-IC algorithm. In PV systems, optimizing efficiency requires identifying the ideal operating point where power output is maximized, a process achieved through advanced strategies. Given the non-linear characteristics of PV systems and the variability of environmental conditions, sophisticated algorithms are essential to consistently locate and maintain this optimal point. Hybrid metaheuristic algorithms, which combine the strengths of multiple optimization techniques, have proven particularly effective in enhancing this process. These approaches are especially adept at addressing complex challenges, such as partial shading conditions, and adapting to dynamic environmental changes, making them a robust solution for improving the performance and reliability of PV systems.

2.1. TTAO algorithm. The TTAO is a global optimization algorithm based on mathematical principles, designed to solve continuous and engineering problems [31]. This algorithm leverages triangular topological similarity to develop 2 main strategies: generic aggregation and local aggregation. These strategies enable the TTAO to effectively explore the search space, avoid local optima, and converge toward the global optimum. The detailed functioning of this algorithm is described by the flowchart (Fig. 4) and the corresponding pseudocode (Fig. 5).

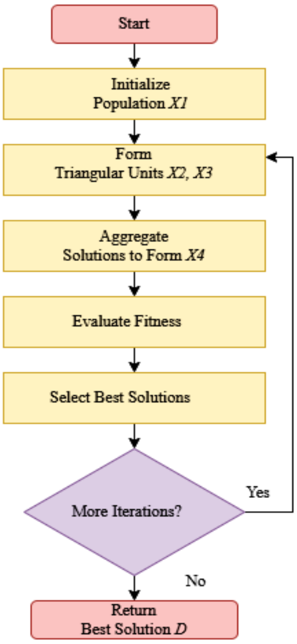

Fig. 4. Flowchart of TTAO algorithm

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Algorithm 1: TTAO algorithm
1: Input: $V_{pv}$, $I_{pv}$ (voltage and current from PV panel)
2: Parameters:
Population size $Pop\ Size = 30$, Iterations $T = 100$
Dimension $Dim = 1$, Bounds ($Low = 0$, $Up = 1$)
$X1$, $X2$, $X3$ and $X4$ : populations
3: Initialize population $X1$ randomly within the bounds.
4: For t = 1 to $T$ do
5; Form triangular units $X2$, $X3$ based on $X1$.
6: Aggregate solutions to form $X4$.
7: Evaluate fitness of $X1$, $X2$, $X3$, $X4$.
8: Select the best solutions and update $X1$.
9: End for
10: Return the best solution $D$
```

Fig. 5. TTAO algorithm

2.2. IC algorithm. The IC algorithm is a popular MPPT method for PV systems, aimed at maximizing energy extraction by dynamically comparing the instantaneous conductance (I/V) with the incremental conductance ($\mathrm{d}I/\mathrm{d}V$) in relation to the voltage. The IC algorithm enhances efficiency by continuously fine-tuning the operating voltage to keep the system close to the MPP while minimizing oscillations. It adjusts the duty cycle (D) of the power converter in response to real-time variations in voltage (V) and current (I), ensuring optimal operation. The MPP condition is mathematically described as follows:

$$\mathrm{d}P/\mathrm{d}V = 0 \text{ where } P = V \cdot I \,. \qquad (8)$$

Expanding this gives:

$$\frac{\mathrm{d}(V \cdot I)}{\mathrm{d}V} = I + V\frac{\mathrm{d}I}{\mathrm{d}V} \,. \qquad (9)$$

The detailed functioning of this algorithm is described by the pseudocode (Fig. 6).

```
Algorithm 2: IC algorithm
Initialize $D_{prev} = 0.5$, $V_{pv\,prev} = V_{pv}$, $I_{pv\,prev} = I_{pv}$
Set step size $\Delta D = 0.0001$
while system is running do
    Measure current voltage $V_{pv}$ and current $I_{pv}$
    Calculate the change in voltage: $\Delta V = V_{pv} - V_{pv\,prev}$
    Calculate the change in current: $\Delta I = I_{pv} - I_{pv\,prev}$
    if ($\Delta V \neq 0$) then
        if ( $\Delta I/\Delta V > -I_{pv}/V_{pv}$ ) then
            Decrease duty cycle : $D = D_{prev} - \Delta D$
        else if ( $\Delta I/\Delta V < -I_{pv}/V_{pv}$ ) then
            Increase duty cycle: $D = D_{prev} + \Delta D$
        else
            No change in duty cycle : $D = D_{prev}$
        end if
    else if ($\Delta V = 0$) then
        if ($\Delta I \neq 0$) then
            Decrease duty cycle : $D = D_{prev} - \Delta D$
        end if
    end if
    Update previous values: $V_{pv\,prev} = V_{pv}$, $I_{pv\,prev} = I_{pv}$
    Set $D_{prev} = D$
end while
```

Fig. 6. IC algorithm

2.3. Hybrid TTAO-IC algorithm. The hybrid TTAO-IC algorithm is a method combining the global search capabilities of the TTAO with the local refinement provided by the IC algorithm. This hybrid approach is designed to optimize MPPT in PV systems. TTAO is used to explore the search space globally and identify regions close to the MPP, while IC refines the duty cycle to achieve precise MPPT. The power generated by the PV system is given as:

$$P_{pv} = V_{pv} I_{pv} \,, \qquad (10)$$

where V_{pv}, I_{pv} are the PV panel voltage and current.

To maximize the power P_{pv} the derivative of power with respect to voltage must be zero:

$$\mathrm{d}P_{pv}/\mathrm{d}V_{pv} = 0 \,; \qquad (11)$$

$$\mathrm{d}P_{pv}/\mathrm{d}V_{pv} = I_{pv} + V_{pv}\frac{\mathrm{d}I_{pv}}{\mathrm{d}V_{pv}} \,. \qquad (12)$$

The hybrid TTAO-IC algorithm can be broken down into the following steps:

- *Initialization*: the algorithm starts by generating a random initial population for the TTAO phase. The initial duty cycle is set to $D_{prev} = 0.5$.
- *Global exploration (TTAO)*: during each iteration of TTAO, triangular units are formed from the population, and solutions are aggregated and evaluated. The best solution from this phase, denoted D_{TTAO}, represents a candidate duty cycle near the MPP.
- *Local refinement (IC)*: the best solution from TTAO is refined using the IC method. IC adjusts the duty cycle based on the change in power relative to voltage, following the conditions:

$$\mathrm{d}I_{pv}/\mathrm{d}V_{pv} = -I_{pv}/V_{pv} \,; \qquad (13)$$

$$D_{prev} = \alpha D_{IC} + (1-\alpha) D_{prev} \,, \qquad (14)$$

where α is the smoothing factor.

- *Termination*: after a predefined number of iterations, or once the duty cycle converges, the final value of D is returned, optimizing the PV system's operation.

The algorithm's detailed operation is visually represented through the flowchart in Fig. 7 and clearly outlined in the pseudocode shown in Fig. 8.

The hybrid TTAO-IC algorithm improves MPPT efficiency in PV systems by combining the global exploration of TTAO with the precision of IC, thus optimizing maximum power tracking. This hybrid approach ensures the system does not get stuck in local optima, while accurately tracking the MPP under varying environmental conditions (e.g., static partial shading conditions).

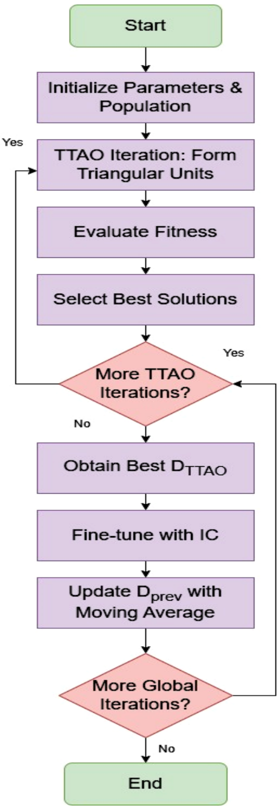

Fig. 7. Flowchart of hybrid TTAO-IC algorithm

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Algorithm 3: Hybrid TTAO-IC Algorithm
Input: $V_{pv}$, $I_{pv}$
Parameters: Population size $PopSize = 10$,
TTAO iterations $T = 10$, maximum iterations $MaxIter = 100$,
dimension $Dim = 1$, $\Delta D = 0.0001$
Initialize population for TTAO
Initialize persistent variables: $V_{pv\text{-}prev} = 0$, $I_{pv\text{-}prev} = 0$, $D_{prev} = 0.5$
for iteration = 1 to $MaxIter$ do
    for $t = 1$ to $T$ do
        Form triangular units and aggregate solutions in TTAO
        Evaluate the fitness and update the population
    end for
    Obtain the best solution $D_{TTAO}$
    Fine-tune using the IC algorithm to get $D_{IC}$
    Update $D_{prev} = \alpha D_{IC} + (1 - \alpha) D_{prev}$ (apply moving average filter)
end for
Output: Final duty cycle $D = D_{prev}$
```

Fig. 8. Hybrid TTAO-IC algorithm

3. Simulation results and discussion.

3.1. Simulation results. To assess the performance of the proposed MPPT control algorithm, a series of simulations were conducted in the MATLAB/Simulink environment. The control architecture used in these simulations is shown in Fig. 9. In this setup, a DC-DC boost converter acts as the interface between the simulated PV system and a DC load. This boost converter is crucial as it regulates the voltage and current, ensuring that the PV system operates at its MPP. Four distinct MPPT algorithm blocks were incorporated into the simulation environment, each tested individually to evaluate their respective performances. The main goal of this study is to evaluate the efficiency and accuracy of 4 different algorithms for tracking the GMPP in a PV system under static partial shading conditions. The algorithms analyzed include IC, P&O, TTAO and a hybrid TTAO-IC approach. The aim of the hybrid algorithm is to optimize the precision and speed of the search process, ensuring reliable and efficient tracking of the GMPP. The selection of these algorithms is based on their complementary characteristics:

- P&O is known for its simplicity and widespread use, though it may struggle to maintain accuracy under variable irradiance.
- IC offers improved precision, particularly in dynamic conditions, as it adjusts to changes in irradiance more effectively.
- TTAO, a metaheuristic optimization technique, excels in locating global maxima in complex search spaces, such as those introduced by partial shading effects.
- The hybrid TTAO-IC algorithm combines the global search capability of TTAO with the local precision of IC, aiming to reduce convergence time and improve tracking accuracy. Efficient MPPT control also directly affects the efficiency of the DC-DC boost converter. Algorithms that minimize oscillations around the MPP reduce switching losses, thereby optimizing the overall system performance. Conversely, slower or less accurate algorithms can lead to higher power losses due to increased switching activity.

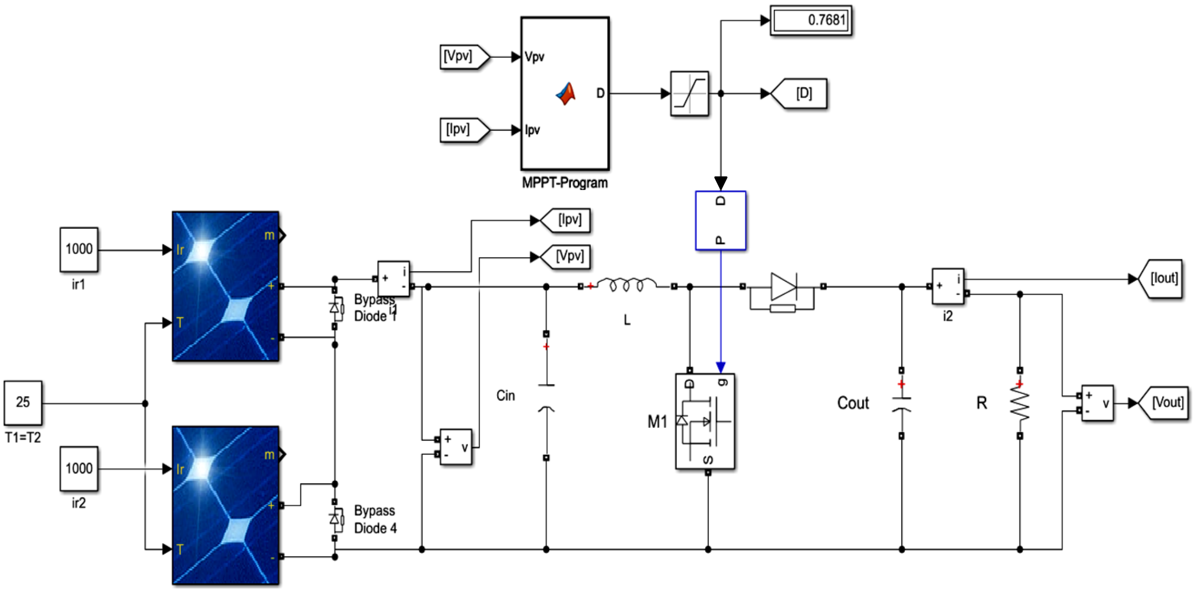

Fig. 9. Schematic representation of the PV system simulated in MATLAB/Simulink

The comparative performance of the algorithms is assessed based on 3 key parameters:

- *Time*. These measures the time required for each algorithm to converge to the MPP (P_{pv}). A shorter tracking time indicates faster adaptation to the MPP.
- *Tracking error*. This parameter evaluates how accurately the algorithm identifies the MPP. It is computed as the percentage difference between the duty cycle determined by the algorithm and the actual global duty cycle, which is obtained from the reference values (Table 3).
- *System efficiency*. This evaluates the overall efficiency of the PV system by computing the ratio of the extracted power to the maximum available power under the given conditions.

3.2. Simulation observations. The simulation results are illustrated in Fig. 10–13, which correspond to 4 scenarios, each highlighting the power (P_{pv}) and duty cycle achieved by the algorithms (IC, P&O, TTAO, and TTAO-IC). According to the simulation results presented in Table 4, the performance of the algorithms is evaluated under various scenarios:

- *Scenario 1*. Both TTAO and TTAO-IC exhibit minimal tracking errors, significantly outperforming the IC and P&O methods, which display much higher error rates.
- *Scenarios 2 and 3*. The IC and P&O techniques show considerable limitations, with tracking errors exceeding 30 %, emphasizing their reduced effectiveness in these conditions. In contrast, TTAO and TTAO-IC maintain notably lower error levels, with TTAO-IC achieving superior performance.
- *Scenario 4*. The same trend is observed, where TTAO-IC consistently records the lowest tracking error, demonstrating its robustness and accuracy across varying conditions.

The results highlight the superior performance of the hybrid TTAO-IC algorithm compared to other methods. This algorithm demonstrates rapid convergence to the GMPP with minimal tracking error, ensuring high efficiency in power extraction. Moreover, it eliminates persistent steady-state oscillations, making it a robust and reliable solution for MPPT under partial shading conditions. The comparative analysis confirms the hybrid TTAO-IC algorithm as the most effective solution for tracking the GMPP in PV systems, particularly under partial shading. By combining global optimization capabilities with precise local adjustments, it ensures rapid convergence, minimal error, and enhanced system efficiency. These findings underscore the critical importance of adopting advanced MPPT methods like TTAO-IC to maximize energy yield and optimize the overall performance of PV systems. The TTAO-IC method excels in maintaining minimal tracking errors across all scenarios, showcasing its superior precision in accurately determining the GMPP.

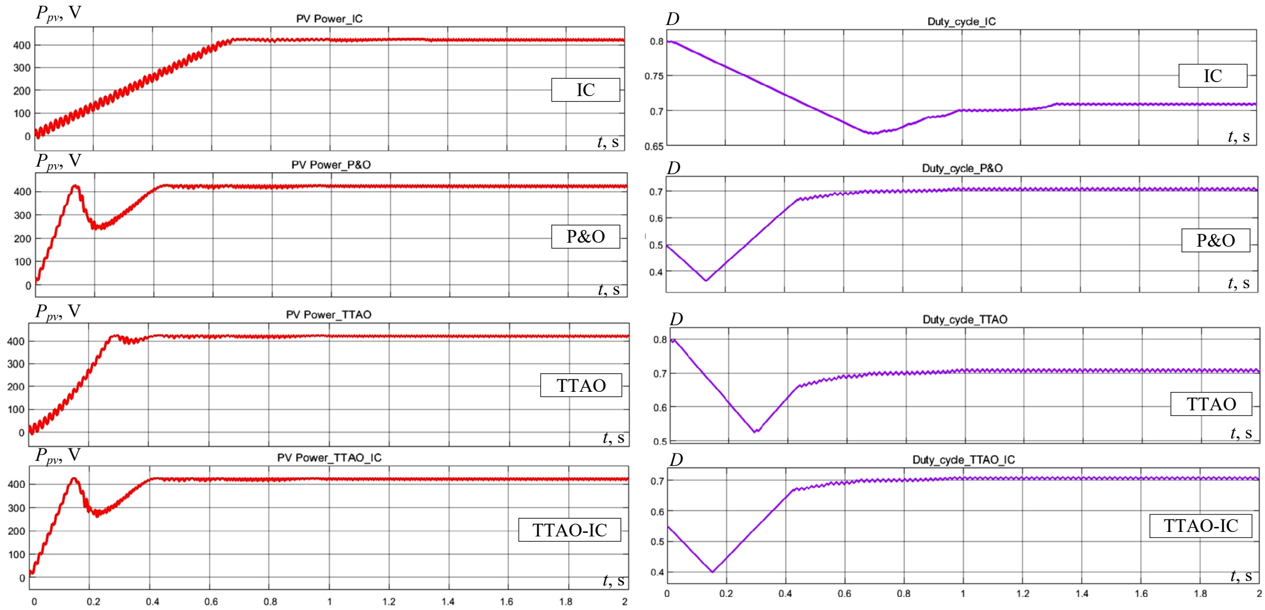

Fig. 10. Power P_{pv} and duty cycle D in scenario 1

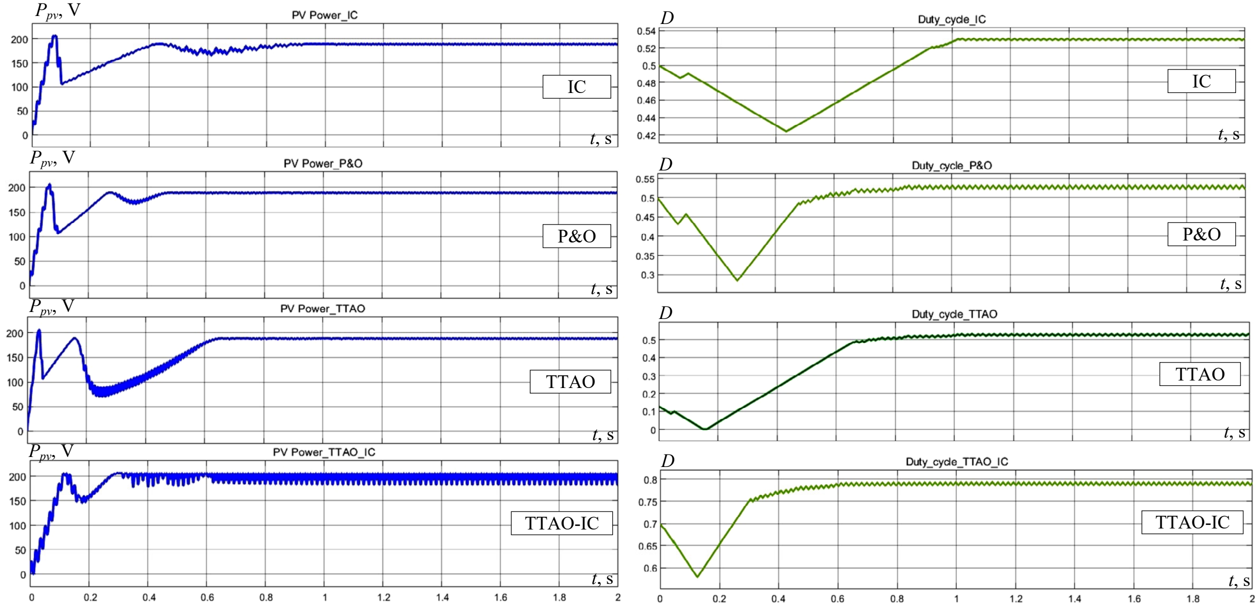

Fig. 11. Power P_{pv} and duty cycle D in scenario 2

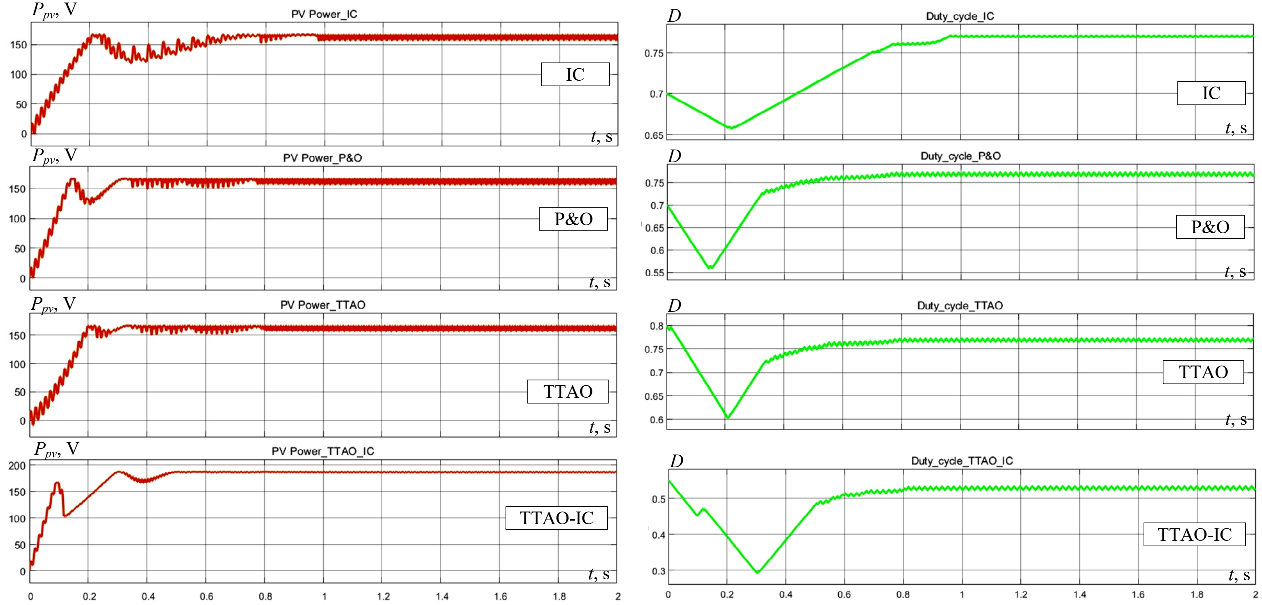

Fig. 12. Power P_{pv} and duty cycle D in scenario 3

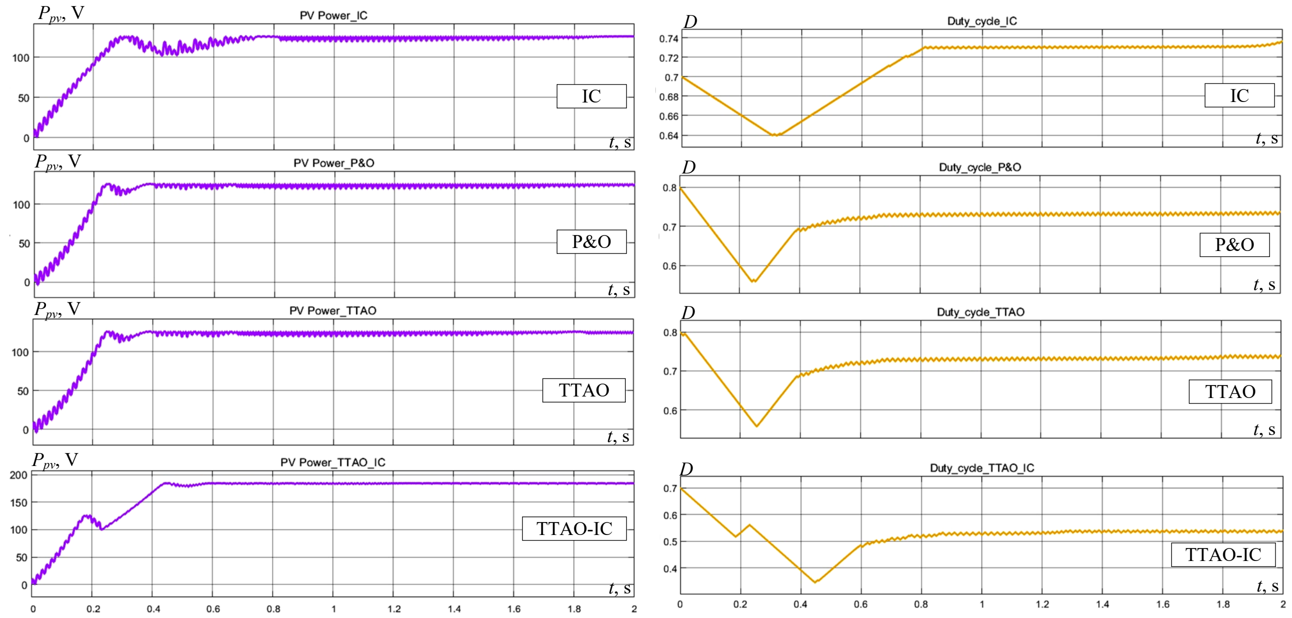

Fig. 13. Power P_{pv} and duty cycle D in scenario 4

Table 4

Performance comparison of algorithms in various scenarios

Algorithm	Convergence time	Duty cycle	Tracking error, %	P_{pv}, W	Efficiency, %
Scenario 1: $G_1 = G_2 = 1000$ W/m^2, $T_1 = T_2 = 25$ °C, $P_{mpp} = 426.3$ W, $D_{opt\ G} = 0.71721435$					
IC	648.689	0.7103	0.9641	426.130	99.96
P&O	628.276	0.7108	0.8943	426.124	99.96
TTAO	352.368	0.7101	0.9919	426.106	99.95
TTAO-IC	**397.775**	**0.7101**	**0 .7808**	**426.130**	**99.96**
Scenario 2: $G_1 = 1000$ W/m^2, $G_2 = 400$ W/m^2, $T_1 = T_2 = 25$ °C, $P_{mpp\ G} = 207.4$ W, $D_{opt\ G} = 0.80383836$					
IC	768.902	0.5305	34.0041	189.453	91.35
P&O	517.483	0.5308	33.9668	189.450	91.35
TTAO	254.545	0.7925	1.4105	204.705	98.70
TTAO-IC	**265.734**	**0.7943**	**1.1866**	**206.400**	**99.75**
Scenario 3: $G_1 = 800$ W/m^2, $G_2 = 400$ W/m^2, $T_1 = T_2 = 25$ °C, $P_{mpp\ G} = 187.6$ W, $D_{opt\ G} = 0.55062217$					
IC	567.832	0.7704	39.9145	167.000	89.02
P&O	405.594	0.7699	39.8236	167.200	89.13
TTAO	271.329	0.7714	40.0961	167.200	89.13
TTAO-IC	**442.281**	**0.5378**	**2.3287**	**187.600**	**100.00**
Scenario 4: $G_1 = 600$ W/m^2, $G_2 = 400$ W/m^2, $T_1 = T_2 = 25$ °C, $P_{mpp\ G} = 184.6$ W, $D_{opt\ G} = 0.55110705$					
IC	623.776	0.7401	34.2933	125.800	68.15
P&O	433.566	0.7400	34.2752	125.900	68.20
TTAO	338.462	0.7391	34.1119	125.700	68.09
TTAO-IC	**443.477**	**0.5311**	**3.3631**	**184.500**	**99.95**

3.3. Statistical analysis. The tracking error of the duty cycle measures how accurately each algorithm identifies the GMPP. Figure 14 presents a comparison of the 4 algorithms' performance across the 4 scenarios.

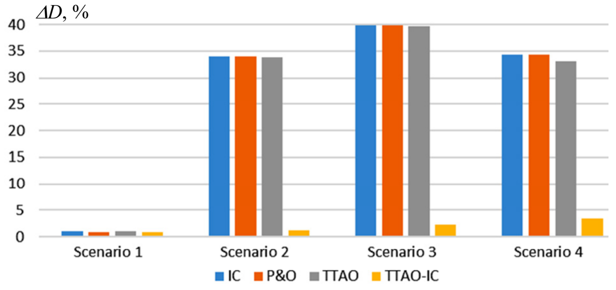

Fig. 14. Duty cycle tracking error

The power extraction efficiency evaluates the capability of each algorithm to maximize the output power from the PV system. The results for the 4 algorithms under the 4 scenarios are shown in Fig. 15. Scenario 1 – all algorithms demonstrate high efficiency (≈99 %) under uniform shading conditions. However, TTAO-IC consistently achieves slightly higher efficiency compared to the other methods. Scenario 2–4: under partial shading conditions, the performance of IC and P&O deteriorates significantly, with efficiency dropping below 70 %. Conversely, TTAO-IC sustains efficiencies close to 100 % with showing a slight edge. The TTAO-IC algorithm achieves near-perfect power extraction efficiency under all conditions, outperforming other methods, especially under partial shading scenarios.

The findings presented in Table 5 highlight the exceptional performance of the TTAO-IC algorithm across several critical metrics. Simulation results were used to calculate the efficiency percentage for each method, showing that the TTAO-IC algorithm delivers substantially higher efficiency compared to the techniques detailed in [11, 12, 29].

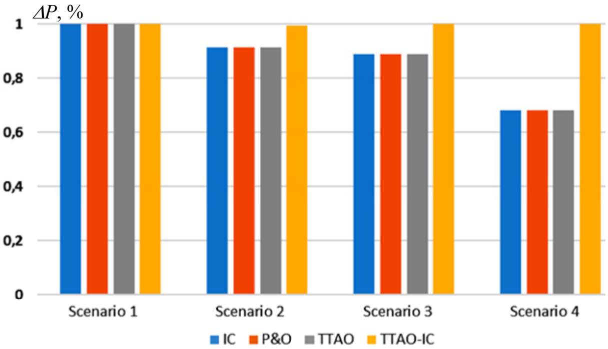

Fig. 15. Power extraction efficiency

Furthermore, the TTAO-IC controller demonstrates a significantly faster response time than PSO, PPA, PSO-OBL, ABC and SSA-GWO when subjected to static shading conditions, emphasizing its capability to quickly reach the GMPP. This enhanced efficiency reduces energy losses by ensuring precise and rapid tracking of the GMPP. These results highlight the exceptional effectiveness and superiority of the TTAO-IC algorithm in optimizing the MPPT process for PV systems. With its accelerated convergence rate and improved efficiency, the algorithm emerges as a highly effective solution for maximizing energy production while addressing shading challenges in PV applications.

Table 5

Comparative performance analysis of the proposed TTAO-IC algorithm and other MPPT techniques

MPPT algorithm	Efficiency, %	Tracking time, s
Particle Swarm Optimization (PSO) [29]	99.71	0.46
Plant Propagation Algorithm (PPA) [11]	99.91	0.68
PSO-Opposition Based Learning (OBL) [12]	99.72	0.69
Artificial Bee Colony (ABC) algorithm [29]	99.54	0.47
Salp Swarm Algorithm with Grey Wolf Optimizer (SSA-GWO [29]	99.84	0.43
Proposed TTAO-IC	99.96	0.398

Conclusions. This research has conducted an in-depth exploration of various MPPT techniques, emphasizing their essential role in optimizing the efficiency of PV systems. By evaluating both individual and hybrid MPPT algorithms, we have provided valuable insights into their performance under different operational conditions. The study focused on key parameters such as response time, stability, performance under partial shading and accuracy, offering a holistic view of the effectiveness of these techniques.

The study successfully achieves the goal through the development of the TTAO-IC algorithm, which combines the global optimization capabilities of TTAO with the precision of the IC method. Simulation results demonstrate that the TTAO-IC algorithm significantly enhances MPPT performance under partial shading conditions, achieving tracking efficiencies exceeding 99 % and outperforming traditional methods like P&O and IC, as well as other hybrid techniques such as PSO, GWO, PSO-OBL, PPA, and ABC.

The algorithm addresses the limitations of conventional methods by delivering faster convergence to GMPP, reducing oscillations around the MPP, and maintaining high tracking efficiency even under non-uniform shading conditions. In conclusion, the TTAO-IC algorithm stands out as a highly efficient and reliable solution for MPPT in PV systems, offering a balance between performance and high efficiency even under challenging conditions makes it a strong contender for large-scale solar energy applications.

Future research should focus on further refining this hybrid approach and validating its performance in real-world scenarios, aiming to enhance the global adoption of solar energy. For further studies, we suggest adjusting key parameters to optimize performance across various PV generator architectures, possibly using advanced optimization techniques. Specifically, we aim to implement the methodology in centralized, decentralized, and hybrid PV systems, as well as with different types of solar panels, including monocrystalline and polycrystalline varieties. Additionally, we plan to evaluate the algorithm under a range of conditions, such as varying irradiance levels and dynamic partial shading situations. By applying the methodology across these different system designs and environmental contexts, we seek to enhance our understanding of its performance and potential adaptations.

Conflict of interest. The authors declare that they have no conflicts of interest.

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Received 06.01.2025
Accepted 04.04.2025
Published 02.09.2025

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How to cite this article:
Jeridi A., Moulahi M.H., Khaterchi H., Zaafouri A. Maximum power point tracking improving of photovoltaic systems based on hybrid triangulation topology aggregation optimizer and incremental conductance algorithm. *Electrical Engineering & Electromechanics*, 2025, no. 5, pp. 17-26. doi: https://doi.org/10.20998/2074-272X.2025.5.03