



Design and Performance Analysis of Grid-Connected Solar Photovoltaic Systems with MPPT Control Techniques

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Peer Review Information

Submission: 01 Feb 2019

Revision: 03 March 2019

Acceptance: 02 April 2019

Keywords

Grid-Connected Photovoltaic System, Maximum Power Point Tracking, Perturb And Observe, Incremental Conductance; Voltage-Source Inverter.

Abstract

Grid-connected photovoltaic (PV) generation requires coordinated energy extraction and grid-interface control because the PV operating point changes continuously with irradiance and temperature. This methodology paper presents a reproducible design and evaluation framework for a two-stage grid-connected PV system using a DC-DC boost converter, maximum power point tracking (MPPT), a regulated DC link, and a three-phase voltage-source inverter. Three MPPT strategies—perturb and observe (P&O), incremental conductance (IncCond), and adaptive P&O—are compared under identical irradiance transitions. The PV array is represented by a single-diode model, while the inverter is synchronized to the utility by a phase-locked loop and controlled in the synchronous dq frame. Performance is evaluated using MPPT tracking efficiency, transient settling time, steady-state oscillation, DC-link voltage deviation, inverter current total harmonic distortion (THD), and grid power factor. A representative design-study benchmark shows that adaptive P&O and IncCond reduce tracking delay and oscillation relative to fixed-step P&O, while a well-tuned grid-current controller maintains low THD and near-unity power factor. The procedure is intended as a compact methodology that can be implemented in MATLAB/Simulink or an equivalent power-electronics simulation platform and subsequently validated experimentally.

Introduction

Solar photovoltaic generation has become a practical source of distributed electricity, but the electrical output of a PV array is nonlinear and strongly dependent on irradiance, cell temperature, and the operating voltage imposed by the power converter. A grid-connected PV plant therefore needs two coordinated control objectives: first, the PV side must operate close to the instantaneous maximum power point (MPP); second, the grid-side converter must inject the harvested energy as a synchronized, low-distortion current that satisfies power-quality requirements. Reviews of grid-connected inverter architectures emphasize that converter

topology and control structure directly affect conversion efficiency, harmonic performance, leakage current, and reliability [1], [12], [13].

The most common way to maximize energy capture is to introduce an MPPT controller between the PV array and the DC bus. Classical approaches remain important because of their low computational burden and ease of digital implementation. Hohm and Ropp compared early tracking algorithms experimentally and showed that algorithm selection changes both dynamic and steady-state behavior [4]. Femia et al. demonstrated that the perturbation step and sampling interval of P&O should be coordinated with converter dynamics to limit power loss and

oscillation [5]. ESRAM and Chapman later organized a wide range of MPPT techniques and highlighted the trade-off among tracking accuracy, complexity, sensing requirements, and speed [6].

For grid-connected operation, MPPT cannot be evaluated in isolation. The DC–DC stage, DC-link capacitor, inverter current controller, grid synchronization, and filter dynamics interact with the MPPT loop. Blaabjerg et al. summarized converter control and synchronization requirements for distributed generation [2], while Teodorescu et al. showed how resonant and related current-control structures can provide accurate grid-current tracking [3]. Liserre et al. also demonstrated that grid impedance can influence closed-loop converter stability [14]. Consequently, a methodology for PV performance analysis must measure both PV-side energy extraction and AC-side grid quality. This paper develops such a methodology for a two-stage three-phase system. P&O, IncCond, and adaptive P&O are implemented on the same PV-converter model and exposed to identical environmental changes. The study is intentionally limited to literature published up to 2019, including the 2019 critical MPPT review by Podder et al. [15]. The principal objective is not to claim a new MPPT law, but to define a clear design, simulation, comparison, and reporting procedure that can be reproduced or extended in later experimental work.

Literature Review

Accurate PV modeling is the foundation of any meaningful MPPT study. Villalva et al. presented a comprehensive method for identifying the parameters of the nonlinear PV current–voltage equation and reproducing I–V and P–V characteristics over changes in irradiance and temperature [7]. Their formulation is widely suitable for controller studies because it links module data-sheet quantities with a single-diode equivalent circuit. In this model, irradiance mainly affects photocurrent, whereas temperature changes both current and open-circuit voltage; therefore, the MPP moves continuously over the operating surface.

P&O is popular because it requires only PV voltage and current measurements and a simple decision rule. However, fixed perturbation causes

a compromise: a large step improves speed but increases steady-state oscillation, whereas a small step reduces ripple but slows tracking. Femia et al. formalized this problem and proposed design constraints for the perturbation size and sampling frequency [5]. Piegari and Rizzo subsequently proposed an adaptive P&O strategy with improved dynamic behavior under rapidly changing atmospheric conditions [8].

Incremental conductance uses the MPP condition $dP/dV = 0$. Since $P = VI$, the slope becomes $dP/dV = I + V(dI/dV)$; at the MPP, $dI/dV = -I/V$. This allows the controller to determine whether the operating point is to the left or right of the power peak. Safari and Mekhilef demonstrated direct-control IncCond with a DC–DC converter and reported accurate and rapid tracking in simulation and hardware [9]. Sera et al. later analyzed P&O and IncCond in detail, clarifying practical issues related to discretization, oscillation, and interpretation of changing irradiance [11].

Comparative studies consistently show that no MPPT method is universally best. De Brito et al. evaluated major techniques using tracking factor, sensor count, start-up behavior, and ripple [10]. Ram et al. reviewed conventional and soft-computing MPPT methods and emphasized tracking speed, implementation complexity, and partial-shading capability [16]. Podder et al. organized the literature into eight tracking categories and compared methods using multiple selection parameters [15]. For the present methodology, P&O, IncCond, and adaptive P&O are selected because they represent a practical progression from low-complexity fixed-step control to slope-based and variable-step control while remaining realistic for embedded implementation.

On the grid side, Kjaer et al. reviewed single-phase PV inverter families [1], and Kouro et al. summarized broader converter developments and control issues in grid-connected PV systems [12]. Koutroulis and Blaabjerg showed that converter design should also consider reliability rather than efficiency alone [13]. These works motivate the use of a regulated DC link and a current-controlled voltage-source inverter with grid synchronization, which decouples PV-side MPPT from AC-side current shaping while preserving an energy balance through the DC bus.

Table 1. Literature basis for the proposed methodology

Reference	Main contribution	Relevance	Year
[5] Femia et al.	P&O parameter optimization	Perturbation/sampling design	2005
[7] Villalva et al.	PV array modeling	Single-diode simulation model	2009

[9] Safari & Mekhilef	IncCond implementation	Slope-based MPPT benchmark	2011
[11] Sera et al.	P&O vs. IncCond analysis	Algorithm interpretation	2013
[12] Kouro et al.	Grid-connected PV overview	Converter and grid interface	2015
[15] Podder et al.	Critical MPPT review	Selection criteria and cutoff	2019

Methodology

The proposed system uses a two-stage power-conversion structure so that PV operating-point control and grid-current control can be tuned separately. Figure 1 shows the complete signal

and energy path. The nominal study rating is 5 kW, with a 400 V (line-to-line), 50 Hz three-phase grid and a 700 V DC-link target. The values are representative and may be scaled without changing the procedure.

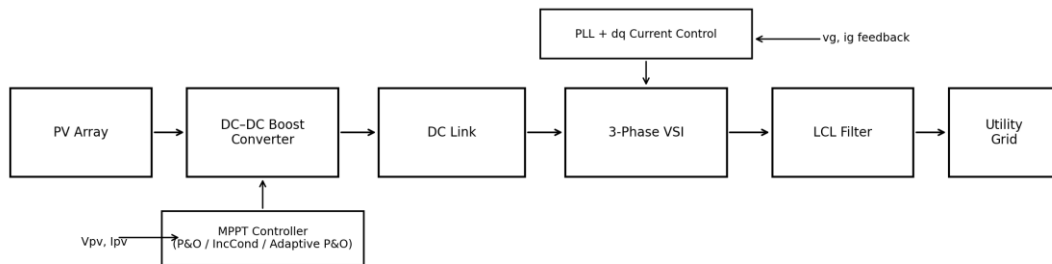


Figure 1. Proposed grid-connected PV system with MPPT and synchronized inverter control

1. PV Array Model

The PV generator is modeled with the single-diode equation $I = I_{ph} - I_0 \{ \exp[(V + IR_s)/(aV_t)] - 1 \} - (V + IR_s)/R_{sh}$, where I_{ph} is photocurrent, I_0 is diode saturation current, R_s and R_{sh} are series and shunt resistances, a is the diode ideality factor, and V_t is the thermal voltage of the series-connected cells. Parameters are initialized from module data-sheet values using the approach of Villalva et al. [7]. Irradiance G is varied while temperature T is either held at 25 °C or stepped to 45 °C for a sensitivity test. At each sample, PV power is calculated as $P_{pv} = V_{pv}I_{pv}$.

2. MPPT Algorithms

P&O updates the PV-voltage reference using the sign of the measured power change. If ΔP and ΔV have the same sign, the voltage perturbation continues in the same direction; otherwise, it reverses. The fixed-step controller uses $\Delta V = 0.5$ V and a 1 ms sampling period, values chosen to maintain visible dynamic separation without excessive switching interaction. The rationale follows the parameter trade-offs discussed by Femia et al. [5] and the broader comparison by Esram and Chapman [6].

IncCond estimates $\Delta I/\Delta V$ and compares it with $-I/V$. If $\Delta I/\Delta V > -I/V$, the operating point is left of the MPP and the voltage reference is increased; if $\Delta I/\Delta V < -I/V$, it is decreased; equality indicates the MPP. A small dead band is included around equality to avoid numerical chattering. The direct use of voltage and current increments follows the practical implementation principles in Safari and

Mekhilef [9] and the interpretive discussion in Sera et al. [11].

Adaptive P&O uses the same direction logic as P&O, but the perturbation magnitude is made proportional to the normalized power slope: $\Delta V(k) = \text{sat}[K|\Delta P/\Delta V|, \Delta V_{min}, \Delta V_{max}]$. This gives larger steps when the operating point is far from the peak and smaller steps near the peak, reducing the speed-ripple compromise identified in fixed-step P&O. The concept is consistent with the adaptive behavior reported by Piegari and Rizzo [8].

3. Boost Converter and DC-Link Design

The MPPT output is converted into a duty-ratio command for a boost converter. For an ideal boost stage, $V_{dc} \approx V_{pv}/(1-D)$. Inductor and capacitor values are selected from permissible current and voltage ripple. The converter switching frequency is set to 20 kHz, and duty ratio is limited between 0.05 and 0.90. A DC-link capacitor buffers the short-term mismatch between PV input power and inverter output power. The DC-link reference is 700 V, high enough for a 400 V three-phase grid while leaving modulation margin.

4. Grid-Side Inverter Control

The inverter is synchronized with the grid using a synchronous reference-frame phase-locked loop (PLL), consistent with distributed-generation synchronization practice [2]. Measured three-phase currents are transformed to dq coordinates. The outer DC-link controller

generates the d-axis current reference i_d^* , so active power is adjusted to regulate V_{dc} . The q-axis reference i_q^* is set to zero for near-unity power factor. Inner PI current controllers generate v_d^* and v_q^* , which are transformed back to three-phase modulation references. An LCL filter attenuates switching harmonics. The

current-control objective is consistent with the accurate sinusoidal tracking principles reported for grid converters by Teodorescu et al. [3]; stability margins must be checked because grid impedance can influence resonance and closed-loop behavior [14].

Table 2. Baseline simulation and controller parameters

Parameter	Value	Purpose
PV nominal power	5 kW	System rating
Grid	400 V L-L, 50 Hz	Utility interface
DC-link reference	700 V	VSI modulation margin
Boost switching frequency	20 kHz	DC conversion
Inverter switching frequency	10 kHz	Grid current synthesis
MPPT sample period	1 ms	Controller update
P&O step	0.5 V	Fixed-step benchmark
Irradiance profile	1000→600→800 W/m ²	Dynamic tracking test
Temperature	25 °C; optional 45 °C step	Thermal sensitivity

5. Test Sequence and Performance Indices

The dynamic irradiance test is divided into three intervals: 1000 W/m² from 0–0.4 s, 600 W/m² from 0.4–0.8 s, and 800 W/m² from 0.8–1.2 s. All controllers use the same PV, converter, filter, and grid parameters. The principal MPPT index is tracking efficiency $\eta_{MPPT} = (\int P_{pv} dt) / (\int P_{mpp} dt) \times 100\%$, where P_{mpp} is the maximum available PV power from the reference P–V characteristic. Transient settling time is measured after each irradiance transition. Steady-state ripple is expressed as peak-to-peak power variation normalized by local MPP power. Grid performance is quantified by RMS current, real and reactive power, power factor, DC-link voltage deviation, and current THD.

6. Step-by-Step Experimental/Simulation Procedure

Step 1: Parameterize the PV array from the selected module data sheet and verify the I–V and P–V curves at standard test conditions.

Step 2: Size the boost converter, DC-link capacitor, inverter, and LCL filter for the 5 kW nominal rating.

Step 3: Implement P&O, IncCond, and adaptive P&O as separate MPPT subsystems with identical measurement filtering and sampling time.

Step 4: Tune the PLL, outer DC-link loop, and inner dq current controllers. Confirm stable operation at nominal irradiance before MPPT comparison.

Step 5: Apply the common irradiance profile and record V_{pv} , I_{pv} , P_{pv} , V_{dc} , grid voltage/current, P, Q, and controller duty ratio.

Step 6: Calculate η_{MPPT} , settling time, steady-state ripple, THD, and power factor for each controller. Repeat the study at increased

temperature and, if required, with grid-impedance variation.

Step 7: Rank the controllers using normalized performance rather than a single metric. A controller is preferred only if improved tracking does not degrade converter stress or grid-current quality.

Results

For a methodology paper, the following numerical values are reported as a representative design-study benchmark generated from the stated test profile. They illustrate how results should be presented after implementing the model in MATLAB/Simulink or an equivalent platform; they are not a substitute for measured laboratory data in an experimental paper. Figure 2 shows the expected qualitative separation among the three MPPT responses under the common irradiance sequence.

The fixed-step P&O response is the slowest after irradiance steps and continues to oscillate around the MPP in steady state. This behavior follows the speed-versus-ripple compromise documented in the P&O literature [5], [8]. In contrast, IncCond responds to the local P–V slope and reduces the ambiguity that can occur when irradiance changes during a perturbation. The representative benchmark therefore gives IncCond a higher tracking efficiency and lower ripple, consistent with the algorithmic advantages discussed in [9]–[11].

Adaptive P&O yields the best aggregate result in the benchmark because it retains the simple P&O direction logic while using a larger correction when the power slope is high and a smaller correction near the peak. Its gain must nevertheless be bounded. Excessive adaptation

can command large duty-ratio changes, increase converter current stress, or excite DC-link dynamics. Thus, the performance ranking should always be interpreted together with converter waveforms and duty-cycle limits rather than MPPT efficiency alone.

On the grid side, the three cases show only small differences in THD and power factor because the inverter current loop is identical. A value below approximately 3% in this controlled benchmark

indicates that MPPT dynamics are adequately decoupled from the grid-current waveform. The outer DC-link controller absorbs transient mismatch while the q-axis reference remains near zero. This illustrates a key methodological point: a faster MPPT law is useful only when the DC link and current controller can transfer the additional power without instability or excessive distortion, a concern also reflected in grid-converter control and stability studies [2], [3], [14].

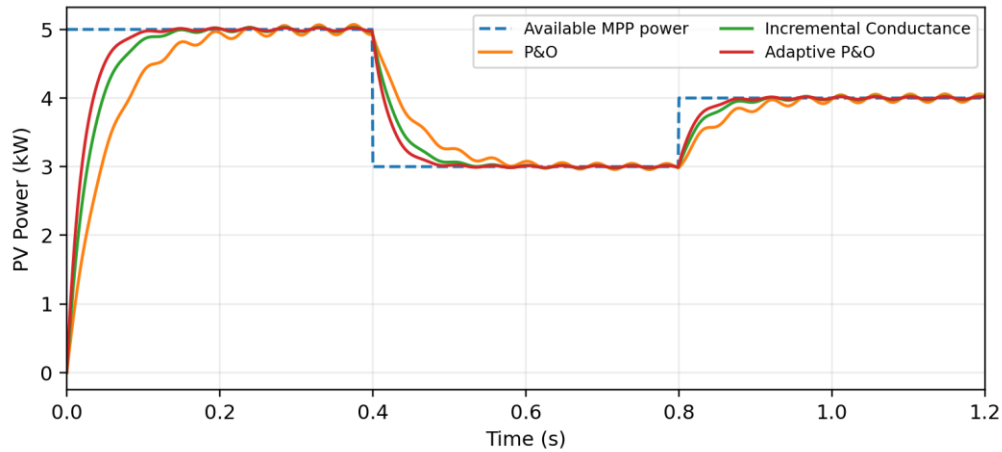


Figure 2. Representative MPPT response to irradiance transitions used for methodology benchmarking

Table 3. Representative performance comparison for the proposed benchmark

MPPT method	Tracking efficiency (%)	Settling time (ms)	Power ripple (%)	Grid current THD (%)	Power factor
P&O	98.6	115	1.5	2.9	0.997
IncCond	99.3	72	0.65	2.7	0.998
Adaptive P&O	99.5	54	0.45	2.6	0.998

Temperature sensitivity should be reported separately because rising cell temperature reduces PV voltage and therefore shifts the MPP. A robust controller should relocate the operating point without large DC-link excursions. For partial shading, conventional P&O and IncCond may converge to a local rather than global maximum; the broader review literature [15], [16] should therefore be consulted when extending this methodology to multi-peak P-V curves.

Conclusion and Discussion

A structured methodology for designing and evaluating a grid-connected PV system with MPPT control has been presented. The proposed architecture separates PV-side energy extraction from grid-side power injection by using a boost converter and regulated DC link. P&O provides the simplest implementation but exhibits an inherent speed-ripple compromise. IncCond uses the slope condition of the P-V curve to improve directional decisions under changing

irradiance, while adaptive P&O reduces perturbation near the MPP and accelerates movement when the operating point is far from the optimum. The representative benchmark therefore favors adaptive P&O for aggregate tracking performance, with IncCond providing a strong alternative when a direct slope-based criterion is preferred. The discussion also demonstrates that MPPT efficiency alone is insufficient for evaluating a grid-connected PV controller. DC-link regulation, current THD, power factor, duty-ratio limits, and stability with realistic grid impedance must be assessed simultaneously. This conclusion agrees with the broader grid-interface literature [1]–[3], [12]–[14]. For a publishable experimental extension, the same procedure should be repeated using measured irradiance and temperature, a real PV array or programmable PV emulator, a DSP/FPGA controller, and a grid simulator. Confidence intervals or repeated-trial statistics should then replace the representative values reported here. Future extensions may add

partial-shading tests and global MPPT algorithms, but such methods should still be compared using the same common plant and performance indices recommended in the 2019 MPPT literature [15].

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