

A NUMERICAL EVALUATION PERFORMANCE OF BIO-INSPIRED METAHEURISTIC MPPT ALGORITHMS FOR LOW-POWER PV SYSTEMS

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Abstract

Photovoltaic (PV) systems require efficient maximum power point tracking (MPPT) to ensure optimal energy utilization. Conventional methods such as Perturb and Observe (P&O) and Incremental Conductance (InC) still exhibit oscillations, slow response, and a tendency to get trapped at local maxima under changing irradiation. This study evaluates five bio-inspired metaheuristic algorithms, consisting of Grey Wolf Optimizer (GWO), Sand Cat Swarm Optimization (SCSO), Horse Herd Optimization (HHO), Chameleon Swarm Algorithm (CSA), and Flying Squirrel Search Optimization (FSSO), to improve tracking accuracy, convergence speed, and MPPT stability. All algorithms were tested under identical parameter settings on a PV model with a DC–DC boost converter, under static and dynamic irradiance conditions, using MATLAB/Simulink. Results show that HHO achieved the best performance, with efficiencies of 99.96% at 1000 W/m² and 98.03% at 800 W/m², tracking time < 0.05 s, and power ripple < 0.3%. Therefore, HHO demonstrates superior performance and shows strong potential for PV system implementation.

Key words: maximum power point tracking (MPPT), metaheuristic algorithm, photovoltaic system, bio-inspired

Introduction. The global energy transition is driven by the urgent need to reduce greenhouse gas (GHG) emissions, enhance energy security, and achieve net-zero emission (NZE) targets through the integration of renewable energy systems.

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The continued dominance of fossil fuels accelerates climate change and increases vulnerability to energy security, particularly for energy-importing countries. Renewable energy sources such as solar, wind, and hydro power provide environmentally friendly alternatives with near-zero operational emissions, with solar energy standing out for its accessibility, flexibility, and scalability. In this context, photovoltaic (PV) technology has become one of the fastest-growing renewable energy solutions, including the increasing adoption of low-power PV systems operating autonomously in off-grid configurations [1].

Unlike large-scale grid-connected systems, low-power photovoltaic systems are heavily based on energy storage and efficient power extraction, where every milliwatt directly contributes to system stability and sustainability [2]. Maximum power point tracking (MPPT) devices are therefore essential to ensure optimal power extraction under varying irradiance and temperature conditions [3]. Conventional algorithms such as Perturb and Observe (P&O) and Incremental Conductance (InC) remain widely used due to their simplicity. However, they suffer from oscillations around the maximum power point (MPP), slow dynamic response, and susceptibility to local maxima under rapidly changing environmental conditions [4].

To overcome these limitations, bio-inspired metaheuristic algorithms have been introduced due to their strong global exploration and exploitation capabilities [5]. Various approaches, including Grey Wolf Optimizer (GWO), Particle Swarm Optimization (PSO), Genetic Algorithm (GA), Sand Cat Swarm Optimization (SCSO), Whale Optimization Algorithm (WOA), and Flying Squirrel Search Optimization (FSSO), have demonstrated improved MPPT effectiveness, particularly in large-scale PV systems. Nevertheless, their evaluation in low-power photovoltaic applications remains limited, despite the distinct characteristics of such systems, including limited capacity and greater sensitivity to irradiance fluctuations.

This study evaluates five bio-inspired metaheuristic algorithms, comprising GWO, Horse Herd Optimization (HHO), Chameleon Swarm Algorithm (CSA), SCSO, and FSSO, for MPPT in low-power PV systems. The assessment focuses on tracking efficiency, convergence speed, and completion time under static and dynamic irradiance conditions. The results are expected to provide a quantitative reference for selecting appropriate MPPT algorithms in low-power PV applications.

System design and MPPT implementation. The proposed system consists of a PV module, a bio-inspired metaheuristic maximum power point tracking (MPPT) controller, and a DC–DC boost converter supplying a resistive load, as shown in Fig. 1. Irradiance (G) and temperature (T) generate the PV voltage (V_{pv}) and current (I_{pv}), which are processed to determine the optimal duty cycle (D) for pulse width modulation (PWM) control to ensure operation at MPP.

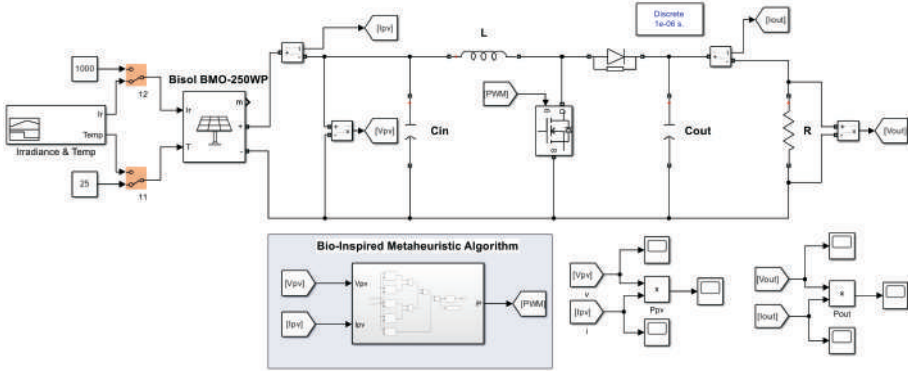


Fig. 1. The proposed PV system

The PV module is modelled using a single-diode equivalent circuit. The current–voltage relationship is expressed as

$$(1) \quad I = I_{ph} - I_s \left(e^{\frac{q(V+IR_s)}{nkT}} - 1 \right) - \frac{V + IR_s}{R_{sh}}$$

and the output power is defined as

$$(2) \quad P = VI.$$

The BISOL BMO-250 W module is employed, with $P_{\max} = 250.10$ W, $V_{mp} = 30.5$ V, $I_{mp} = 8.20$ A, $V_{oc} = 37.9$ V, and $I_{sc} = 8.80$ A.

The boost converter regulates the PV operating point through duty cycle adjustment, following the voltage conversion relation

$$(3) \quad V_o = \frac{V_{in}}{1 - D}.$$

Five bio-inspired metaheuristic algorithms, consisting of GWO, HHO, SCSO, FSSO, and CSA, are implemented to optimize the duty cycle within $D \in [0.1, 0.9]$. The objective function is defined as

$$(4) \quad f(D) = P_{pv}(D).$$

All algorithms use the same population size of 10 and a maximum of 50 iterations to ensure a fair comparison. Simulations are conducted for 1 s with a sampling period of $T_s = 1 \times 10^{-6}$ s under two scenarios: (i) standard test conditions (STC) at 1000 W/m^2 and 25°C , and (ii) dynamic irradiance variation from 600 to 800 to 1000 W/m^2 .

MPPT performance is evaluated using tracking efficiency, convergence time, and power ripple. Tracking efficiency and ripple are calculated as

$$(5) \quad \eta_{MPPT} = \frac{P_{MPPT}}{P_{MPP,ideal}} \times 100\%,$$

$$(6) \quad \Delta P = \frac{P_{\max,ss} - P_{\min,ss}}{P_{MPP,ideal}} \times 100\%,$$

where convergence time represents the duration required to reach and maintain operation near the MPP after initialization or irradiance change.

Results and discussion. The proposed system was simulated in MATLAB/Simulink for 1 s with a sampling period of $T_s = 1 \times 10^{-6}$ s, consisting of a PV module, bio-inspired metaheuristic MPPT controller, PWM, and a resistive load. Performance was evaluated in terms of tracking efficiency (η_{MPPT}), power ripple, and convergence time under STC and dynamic irradiance conditions.

As shown in Fig. 2(a), all algorithms rapidly increased the PV voltage and stabilized around the nominal MPP value of 30.5 V. HHO and GWO exhibited smoother convergence with minimal oscillation, whereas FSSO and CSA showed larger transient fluctuations. The current responses in Fig. 2(b) stabilized near 8.2 A, with HHO and GWO achieving faster settling and lower ripple. These char-

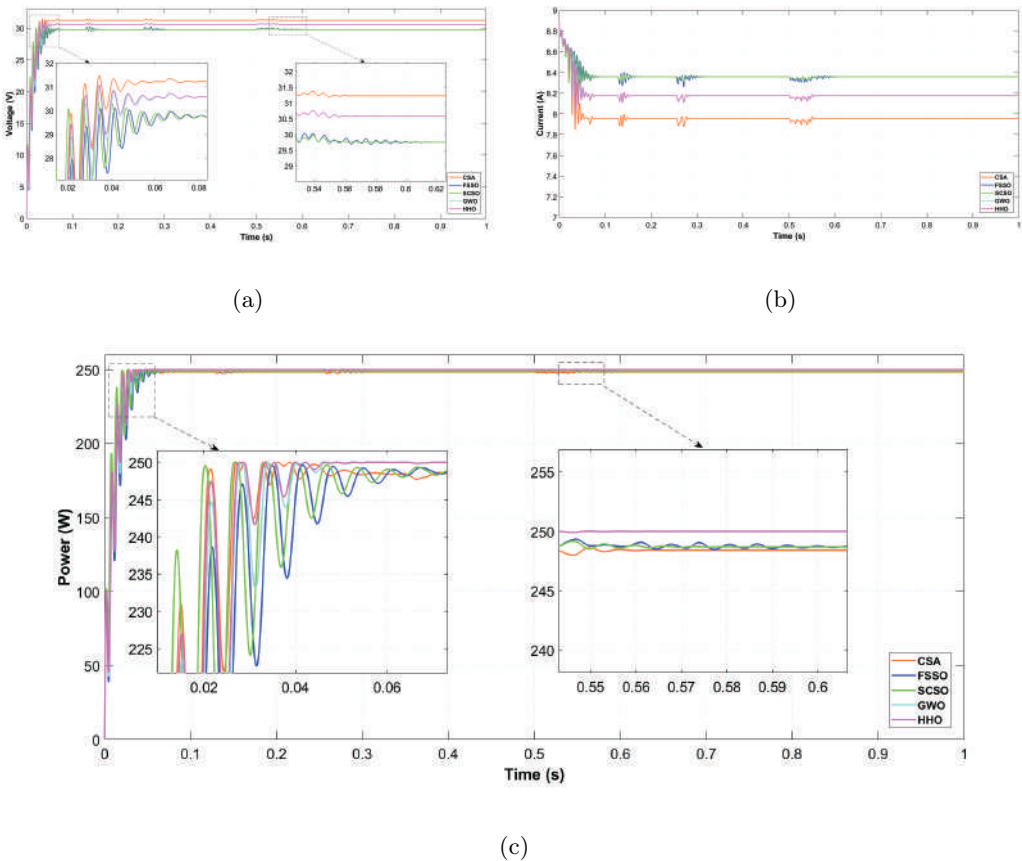


Fig. 2. MPPT algorithm performance under STC (1000 W/m², 25 °C): (a) PV voltage, (b) PV current, and (c) power extraction

acteristics are reflected in the power response in Fig. 2(c), where HHO and GWO reached values closest to the ideal 250 W, with ripples of 0.08% and convergence times of 0.046 s and 0.04 s, respectively. SCSO and FSSO achieved 248.7 W in 0.074 s and 0.081 s, while CSA required 0.051 s to reach 248.4 W. Although FSSO showed the largest ripple (0.88%), it remained within acceptable tracking stability ($< 1\%$), with corresponding efficiency and power values under varying irradiance summarized in Table 1.

T a b l e 1
MPPT efficiency under different irradiance levels

Irradiance (W/m^2)		600	800	1000
Maximum power (W)		153.50	202.60	250.10
HHO	Extracted power (W)	150.60	198.60	250.00
	Efficiency (%)	98.13	98.03	99.96
GWO	Extracted power (W)	147.00	198.20	250.00
	Efficiency (%)	95.78	97.84	99.96
SCSO	Extracted power (W)	147.00	198.40	248.70
	Efficiency (%)	95.78	97.93	99.44
FSSO	Extracted power (W)	149.50	198.50	248.70
	Efficiency (%)	97.41	97.98	99.44
CSA	Extracted power (W)	149.50	198.00	248.40
	Efficiency (%)	97.41	97.74	99.32

Dynamic evaluation was performed under irradiance variations from 1000 to 800 and 600 W/m^2 . The voltage response of each algorithm is presented in Fig. 3(a). When irradiance decreased to 800 W/m^2 , the PV voltage dropped proportionally, with HHO stabilizing around 29.20 V. Although GWO showed slight voltage oscillations, its steady-state value remained stable. CSA exhibited the largest voltage fluctuation, corresponding to its higher dynamic ripple.

The corresponding current responses are shown in Fig. 3(b). As irradiance decreased, the current was reduced consistently across all algorithms. HHO and FSSO maintained smoother transitions, while CSA experienced more pronounced transient oscillations during irradiance changes.

The resulting power extraction is illustrated in Fig. 3(c). At 800 W/m^2 , HHO achieved 198.60 W, followed closely by FSSO with 198.50 W. CSA showed the largest oscillation (1.38%), whereas GWO maintained relatively stable power. When irradiance decreased to 600 W/m^2 , HHO again achieved the highest power of 150.6 W with the fastest convergence time of 0.02 s. GWO and SCSO produced approximately 147 W, with settling times of 0.022 s and 0.026 s. CSA and FSSO showed initial oscillations of 2.22% and 1.89%, respectively.

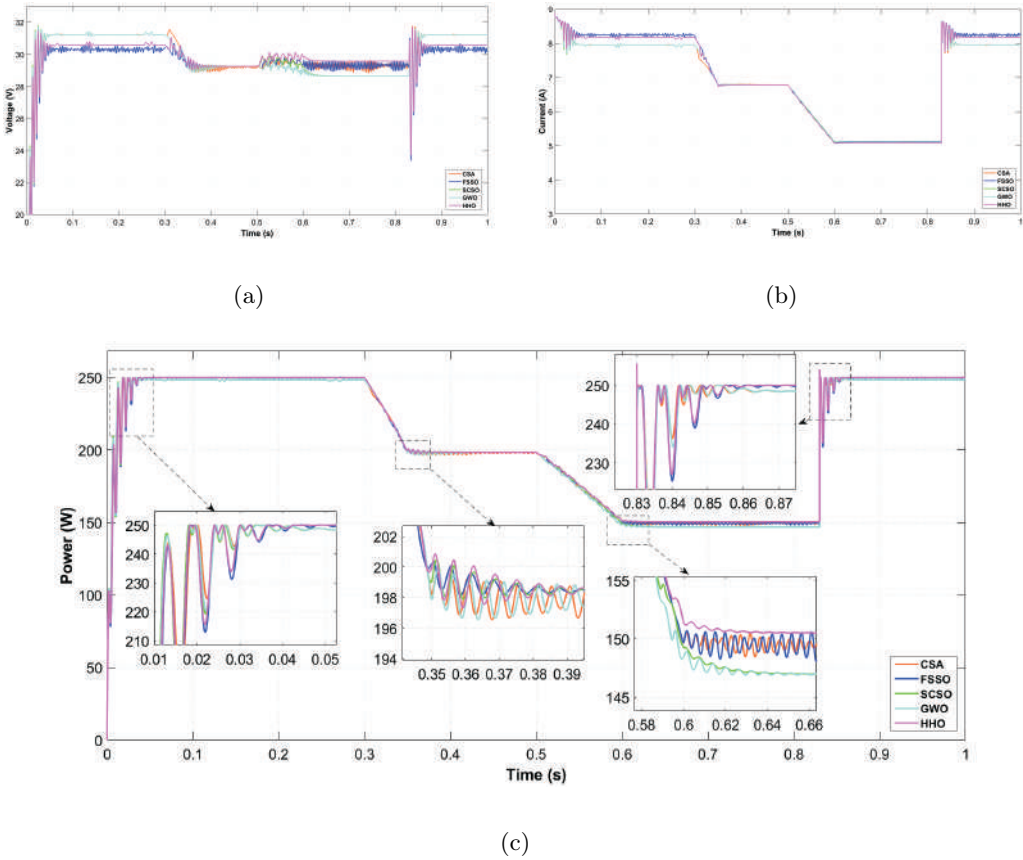


Fig. 3. MPPT algorithm performance under varying irradiance (1000–800–600 W/m²): (a) PV voltage response, (b) PV current response, and (c) power extraction

When irradiance returned to 1000 W/m², all algorithms rapidly recovered toward the 250 W MPP. HHO and FSSO exhibited brief transient surges before stabilizing.

Overall, HHO demonstrated the most favourable performance among CSA, FSSO, SCSO, and GWO. It achieved the fastest tracking time, steady-state power closest to the MPP, and the smallest voltage, current, and power ripple. Its adaptive exploration–exploitation mechanism enables rapid convergence with minimal oscillation. The 99.96% efficiency achieved by HHO here is consistent with HHO-based MPPT results reported for PV systems of differing scale, ranging from 99.64% to 99.98% across nominal powers of 250.1–1721 W [6–9], indicating stable convergence behaviour independent of system size. These results reinforce the suitability of HHO for MPPT optimization in PV systems.

Conclusion. This study numerically evaluated five metaheuristic algorithms: HHO, GWO, CSA, SCSO, and FSSO, for MPPT in a PV system with a sin-

gle module and DC–DC boost converter. While all methods achieved satisfactory MPP tracking, CSA and FSSO showed initial oscillations under irradiance changes, and GWO and SCSO experienced reduced efficiency at low irradiance. HHO consistently demonstrated the best overall performance and highest efficiency. The reported results are based on single-run simulations without a direct comparison against conventional P&O or InC baselines, so the observed efficiency margins should be interpreted as indicative rather than statistically confirmed. Future work will address hardware implementation, testing under complex temperature variations and partial shading, multiple independent trials with statistical validation, and direct comparison against conventional MPPT methods, considering practical nonidealities.

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