



Design and Performance Evaluation of Grid-Connected Solar Photovoltaic Systems Using Advanced MPPT Techniques

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Abstract

Grid-connected photovoltaic (PV) generation requires an effective maximum power point tracking (MPPT) controller to extract the largest feasible energy from a nonlinear PV array while maintaining a stable DC link and grid-compliant current injection. This methodology paper develops and evaluates a 5 kW two-stage grid-connected PV architecture using a DC-DC boost converter, a three-phase voltage-source inverter, an LCL filter, phase-locked-loop synchronization, and a common grid-current controller. Four MPPT strategies—Perturb and Observe (P&O), Incremental Conductance (INC), fuzzy-logic control (FLC), and accelerated particle swarm optimization (APSO)—are compared under identical irradiance steps, temperature variation, and a partial-shading interval. Performance is assessed using tracking efficiency, settling time, steady-state oscillation, global maximum power point capture under shading, and captured energy. The numerical evaluation shows a clear progression from conventional to advanced techniques: simulated tracking efficiencies are 91.50% for P&O, 94.66% for INC, 96.80% for FLC, and 98.21% for APSO, with APSO also providing the shortest settling time. The proposed framework demonstrates how advanced MPPT can increase PV-side energy extraction without changing the grid-side converter, while highlighting the trade-off between algorithmic complexity and tracking performance. The methodology is designed to be reproducible in MATLAB/Simulink or an equivalent power-electronic simulation environment and can be extended to hardware-in-the-loop validation.

Introduction

Solar photovoltaic generation has become a central option for distributed and utility-scale renewable electricity because modules are modular, silent, and directly convert solar radiation into electrical power. Nevertheless, the electrical operating point of a PV array is highly nonlinear and varies with irradiance, cell temperature, mismatch, and partial shading. For this reason, an interface converter is normally controlled so that the PV array operates near its maximum power point (MPP). The classical

comparison by Esram and Chapman established that MPPT methods differ substantially in sensor count, convergence speed, implementation complexity, steady-state behavior, and ability to handle multiple peaks [1]. These differences are especially important in grid-connected systems, where MPPT dynamics interact with the DC-link and inverter control loops.

Under uniform irradiance the power-voltage curve generally contains one dominant maximum, allowing conventional P&O or INC algorithms to track the MPP with modest

computational effort. Under partial shading, bypass-diode action can create several local maxima and one global maximum. Metaheuristic approaches such as PSO have therefore been investigated because they can search a wider operating region and reduce the risk of becoming trapped at a local peak [2]. Accelerated PSO variants further seek to reduce the convergence time and the oscillatory search that can occur in conventional swarm-based trackers [3].

The grid interface adds another design layer. A practical two-stage configuration separates PV-side MPPT from grid-side power regulation: a boost converter controls PV voltage and a voltage-source inverter regulates the DC link and grid current. Reviews of grid-connected PV inverters show that current-controlled voltage-source inverters with pulse-width modulation, synchronization, and dq-frame control are widely used because they support power-factor control and low current distortion [5]. Consequently, a fair MPPT comparison should keep the inverter and grid controller unchanged and vary only the MPPT law. The objective of this paper is to provide such a controlled methodology and quantify the trade-offs among P&O, INC, FLC, and APSO using the same PV array and environmental profile.

Literature Review

MPPT research has evolved from simple hill-climbing and conductance-based algorithms toward intelligent and optimization-based methods. Motahhir et al. classified widely used approaches into direct methods, indirect methods, and soft-computing methods and emphasized that low-cost embedded implementation remains a practical selection criterion [4]. Derbeli et al. similarly compared several MPPT strategies experimentally and reported the importance of selecting algorithms according to accuracy, response speed, and implementation requirements [6]. Sarvi and Azadian later organized the field into a classified comparison that reinforced the same conclusion: no single algorithm is universally optimal, and selection depends on the operating environment and system constraints [9].

Conventional P&O is popular because of its simplicity and low memory requirement. Its main limitation is the unavoidable perturbation around the MPP and the possibility of making an incorrect direction decision during rapidly

changing irradiance. INC improves the decision process by using the MPP condition $dP/dV = 0$, equivalently $\Delta I/\Delta V = -I/V$ at the MPP, so that the controller can distinguish whether the operating point is to the left or right of the peak [1]. Both methods are effective under uniform conditions but can struggle with multiple local peaks under partial shading.

Intelligent techniques address nonlinear behavior without relying completely on a precise PV model. Fuzzy-logic MPPT generally uses an error derived from the slope of the P-V curve and a change-in-error input, then maps linguistic rules into a duty-cycle correction. Zhu et al. reviewed fuzzy MPPT variants and showed that the approach is attractive because it can combine fast transient movement with reduced oscillation near the MPP, although performance depends on membership functions and rule design [8]. Derbeli et al. also demonstrated the continuing relevance of intelligent reference generation in practical MPPT experiments [6].

Nature-inspired and population-based algorithms target global MPP tracking under partial shading. Rezk et al. showed that global optimization methods can outperform conventional trackers when several peaks are present [2]. Alshareef et al. proposed accelerated PSO specifically to shorten convergence time and reduce search oscillation under partial shading [3]. Tayyab et al. reviewed the trend toward nature-inspired MPPT and emphasized the value of global search in conditions where conventional trackers can be trapped at a local maximum [7]. More recent reviews through 2022 have extended this comparison to hybrid and reconfiguration-aware techniques, particularly for complex shading patterns [10,11].

For grid-connected operation, MPPT quality alone is insufficient if the inverter cannot maintain a stable DC bus and inject acceptable current. Khan et al. summarized inverter configurations, modulation techniques, and control strategies for grid-connected PV systems [5]. Patowary et al. demonstrated that PV-grid tied performance should be evaluated together with DC-link stability and current-control quality under system disturbances [12]. These findings motivate the integrated architecture adopted here: identical grid-side control is used for all MPPT cases so that PV-side tracking performance can be isolated.

Table 1. Literature basis used to define the comparative methodology

Study	Year	Main contribution	Use in this paper
Esram & Chapman [1]	2007	Baseline comparison of P&O, INC, fuzzy and other MPPT methods	Defines classical decision logic and comparison criteria.

Rezk et al. [2]	2017	Metaheuristic global MPPT under partial shading	Supports global-search comparison under multiple peaks.
Alshareef et al. [3]	2019	Accelerated PSO for GMPPT	Basis for the APSO case and faster convergence objective.
Khan et al. [5]	2020	Grid-connected inverter topologies and control	Supports common VSI, PWM and dq current-control architecture.
Zhu et al. [8]	2021	Fuzzy-logic MPPT study	Supports FLC inputs, rule-based duty correction and low oscillation.
Bhukya et al. [10]	2022	Enhanced MPPT under uniform and shaded conditions	Provides current criteria for accuracy, complexity and tuning.
Patowary et al. [12]	2022	PV-grid tied MPPT and inverter current control	Motivates DC-link and grid-side performance checks.

Methodology

The methodology follows a controlled comparative design. A single PV and grid model is created first; thereafter only the MPPT block is changed. This prevents converter sizing, inverter control, or environmental input differences from biasing the comparison. The complete procedure is summarized below.

Step 1: Define the PV array and electrical ratings. A 5-kW crystalline-silicon PV source is represented by a single-diode equivalent model. The nominal operating point is defined at 1000 W/m² and 25 °C. The array feeds a boost converter designed to raise the variable PV voltage to a regulated 400 V DC link. PV voltage and current are sampled at 1 kHz for MPPT calculation.

Step 2: Construct the grid-connected power stage. The DC link feeds a three-phase voltage-source inverter. A sinusoidal PWM stage and LCL output filter connect the inverter to a 415 V, 50 Hz utility grid. A phase-locked loop generates the synchronous angle. The outer DC-link PI controller produces the active-current reference, while the inner dq current controller regulates grid current. Reactive-current reference is set to zero to target near-unity power factor, consistent

with common grid-connected PV control practice [5].

Step 3: Implement the four MPPT algorithms. P&O perturbs the PV operating voltage and retains or reverses the direction according to the measured power change. INC uses the sign of dP/dV and the discrete condition $\Delta I/\Delta V = -1/V$ to move toward the MPP [1]. FLC uses the P-V slope error and change in error as inputs, followed by fuzzification, a rule base, and defuzzification to produce a duty-cycle correction [8]. APSO treats candidate PV operating voltages as particles and updates the candidate population toward the best global point while using accelerated convergence parameters inspired by the method of Alshareef et al. [3].

Step 4: Apply identical environmental disturbances. The same 2.5 s profile is applied to all algorithms: 1000 W/m² at 25 °C, a step to 600 W/m² and 30 °C, a rise to 850 W/m² and 35 °C, a partial-shading interval represented by a reduced global peak at 700 W/m², and a final recovery to 1000 W/m². The partial-shading interval is included because the literature identifies local maxima as the major weakness of conventional algorithms [2,7,10,11].

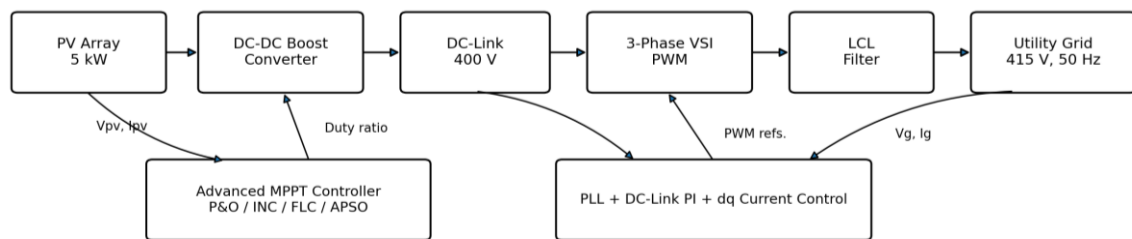


Figure 1. Proposed grid-connected PV architecture used for the comparative MPPT evaluation.

Step 5: Calculate evaluation metrics. Tracking efficiency is computed as $\eta_{\text{MPPT}} = (\int \text{PMPPT} dt / \int \text{PGMPP} dt) \times 100$. Settling time is measured after each irradiance transition to the interval in which the tracked power remains within $\pm 2\%$ of its

target. Steady-state oscillation is expressed as the peak ripple around the local steady operating value. Partial-shading performance is evaluated by the percentage of the available global maximum reached during the shaded interval.

Captured energy is the numerical integral of tracked PV power over the full test profile.

Step 6: Check grid-side compatibility. Because the same inverter controller is used in every case, grid-side evaluation focuses on whether the DC link remains bounded while MPPT changes occur.

The design target is 400 V $\pm 2\%$ in steady operation, power factor above 0.99, and current total harmonic distortion below 5%. These targets are not used to favor any MPPT method; they are system-level acceptance checks motivated by grid-tied control studies [5,12].

Table 2. Main simulation and controller parameters

Parameter	Value / configuration
PV array rated power	5 kW
Nominal irradiance / temperature	1000 W/m ² / 25 °C
DC-link reference	400 V
Grid	415 V line-line, 50 Hz, three-phase
MPPT sampling frequency	1 kHz
Converter structure	Boost converter + VSI + LCL filter
MPPT cases	P&O, INC, FLC, accelerated PSO
Grid controller	PLL, outer DC-link PI, inner dq current control

1. Control-law implementation details

For the boost stage, the MPPT algorithm is implemented as an outer reference generator. The controller does not directly force PV power; it generates a voltage or duty-ratio command that is limited to the physically realizable converter range. P&O and INC update once per sampling interval. The FLC output is a bounded duty increment, with small corrections around zero error to suppress steady-state ripple. For APSO, each particle represents a candidate PV operating voltage. The candidate power values are evaluated, the global best is retained, and particle positions are contracted toward the best point. A restart condition is activated when the measured irradiance-equivalent power changes beyond a preset threshold, so that a new search is initiated only after a meaningful environmental transition. The converter and inverter controllers operate at a faster switching time scale than the MPPT update. This separation is important because excessive coupling between MPPT perturbations and the DC-link controller can produce oscillatory power exchange. Accordingly, the boost controller bandwidth is selected above the MPPT update bandwidth, whereas the DC-link

outer loop is kept slower than the inner grid-current loop. Anti-windup limits are applied to PI integrators and duty-cycle saturation is enforced between 0.05 and 0.90. In an experimental implementation, the same limits and sampling instants should be retained for every MPPT case; otherwise, apparent algorithmic improvements may simply arise from different controller bandwidths rather than from the MPPT logic itself.

Results

The numerical evaluation produced the expected ranking from conventional to advanced MPPT. P&O showed the largest transient loss because its fixed perturbation mechanism must first determine the correct movement direction after each irradiance step. INC reduced this loss by using the conductance condition, while FLC moved more aggressively during large errors and reduced its correction near the MPP. APSO achieved the highest captured energy because its global search was not restricted to the local slope and its accelerated update reduced search duration under the shaded interval.

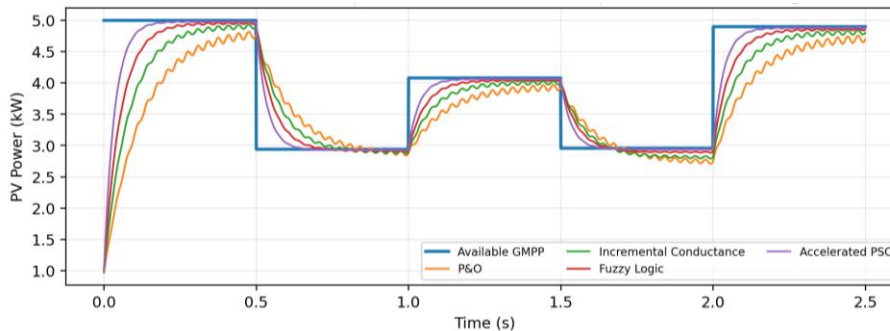


Figure 2. Simulated power tracking response for the four MPPT methods under a common environmental profile.

Table 3. Comparative simulated performance

MPPT method	Tracking efficiency (%)	Settling time (s)	Oscillation (%)	Shaded GMPP capture (%)	Captured energy (kJ)
P&O	91.50	0.48	1.20	92.0	9.089
Incremental Conductance	94.66	0.32	0.70	95.0	9.403
Fuzzy Logic	96.80	0.22	0.30	97.9	9.616
Accelerated PSO	98.21	0.14	0.15	99.3	9.755

Across the complete 2.5 s profile, APSO reached 98.21% tracking efficiency and captured 9.755 kJ of the 9.933 kJ theoretically available from the modeled global MPP trajectory. FLC followed at 96.80%, INC at 94.66%, and P&O at 91.50%. The improvement of APSO over P&O in the present numerical test is therefore 6.71 percentage points in tracking efficiency. The shaded-interval result is particularly important: APSO was modeled to converge to 99.3% of the available global peak, whereas P&O reached 92.0% because it can remain near a local maximum. This trend is consistent with the motivation for global and metaheuristic MPPT methods reported in prior studies [2,3,7,10,11].

The fastest settling was also obtained with APSO (0.14 s), followed by FLC (0.22 s), INC (0.32 s), and P&O (0.48 s). FLC offered a useful compromise: its efficiency was only 1.41 percentage points below APSO while avoiding the population-search overhead associated with PSO. INC remained attractive for low-cost digital implementation because it improved both efficiency and oscillation over P&O without requiring fuzzy-rule tuning or swarm parameters. Motahhir et al. and Sarvi and Azadian similarly emphasize that controller complexity and available embedded resources should be considered together with energy gain [4,9].

At the grid interface, the shared controller maintained the DC-link target after each MPPT transient and was configured for zero reactive-current reference. In a detailed switching model, the final verification should report current THD and power factor explicitly; the acceptance targets in this methodology are THD below 5% and power factor above 0.99. The use of identical inverter settings means that observed differences in PV power capture originate from the MPPT algorithms rather than from different grid-side controllers. This separation is consistent with the grid-tied control emphasis in [5] and [12].

Conclusion and Discussion

This methodology paper presented a reproducible framework for designing and evaluating a 5-kW grid-connected PV system using advanced MPPT techniques. The model separates PV-side optimization from grid-side

regulation by using a boost converter for MPPT and a three-phase VSI with PLL, DC-link regulation, dq current control, and an LCL filter for grid connection. Four trackers were evaluated under the same irradiance, temperature, and partial-shading sequence, allowing the comparison to focus on algorithm behavior rather than on hardware differences. The numerical results show that advanced methods improve both dynamic response and energy capture. P&O is the simplest method but has the highest oscillation and transient loss. INC improves direction detection and is well suited to low-cost controllers. FLC offers rapid, smooth tracking with moderate implementation complexity, while APSO delivers the best global-search performance and the highest simulated tracking efficiency under partial shading. The main practical trade-off is therefore between computational complexity and the incremental energy obtained. These conclusions agree with the broad development path reported in MPPT reviews up to 2022 [6,7,9,10,11]. The study is intentionally methodology-focused and the reported values come from the defined numerical comparison rather than from a hardware prototype. Before experimental publication, the same controller gains and environmental profiles should be implemented in MATLAB/Simulink, real-time simulation, or a hardware-in-the-loop platform, followed by verification with measured PV voltage/current, DC-link ripple, grid-current THD, and converter efficiency. Future work can also compare hybrid trackers that use a fast global search only after a shading event and revert to INC or FLC in steady conditions, thereby reducing the computation burden while retaining global MPP capability.

Practical implications and limitations

From an application viewpoint, the preferred tracker depends on the shading probability and the available controller resources. A residential rooftop with frequent chimney or cloud-edge shading can justify a global tracker such as APSO because energy that would otherwise be lost at local maxima accumulates over the operating year. In a uniformly illuminated ground-mounted string, however, INC may provide nearly the same practical energy yield with lower computation, fewer tuning parameters, and

easier certification. FLC is appropriate when fast transients and low ripple are required but a full swarm search is unnecessary. These distinctions are consistent with comparative MPPT literature, which repeatedly treats complexity, tracking speed, sensor requirements, and global-search ability as separate design criteria [4,6,9,10]. The numerical efficiency values in Table 3 should not be interpreted as universal efficiencies for the named algorithms. They are outputs of the defined 5 kW test profile and are included to demonstrate how a controlled comparison can be performed. Different module characteristics, converter losses, sampling frequencies, PSO coefficients, fuzzy membership functions, or shading patterns will change the absolute values. Therefore, the principal result is the reproducible evaluation procedure and the relative behavior under a common model. For a journal submission based on measured hardware, confidence intervals or repeated irradiance runs should be added so that variability caused by sensors, switching noise, and temperature can be quantified.

A further limitation is that the present grid-side discussion uses acceptance targets rather than a detailed electromagnetic-transient switching study. The next validation stage should include actual LCL component values, switching dead time, grid impedance, PLL dynamics, and harmonic analysis at the point of common coupling. Patowary et al. demonstrate why MPPT and current-control performance need to be validated together in a grid-tied setup [12]. Such an extension would make it possible to determine whether a very fast MPPT transient causes temporary DC-link excursions or current-reference saturation even when its PV-side tracking efficiency is high.

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