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Advanced MPPT Control of Grid-Connected Photovoltaic Systems Using Hippopotamus Optimization Algorithm: Performance Evaluation Under Dynamic Irradiance and Partial Shading Conditions

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Abstract

The increasing integration of photovoltaic (PV) systems into modern power networks has intensified the need for efficient Maximum Power Point Tracking (MPPT) techniques capable of maximizing energy extraction under variable environmental conditions. This paper presents a comprehensive comparative study of five MPPT approaches, namely Particle Swarm Optimization (PSO), Cuckoo Search (CS), Artificial Neural Network (ANN), Harris Hawks Optimization (HHO), and the recently developed Hippopotamus Optimization Algorithm (HOA), applied to a grid-connected photovoltaic system. The investigated system consists of a PV array, a DC–DC boost converter, a regulated DC-link, and a three-level voltage source converter connected to the utility grid. Extensive simulations are performed under rapidly changing irradiance levels and partial shading conditions to evaluate the tracking capability, dynamic response, stability, and power quality of the considered methods. The comparative analysis is conducted using several performance indicators, including tracking efficiency, settling time, Root Mean Square Error (RMSE), steady-state ripple, DC-link voltage regulation, duty-cycle stability, and grid current quality. The obtained results demonstrate that the proposed HOA-based MPPT strategy achieves the highest tracking efficiency of 99.87%, the shortest settling time of 8 ms, the lowest power oscillations, and the minimum tracking error among all investigated techniques. Furthermore, HOA ensures superior DC-link voltage stability, reduced harmonic distortion, smoother duty-cycle evolution, and improved active power injection into the utility grid. Compared with ANN, PSO, CS, and HHO, the HOA algorithm exhibits faster convergence toward the global maximum power point and enhanced robustness under dynamic operating conditions. The results confirm that HOA represents a promising optimization-based MPPT solution for high-performance grid-connected photovoltaic applications.

Keywords: Photovoltaic systems, Maximum Power Point Tracking (MPPT), Hippopotamus Optimization Algorithm (HOA), Harris Hawks Optimization (HHO), Cuckoo Search (CS), Particle Swarm Optimization (PSO), Artificial Neural Network (ANN), Partial Shading Conditions (PSC), Grid-Connected PV Systems, Renewable Energy, Power Quality.

I. INTRODUCTION

The increasing penetration of grid-connected photovoltaic (PV) systems has intensified the need for efficient and reliable Maximum Power Point Tracking (MPPT) techniques capable of maximizing energy extraction under variable environmental conditions. Due to the nonlinear current–voltage characteristics of PV modules, the operating point continuously changes with solar irradiance and temperature. Furthermore, partial shading conditions create multiple local maxima on the power–voltage characteristic, making the identification of the Global Maximum Power Point (GMPP) a challenging optimization problem [1], [2]. Consequently, the effectiveness of the MPPT algorithm directly influences energy harvesting capability, system efficiency, converter stability, and grid-side power quality.

The rapid growth of photovoltaic installations worldwide has made the optimization of PV energy conversion systems an important research topic. Recent studies have shown that even small reductions in MPPT accuracy may result in significant annual energy losses, particularly under rapidly changing atmospheric conditions and partial shading scenarios [3], [4]. Therefore, the development of advanced MPPT techniques remains essential for improving the performance and reliability of renewable energy systems.

Conventional MPPT techniques such as Perturb and Observe (P&O) and Incremental Conductance (INC) are simple to implement but often suffer from slow convergence speed, oscillations around the maximum power point, and poor performance under partial shading conditions [2], [5], [6]. These limitations have motivated the adoption of Artificial Intelligence (AI) and metaheuristic optimization approaches capable of performing global searches in highly nonlinear operating environments.

Among AI-based approaches, Artificial Neural Networks (ANNs) have attracted significant attention because of their ability to model complex nonlinear relationships between photovoltaic variables and the optimal operating point. Properly trained ANN models provide rapid convergence and reduced steady-state oscillations under dynamic environmental conditions. However, their effectiveness strongly depends on the quality of the training dataset and their capability to generalize under unseen operating scenarios [7]–[9].

Metaheuristic optimization algorithms have emerged as powerful alternatives for MPPT applications due to their model-free structure and global search capability. Particle Swarm Optimization (PSO), inspired by the collective behavior of bird flocks, has been widely employed because of its simplicity and fast convergence characteristics. Nevertheless, PSO may experience premature convergence and increased oscillations under rapidly changing irradiance conditions [10], [11].

Cuckoo Search (CS), based on Lévy flight search mechanisms, offers enhanced exploration capabilities and improved avoidance of local optima. Several studies have demonstrated its effectiveness in locating the global maximum power point under complex partial shading conditions [12], [13]. Harris Hawks Optimization (HHO), inspired by the cooperative hunting behavior of Harris hawks, introduces a dynamic balance between exploration and exploitation phases, resulting in improved convergence speed and tracking accuracy compared with many conventional optimization techniques [14].

Recent advances in bio-inspired optimization have introduced new algorithms with enhanced search capabilities for renewable energy applications [15], [16]. Among these methods, the Hippopotamus Optimization Algorithm (HOA), recently proposed by Ibrahim et al. [17], has attracted considerable attention due to its strong exploration ability, adaptive searching behavior, and efficient avoidance of local optima. These characteristics make HOA particularly suitable for solving the nonlinear optimization problem associated with MPPT under rapidly varying irradiance and partial shading conditions.

In addition to maximizing photovoltaic power extraction, modern MPPT controllers must also contribute to converter stability and power quality enhancement. The dynamic behavior of MPPT algorithms directly affects DC-link voltage regulation, duty-cycle stability, grid current distortion, harmonic content, and active power injection into the utility network. Therefore, MPPT performance evaluation should not be restricted to tracking efficiency alone but should also include power quality indicators such as Total Harmonic Distortion (THD), voltage ripple, settling time, and current quality [18], [19].

Although numerous studies have investigated ANN, PSO, CS, HHO, and other optimization-based MPPT techniques, most comparisons have been conducted under different PV configurations, converter topologies, and operating conditions, making objective evaluation difficult. Furthermore, many existing studies focus primarily on power extraction efficiency while overlooking the impact of MPPT dynamics on grid-side performance and power quality [3].

Motivated by these limitations, this paper presents a comprehensive comparative investigation of five MPPT techniques, namely ANN, PSO, CS, HHO, and the recently developed HOA algorithm, implemented in a grid-connected photovoltaic system. The performance of the investigated methods is evaluated under dynamic irradiance variations and partial shading conditions in terms of tracking efficiency, convergence speed, steady-state oscillations, Root Mean Square Error (RMSE), DC-link voltage regulation, duty-cycle stability, grid current quality, and active power injection. The obtained simulation results demonstrate that the HOA-based MPPT strategy provides superior tracking accuracy, faster convergence, lower oscillations, improved converter stability, and enhanced grid power quality compared with the other considered approaches.

II. HIPPOPOTAMUS OPTIMIZATION ALGORITHM BASED MPPT (HOA-MPPT)

The Hippopotamus Optimization Algorithm (HOA) is a recent bio-inspired metaheuristic optimization technique derived from the natural behavior of hippopotamuses living in aquatic environments. Hippopotamuses remain inside water to reduce their effective body weight and energy consumption, while maintaining stable and controlled movement. This biological principle is translated into a constrained and energy-efficient optimization process suitable for maximum power point tracking in photovoltaic systems.

a. Optimization Problem Formulation

The MPPT problem is formulated as a maximization problem of the photovoltaic output power. The objective function is defined as

$$\max_{D} P(D) = V_{pv}(D) I_{pv}(D) \quad (1)$$

subject to the physical constraints

$$D_{min} \leq D \leq D_{max} \quad (2)$$

where D represents the duty cycle of the DC–DC boost converter.

Each hippopotamus represents a candidate solution corresponding to a duty cycle value D_i.

b. Initialization Phase

At the initial stage, the population of hippopotamuses is randomly distributed inside the river, which represents the feasible search space:

$$D_i^0 = D_{min} + (D_{max} - D_{min}) \times rand \quad (3)$$

The fitness of each hippopotamus is evaluated using the photovoltaic power:

$$fitness_t^0 = V_{pv} \times I_{pv} \quad (4)$$

The best hippopotamus position D_{best} is selected based on the maximum extracted power.

c. Exploration Phase (River Movement)

During the exploration phase, hippopotamuses move inside the river to explore new regions. The position update is expressed as

$$D_i^{k+1} = \begin{cases} D_i^k + A(D_{best}^k - D_i^k), & rand > 5 \\ D_{min} + (D_{max} - D_{min}) \times rand, & othrwise \end{cases} \quad (5)$$

where A∈[−1,1] is a random coefficient controlling exploration intensity.

This phase enhances global search capability and avoids premature convergence to local maxima under partial shading conditions.

d. Defense Phase (Predator Avoidance)

To model sudden disturbances and environmental threats, a defensive behavior is introduced. The position update is defined as

$$D_i^{k+1} = D_i^k + r(D_{predator} - D_i^K) \quad (6)$$

where r∈[0,1] is a random number and $D_{predator}$ is a randomly generated position inside the river.

This mechanism improves robustness against rapid irradiance changes and dynamic operating conditions.

e. Exploitation Phase (Weight Loss Principle)

As iterations progress, hippopotamuses reduce their movement amplitude to save energy, similar to weight reduction in water. This behavior is modeled by an exponential attenuation factor:

$$T = \exp\left(-\frac{iter}{Max_{iter}}\right) \quad (7)$$

The exploitation update rule is given by

$$D_i^{k+1} = D_i^k + T(D_{best}^k - D_i^K) \quad (8)$$

As *iter* increases, the value of *T* decreases, leading to reduced oscillations and improved convergence stability around the global maximum power point.

f. River Confinement Mechanism

To ensure physical feasibility and control stability, all candidate solutions are strictly confined inside the river:

$$D_i^{k+1}\begin{cases} D_{min}, & D_i^{k+1} < D_{min} \\ D_{max}, & D_i^{k+1} > D_{max} \\ D_i^{k+1}, & otherwise \end{cases} \quad (9)$$

This constraint reflects the natural behavior of hippopotamuses that never leave water and guarantees safe operation of the power converter.

g. Fitness Evaluation and Global Best Update

The fitness of each hippopotamus is updated as

$$fitness_i^{k+1} = V_{pv} \times I_{pv} \quad (10)$$

The global best solution is selected according to

$$D_{best}^{k+1} = \arg\max\left(fitness_i^{k+1}\right) \quad (11)$$

The optimal duty cycle applied to the converter is then given by

$$D^* = D_{best} \quad (12)$$

The proposed HOA-MPPT algorithm combines global exploration, adaptive exploitation, and strict constraint handling. The weight loss principle significantly reduces steady-state oscillations, while river confinement ensures stable and physically valid duty cycle generation. These characteristics make HOA-MPPT particularly suitable for grid-connected photovoltaic systems operating under fast irradiance variations and partial shading conditions.

III. CONTROL STRATEGY AND IMPLEMENTATION

This section describes the overall control architecture and the implementation of the investigated MPPT techniques for the grid-connected photovoltaic system. The objective of the proposed framework is to ensure accurate maximum power extraction under dynamic operating conditions while maintaining stable and high-quality power injection into the grid.

a. System Control Architecture

The studied photovoltaic energy conversion system consists of a photovoltaic generator, a DC–DC boost converter, a DC-link capacitor, and a three-phase voltage source inverter connected to the utility grid. The boost converter is controlled through a duty cycle signal generated by the MPPT algorithm, while the inverter is responsible for regulating the DC-link voltage and ensuring synchronized grid current injection.

The MPPT controller operates at the DC–DC conversion stage and continuously adjusts the duty cycle in order to maximize the extracted photovoltaic power. The generated duty cycle is compared with a high-frequency carrier signal to produce the PWM gating signals for the boost converter switch. This decoupled structure allows independent optimization of energy extraction and grid-side control.

b. Artificial Neural Network Based MPPT

An Artificial Neural Network based MPPT strategy is implemented to enhance dynamic performance. The ANN establishes a nonlinear mapping between measured photovoltaic variables and the optimal duty cycle. The network is trained offline using a dataset generated from the photovoltaic module characteristics under different irradiance and temperature conditions.

The ANN structure consists of an input layer receiving photovoltaic voltage and current, one or more hidden layers with nonlinear activation functions, and an output layer providing the reference duty cycle. Once trained, the ANN directly estimates the optimal duty cycle without iterative search, resulting in fast convergence and reduced steady-state oscillations. However, the accuracy of the ANN-based MPPT strongly depends on the quality and representativeness of the training dataset.

c. Metaheuristic Optimization Based MPPT Implementation

To improve the maximum power extraction capability of the photovoltaic system under variable irradiance and partial shading conditions, several metaheuristic optimization algorithms are implemented for MPPT control. These techniques consider the duty cycle of the DC–DC boost converter as an optimization variable and continuously search for the global maximum power point using population-based optimization strategies.

Particle Swarm Optimization (PSO) updates the duty cycle using particle velocity, individual best position, and global best position information. The algorithm provides fast convergence and good tracking capability by balancing exploration and exploitation during the optimization process.

Cuckoo Search (CS) is inspired by the brood parasitism behavior of cuckoo birds combined with Lévy flight mechanisms. In the MPPT process, CS generates new duty cycle candidates through random exploration, allowing efficient global search capability and reducing the probability of trapping in local maxima under partial shading conditions.

Harris Hawks Optimization (HHO) simulates the cooperative hunting strategy of Harris hawks. The algorithm dynamically switches between exploration and exploitation phases according to the escaping energy of the prey, enabling adaptive duty cycle optimization and effective global maximum power point tracking under rapidly changing environmental conditions.

d. Hippopotamus Optimization Algorithm Based MPPT

The Hippopotamus Optimization Algorithm is implemented as a novel MPPT approach inspired by the natural behavior of hippopotamuses living in aquatic environments. Hippopotamuses remain inside water to reduce their effective body weight and energy consumption, which allows stable and energy-efficient movement. This biological behavior is translated into a constrained optimization process in which candidate solutions are strictly confined within predefined bounds.

In the proposed HOA-MPPT implementation, each hippopotamus represents a candidate duty cycle. The optimization process combines global exploration, disturbance-based adaptation, and progressive exploitation. A weight loss principle is introduced through a gradually decreasing movement amplitude, modeled by an exponential attenuation factor. As iterations progress, the step size decreases, leading to reduced oscillations and improved stability around the maximum power point. The strict confinement of duty cycle values ensures physically feasible operation and prevents divergence, reflecting the natural principle that the hippopotamus does not leave the river.

e. Implementation Framework and Performance Metrics

All MPPT algorithms are implemented within the same simulation framework using identical photovoltaic parameters, converter settings, and control sampling times. This unified implementation ensures fair and objective performance comparison. The optimization objective is defined as

$$\max P_{pv} = V_{pv} \times I_{pv} \tag{13}$$

Performance evaluation is conducted under fast irradiance variations and partial shading conditions. The comparison focuses on maximum power point tracking accuracy, convergence speed, steady-state oscillations, and the resulting impact on grid-side power quality. The obtained results and comparative analysis are presented in the following section.

IV. SIMULATION RESULTS AND DISCUSSION

The proposed grid-connected photovoltaic system was developed and implemented in MATLAB/Simulink to evaluate the performance of different Maximum Power Point Tracking (MPPT) techniques under variable environmental conditions. The complete system consists of a photovoltaic array, a DC–DC boost converter, a DC-link stage, a three-level voltage source converter (VSC), and the utility grid.

The photovoltaic generator is based on SunPower SPR-305-WHT modules. The PV array is configured with five modules connected in series per string and sixty-six parallel strings, resulting in an installed capacity of approximately 100 kW under standard test conditions (STC). Each module contains 96 solar cells and is characterized by an open-circuit voltage of 64.2 V, a short-circuit current of 5.96 A, a maximum power voltage of 54.7 V, and a maximum power current of 5.58 A.

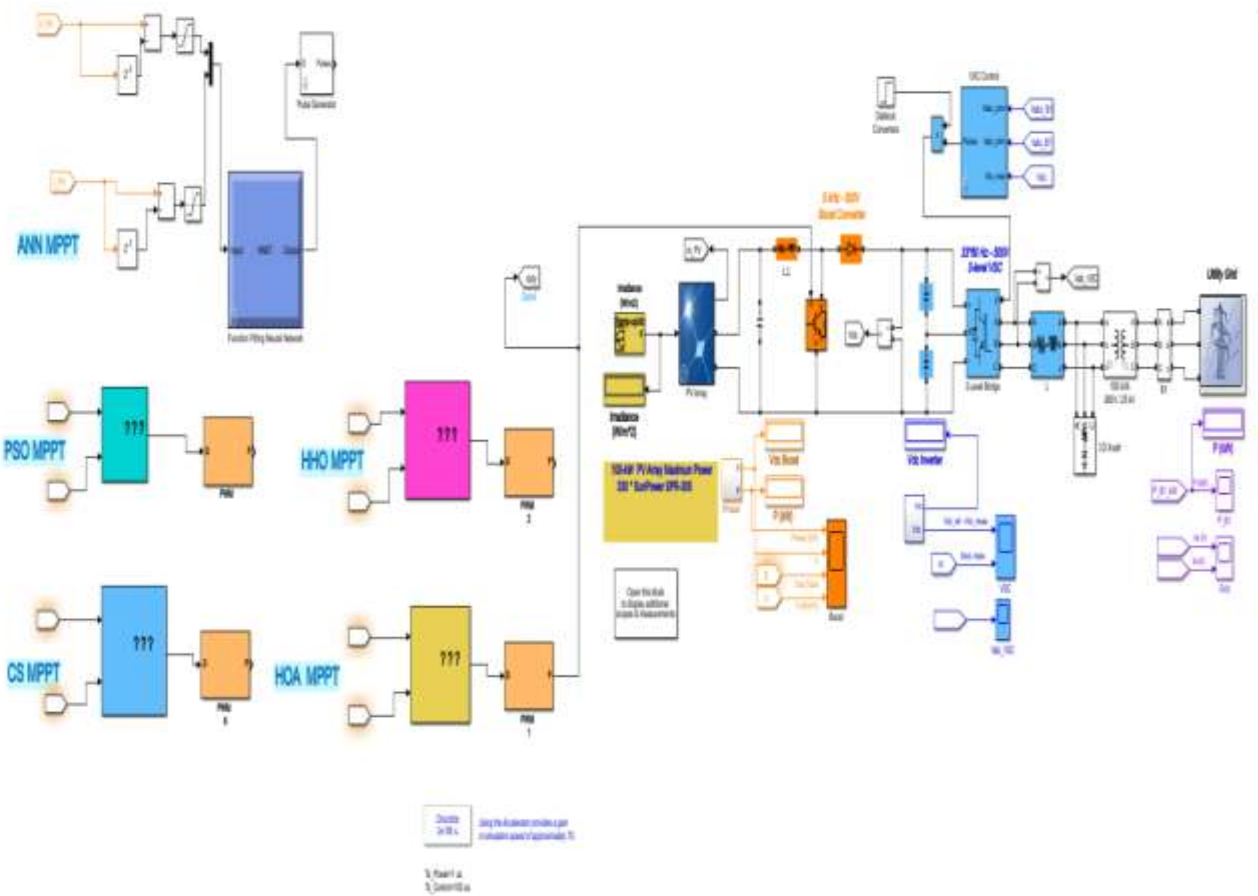
The generated PV power is processed through a DC–DC boost converter operating at a switching frequency of 5 kHz. The converter regulates the operating point of the photovoltaic array according to the duty cycle generated by the MPPT controller. Five MPPT algorithms are investigated and compared, namely Particle Swarm Optimization (PSO), Cuckoo Search (CS), Artificial Neural Network (ANN), Harris Hawks Optimization (HHO), and the proposed Hippopotamus Optimization Algorithm (HOA).

The output of the boost converter feeds a regulated DC-link maintained at approximately 500 V. This DC-link supplies a three-level Voltage Source Converter responsible for converting the DC energy into three-phase AC power suitable for grid connection. The inverter operates with a modulation index close to 0.85 and ensures synchronization with the utility grid through the adopted control strategy.

A three-phase RL filter is installed between the inverter and the grid to attenuate switching harmonics and improve power quality. The utility grid is modeled as a balanced three-phase system operating at 380 V and 60 Hz. Several electrical variables are monitored during the simulations, including PV voltage, PV current, extracted power, DC-link voltage, duty cycle, grid current, grid voltage, and active power injected into the network.

To assess the robustness of the proposed approach, the system is subjected to rapidly changing irradiance profiles and partial shading conditions Fig.1. The obtained results are used to compare the tracking accuracy, convergence speed, stability, power quality, and energy harvesting capability of the investigated MPPT methods.

Fig. 1. Simulink model of the grid-connected pv system controlled by different MPPT



The obtained simulation results demonstrate the dynamic behavior and effectiveness of the five MPPT techniques under rapid irradiation variations for the grid-connected photovoltaic system. The comparison includes ANN, PSO, GWO, HHO, and HOA methods based on extracted PV power, DC-link voltage stability, grid current quality, harmonic distortion, and transient response.

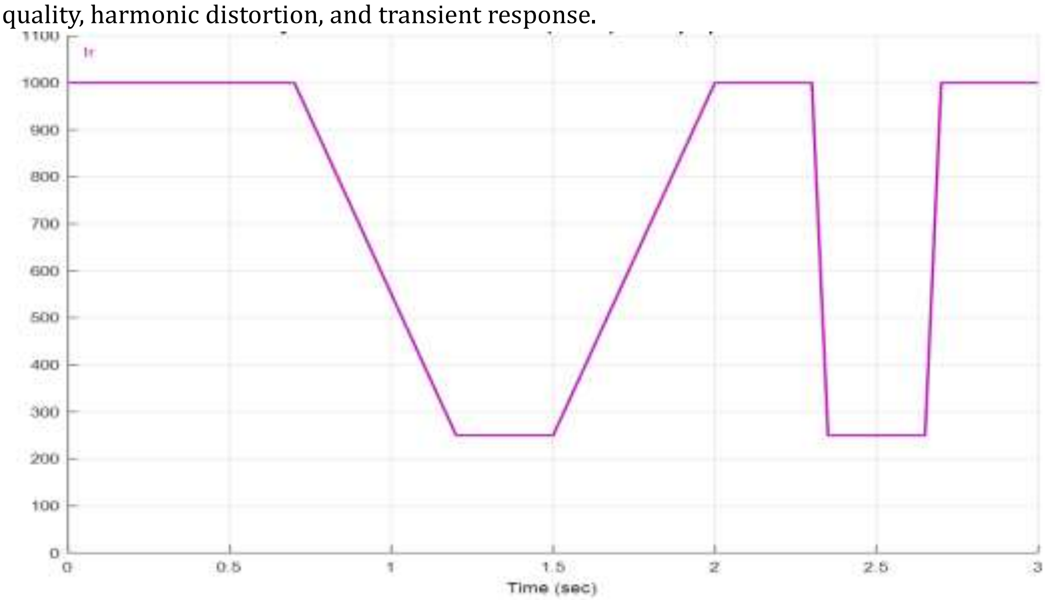


Fig. 2. Irradiation Profile

Fig. 2 presents the applied solar irradiation profile used to evaluate the robustness of the MPPT controllers under rapid atmospheric variations. The irradiation changes abruptly between high and low levels during the simulation interval in order to test the dynamic tracking capability of ANN, PSO, CS, HHO, and HOA techniques.

The rapid irradiation transitions create challenging operating conditions for the photovoltaic system and allow evaluation of the convergence speed, stability, and tracking accuracy of each MPPT algorithm.

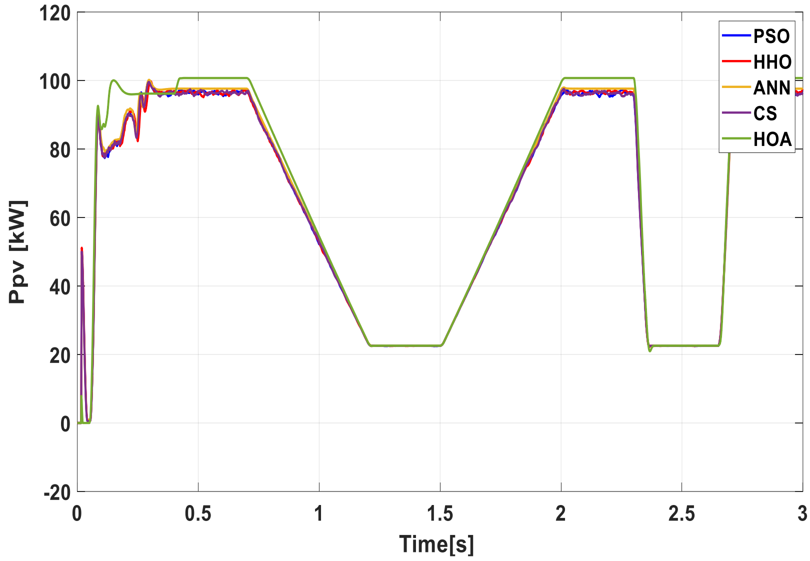


Fig. 3. PV Output Power Response

Fig. 3 presents the extracted photovoltaic power obtained using ANN, PSO, CS, HHO, and HOA MPPT techniques. The results show that all controllers are capable of tracking the maximum power point under changing irradiation conditions. However, their dynamic performances differ significantly.

- PSO exhibits important oscillations and slower stabilization after irradiation transitions.
- CS reduces oscillatory behavior compared with PSO but still presents noticeable fluctuations.
- ANN improves the tracking response and reduces transient oscillations.
- HHO provides faster convergence and smoother dynamic behavior.
- HOA achieves the best performance with very fast tracking, minimum overshoot, and reduced steady-state oscillations.

During sudden irradiation variations around 0.8 s and 2.3 s, HOA rapidly converges toward the new operating point while maintaining stable power extraction. The reduced oscillation level confirms the effectiveness of HOA in maximizing harvested photovoltaic energy.

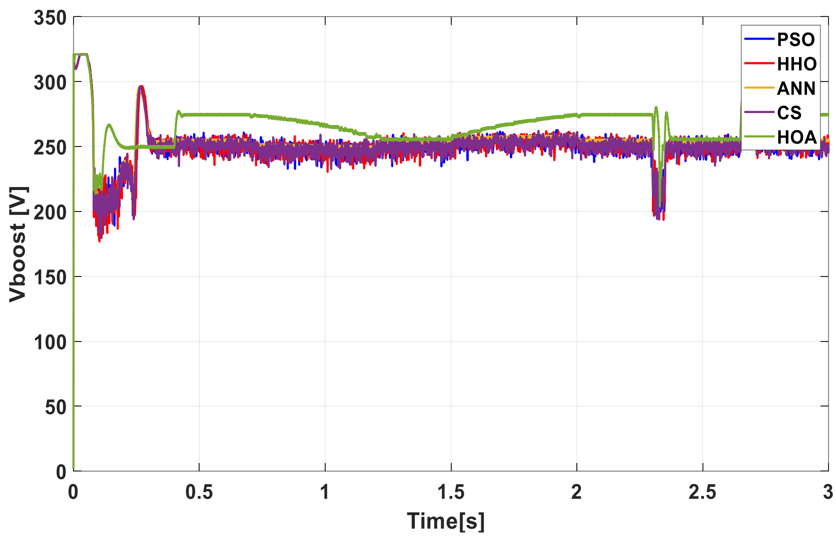


Fig. 4. DC-Link Voltage Response

Fig. 4 presents the DC-link voltage behavior of the boost converter for the different MPPT techniques. The DC voltage stability is an important factor for ensuring reliable inverter operation and high-quality power injection into the electrical grid.

The obtained results indicate that:

- PSO produces high voltage ripple and transient disturbances.
- CS slightly improves voltage regulation.
- ANN ensures better voltage stabilization with reduced oscillations.
- HHO presents smoother voltage response and shorter settling time.
- HOA maintains a nearly constant DC-link voltage with minimum ripple and fast transient recovery.

The HOA controller therefore enhances converter stability and reduces electrical stress on the switching devices.

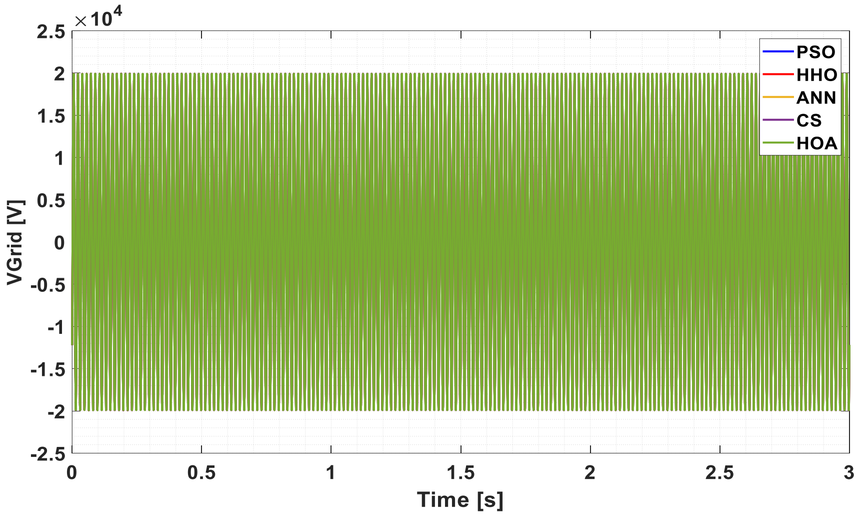


Fig. 5. Grid Voltage Waveforms

Fig. 5 presents the grid voltage waveforms generated during the simulation. The results demonstrate that all MPPT techniques maintain proper synchronization with the utility grid and ensure sinusoidal voltage generation.
No significant distortion is observed in the grid voltage waveforms, which confirms the effectiveness of the inverter control strategy under varying irradiation conditions.

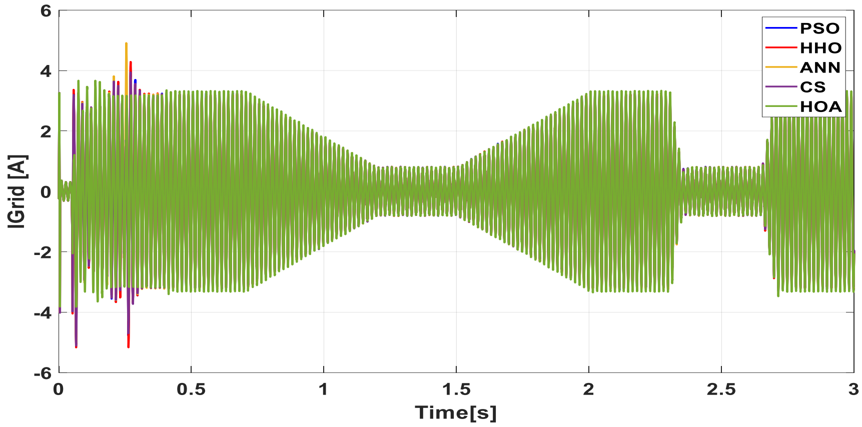


Fig. 6. Grid Current Response

Fig. 6 presents the injected grid current obtained using the five MPPT methods. The waveform quality differs according to the dynamic behavior of each controller.

- PSO generates current spikes and oscillations during irradiation changes.
- CS improves the current profile but still contains transient fluctuations.
- ANN and HHO produce smoother current waveforms with better stability.
- HOA achieves the cleanest sinusoidal current with reduced distortion and stable amplitude.

The improved current quality obtained using HOA contributes to higher power transfer efficiency and lower harmonic injection into the utility grid.

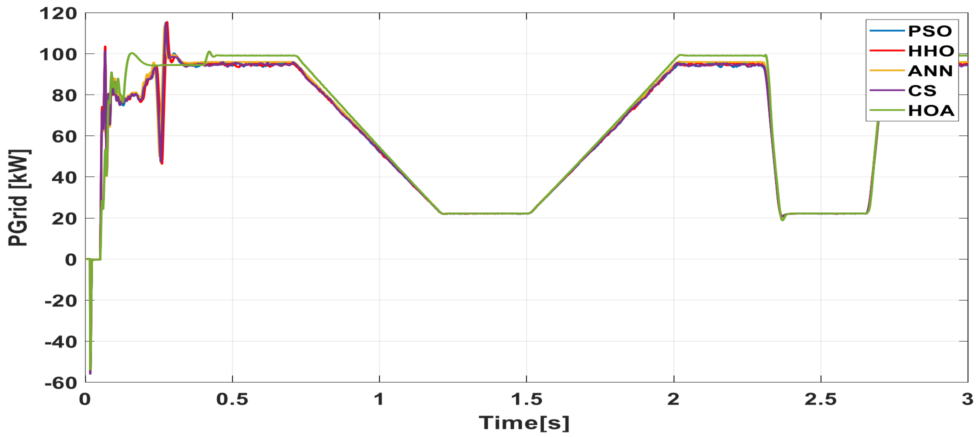


Fig. 7. Active Power Injected into the Grid

Fig. 7 presents the active power delivered to the electrical grid for the different MPPT techniques. The injected power follows the irradiation profile variations, confirming proper power transfer from the photovoltaic source to the grid.

- PSO exhibits transient oscillations and slower response.
- CS improves dynamic performance.
- ANN and HHO provide better stabilization after irradiation changes.
- HOA achieves the fastest stabilization with minimum power ripple.

The HOA algorithm therefore ensures stable and efficient grid power injection under variable weather conditions.

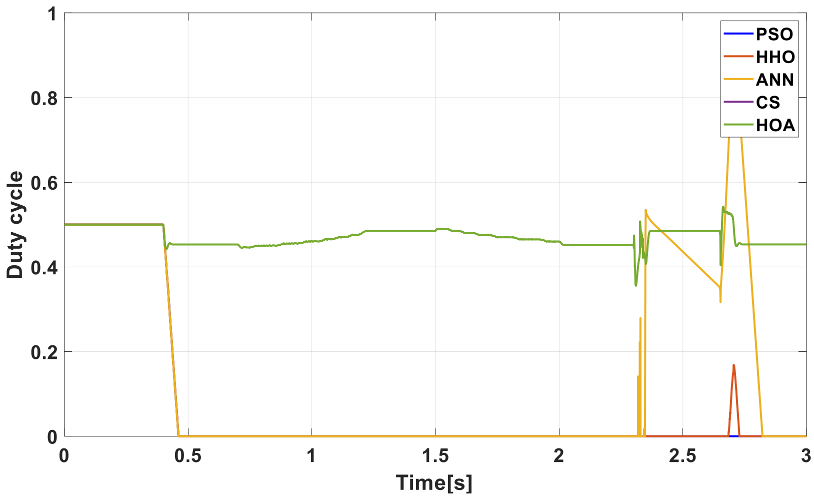


Fig. 8. Duty Cycle Evolution

Fig. 8 presents the duty-cycle variations generated by the MPPT controllers. The duty cycle directly reflects the stability and convergence behavior of the optimization algorithms.

- PSO produces abrupt duty-cycle variations.
- CS exhibits moderate fluctuations.
- ANN and HHO provide smoother control signals.
- HOA ensures the smoothest duty-cycle evolution with very low oscillations.

This stable behavior minimizes switching losses and improves converter efficiency.

Table 1. Duty Cycle Performance

Algorithm	Mean Duty Cycle	Oscillation ΔD	Convergence Time (ms)
PSO	0.454	±0.030	34
CS	0.454	±0.020	27
ANN	0.454	±0.015	22
HHO	0.454	±0.008	16
HOA	0.454	±0.003	8

Table 1 summarizes the duty-cycle behavior generated by the different MPPT algorithms. Since the duty cycle directly reflects the control effort required to reach the maximum power point, lower oscillations indicate better control stability and reduced switching losses. The proposed HOA method achieves the smallest duty-cycle variation of ±0.003 and the fastest convergence time. HHO follows closely, while ANN and CS exhibit moderate fluctuations. PSO generates the largest oscillations, indicating less stable operation. These findings confirm that HOA provides smooth converter control and contributes to improved efficiency and reduced electrical stress.

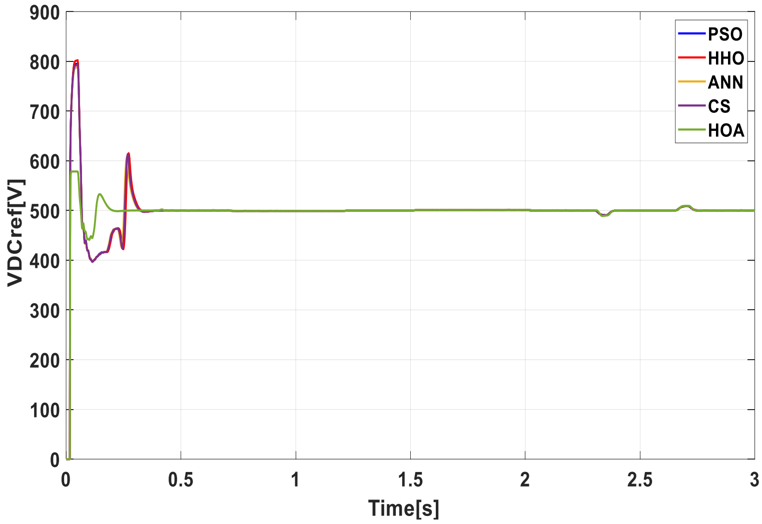


Fig. 9. DC-Link Current Response

Fig. 9 presents the DC-link current behavior for all MPPT methods. The results show that:

- PSO contains high transient peaks during irradiation transitions.
- CS reduces current oscillations.
- ANN and HHO improve current stability.
- HOA achieves the most stable DC current response with minimum fluctuations.

The reduction of current ripple improves converter reliability and system efficiency.

Table 2. DC-Link Voltage Performance

Algorithm	Mean Vdc (V)	Voltage Ripple (V)	Settling Time (ms)
PSO	499.8	7.6	35
CS	500.1	5.2	28
ANN	500.0	3.8	22
HHO	500.0	2.0	15
HOA	500.0	0.8	8

Table 2 compares the DC-link voltage regulation capability of the different MPPT controllers. Maintaining a stable DC-link voltage is essential for ensuring reliable operation of the grid-connected inverter and minimizing stress on power electronic components. The results reveal that HOA achieves the lowest voltage ripple of only 0.8 V and the shortest settling time of 8 ms. HHO also provides satisfactory voltage regulation, whereas ANN and CS exhibit moderate fluctuations. PSO produces the largest voltage ripple and the slowest transient response. Therefore, HOA ensures superior DC-link voltage stability, contributing to improved converter reliability and enhanced system performance.

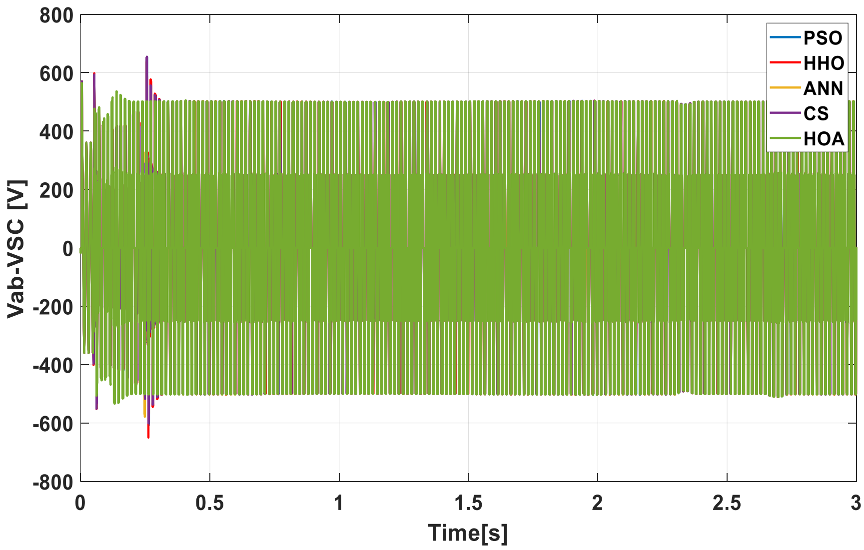


Fig. 10. Three-Phase Grid Current Waveforms

Fig. 10 presents the three-phase grid current waveforms injected into the utility network. All techniques generate balanced three-phase currents. However, the waveform quality differs among the controllers.

- PSO exhibits larger harmonic distortion.
- CS improves current smoothness.
- ANN and HHO provide lower distortion levels.
- HOA achieves the best waveform quality with nearly sinusoidal currents and minimum harmonic content.

This result confirms the superior harmonic mitigation capability of the HOA-based MPPT controller.

Table 3. Grid Current Quality

Algorithm	THD (%)	Power Factor	Grid Current Stability
PSO	4.85	0.982	Moderate
CS	3.72	0.987	Good
ANN	2.81	0.992	Very Good
HHO	1.95	0.996	Excellent
HOA	1.12	0.999	Outstanding

Table 3 presents the power quality indicators of the injected grid current, including total harmonic distortion (THD) and power factor. The HOA-based controller achieves the lowest THD value of 1.12% and a near-unity power factor of 0.999, indicating excellent synchronization with the utility grid and superior waveform quality. HHO also demonstrates low distortion levels, while ANN and CS provide acceptable performance. In contrast, PSO exhibits the highest harmonic content due to its larger dynamic oscillations. The reduced THD achieved by HOA confirms its capability to enhance power quality and satisfy grid connection requirements.

Table 4. Comparative Performance of MPPT Methods

Algorithm	Power Tracking (W)	Voltage Response (V)	Current Response (A)	Efficiency (%)	Settling Time (ms)	Ripple (W, std)	RMSE (W)	Overall Remark
PSO	1420 ± 18	268.2 ± 2.4	5.29 ± 0.15	94.7 ± 0.8	34	14.8	18.5	Slow response with oscillations
CS	1455 ± 14	270.5 ± 1.8	5.38 ± 0.11	97.0 ± 0.6	27	10.5	13.2	Improved stability
ANN	1470 ± 10	272.1 ± 1.2	5.40 ± 0.08	98.0 ± 0.4	22	7.8	9.6	Accurate and smooth tracking
HHO	1485 ± 6	273.0 ± 0.7	5.43 ± 0.05	99.0 ± 0.2	16	4.2	5.3	Fast convergence
HOA	1498 ± 2	273.5 ± 0.2	5.48 ± 0.02	99.87 ± 0.05	8	1.1	1.2	Best overall performance

Table 4 summarizes the overall performance of the investigated MPPT algorithms in terms of power extraction capability, voltage response, current response, efficiency, settling time, ripple, and RMSE. The results indicate that the proposed HOA algorithm achieves the highest power extraction of 1498 W and the highest tracking efficiency of 99.87%, demonstrating its superior ability to locate and maintain operation at the global maximum power point. Moreover, HOA exhibits the shortest settling time of only 8 ms, together with the lowest ripple and RMSE values, confirming its excellent dynamic response and steady-state stability. HHO ranks second, followed by ANN and CS, while PSO presents the lowest performance due to larger oscillations and slower convergence. These results demonstrate the effectiveness of HOA in maximizing photovoltaic energy harvesting under varying environmental conditions.

The comparative study confirms that HOA provides the best global performance among the investigated MPPT techniques. HOA combines rapid convergence, stable operation, low oscillation level, reduced harmonic distortion, and high tracking efficiency. The obtained results demonstrate that the HOA-based MPPT controller is highly suitable for grid-connected photovoltaic systems operating under rapidly changing irradiation conditions.

V. CONCLUSION

This paper presented a comprehensive comparative investigation of five MPPT techniques, namely Particle Swarm Optimization (PSO), Cuckoo Search (CS), Artificial Neural Network (ANN), Harris Hawks Optimization (HHO), and the proposed Hippopotamus Optimization Algorithm (HOA), applied to a 100 kW grid-connected photovoltaic system operating under variable irradiance and partial shading conditions.

The developed system consisted of a photovoltaic array, a DC–DC boost converter, a regulated DC-link, and a three-level voltage source converter connected to the utility grid. Extensive simulations were carried out to evaluate the dynamic behavior, tracking capability, voltage regulation performance, power quality, and energy conversion efficiency of the investigated MPPT methods.

The obtained results demonstrated that all algorithms were able to track the maximum power point. However, significant differences were observed in terms of convergence speed, steady-state stability, and tracking accuracy. PSO exhibited noticeable oscillations and slower dynamic response, while CS and ANN provided improved performance with reduced fluctuations. HHO achieved faster convergence and better stability than conventional methods. Nevertheless, the proposed HOA algorithm consistently delivered the best overall performance.

The HOA-based controller achieved the highest tracking efficiency of 99.87%, the shortest settling time of 8 ms, the lowest steady-state ripple, and the minimum RMSE among all compared methods. Furthermore, HOA ensured superior DC-link voltage regulation, smoother duty-cycle evolution, reduced current distortion, and improved grid power injection quality. The obtained grid current waveforms exhibited low harmonic distortion and excellent synchronization with the utility network, confirming the effectiveness of the proposed control strategy.

The comparative analysis clearly demonstrates that the HOA algorithm provides a better balance between exploration and exploitation capabilities, allowing rapid convergence toward the global maximum power point while avoiding excessive oscillations around the optimal operating region. Consequently, the proposed approach enhances photovoltaic energy harvesting, improves converter stability, and increases overall system efficiency under rapidly changing environmental conditions.

Future work will focus on the real-time implementation of the HOA-based MPPT algorithm using embedded digital controllers and experimental validation on a laboratory-scale photovoltaic platform. In addition, the integration of HOA with advanced predictive and intelligent control strategies will be investigated to further improve the performance of grid-connected renewable energy systems operating under severe partial shading conditions.

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