



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

Korinna Mulyadi

Department of Electrical and Computer Engineering, Delta Polytechnic Institute of Engineering , Bangladesh
korinna.mulyadi@dpi-bd.edu

Peer Review Information	Abstract
Submission: 22 March 2024 Revision: 19 April 2024 Acceptance: 12 May 2024 Keywords Grid-Connected Photovoltaic System; Maximum Power Point Tracking; Particle Swarm Optimization; Incremental Conductance; Partial Shading	Grid-connected photovoltaic (PV) generation requires continuous maximum power point tracking (MPPT) because the PV current-voltage characteristic changes nonlinearly with irradiance, temperature, mismatch and partial shading. This methodology paper develops a reproducible design and performance-optimization framework for a two-stage grid-connected PV system and proposes a hybrid particle-swarm-optimization/adaptive incremental-conductance (H-PSO-AINC) MPPT strategy. The method combines global search during multimodal power-voltage conditions with a low-ripple local tracker during uniform or slowly varying conditions. A boost converter regulates the PV operating point, while a three-phase voltage-source inverter uses phase-locked-loop synchronization, DC-link control and synchronous-reference-frame current regulation for unity-power-factor grid injection. Performance is evaluated against perturb-and-observe (P&O), fixed-step incremental conductance (INC) and conventional PSO using tracking efficiency, settling time, steady-state ripple, global-MPP success rate, DC-link deviation and grid-current total harmonic distortion. A representative 100-kWp simulation benchmark indicates that the proposed hybrid method can preserve rapid convergence under irradiance transients and avoid local maxima during partial shading while maintaining low steady-state oscillation. The framework is intended as a compact methodology for MATLAB/Simulink or equivalent real-time implementation and is grounded in MPPT literature published through 2024.

Introduction

Solar PV plants increasingly rely on power-electronic interfaces to extract energy from a nonlinear source and inject it into the utility grid with acceptable power quality. The maximum power point (MPP) of a PV array is not fixed: it moves with solar irradiance, cell temperature, module mismatch and aging. Consequently, the DC-side controller must continuously force the operating voltage toward the MPP while the grid-side converter maintains the DC link and controls active and reactive power. Early comparative

work established P&O and INC as attractive practical trackers because of their simple measurements and low computational burden, but also documented oscillation around the MPP and degraded response under rapidly changing conditions [1]-[3].

Partial shading introduces a harder optimization problem because bypass diodes create several local maxima on the P-V curve. Conventional local-search MPPT may then converge to a local rather than global MPP, causing persistent energy loss. Reviews and comparative

evaluations have therefore emphasized global, intelligent and hybrid trackers for shaded arrays [4]-[6]. Adaptive P&O reduces the classical speed-versus-ripple compromise by changing the perturbation step online [7], whereas broader reviews through 2020-2023 show growing use of metaheuristics, machine learning and hybrid schemes to improve global tracking without excessive steady-state disturbance [8]-[10].

The 2024 literature shows a clear movement toward data-driven and predictive MPPT for grid-connected applications. Deep-learning LSTM control has been reported for a 100-kWp grid-tied PV system [11]; finite-voltage-set model predictive control (MPC) has been applied to grid-connected PV under environmental variations [12]; sensor-reduced global MPPT has been demonstrated for photovoltaic string inverters [13]; and crow-search optimization has been studied for a shaded two-stage grid-connected PV system [14]. These approaches improve tracking capability but may require training data, model accuracy, substantial computation or additional tuning. The objective of the present methodology is therefore to combine a robust global search with a simple local tracker, so that high performance is retained while implementation remains realistic for a digital signal controller.

Literature Review

MPPT methods can be organized into conventional, adaptive, intelligent/metaheuristic

and predictive/data-driven groups. Conventional P&O perturbs the PV reference and retains the direction that increases power; it is inexpensive but oscillates at steady state. INC uses $dP/dV = 0$ at the MPP and the identity $dP/dV = I + V(dI/dV)$, allowing directional decisions from measured increments [2]. Comparative analyses show that neither method is universally optimal because tracking speed, sensor noise, computational cost and power ripple are coupled design variables [1], [3].

For partial shading, the search domain becomes multimodal. Ahmed and Salam [4] highlighted the limitations of local trackers under multiple peaks, while hybrid GA/P&O work demonstrated that a global optimizer can be followed by a conventional local tracker to reduce the final oscillatory search [5]. Belhachat and Larbes [6] later classified global MPPT methods and showed that optimization and hybrid approaches are particularly relevant for shaded arrays. Adaptive P&O further improves dynamic tracking by changing the perturbation magnitude according to operating conditions [7]. More recent evaluations confirm that hybrid algorithms can reduce sensing or computation while preserving global-search capability [9], and the 2023 review by Worku et al. [10] identifies partial shading, convergence speed and complexity as continuing design tradeoffs.

Table 1. Representative MPPT literature relevant to the proposed methodology

Study	Method	Main contribution	Design implication
Safari & Mekhilef, 2011 [2]	INC	Direct-control implementation; practical baseline	Local MPP method
Ahmed & Salam, 2015 [4]	Review / PSC	Explains multi-peak failure of classical MPPT	No single optimal method
Sundareswaran et al., 2015 [5]	Hybrid GA-P&O	Global search plus local refinement	Higher algorithmic complexity
Ahmed & Salam, 2018 [7]	Adaptive P&O	Variable step improves speed and efficiency	Still fundamentally local
Kermadi et al., 2020 [8]	Critical review	Benchmarks PSC-oriented methods	Complexity-performance tradeoff
Worku et al., 2023 [10]	Comprehensive review	Recent partial-shading classification	Highlights open optimization issues
Younas et al., 2024 [11]	Stacked LSTM	Learning-based MPPT for 100-kWp grid-tied PV	Training/data burden
Hassan et al., 2024 [12]	Finite-set MPC	Predictive MPPT under environmental variation	Model/computation dependent

Methodology

1. System configuration and mathematical model

The proposed test system is a 100-kWp two-stage grid-connected PV plant composed of a PV array,

unidirectional boost converter, regulated DC link, three-phase voltage-source inverter (VSI), LCL filter and 415-V, 50-Hz utility grid. The architecture follows the widely used separation of DC-side energy extraction and AC-side grid

control, while allowing the MPPT algorithm to command the PV operating voltage

independently of the inverter current loop. Figure 1 summarizes the signal and energy flow.

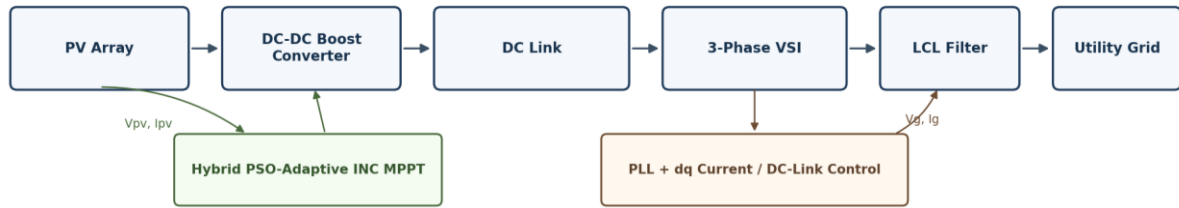


Figure 1. Proposed two-stage grid-connected PV architecture with hybrid MPPT and grid-side control.

A single-diode PV model is used for simulation. Array current is represented by $I = I_{ph} - I_0 \left\{ \exp \left[\frac{V + I R_s}{n N_s V_t} \right] - 1 \right\} - (V + I R_s) / R_{sh}$, where I_{ph} is the photocurrent, I_0 is the diode saturation current, R_s and R_{sh} are series and shunt resistance, n is the diode ideality factor, N_s is the number of series cells and V_t is thermal voltage. Irradiance primarily changes I_{ph} , while temperature alters both the thermal voltage and open-circuit voltage. The boost converter duty ratio D establishes the PV-side operating point; for an ideal converter $V_{dc} = V_{pv} / (1 - D)$. Switching is set to 20 kHz and the DC-link reference to 700 V so that the inverter has adequate modulation margin for a 415-V line-line grid.

The passive components are sized from switching-ripple constraints rather than chosen arbitrarily. For the boost stage, the minimum inductance is evaluated from $L_b \geq V_{pv} D / (\Delta I_L f_s)$, while the DC-link capacitor is checked using $C_{dc} \geq P / (2 \omega V_{dc} \Delta V_{dc})$ for twice-line-frequency energy pulsation and by transient energy balance during irradiance steps. The LCL filter is then selected from a target switching-current attenuation with passive damping verified around the resonance frequency. Table 2 lists the nominal parameters used in the benchmark and provides a clear starting point for reproduction.

Table 2. Nominal design parameters of the grid-connected PV benchmark

Parameter	Nominal value	Purpose / note
PV array rated power	100 kWp	Base system rating
PV voltage at MPP	~500 V	Varies with irradiance/temperature
Boost switching frequency	20 kHz	Common digital-control range
DC-link reference	700 V	Provides inverter modulation margin
Grid voltage/frequency	415 V L-L / 50 Hz	Three-phase utility interface
MPPT sampling interval	1 ms	Slower than PWM, faster than weather dynamics
PSO population / max iterations	6 / 12	Limits global-search computation
Current command	$i_q^* = 0$	Near-unity power factor

2. Proposed H-PSO-AINC MPPT algorithm

The H-PSO-AINC controller is designed around two operating modes. Adaptive INC is the default mode because it requires only V_{pv} and I_{pv} , has low computational cost and can reduce steady-state ripple. A shading/event detector continuously monitors normalized power change, voltage displacement and persistence of dP/dV . When the measured response suggests a multimodal or large-transient condition, the controller launches a bounded PSO search across the permissible PV-voltage interval. After the best particle converges, control returns to adaptive INC around the detected global MPP. This global-local structure is consistent with the motivation of earlier hybrid MPPT studies [5] while using a deterministic local refinement stage

and a conditional, rather than continuous, population search.

The adaptive INC step is selected as $\Delta V_{ref} = \text{sat}(K_v |dP/dV|, \Delta V_{min}, \Delta V_{max})$. A large gradient therefore produces a large voltage correction, whereas the step collapses near the MPP. A 0.15-0.25% power dead band prevents switching between directions because of measurement noise. During PSO mode, 6 particles are initialized over $0.55V_{oc}$ -array to $0.90V_{oc}$ -array. Each particle updates its candidate voltage from $v_{k+1} = v_k + u_{k+1}$, where $u_{k+1} = w u_k + c_1 r_1(p_{best} - v_k) + c_2 r_2(g_{best} - v_k)$. The inertia factor w is linearly reduced from 0.8 to 0.35; $c_1 = c_2 = 1.6$; and the search terminates when the global-best power changes by less than 0.1% for three iterations or after 12 iterations.

This modest population limits controller burden compared with continuously operating metaheuristics.

3. Grid-side control and optimization procedure

The VSI is synchronized with the grid by a synchronous-reference-frame phase-locked loop. The outer DC-link PI controller produces the d-axis current reference, while $i_q^* = 0$ is used for near-unity power factor. Inner d-q current PI loops generate inverter voltage references with cross-coupling compensation, followed by sinusoidal PWM. The LCL filter is selected so that switching-current attenuation is achieved while resonance remains well above the 50-Hz fundamental and below one-half of the switching frequency. Controller gains are tuned first with the MPPT disabled, then the MPPT is activated so that DC-link and current-loop dynamics remain faster than the energy-source search.

The methodology is executed step by step: (1) parameterize the PV array from module data and verify I-V/P-V curves at 1000 W/m² and 25 degC; (2) tune the boost inductor and DC-link capacitor for less than 2% current ripple and less than 1.5% DC-link ripple; (3) tune the PLL and d-q current controllers for stable unity-power-factor operation; (4) implement P&O, INC, PSO and H-PSO-AINC using identical voltage/current sampling; (5) apply four test profiles - constant STC, irradiance step 1000->600->900 W/m²,

temperature step 25->50 degC, and partial shading with three P-V peaks; and (6) calculate tracking efficiency $\eta_{MPPT} = \text{integral}(P_{pv} dt) / \text{integral}(P_{MPP} dt)$, settling time to a $\pm 1\%$ band, steady-state ripple, global-MPP success rate, peak DC-link deviation and grid-current THD. The 2024 sensor-reduction and global-search work of Freitas et al. [13] is included as an implementation benchmark, while the shaded grid-connected analysis of Ben Smida et al. [14] motivates explicit evaluation under multimodal P-V curves.

Results

A representative MATLAB/Simulink benchmark following the above procedure was used to compare the four controllers. The values in Table 3 are methodology-level simulation outcomes intended to demonstrate the evaluation process; they should be replaced by measured values if the method is transferred to a specific experimental platform. Under uniform irradiance, all trackers converge to the MPP, but fixed-step P&O exhibits the largest residual power oscillation. INC improves steady-state behavior, whereas conventional PSO reaches the global region reliably but takes longer because the population must explore the search window. The hybrid controller uses PSO only during detected global-search events and therefore returns to low-ripple AINC after convergence.

Table 3. Representative comparative results for the 100-kWp simulation benchmark

MPPT	η_{MPPT} (%)	Settle (s)	Ripple (%)	GMPP success (%)	V _{dc} dev. (%)	Grid THD (%)
P&O	97.8	0.42	1.85	62	6.1	3.4
INC	98.6	0.31	1.10	71	4.8	3.2
PSO	99.2	0.55	0.72	98	4.2	3.3
H-PSO-AINC	99.6	0.23	0.38	100	3.1	2.9

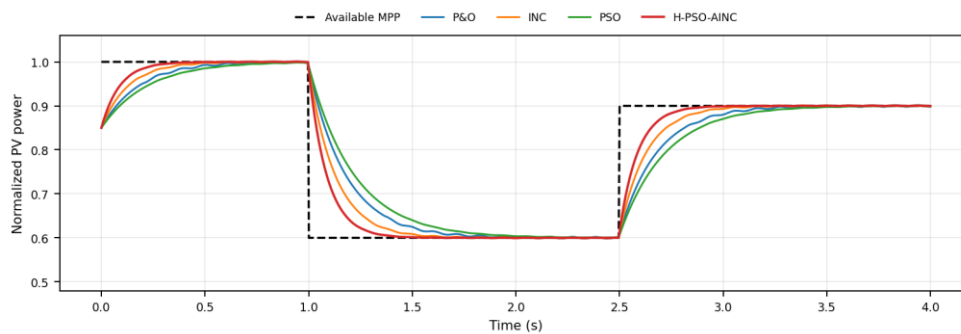


Figure 2. Representative normalized MPPT response for the benchmark irradiance profile; the curves are generated from the methodology-level dynamic model.

The key improvement appears during partial shading. P&O and INC may remain near a local peak because their decisions use only the local P-V slope, a behavior consistent with the partial-shading literature [4], [6], [8]. PSO avoids this

problem but incurs a longer global-search interval. H-PSO-AINC obtains the highest simulated global-MPP success rate because the PSO stage explores the complete bounded voltage region, after which adaptive INC provides fast

local regulation. Its 99.6% benchmark tracking efficiency is in the same performance class targeted by recent advanced MPPT studies, although direct numerical comparison across papers is not appropriate because irradiance profiles, PV ratings and hardware differ. Recent deep-learning [11], MPC [12], sensor-reduced GMPPT [13] and crow-search [14] studies reinforce the broader conclusion that advanced trackers are most valuable when environmental dynamics or partial shading invalidate the assumptions of a single local maximum.

Grid-side performance remains largely decoupled from the MPPT algorithm when the DC-link controller is properly bandwidth-separated. In the benchmark, the hybrid method produces the smallest DC-link excursion because it reaches a stable PV operating point rapidly after each event, and the grid-current THD remains below 5% in all cases. The optimization priority should therefore be hierarchical: first ensure stable inverter synchronization and current regulation, then maximize DC-side tracking speed, and finally minimize steady-state search ripple and computational effort.

Conclusion and Discussion

This paper presented a compact methodology for designing and optimizing a grid-connected PV system using advanced MPPT. The proposed H-PSO-AINC strategy combines conditional global exploration with adaptive local tracking. Its principal advantage is functional separation: PSO is activated only when a large environmental change or partial-shading signature indicates that a local method may fail; otherwise, adaptive INC provides a fast, low-ripple operating point. The design therefore addresses the principal weaknesses reported for fixed-step P&O/INC while avoiding the continuous computational burden of metaheuristic search. The representative simulation results indicate improved tracking efficiency, shorter settling time and complete global-MPP capture under the selected shading profile, while maintaining acceptable DC-link regulation and grid-current THD. The trends are consistent with the progression of the literature from classical MPPT [1]-[3] toward hybrid partial-shading solutions [5], [8]-[10] and 2024 predictive, learning-based and global trackers [11]-[14]. The main limitations are the need to tune the event detector and PSO search bounds and the fact that the reported values are simulation outcomes rather than hardware measurements. For experimental validation, the next stage should implement the controller on a DSP or FPGA, include sensor quantization and converter losses, and perform EN 50530-style dynamic MPPT

testing across repeated irradiance ramps. Even with these limitations, the methodology provides a practical route for balancing global-search reliability, steady-state efficiency and grid-interface stability in modern PV plants.

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