

# Particle Swarm Optimization–Based Global MPPT for a Standalone PV Water Pumping System Under Partial Shading

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**Abstract.** Partial shading conditions (PSCs) distort the photovoltaic (PV) power–voltage characteristic and generate multiple local maxima, potentially trapping conventional maximum power point tracking (MPPT) algorithms and reducing the energy available to motor–pump systems. This paper investigates a particle swarm optimization (PSO)–based global MPPT (GMPPT) strategy for a low-power standalone photovoltaic water pumping system (PVWPS) composed of a bypass-diode-protected PV module, a DC–DC boost converter, a permanent-magnet DC (PMDC) motor, and a centrifugal pump. The PSO algorithm directly searches for the optimal boost duty ratio that maximizes PV power under PSCs. To improve practical applicability, a holding-stage and averaged-fitness evaluation are introduced to reduce transient influence and limit steady-state oscillations. MATLAB/Simulink simulations are performed under uniform irradiance and a representative PSC pattern (1000–1000–200 W/m<sup>2</sup>). In addition to electrical indicators, pumping-oriented metrics such as hydraulic power, motor speed, and flow rate are analyzed. Results show that PSO successfully converges to the global peak region under PSCs, improving hydraulic power by approximately 34% and increasing flow rate and motor speed by about 10% compared to the Incremental Conductance (INC) method, while maintaining a low ripple.

## 1 Introduction

Standalone photovoltaic (PV) water pumping systems (PVWPS) are increasingly deployed in remote and rural regions where grid extension is impractical and diesel pumping is costly and carbon intensive. A typical PVWPS couples a PV generator to a motor–pump set through a DC–DC converter, allowing the PV operating point to be adjusted to maximize harvested energy and, consequently, delivered water volume [1, 2].

Conventional MPPT methods such as Perturb and Observe (P&O) and Incremental Conductance (INC) remain popular due to their simplicity and low sensing requirements [3]. However, under partial shading conditions (PSCs) caused by clouds, soiling, nearby obstacles, or array mismatch, bypass diodes activate and the PV P–V curve can exhibit multiple peaks [4]. In such multi-modal landscapes, local trackers may converge to a local maximum power point (LMPP) rather than the global maximum power point (GMPP), reducing energy capture and pump productivity.

To address PSCs, global MPPT (GMPPT) approaches have been proposed, including deterministic scans and metaheuristic optimization [5, 6]. Among swarm-based methods, particle swarm optimization (PSO) offers a favorable exploration–exploitation balance, simple update equations, and strong empirical performance for GMPPT. Nevertheless, continuous stochastic search can increase steady-state oscillations and computational load, motivating implementation strategies that combine

global search with a holding stage and averaged fitness evaluation to enhance stability in dynamic PVWPS applications.

### 1.1 Contributions

This conference paper makes the following contributions:

- (i) A PSO-based GMPPT controller is formulated to maximize PV power by directly searching the boost duty ratio under PSCs.
- (ii) A holding-stage with averaged-fitness evaluation is integrated within the PSO procedure to account for motor–pump settling dynamics and mitigate steady-state oscillations.
- (iii) Beyond conventional electrical MPPT indicators, pumping-oriented metrics (motor speed, flow-rate proxy, and hydraulic power) are reported to explicitly connect GMPPT behavior to hydraulic performance in a standalone PVWPS.

### 1.2 Paper organization

Section 2 summarizes related work and motivates PSO-based GMPPT for PVWPS. Section 3 presents the PVWPS configuration and component models. Section 4 details the proposed PSO-GMPPT strategy and its holding-based implementation. Section 5 describes the simulation setup and test cases. Section 6 discusses

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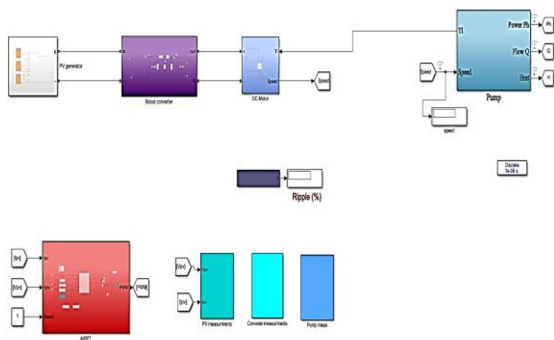
results under uniform and partial shading conditions, including pumping metrics. Section 7 concludes the paper.

## 2 Related work and motivation

GMPPT under PSCs has been widely studied because multi-peak P–V characteristics can significantly degrade energy harvesting [4, 5]. Surveys report strong growth of bio-inspired and swarm-based GMPPT algorithms that can escape local maxima without requiring an explicit PV model, including PSO, grey wolf optimizer (GWO), whale optimization algorithm (WOA), and hybrids [6,7].

In PV water pumping, many studies still evaluate MPPT using only electrical indicators, whereas irrigation and water delivery applications benefit from reporting water-oriented measures (e.g., speed/flow stability and pumped volume) [8, 9]. Recent PVWPS works using metaheuristics suggest that improved tracking can translate to higher motor speed and increased water flow, especially under low irradiance or shading. The present paper focuses on PSO due to its wide adoption, theoretical foundation, and proven GMPPT capability under PSCs.

## 3 System configuration and modelling



**Fig. 1.** Overall configuration of the standalone PV water pumping system (PV module–boost converter–PMDC motor–centrifugal pump).

### 3.1 PV module model and partial shading representation

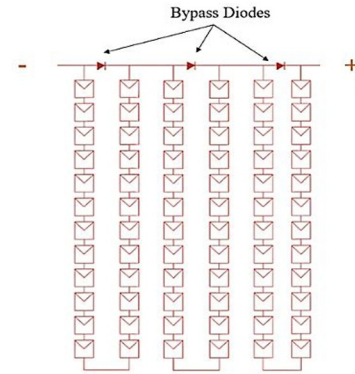
The PV generator is modeled using the single-diode equivalent circuit with series and shunt resistances [10]. The PV current is expressed as:

$$I = I_{ph} - I_s \left( e^{\frac{V+R_s I}{nN_s V_t}} - 1 \right) - \frac{V+R_s I}{R_{sh}} \quad (1)$$

where  $I_{ph}$  is the photo-generated current,  $I_s$  is the diode saturation current,  $R_s$  and  $R_{sh}$  are the series and shunt resistances,  $n$  is the ideality factor, and  $V_t$  is the thermal voltage.

To emulate PSCs, the 72-cell module is represented as three substrings (3×24 cells) protected by bypass diodes

[4, 11, 12]. Substring-level irradiance patterns create mismatch and multiple peaks on the P–V curve.



**Fig. 2.** PV substring model with bypass diodes

### 3.2 Boost converter and DC-link dynamics

A DC–DC boost converter interfaces the PV module to the motor drive. In continuous conduction mode [13], the ideal conversion ratio is:

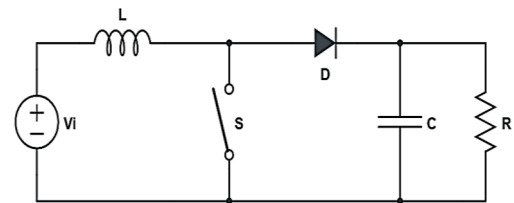
$$V_{dc} \approx \frac{V_{pv}}{1-D} \quad (2)$$

Inductor current and capacitor voltage dynamics can be modeled to capture ripple and transient behavior [13]:

$$L \frac{dI_L}{dt} = V_{pv} - (1-D)V_{dc} \quad (3)$$

$$C \frac{dV_{dc}}{dt} = (1-D)I_L - I_{load} \quad (4)$$

The duty ratio is  $D \in [D_{min}, D_{max}]$  to ensure safe operation and limit current stress.



**Fig. 3.** Boost converter basic model.

### 3.3 PMDC motor and centrifugal pump model

The pump is driven by a PMDC motor. Electrical and mechanical equations are [2]:

$$V_a = K_e \omega + R_a I_a + L_a \frac{dI_a}{dt} \quad (5)$$

$$T_e = K_t I_a \quad (6)$$

$$T_e - T_L(\omega) = J \frac{d\omega}{dt} + B\omega \quad (7)$$

where  $V_a$  and  $I_a$  are armature voltage and current;  $R_a$  and  $L_a$  are armature resistance and inductance;  $K_e$  and  $K_t$  are back-EMF and torque constants; and  $J$  is combined inertia.

For a centrifugal pump, affinity laws provide a convenient pumping-oriented evaluation:

$$Q \propto \omega \quad (8)$$

$$H \propto \omega^2 \quad (9)$$

$$P_h = \rho g H Q \propto \omega^3 \quad (10)$$

## 4 PSO-based global MPPT strategy

### 4.1 Optimization problem formulation

The GMPPT objective is to maximize PV power by selecting an appropriate boost duty ratio:

$$\max P_{pv}(D) = V_{pv}(D) I_{pv}(D) \quad (11)$$

The duty ratio is  $D \in [D_{min}, D_{max}]$ .

Under PSCs,  $P_{pv}(D)$  may exhibit multiple local maxima motivating a global optimizer.

### 4.2 Particle swarm update equations

In PSO, each particle  $i$  represents a candidate duty ratio  $D_i$  with velocity  $v_i$ . At iteration  $k$ , velocity and position are updated as [13, 14]:

$$V_i(k+1) = \chi \left( V_i(k) + C_1 r_1 (pbest_i - D_i(k)) + C_2 r_2 (gbest - D_i(k)) \right) \quad (12)$$

$$D_i(k+1) = \text{sat}(D_i(k) + V_i(k+1), D_{min}, D_{max}) \quad (13)$$

### 4.3 Holding stage and averaged-fitness evaluation (duty-cycle PSO)

In PV water pumping applications, the electrical and mechanical dynamics of the DC–DC converter, motor, and pump introduce a non-negligible settling time after each duty-cycle change. If the PV power is evaluated immediately after updating the duty ratio, the measured value may be dominated by transient behavior, leading to inaccurate fitness assessment and unstable search. To address this issue, the proposed PSO-GMPPT adopts a holding stage combined with an averaged-fitness evaluation.

At each PSO iteration, the duty ratio commanded by particle  $i$ , denoted  $D_i$ , is kept constant for a fixed number of controller calls (or sampling instants), noted  $N_h$  (“hold steps”). During this holding window, the converter–motor–pump system is allowed to reach a quasi-steady operating point. To further reduce the influence of initial transients, the first  $N_d$  samples (“discard steps”) after applying  $D_i$  are ignored. The remaining samples are used to compute the particle fitness as the average PV power:

$$\bar{P}_{PV,i} = \frac{1}{N_h - N_d} \sum_{n=N_d+1}^{N_h} P_{PV,i}[n] \quad (14)$$

where  $P_{PV,i}[n]$  is the instantaneous PV power measured while the duty ratio is held at  $D_i$ , and  $N_h > N_d$ . The computed  $\bar{P}_{PV,i}$  is then used to update the personal best  $pbest_i$  and global best  $gbest$  solutions. After the fitness evaluation is completed, the algorithm

proceeds to the next particle and repeats the same hold-and-average procedure.

This approach provides two benefits:

- It yields a more reliable fitness value that reflects the steady operating condition of the PVWPS.
- It inherently limits rapid duty-cycle variations, thereby reducing steady-state oscillations and mechanical stress. Once all particles are evaluated (one swarm cycle), an “elite” retention strategy can be applied by keeping one particle fixed at the best duty ratio  $gbest$ , which helps prevent drift and maintains stable operation around the identified GMPP region.

## 5 Simulation setup and test cases

### 5.1 System overview and modeling assumptions

Simulations are carried out in MATLAB/Simulink for a standalone photovoltaic water pumping system (PVWPS) composed of a PV generator, a DC–DC boost converter, and a PMDC motor driving a centrifugal pump. The PV source corresponds to a 174 W class module (72 cells) and is represented as three bypass-protected substrings, as mentioned and illustrated before, to reproduce multi-peak P–V characteristics under partial shading conditions (PSCs).

All components are sized to ensure stable operation of the closed-loop system and to keep the boost converter in continuous conduction mode under the considered operating range. The same plant model and controller sampling time are used for all methods to ensure a fair comparison.

**Table 1.** PVWPS configuration summary.

Item	Description
PV generator	174 W class module, 72 cells
PSC representation	3 substrings + bypass diodes
Power stage	DC–DC boost converter (duty cycle command $D$ )
Load	PMDC motor + centrifugal pump (dynamic load)
Pumping outputs	Hydraulic power $P_h$ , motor speed $\omega$ , flow rate $Q$

### 5.2 Irradiance scenario

The following irradiance scenario is considered to keep the study compact and focused: **Static partial shading (multi-peak case):**

- $G_1=1000, G_2=1000, G_3=200 \text{ W/m}^2$
- $T=25^\circ\text{C}$

This irradiance distribution generates a multi-peak P–V characteristic, as discussed in Section 6.

### 5.3 Baseline method

Incremental Conductance (INC) MPPT is used as a baseline tracking method. INC is selected because it is widely accepted, simple to implement, and typically offers better steady-state behavior than fixed-step P&O under uniform irradiance [2, 15]. Under PSCs, INC may still converge to a local peak depending on the operating region [5], which motivates comparison with PSO-based global search. Its flowchart is given on Fig. 4.

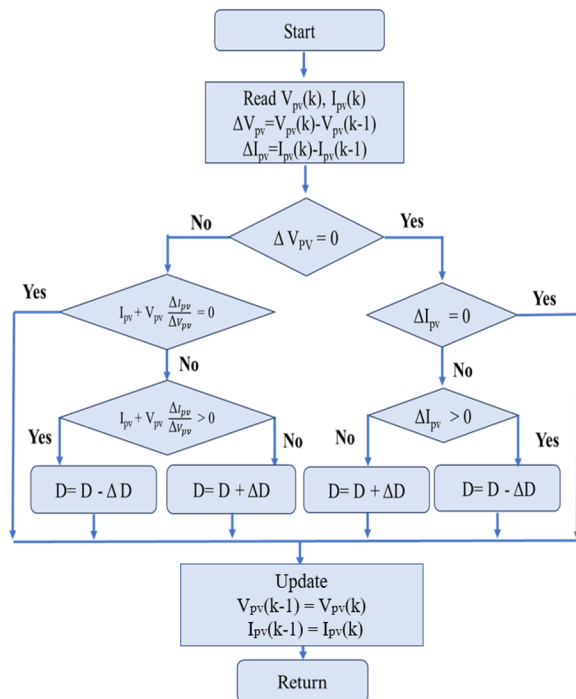


Fig. 4. INC flowchart

## 6 Results and discussion

### 6.1 P–V characteristic under partial shading

Under PSCs, bypass diode activation produces a multi-peak P–V characteristic. In the considered static PSC pattern (1000–1000–200 W/m<sup>2</sup>), the PV curve exhibits at least one local maximum in addition to the global maximum, as shown in Fig.5. This section presents the corresponding P–V curve and highlights the LMPP and GMPP regions used as a reference when interpreting tracking responses.

The hydraulic power  $P_h$ , defined as  $P_h = \rho gQH$ , represents the effective power transferred to the pumped water. Under the considered partial shading configuration, a significant performance difference is observed between the two MPPT strategies.

The INC method stabilizes at a lower operating region associated with the local maximum of the shaded P–V curve. In contrast, the PSO-based GMPPT converges toward the global maximum region, resulting in approximately 34% higher steady-state hydraulic power.

This substantial increase confirms that local tracking methods may fail under multi-peak conditions, whereas

global search strategies enable superior energy extraction and improved system operation.

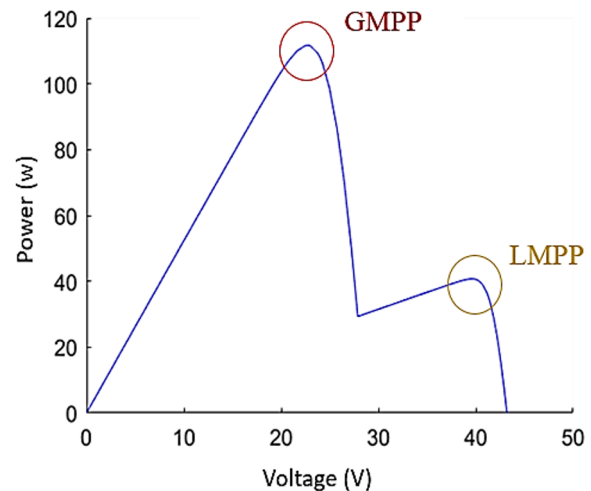


Fig. 5. PV P–V characteristic under partial shading (1000–1000–200 W/m<sup>2</sup>), showing multiple peaks (LMPP and GMPP)

### 6.2 Dynamic Tracking Performance Under PSC

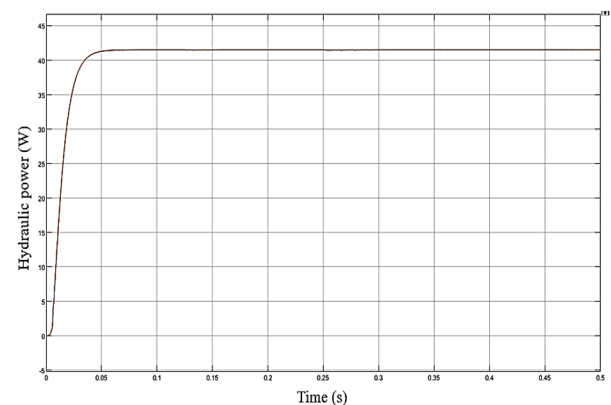


Fig. 6. Hydraulic power vs time using INC

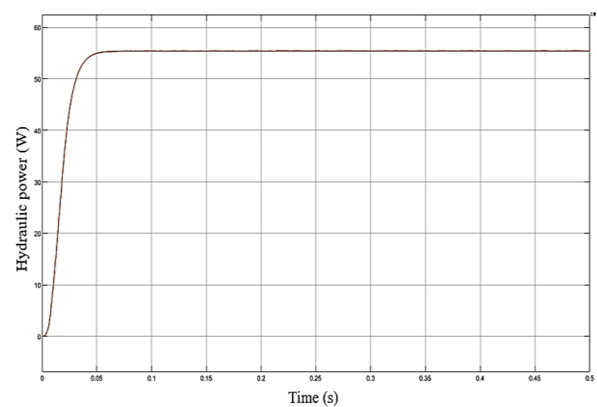
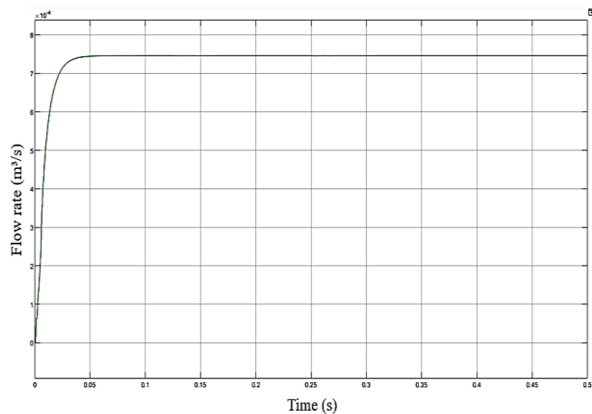
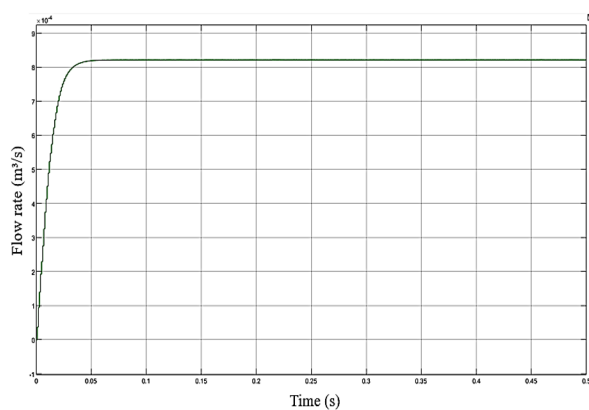


Fig. 7. Hydraulic power vs time using PSO

### 6.3 Flow Rate Performance



**Fig. 8.** Flow rate vs time using INC



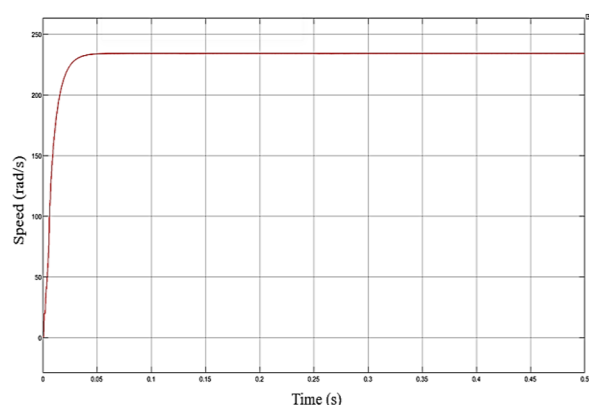
**Fig. 9.** Flow rate vs time using PSO

The flow rate  $Q$  directly represents the delivered water volume rate. Under PSC, the PSO controller achieves approximately a 10% increase in steady-state flow rate compared to INC.

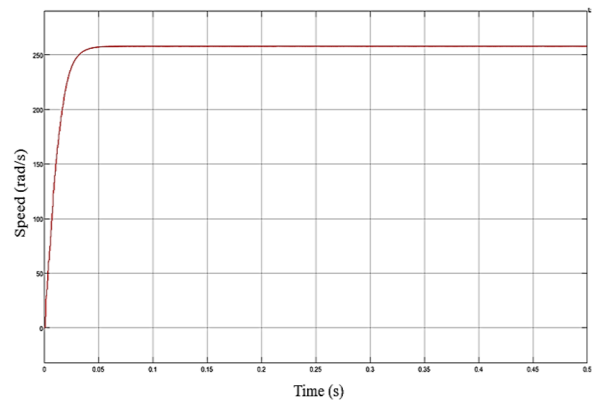
Although the percentage increase in flow is smaller than the increase in hydraulic power, it remains practically significant. In real pumping applications, even moderate improvements in flow rate can translate into considerable gains in daily pumped water volume.

The improvement demonstrates that enhanced electrical tracking under PSC effectively translates into improved hydraulic output.

### 6.4 Motor Speed Analysis



**Fig. 10.** Speed vs time using INC



**Fig. 11.** Speed vs time using PSO

Motor speed also increases by approximately 10% when the PSO-based GMPPT is applied. This proportional increase between speed and flow rate is consistent with centrifugal pump affinity laws, where flow rate is approximately proportional to rotational speed.

The improved operating speed confirms that the pump is driven closer to its optimal mechanical operating region when the PV array operates near the GMPP.

### 6.5 Ripple and Stability Analysis

To evaluate the dynamic stability of both MPPT strategies, steady-state ripple was analyzed for hydraulic power, flow rate, and motor speed. Ripple was quantified using peak-to-peak variation relative to the steady-state average value.

The results indicate that the PSO-based GMPPT maintains comparable oscillation levels compared to INC. The use of a holding stage and averaged fitness evaluation significantly limits rapid duty-cycle variations, thereby reducing mechanical and hydraulic oscillations.

This confirms that the proposed PSO strategy not only improves steady-state performance but also preserves acceptable dynamic stability, making it suitable for practical PV water pumping applications.

### 6.6 Overall Discussion

The results under the considered partial shading condition (1000–1000–200 W/m<sup>2</sup>) demonstrate the clear advantage of global optimization for PV water pumping systems operating under mismatch conditions. The multi-peak nature of the shaded P–V characteristic makes local tracking strategies vulnerable to convergence toward sub-optimal operating points. As observed, the INC algorithm stabilizes near the local maximum, limiting both electrical extraction and hydraulic performance.

In contrast, the PSO-based GMPPT successfully identifies and maintains operation near the global maximum region. This results in a substantial improvement in hydraulic output, with an increase of approximately 34% in hydraulic power and around 10% in both flow rate and motor speed. These improvements confirm that enhanced electrical tracking directly

translates into meaningful gains in water delivery performance.

Importantly, the performance enhancement is achieved without compromising system stability. The steady-state hydraulic power ripple remains below 0.5% for both methods, with only a marginal increase observed in the PSO case. Such low ripple levels indicate that the holding and averaged-fitness strategy effectively mitigates excessive duty-cycle oscillations and prevents mechanical stress on the motor–pump system.

From a practical perspective, the demonstrated improvements are highly relevant. In real-world installations, partial shading is unavoidable due to environmental factors such as obstacles, dust, or non-uniform irradiance. Under such conditions, reliance on local MPPT techniques can significantly reduce water delivery capacity. The proposed PSO-based approach provides a robust solution that enhances energy utilization while maintaining stable hydraulic operation. Overall, the findings confirm that global MPPT strategies are particularly beneficial for PV water pumping systems exposed to partial shading, offering a favorable balance between performance improvement and operational stability.

## 7 Conclusion

This paper presented a PSO-based global maximum power point tracking (GMPPT) strategy for a standalone photovoltaic water pumping system operating under partial shading conditions. The investigated shading profile (1000–1000–200 W/m<sup>2</sup>) generated a multi-peak P–V characteristic with distinct local and global maxima, representing a challenging scenario for conventional local MPPT techniques.

Simulation results demonstrate that the proposed PSO approach successfully avoids convergence to the local maximum and operates near the global maximum power point. Compared to the Incremental Conductance (INC) method, PSO achieved:

- Approximately 34% increase in hydraulic power,
- Nearly 10% improvement in flow rate,
- Around 10% increase in motor speed,

while maintaining excellent dynamic stability, with steady-state hydraulic power ripple remaining small for both methods.

These results confirm that global optimization strategies significantly enhance hydraulic performance in PV water pumping systems exposed to mismatch conditions. Importantly, the substantial gain in useful water power is achieved without introducing excessive oscillations, validating the effectiveness of the holding and averaged-fitness implementation of the PSO controller.

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