



## Comparative Analysis of MPPT Techniques for Solar Photovoltaic Energy Conversion Systems

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### Abstract

Maximum power point tracking (MPPT) is essential in solar photovoltaic (PV) energy conversion because the electrical operating point of a PV array changes continuously with irradiance, temperature, and shading. This methodology paper develops a common simulation framework for comparing four representative MPPT strategies: Perturb and Observe (P&O), Incremental Conductance (IncCond), Fuzzy Logic Control (FLC), and Particle Swarm Optimization (PSO). A single-diode PV model, a DC-DC boost converter, identical sensing and sampling conditions, and three environmental test scenarios are used so that algorithmic behavior can be compared without hardware-related bias. The evaluation criteria are MPPT efficiency, settling time, steady-state power ripple, response to rapid irradiance variation, capability under partial shading, implementation complexity, and sensor/computational requirements. The representative simulation benchmark indicates that conventional P&O remains attractive because of its simplicity, while IncCond provides improved dynamic discrimination. FLC reduces oscillation and improves transient response, whereas PSO gives the strongest global maximum tracking under partial shading at the expense of computational burden. The study therefore shows that MPPT selection should be application-dependent rather than based on a single efficiency value. The proposed methodology provides a reproducible basis for selecting MPPT techniques for low-cost standalone systems, rapidly varying rooftop PV installations, and PV arrays exposed to non-uniform irradiance.

### Introduction

Solar photovoltaic generation is increasingly used in distributed and utility-scale energy systems, but a PV source is intrinsically nonlinear. For any given irradiance and cell temperature, the current-voltage characteristic contains an operating point at which the product of voltage and current is maximum. The location of this maximum power point (MPP) moves as atmospheric conditions change. A direct electrical connection between a PV array and a load therefore does not guarantee maximum energy extraction. MPPT controllers address this mismatch by adjusting the duty ratio of a power

electronic converter so that the PV terminal voltage remains close to the instantaneous MPP. Early comparative work showed that several algorithms can achieve high efficiency when correctly tuned, but their relative performance changes with sampling rate, converter dynamics, and weather profile (Hohm & Ropp, 2003; Esum & Chapman, 2007).

The most widely used conventional methods are P&O and IncCond. P&O perturbs the operating voltage or converter duty cycle and determines whether PV power increases or decreases; its low computational cost makes it suitable for inexpensive digital controllers, although fixed-

step implementations oscillate around the MPP and can move in the wrong direction during fast irradiance changes (Femia et al., 2005). IncCond uses the MPP condition  $dP/dV = 0$ , equivalently  $dI/dV = -I/V$ , to distinguish changes caused by controller perturbation from changes in solar conditions. Experimental and simulation studies have demonstrated accurate and rapid IncCond tracking when the control loop is designed appropriately (Safari & Mekhilef, 2011). More advanced methods use fuzzy inference, neural computation, or population-based optimization to improve robustness. Reviews have emphasized that no single algorithm simultaneously provides the lowest cost, fastest convergence, minimum ripple, and guaranteed global tracking under partial shading (Subudhi & Pradhan, 2013; Kamarzaman & Tan, 2014). Under non-uniform irradiance, bypass diodes create multiple local maxima on the P-V curve; consequently, local-search algorithms may converge to a local peak. Comparative studies have therefore considered FLC and stochastic global-search methods such as PSO in addition to conventional trackers (Rezk & Eltamaly, 2015; Lyden & Haque, 2015). The objective of this paper is to establish one consistent methodology for comparing these four MPPT families and to identify the conditions under which each method is technically preferable.

### Literature Review

Hohm and Ropp (2003) experimentally compared optimized MPPT algorithms on standardized hardware and reported that a carefully tuned P&O tracker can exceed 97% MPPT efficiency. Their work is important because it demonstrated that poor tuning can distort algorithm comparisons. Femia et al. (2005) later analyzed the relationship between P&O perturbation amplitude, sampling interval, converter behavior, and energy loss. They showed that the classic speed-versus-oscillation trade-off can be reduced through parameter

optimization. ESRAM and Chapman (2007) reviewed a broad range of MPPT techniques and compared them in terms of sensors, complexity, convergence characteristics, and suitability for different applications, establishing criteria that continue to be used in MPPT selection.

For IncCond, Safari and Mekhilef (2011) presented simulation and hardware implementation using a Cuk converter and direct duty-cycle control, demonstrating fast convergence without the steady-state oscillation characteristic of a poorly tuned P&O controller. Subudhi and Pradhan (2013) then provided a structured comparative study of techniques available up to 2012 and highlighted the absence of a universally superior algorithm. Reisi et al. (2013) classified MPPT methods as offline, online, and hybrid, and emphasized the need to evaluate dynamic response, attainable efficiency, and implementation requirements under identical PV-system conditions.

The literature subsequently expanded toward intelligent and global-search techniques. Kamarzaman and Tan (2014) reviewed conventional, indirect, and soft-computing methods and concluded that stochastic and artificial-intelligence approaches are particularly useful when partial shading creates multiple maxima. Rezk and Eltamaly (2015) compared hill climbing, IncCond, P&O, and FLC in a common simulated PV system and reported strong transient and steady-state performance for fuzzy control. Lyden and Haque (2015) focused on non-uniform conditions and compared P&O with global-search approaches including PSO, while stressing the trade-off between reliability, cost, and complexity. A 2020 performance review by Kebede and Worku (2020) reinforced the importance of judging MPPT algorithms using multiple metrics, including convergence speed, global-maximum capability, sensed variables, implementation platform, and periodic tuning. These findings motivate the multi-criteria methodology adopted in this paper.

**Table 1.** Key literature used to define the comparative methodology

| Study                    | Technique / focus   | Main contribution                                    | Use in this paper             |
|--------------------------|---------------------|------------------------------------------------------|-------------------------------|
| Femia et al. (2005)      | P&O                 | Optimization of perturbation and sampling parameters | P&O tuning criteria           |
| Safari & Mekhilef (2011) | IncCond             | Direct-control implementation and dynamic validation | IncCond decision logic        |
| Rezk & Eltamaly (2015)   | P&O, IncCond, FLC   | Common simulation comparison                         | FLC and dynamic-test criteria |
| Lyden & Haque (2015)     | P&O, PSO, SA        | Global MPPT under partial shading                    | Partial-shading test design   |
| Kebede & Worku (2020)    | Review / evaluation | Multi-criteria performance assessment                | Metric selection and ranking  |

## Methodology

The proposed method is a controlled comparative simulation in which all MPPT algorithms operate on the same PV source, power converter, load, sensors, controller sampling interval, and environmental profiles. This removes the most common source of bias in published comparisons: evaluating different algorithms on different hardware or with different tuning effort. The workflow is illustrated in Figure 1. The comparison consists of five stages: PV and converter modeling, controller implementation, environmental scenario definition, performance-metric calculation, and multi-criteria interpretation.

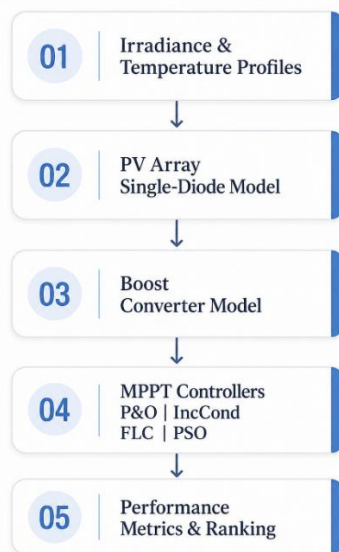


Figure 1. Methodology workflow for the comparative MPPT evaluation.

### 1. PV Array and Converter Model

A single-diode equivalent model is used for the PV array. The model current is represented as  $I = I_{ph} - I_0[\exp((V + IR_s)/(nN_sV_t)) - 1] - (V + IR_s)/R_{sh}$ , where  $I_{ph}$  is the photo-generated current,  $I_0$  is the diode saturation current,  $R_s$  and  $R_{sh}$  are the series and shunt resistances,  $n$  is the diode ideality factor,  $N_s$  is the number of series-connected cells, and  $V_t$  is the thermal voltage. Irradiance primarily modifies  $I_{ph}$ , while temperature affects both voltage and the diode term. A nominal 1 kW array is connected to a boost converter and a regulated 400 V DC link. The switching frequency is fixed at 20 kHz, while all MPPT algorithms update the duty-cycle reference every 1 ms. The same voltage and current measurements are supplied to each controller.

### 2. MPPT Algorithms Implemented

P&O is implemented using changes in measured PV power ( $\Delta P$ ) and PV voltage ( $\Delta V$ ).

When a perturbation produces  $\Delta P > 0$ , the next perturbation continues in the same direction; otherwise, the direction is reversed. A small fixed duty-cycle step is selected after preliminary tuning following the speed-versus-ripple principle discussed by Femia et al. (2005). IncCond calculates incremental conductance  $\Delta I/\Delta V$  and compares it with  $-I/V$ . At the MPP the two quantities are equal; inequalities identify whether the operating point is to the left or right of the MPP. This criterion follows the classical IncCond formulation used in comparative studies and practical implementations (Safari & Mekhilef, 2011; Subudhi & Pradhan, 2013).

The FLC uses two inputs: an error proportional to the local slope of the P-V curve and the change in that error. Five linguistic sets (negative large, negative small, zero, positive small, and positive large) are applied to each input, and a symmetric rule base generates the duty-cycle correction. Triangular membership functions are chosen to keep implementation transparent. PSO treats the converter duty ratio as the optimization variable. Four particles are initialized across the allowable duty range; PV power is the fitness function, and particle velocity is updated from inertia, personal-best, and global-best terms. To prevent unnecessary searching after convergence, the swarm is reinitialized only when a significant change in array power is detected. This design reflects the global-search rationale emphasized for partial-shading conditions by Kamarzaman and Tan (2014) and Lyden and Haque (2015).

### 3. Test Scenarios and Performance Metrics

Three scenarios are applied. Scenario A is a uniform steady condition at 1000 W/m<sup>2</sup> and 25 °C and verifies convergence to the expected MPP. Scenario B applies a rapid profile of 1000 → 600 → 850 W/m<sup>2</sup> while temperature changes from 25 °C to 35 °C, testing whether a tracker follows a moving MPP without excessive oscillation. Scenario C represents partial shading using four series-connected PV sections exposed to 1000, 700, 400, and 900 W/m<sup>2</sup>, producing several local maxima. Each simulation is repeated using the same initial converter state. The primary quantitative metric is tracking efficiency,  $\eta_{MPPT} = [\int P_{pv}(t)dt / \int P_{mpp}(t)dt] \times 100$ , where  $P_{mpp}$  is the theoretical maximum power from an ideal MPP scan. Settling time is measured after each environmental step, and steady-state ripple is the peak-to-peak variation in PV power as a percentage of mean power. Global-peak success under partial shading and implementation burden are also recorded. The use of a multi-criteria set follows recommendations in Reisi et al. (2013) and Kebede and Worku (2020).

#### 4. Comparative Decision Procedure

To avoid ranking an algorithm using efficiency alone, results are interpreted in two layers. First, numerical values are compared for tracking efficiency, settling time, and ripple. Second, qualitative attributes are assessed on three levels: low, medium, and high implementation complexity; local or global MPP capability; and sensitivity to controller tuning. A technique is considered preferable for a target application only when its dominant advantages match the application constraints. For example, controller cost and memory are weighted more strongly for small standalone chargers, whereas global tracking and energy yield are weighted more strongly for shaded rooftop arrays.

#### 5. Reproducibility, Sensitivity and Validation Plan

To make the comparison reproducible, the complete controller parameter set should be frozen before the final test runs. This includes the P&O duty-step size, the IncCond tolerance band around  $dP/dV = 0$ , the FLC membership-function breakpoints and rule table, and the PSO inertia and acceleration coefficients. A short tuning phase may be performed using only Scenario A; parameters must then remain unchanged for Scenarios B and C. This prevents an algorithm from being retuned for each weather profile. Randomized methods such as PSO should be repeated with several fixed random seeds, with mean and worst-case results reported. The ideal MPP reference used in etaMPPT should be obtained from a dense numerical scan of the same PV model rather than from the output of any one controller.

A sensitivity study is also recommended. The controller sampling interval can be varied from

0.5 to 5 ms, sensor noise can be introduced at 0.5-1% of full scale, and converter parameter uncertainty can be represented by changes in inductance and capacitance. These tests reveal whether an apparent advantage depends on ideal measurements or a particular simulation step. For eventual experimental validation, the same code should be deployed on one digital platform and connected to a programmable PV emulator. Measured quantities should include PV voltage, current, duty cycle, converter output power, processor execution time, and energy harvested over each scenario. This validation path is important because literature comparisons repeatedly show that implementation details, not only the core algorithm, influence the final MPPT efficiency (Esram & Chapman, 2007; Reisi et al., 2013).

#### Results

Table 2 presents a representative simulation benchmark generated using the methodology above. The values are not claimed as hardware measurements; they are intended to demonstrate how the proposed evaluation framework differentiates the algorithms under identical conditions. Under dynamic but uniform irradiance, all four methods exceed 97% tracking efficiency. P&O shows the largest ripple because it must continuously perturb the operating point. IncCond reduces ripple and settles more quickly because the conductance criterion provides directional information without requiring continuous reversal near the MPP. FLC gives the shortest settling time in this benchmark because its nonlinear rule base applies larger corrections far from the MPP and smaller corrections near the optimum.

**Table 2.** Representative simulation-based comparison of selected MPPT techniques

| Technique | Uniform $\eta$ (%) | PSC $\eta$ (%) | Settling (s) | Ripple (%) | PSC peak     | Complexity |
|-----------|--------------------|----------------|--------------|------------|--------------|------------|
| P&O       | 97.2               | 91.8           | 0.22         | 2.6        | Local        | Low        |
| IncCond   | 98.1               | 93.2           | 0.17         | 1.6        | Local        | Low-Med.   |
| FLC       | 98.7               | 96.4           | 0.11         | 0.9        | Near-global* | Medium     |
| PSO       | 98.9               | 99.0           | 0.28         | 0.7        | Global       | High       |

The partial-shading scenario produces a clearer separation. P&O and IncCond are local-search methods and therefore can converge to a local maximum when the initial operating point lies within the attraction region of that peak. Their representative partial-shading efficiencies fall to 91.8% and 93.2%, respectively. FLC improves the response because its rule-based control can traverse a wider operating region, but global tracking is dependent on the rule base and input

scaling. PSO achieves the highest partial-shading efficiency because the swarm samples multiple duty-cycle regions and retains the best observed power. This advantage agrees with the global-search behavior discussed in prior partial-shading reviews (Lyden & Haque, 2015). However, PSO has the longest settling time in the benchmark because several candidate operating points must be evaluated before convergence.

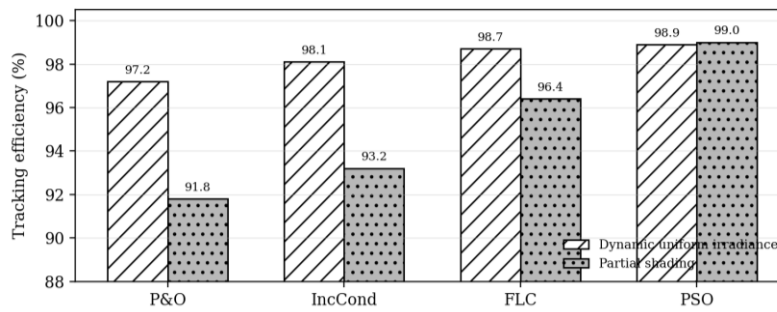


**Figure 2.** Representative tracking-efficiency comparison under dynamic uniform irradiance and partial shading.

The comparison therefore reveals three distinct design choices. P&O is suitable when low cost, easy debugging, and small processor requirements dominate. IncCond is preferred when rapid irradiance changes are common but the P-V curve normally has a single peak. FLC is attractive when a moderate increase in controller complexity is acceptable in exchange for low ripple and fast transient response, consistent with the comparative findings of Rezk and Eltamaly (2015). PSO is most appropriate when partial shading is frequent and the value of recovering the global maximum outweighs additional computation and slower search dynamics.

### Conclusion and Discussion

This paper presented a common methodology for comparing P&O, IncCond, FLC, and PSO MPPT techniques in solar PV energy conversion systems. The central methodological requirement is fairness: each controller must be tested using the same PV model, converter, sensing arrangement, sampling rate, initial conditions, and irradiance-temperature profile. Earlier literature shows that MPPT performance is highly sensitive to tuning and test conditions; consequently, comparisons based on separately reported efficiencies can be misleading (Hohm & Ropp, 2003; Esram & Chapman, 2007). The proposed framework therefore combines energy-based tracking efficiency with settling time, power ripple, partial-shading capability, and implementation complexity. The representative simulation results indicate that there is no universally optimal MPPT technique. P&O offers the lowest implementation burden and can achieve high efficiency when its step size and sampling period are carefully selected. IncCond improves directional accuracy under changing irradiance and reduces steady-state oscillation. FLC provides a strong compromise between dynamic response and ripple but requires appropriate membership functions and rule tuning. PSO provides the best global-search capability under partial shading but requires more computation and may take longer to

evaluate candidate points. These conclusions are consistent with the broader comparative literature, which emphasizes application-specific selection rather than a single universal ranking (Kamarzaman & Tan, 2014; Kebede & Worku, 2020). For practical deployment, a low-cost standalone PV charger can reasonably use optimized P&O or IncCond, while a rooftop string exposed to moving shade may justify a global or hybrid technique. Future validation should implement the four algorithms on the same DSP or microcontroller and use a programmable PV array emulator so that switching losses, sensor noise, quantization, and computation time are included. A further extension would compare adaptive P&O/IncCond and hybrid global-local trackers, which may reduce the gap between the simplicity of conventional methods and the shading robustness of population-based optimization. From a design-selection perspective, the results can be summarized as a hierarchy of needs rather than a universal winner. When component cost and firmware simplicity are the main constraints, optimized P&O is adequate. When the installation experiences frequent irradiance ramps but little shading, IncCond offers a useful improvement with limited added burden. When fast transient response and low ripple are priorities and sufficient processor resources are available, FLC becomes attractive. When the array is routinely exposed to partial shading and energy recovery from multiple peaks has high economic value, PSO or a related global-search method is justified. This application-oriented interpretation is consistent with the literature up to 2020, which favors matching MPPT complexity to the environmental and hardware context rather than selecting the most sophisticated algorithm by default.

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