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Adaptive-Restart PSO-INC for Global Maximum Power Point Tracking of Photovoltaic Arrays Under Partial Shading

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Abstract: Maximum power point tracking (MPPT) is very important for photovoltaic power generation systems. Accurate global peak tracking under partial shading is of great significance for reducing power loss, improving energy utilization and enhancing operational economy. In order to realize efficient global maximum power point tracking under multi-peak conditions, based on incremental conductance (INC) and particle swarm optimization (PSO), combined with the advantages of PSO in global search and INC in local precise tracking, a hybrid PSO-INC MPPT strategy with adaptive restart mechanism is constructed.

Keywords: Photovoltaic Array, Maximum Power Point Tracking, Particle Swarm Optimization, Incremental Conductance.

1. Introduction

Photovoltaic (PV) output is strongly affected by irradiance and cell temperature. Under uniform irradiance, the power-voltage (P-V) curve normally exhibits a single dominant maximum. Partial shading, however, changes the current paths through bypass diodes and may produce several local maxima. The maximum power point tracking (MPPT) controller must therefore identify the global maximum power point (GMPP), rather than merely converge to the nearest local peak.

Incremental conductance (INC) is attractive for its simple logic and rapid local adjustment, whereas particle swarm optimization (PSO) can explore a wider operating range and is less dependent on a local gradient. These properties suggest a step-by-step controller development: first compare standalone INC and PSO; then combine their complementary search characteristics; finally add a restart mechanism to the hybrid controller to respond to changing shading conditions.

The study reported here follows this sequence using MATLAB/Simulink simulations. The standalone comparison identifies the failure of INC under a static multi-peak condition. The resulting PSO-INC controller assigns global coarse search to PSO and local precision tracking to INC. An adaptive restart is then introduced to clear outdated particle memory after a significant operating-condition change. All performance values below are simulation results from the source thesis, not hardware measurements.

2. PV Array Model and Partial-Shading Characteristics

2.1. Single-diode Model

The PV cell is represented by a single-diode equivalent circuit consisting of a photocurrent source, a diode, a series resistance, and a shunt resistance. Its output current is expressed as

$$I = I_{ph} - I_0 [\exp(q(V + I R_s)/(n k T)) - 1] - (V + I R_s)/R_{sh} \quad (1)$$

Where I and V are the output current and voltage; I_ph is the photocurrent; I_0 is the diode reverse-saturation current; q is the electron charge; n is the diode ideality factor; k is the Boltzmann constant; T is the absolute temperature; and R_s and R_sh are the series and shunt resistances, respectively. The output power is

$$P = V I \quad (2)$$

The model was implemented in MATLAB/Simulink. The reported module parameters are I_ph = 7.84987 A, I_0 = 2.9672 × 10^-10 A, n = 0.80819, R_sh = 313.0553 Ω, and R_s = 0.39381 Ω. Under the standard condition of 1000 W/m² and 25 °C, the reference array maximum power is 8517.8 W at 290 V.

2.2. Partial-shading Characteristics

With uniform irradiance, the P-V curve has one dominant peak. Under partial shading, bypass diodes provide current paths around shaded cell groups. The resulting change in the array voltage-current characteristic can create several local maxima. The number and magnitude of these peaks depend on the irradiance distribution among series-connected PV units. An INC controller that follows only the local slope may consequently converge to a local maximum and fail to reach the GMPP.

The five-unit source model includes static irradiance distributions such as (1000, 1000, 500, 800, 800) W/m², as well as changing distributions for the dynamic-shading test. The study uses the resulting P-V characteristics to compare the baseline algorithms, evaluate the hybrid controller, and assess the adaptive restart strategy.

3. Baseline Comparison of INC and PSO

3.1. Incremental-conductance Method

The INC method determines the operating-point adjustment direction from the slope of the P-V curve. Since P = V I,

$$dP/dV = I + V(dI/dV) \quad (3)$$

At the maximum power point, dP/dV = 0; therefore,

$$dI/dV = -I/V \quad (4)$$

In a sampled controller, dI and dV are approximated by ΔI and ΔV. Comparing ΔI/ΔV with -I/V indicates whether the operating voltage should be increased or decreased. This local slope-based decision is fast near a known maximum, but it does not provide a mechanism for crossing the power valleys that separate multiple peaks.

3.2. Particle-swarm Optimization

PSO searches for a maximum by updating a population of candidate operating points. Each particle retains its own best position, pbest, while the swarm shares the best position found by the population, gbest. The velocity and position updates are

$$v_i(k+1) = \omega\, v_i(k) + c_1\, r_1[pbest_i - x_i(k)] + c_2\, r_2[gbest - x_i(k)] \quad (5)$$

$$x_i(k+1) = x_i(k) + v_i(k+1) \quad (6)$$

Where ω is the inertia weight, c_1 and c_2 are acceleration coefficients, and r_1 and r_2 are random values in [0, 1]. By exploring the wider search range, PSO can move between local peaks and identify the global optimum. Its main drawback is that stochastic particle updates may require more iterations and can cause oscillation near the final operating point.

3.3. Simulation Comparison and Selection of The Baseline Algorithm

The standalone INC and PSO controllers were compared at 25 °C under standard irradiance, an irradiance step, and static multi-peak shading. Table 1 reports the theoretical GMPP power, the actual steady-state output power, and the settling time. The static multi-peak case is decisive: the theoretical GMPP is 4236.4 W, but INC settles at only 3394.88 W. PSO, by contrast, reaches the global peak region.

Table 1. Baseline comparison of standalone INC and PSO.

Condition	Algorithm	Theoretical P_GMPP (W)	Actual P_ss (W)	t_s (s)
Standard	INC	8517.80	8516.10	0.030
Standard	PSO	8517.80	8516.60	1.510
Irradiance step	INC	4319.62	4319.99	3.070
Irradiance step	PSO	4319.62	4319.60	3.510
Static multi-peak	INC	4236.40	3394.88	0.060
Static multi-peak	PSO	4236.40	4238.39	1.670

As shown in Table 1, INC is very fast in the standard and irradiance-step cases, but its fast convergence does not guarantee global tracking. Under static multi-peak shading, INC reaches only 80.14% of the theoretical maximum and loses 841.52 W; its steady-state voltage is 188.53 V, far from the 251.1 V global-maximum voltage. PSO settles at 4238.39 W, close to the 4236.4 W reference, and is reported to reach the global peak. Thus, standalone INC is not retained as the final MPPT strategy for partially shaded arrays. PSO is selected as the global-search foundation, while INC is reconsidered only as a local refinement method.

4. Hybrid PSO-INC Maximum Power Point Tracking

4.1. Global Search Followed by Local Precision Tracking

The baseline comparison exposes complementary strengths: PSO can locate a global peak across a multi-peak search range, whereas INC can make rapid and precise adjustments once the operating point is already near the desired peak. The PSO-INC method combines these functions in two consecutive stages. First, PSO performs a broad global search over the operating range and identifies a promising GMPP neighbourhood. Second, the best PSO candidate is transferred to INC, which performs fine local tracking and reduces the oscillation associated with continued stochastic PSO updates.

The transition is governed by the particle distribution. In the source implementation, the spread of particle duty-ratio positions is calculated as d_d = d_max - d_min. When d_d < 0.2, the swarm is regarded as converged to an extremum neighbourhood and the controller switches from PSO to INC. The two-stage structure therefore avoids asking INC to solve the global multi-peak problem, while avoiding the unnecessary global exploration of PSO during final local adjustment.

4.2. Comparison of PSO-INC with Standalone PSO

The hybrid controller and standalone PSO were evaluated under the same standard, irradiance-step, and static multi-peak conditions. Table 2 compares the theoretical GMPP with the actual steady-state power and settling time. The values follow the consolidated comparison table in the source thesis.

Table 2. Theoretical and actual power comparison between PSO and PSO-INC.

Condition	Algorithm	Theoretical P_GMPP (W)	Actual P_ss (W)	t_s (s)
Standard	PSO	8517.80	8515.94	1.510
Standard	PSO-INC	8517.80	8517.07	0.470
Irradiance step	PSO	4319.62	4319.60	3.510
Irradiance step	PSO-INC	4319.62	4319.82	3.300
Static shading	PSO	5761.56	5760.05	1.250
Static shading	PSO-INC	5761.56	5761.29	0.480

The results show that PSO-INC improves both convergence speed and steady-state power matching in the standard and static-shading cases. Under standard conditions, the settling time decreases from 1.510 s for PSO to 0.470 s for PSO-INC, while the actual output approaches the 8517.80 W reference. Under static shading, the settling time decreases from 1.250 s to 0.480 s, and the actual output is 5761.29 W against a theoretical 5761.56 W. In the irradiance-step case, both algorithms track close to the 4319.62 W reference and their settling times are similar (3.510 s for PSO and 3.300 s for PSO-INC). Overall, the hybrid method provides a more favourable speed-accuracy balance in the tested cases, particularly under static multi-peak shading.

5. Adaptive-Restart PSO-INC Strategy

5.1. Restart Trigger and Particle Reinitialization

After PSO-INC enters steady INC operation, a change in irradiance or shading may move the GMPP or alter the number of local peaks. The current operating point may then become suboptimal. To address this issue, an adaptive restart mechanism monitors the PV output and initiates a new PSO global search when a significant operating-condition change is detected.

A steady-state counter n_n is accumulated after the controller enters INC operation. Disturbance detection is enabled only when n_n > 300 control periods, preventing initial search transients from being mistaken for environmental changes. The absolute output-power change relative to the previous steady-state reference P_old is

$$\Delta P(k) = |P(k) - P_old| \quad (7)$$

When $\Delta P(k) > 0.1$ P_old, corresponding to a relative power change greater than 10%, the controller triggers a restart. It clears the particles' historical best positions, velocities, and recorded power values, and uniformly redistributes the duty-ratio positions across the search range. The previous gbest is discarded so that an obsolete local optimum from the former shading pattern cannot bias the new search. PSO then performs global coarse search again, followed by INC local refinement.

The restart is also linked to the PSO-to-INC handover condition: when the particle spread d_d = d_max - d_min falls below 0.2, the swarm is treated as having converged to an extremum neighbourhood and INC takes over. The 300-period delay and 10% power-change threshold are intended to avoid unnecessary restarts during normal transients while preserving the ability to respond to significant changes.

5.2. Dynamic-shading Simulation and Particle-Number Comparison

The dynamic test changes the irradiance distribution among five PV units. The reported cases include (1000, 1000, 1000, 1000, 900), (1000, 1000, 800, 500, 1000), and (1000, 1000, 600, 600, 800) W/m². The reference global maximum in the comparison is 8167.31 W. Table 3 compares the conventional PSO-INC controller with adaptive-restart variants using four and six particles.

Table 3. Dynamic-shading comparison of conventional and adaptive-restart PSO-INC.

Controller	Theoretical P_GMPP (W)	Actual P_ss (W)	Power deviation (W)	t_s (s)
Conventional PSO-INC	8167.31	8166.94	-0.37	4.30
Adaptive PSO-INC (4 particles)	8167.31	8167.90	+0.59	4.11
Adaptive PSO-INC (6 particles)	8167.31	8165.62	-1.69	4.25

The four-particle adaptive-restart PSO-INC reaches steady state in 4.11 s, compared with 4.30 s for conventional PSO-INC and 4.25 s for the six-particle variant. It is therefore the fastest of the three configurations in this dynamic-shading simulation. The four-particle version also avoids the prolonged power drop reported for the conventional controller during the transition between competing peaks. Its steady output is 8167.90 W, only 0.59 W above the 8167.31 W reference. The six-particle variant reaches 8165.62 W in 4.25 s. These results indicate that increasing the swarm size does not necessarily improve response speed; in the tested configuration, four particles provide the faster dynamic response.

6. Discussion and Limitations

The simulation evidence supports the staged development of the controller. Standalone INC is rejected as the global MPPT solution because it can become trapped at a local maximum under static multi-peak shading. PSO overcomes this limitation through broad search, but stochastic exploration can increase settling time and produce oscillation. The hybrid PSO-INC controller assigns the global and local tasks to the algorithms best suited to them. Adaptive restart further enables the hybrid controller to discard stale particle information and re-search after significant power changes.

The results are limited to the MATLAB/Simulink cases and parameter settings reported in the source thesis. Hardware-in-the-loop validation, prototype experiments, repeated randomized trials, and sensitivity analysis of the 10% and d_d < 0.2 thresholds are not reported. In addition, the source thesis contains a few inconsistencies between detailed passages and consolidated summary tables. The hybrid comparison in Table 2 therefore follows the consolidated source comparison table; the corresponding raw simulation records should be checked before final journal submission. The reported settling times should be interpreted as case-specific simulation results rather than universal real-time guarantees.

7. Conclusion

A staged MPPT development strategy for PV arrays under partial shading has been presented. The initial comparison of INC and PSO shows that INC is fast in single-peak conditions but fails to reach the GMPP in the tested static multi-peak case: its output is 3394.88 W against a theoretical 4236.4 W, whereas PSO reaches the global peak. The standalone INC method is therefore not selected for global tracking. Instead, PSO-INC combines broad PSO global search with precise INC local refinement, improving the speed-accuracy balance over standalone PSO in the standard and static-shading cases. Finally, adaptive restart clears outdated particle states when a significant power change is detected. Among the tested dynamic-shading configurations, the four-particle adaptive-restart PSO-INC achieves the shortest settling time of 4.11 s. Further hardware validation and parameter-robustness testing are required before practical deployment.

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