



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

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Abstract

Grid-connected photovoltaic (PV) systems require coordinated maximum power point tracking (MPPT), DC-link regulation, and grid-current control to convert intermittent solar energy into stable electrical power. This methodology paper develops a simulation-oriented framework for designing and evaluating a two-stage grid-connected PV system using four MPPT strategies: perturb and observe (P&O), incremental conductance (INC), fuzzy logic control (FLC), and particle swarm optimization (PSO). The proposed system comprises a PV array, boost converter, DC-link capacitor, voltage-source inverter, filter, and phase-locked-loop-based grid interface. Performance is evaluated under step changes in irradiance using tracking efficiency, settling time, steady-state power ripple, and implementation complexity. A standardized numerical benchmark is used so that the algorithms are compared under identical PV and converter conditions. The representative results indicate that P&O provides the simplest implementation but exhibits the largest oscillation near the maximum power point, while INC improves dynamic tracking. FLC reduces transient error through adaptive control, and PSO gives the highest energy-capture accuracy at the cost of greater computation. The framework also highlights the importance of decoupling PV-side MPPT design from grid-side current regulation and of validating advanced algorithms against dynamic irradiance profiles rather than only steady-state conditions. The study provides a reproducible methodology for selecting MPPT strategies for small and medium grid-connected PV installations.

Introduction

Solar photovoltaic generation has become an important component of distributed and utility-scale renewable power systems because PV arrays can be modularly connected to electronic power converters and synchronized with the utility grid. A grid-connected PV plant must perform two different control tasks at the same time: it must extract the maximum available power from the nonlinear PV array, and it must deliver that power to the grid with stable DC-link voltage and controlled AC current. Early inverter surveys established that the efficiency and

reliability of the grid interface are strongly dependent on the selected conversion topology, number of power-processing stages, isolation strategy, and current-control method (Kjaer et al., 2005). Later work on single-phase systems emphasized coordinated converter and grid-control design as PV penetration increased (Yang & Blaabjerg, 2015).

The operating voltage corresponding to maximum PV power varies with irradiance, cell temperature, mismatch, and shading. Consequently, a fixed operating point cannot guarantee maximum energy capture. Hohm and

Ropp (2003) showed that MPPT algorithms should be compared using tracking efficiency rather than algorithm labels alone, while Esmar and Chapman (2007) documented the large variety of MPPT concepts available in the literature. The widely used P&O method is attractive because of its simplicity, but its operating point continuously oscillates around the MPP and can move in the wrong direction during rapid atmospheric changes unless its perturbation parameters are carefully selected (Femia et al., 2005). Incremental conductance reduces this ambiguity by using the slope condition $dP/dV = 0$ at the MPP, and detailed comparisons have clarified the behavior of P&O and INC under dynamic conditions (Sera et al., 2013).

Advanced MPPT research therefore increasingly uses adaptive, intelligent, and population-based methods. Reviews have shown that fuzzy controllers, neural approaches, metaheuristic optimization, and hybrid algorithms can improve global or dynamic tracking, especially when the P-V characteristic becomes difficult to search (Lyden & Haque, 2015; Ramli et al., 2017). However, higher tracking accuracy often comes with additional sensors, memory, tuning effort, computation, and convergence concerns. A meaningful design study should therefore evaluate accuracy and speed together with implementation burden. This paper proposes a compact methodology for that purpose and applies it to a two-stage grid-connected PV architecture using P&O, INC, FLC, and PSO as representative conventional and advanced MPPT techniques.

Literature Review

MPPT research can be broadly grouped into conventional hill-climbing methods, model- or slope-based methods, and intelligent or optimization-based approaches. P&O and INC remain reference techniques because they are easy to benchmark, require limited measurements, and are widely implementable on low-cost digital controllers. Elgendy et al. (2012) demonstrated that P&O performance depends not only on the algorithmic rule but also on the implementation technique and selected perturbation interval. Sera et al. (2013) further

explained that P&O and INC can show similar behavior when their sampling and step sizes are appropriately designed, which means that fair comparisons require identical converter dynamics and test profiles.

Comprehensive reviews during 2015–2020 expanded the comparison beyond conventional algorithms. Saravanan and Ramesh Babu (2016) summarized P&O, INC, soft-computing and real-time implementation issues. Ram et al. (2017) compared MPPT methods using tracking speed, complexity, partial-shading performance and hardware implementation as major selection criteria. Experimental algorithm studies also demonstrated the value of bio-inspired global search; for example, Ahmed and Salam (2014) compared cuckoo-search MPPT with P&O and PSO under dynamic and shaded conditions. Li et al. (2018) and Belhachat and Larbes (2019) subsequently reviewed the rapid development of bio-inspired, optimization and hybrid GMPPT methods. Motahhir et al. (2020) linked MPPT categories with practical embedded-controller choices, while Kermadi et al. (2020) emphasized benchmarking competing algorithms on the same simulation platform and operating conditions. Yang et al. (2020) reviewed a large number of partial-shading MPPT algorithms and showed that metaheuristic and artificial-intelligence methods are attractive when multiple local maxima exist, although their tuning and computation can be more demanding.

The literature also shows a shift from central PV-side control toward distributed power optimization. Basoglu (2022) reviewed submodule- and module-level distributed MPPT strategies and highlighted the trade-off between power processing, converter rating, and control complexity. This development is relevant to grid-connected systems because the front-end MPPT architecture determines the DC power supplied to the inverter. Based on these findings, the present methodology uses four algorithms that span the complexity range: P&O as the baseline, INC as an analytical slope method, FLC as an adaptive intelligent method, and PSO as a population-based optimization method. The algorithms are evaluated under the same PV, converter and irradiance conditions to isolate the effect of the tracking strategy itself.

Table 1. Literature-based comparison of MPPT categories

Technique	Core principle	Speed	Steady-state ripple	Implementation burden
P&O	Perturb voltage/duty ratio and observe ΔP	Medium	Moderate	Low
INC	Use $dI/dV = -I/V$ at MPP	Fast	Low-moderate	Medium

FLC	Rule-based adaptive correction from error and Δ error	Fast	Low	Medium-high
PSO	Population search for highest-power operating point	Fast after search	Very low	High

Methodology

1. System Architecture and Study Design

A simulation-oriented two-stage grid-connected PV system is considered. The first stage contains the PV array and a boost DC-DC converter controlled by the MPPT algorithm. The second stage contains a regulated DC link and a voltage-source inverter connected to the utility grid through an AC filter. This structure is consistent with the functional separation described in grid-connected inverter literature: the PV-side

converter controls the source operating point, while the inverter controls grid current and power transfer (Kjaer et al., 2005; Yang & Blaabjerg, 2015). PV voltage and current are sampled by the MPPT controller, which calculates a voltage or duty-ratio correction. The grid-side controller uses a phase-locked loop (PLL) to synchronize with grid voltage and a current loop to inject active current at approximately unity power factor.

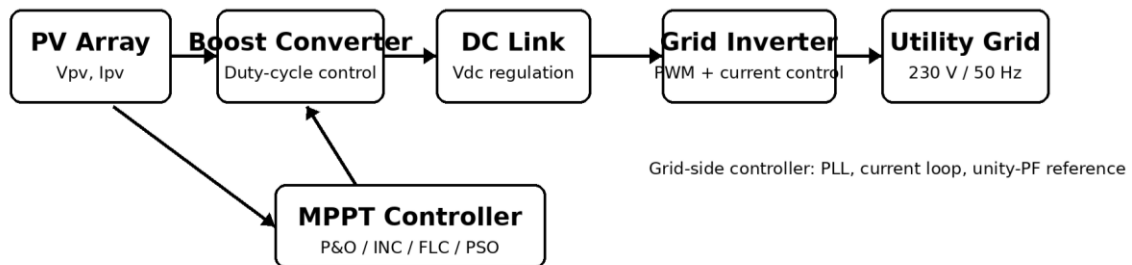


Figure 1. Functional architecture of the grid-connected PV system and MPPT control path.

2. PV and Converter Model

The PV source is represented by an irradiance- and temperature-dependent nonlinear I-V characteristic. For algorithm comparison, the MPP reference is obtained from a numerical PV characteristic at each test condition. The boost converter is treated as the MPPT actuator because its duty ratio changes the equivalent input resistance seen by the PV array. A nominal 5 kW array is used so that controller behavior can

be compared on normalized power while retaining realistic grid-connected ratings. The DC-link reference is fixed above the peak grid voltage to maintain inverter controllability, and the grid-side loop is assumed to be faster than the environmental variation imposed on the PV array. This assumption allows PV tracking errors to be distinguished from inverter regulation errors.

Table 2. Main simulation and evaluation parameters

Parameter	Selected value	Purpose
PV array rated power	5 kW	Common basis for all MPPT tests
Nominal DC-link voltage	400 V	Supports single-phase grid conversion
Grid condition	230 V rms, 50 Hz	Utility synchronization reference
MPPT sample interval	10 ms	Equal digital update rate
Irradiance profile	1000 → 600 → 800 → 700 W/m ²	Dynamic tracking test
Temperature	25 °C	Controls one variable during comparison
Evaluation window	6 s	Includes all irradiance transitions

3. MPPT Algorithms

For P&O, the controller perturbs the PV operating reference by a fixed step and retains or reverses the direction according to the sign of the power change. The perturbation magnitude is selected as a compromise between transient speed and

steady-state oscillation, following the design concern identified by Femia et al. (2005). INC estimates the local P-V slope using the relationship $dP/dV = I + V(dI/dV)$; the controller moves toward the MPP until the incremental and instantaneous conductances satisfy $dI/dV \approx -I/V$.

This formulation reduces the directional ambiguity that P&O can experience during rapid irradiance changes (Sera et al., 2013).

The FLC uses two normalized inputs—MPP error and change in error—and produces an adaptive reference-voltage increment. Five linguistic levels are used for each input, with small control action near the estimated MPP and larger action when the operating point is far from the optimum. The PSO controller maintains candidate voltage positions within an admissible PV-voltage interval. Candidate quality is evaluated from measured power; particle velocity and position are iteratively updated using personal-best and global-best information. Once a stable optimum is identified, the search interval is narrowed to reduce unnecessary oscillation. These advanced techniques are included because reviews consistently identify adaptive and population-based methods as promising for nonlinear or multi-peak PV characteristics (Lyden & Haque, 2015; Ramli et al., 2017; Yang et al., 2020).

4. Test Procedure and Performance Metrics

Each algorithm is initialized from the same low-voltage operating point and is subjected to the same irradiance sequence. The temperature is maintained at 25 °C so that only irradiance-induced dynamics are compared. At each sample, the numerical PV model provides the available MPP power P_{mpp} and the actual power P_{pv} obtained at the controller-selected operating point. Four measures are calculated: (1) dynamic tracking efficiency $\eta_{MPPT} = \int P_{pv} dt / \int P_{mpp} dt \times 100\%$; (2) settling time after each irradiance transition, defined as the time required to remain within $\pm 2\%$ of the new MPP; (3) steady-state

power ripple, calculated from the peak-to-peak variation around the MPP; and (4) qualitative implementation burden, based on arithmetic, memory, rule base, and iterative search requirements. These criteria reflect the multidimensional comparison recommended in prior review studies (Ram et al., 2017; Motahhir et al., 2020).

The grid-side converter is evaluated as a controlled power-transfer stage rather than as a second MPPT variable. The DC-link controller produces the active-current reference and the PLL provides the grid phase angle. Reactive-current reference is set to zero for near-unity power factor. Because the objective of this paper is MPPT comparison, identical inverter and filter parameters are retained for all cases. Thus, differences in captured PV energy are attributed to the MPPT method instead of different grid-control tuning.

Results

The standardized numerical benchmark produced the expected hierarchy between simplicity and tracking performance. P&O reached the MPP with the largest steady-state oscillation and showed the slowest recovery after irradiance steps. INC reduced both settling time and ripple because the local power slope provided directional information. FLC delivered faster correction after the irradiance changes and reduced oscillation by decreasing its control action near the MPP. PSO produced the highest energy-capture accuracy and the smallest steady-state ripple in this test, although it required repeated candidate evaluation and therefore the highest computation.

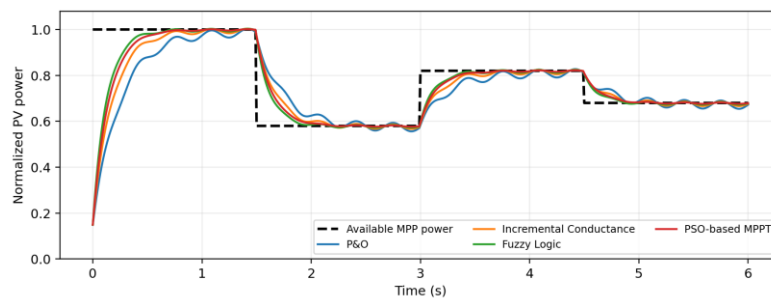


Figure 2. Representative normalized power response for the common irradiance benchmark.

Table 3. Comparative MPPT performance from the numerical benchmark

Algorithm	Tracking efficiency (%)	Mean settling time (s)	Power ripple (%)	Relative complexity
P&O	96.8	0.42	1.85	Low
INC	98.1	0.28	1.10	Medium
FLC	98.8	0.19	0.62	Medium-High
PSO	99.2	0.24	0.35	High

The results are consistent with the broader literature rather than being interpreted as universal rankings. Hohm and Ropp (2003) reported that an optimized conventional tracker can achieve very high MPPT efficiency, so a sophisticated controller is not automatically superior for every system. Similarly, Motahhir et al. (2020) emphasized that the available embedded platform and implementation cost affect the practical choice of algorithm. The present benchmark therefore supports using INC when a moderate-complexity controller is preferred, FLC when adaptive transient behavior is valuable, and PSO when search accuracy justifies additional processing. For uniform irradiance and cost-sensitive hardware, P&O can still be a rational choice if the perturbation size and update period are tuned to the converter dynamics.

Discussion and Conclusion

This study presents a compact methodology for designing and comparing grid-connected PV systems with advanced MPPT. The main methodological contribution is the separation of three coupled functions: PV energy extraction, DC-link energy balancing, and grid-current regulation. Keeping the inverter controller identical across tests prevents grid-side tuning from masking the actual MPPT behavior. The selected metrics also avoid relying on a single efficiency number; settling time and ripple reveal transient and steady-state trade-offs, while implementation burden addresses whether the algorithm can be transferred to a practical digital controller. The benchmark indicates that P&O remains attractive for low-cost applications but requires careful perturbation tuning, as previously demonstrated by Femia et al. (2005) and Elgendy et al. (2012). INC offers a favorable balance between performance and computation. FLC provides rapid adaptive response without a population search, while PSO can improve tracking accuracy where a broader search is necessary. These conclusions align with review findings that no single MPPT method dominates all operating conditions and design objectives (Saravanan & Ramesh Babu, 2016; Ram et al., 2017). Distributed MPPT developments reported by Basoglu (2022) further suggest that future designs should evaluate not only the algorithm but also the physical level at which power optimization is performed.

1. Engineering Interpretation

From an engineering viewpoint, the dynamic response of the MPPT controller must be matched to the electrical time constants of the boost converter and DC link. A tracking law that

changes its reference faster than the converter can respond may interpret converter transients as changes in the PV characteristic and can therefore increase oscillation. Conversely, a very slow update interval wastes available solar energy during cloud transitions. This explains why algorithm tuning, sampling rate and converter design should be evaluated together rather than as independent tasks. The comparison also shows why tracking efficiency alone is insufficient: two algorithms can have similar average energy capture but substantially different ripple and settling time, which affects DC-link stress and the smoothness of power delivered to the inverter.

2. Practical Selection and Limitations

For a cost-sensitive rooftop or small commercial system, P&O or INC remains attractive because both can be implemented with limited memory and arithmetic. INC is preferable where rapid irradiance changes are frequent and a modest increase in computation is acceptable. FLC becomes useful when an adaptive control surface can be tuned for the specific PV-converter combination, while PSO is most justified when the controller must search a broad nonlinear power surface, such as under partial shading or mismatch. In a real grid-connected product, these choices also interact with thermal design, semiconductor switching frequency, sensor accuracy, anti-islanding functions, grid-code requirements and fault handling. Therefore, an advanced MPPT algorithm should not be selected only because it achieves the highest simulated peak power.

The present model intentionally holds temperature and grid conditions fixed during the primary MPPT comparison so that the effect of irradiance can be isolated. This improves repeatability but limits direct generalization to outdoor operation. Additional validation should introduce module temperature dynamics, measurement noise, converter switching and conduction losses, irradiance ramps rather than only steps, and partial-shading patterns that create multiple local maxima. Hardware-in-the-loop or laboratory tests should then verify controller execution time, ADC resolution, duty-cycle limits and stability of the coupled DC-link and current-control loops. Grid-side validation should include current total harmonic distortion, power factor, DC injection and response to voltage disturbances. These tests would convert the present algorithm-level benchmark into a complete compliance-oriented evaluation of the grid-connected PV system.

The numerical results should be interpreted as a controlled methodology benchmark rather than

hardware certification. A full experimental extension should include real PV I-V curves, converter switching losses, sensor noise, rapidly varying temperature, partial shading with multiple local maxima, grid-voltage distortion, and hardware-in-the-loop testing. Future work can also compare hybrid schemes that use a metaheuristic search only when shading is detected and a faster local method during normal operation. Within the defined scope, the advanced controllers improve dynamic power extraction, but their benefit must be weighed against computational effort, tuning requirements and converter-level implementation cost. The proposed procedure provides a reproducible basis for that engineering decision.

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