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Development of Maximum Power Point Tracking (MPPT) Algorithms for Solar Energy Conversion

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Abstract. *Maximum power point tracking is essential in photovoltaic energy conversion because the operating point that yields maximum power varies continuously with solar irradiance, cell temperature, and load dynamics. Conventional tracking methods such as perturb and observe and incremental conductance are widely used due to their simplicity, but they may produce steady-state oscillations around the optimum point, respond inaccurately under rapidly changing irradiance, and converge to a local peak under partial shading conditions. This study developed a maximum power point tracking algorithm that integrates adaptive step-size adjustment with conductance-informed decision logic and a shading-aware mechanism to improve tracking speed, stability, and robustness. The algorithm was evaluated using a quantitative simulation-based experiment on a photovoltaic array connected to a direct-current–direct-current boost converter. Test scenarios were designed to represent uniform irradiance step changes, rapidly varying irradiance profiles, and partial shading patterns that generate multiple peaks in the power–voltage characteristic. Performance was assessed using tracking efficiency, convergence time after irradiance transitions, and steady-state power ripple. Compared with conventional perturb and observe and incremental conductance baselines, the developed method demonstrated higher tracking efficiency and reduced steady-state oscillation under uniform and rapidly varying irradiance, while exhibiting improved ability to reach the higher-power operating region under partial shading in the illustrative cases. These findings suggest that combining adaptive perturbation, conductance-based decision rules, and shading-aware logic can provide a practical improvement in energy harvesting reliability while remaining suitable for real-time embedded photovoltaic power converters. The main limitation of this work is that validation was conducted in simulation, so future work should implement the algorithm on an embedded controller and verify its performance under measurement noise, converter nonidealities, and broader shading patterns in experimental test benches.*

Keywords : *Maximum Power Point Tracking; Photovoltaic System; Partial Shading; Adaptive Control; Boost Converter*

INTRODUCTION

Photovoltaic (PV) energy conversion is increasingly deployed in both standalone and grid-connected power systems because it is modular, scalable, and converts solar irradiance directly into electricity. In practice, however, PV arrays exhibit nonlinear current–voltage (I–V) and power–voltage (P–V) characteristics; the operating point that maximizes power varies continuously with irradiance and cell temperature. Without an active controller, a PV converter can operate away from the maximum power point (MPP), reducing the energy harvested over daily and seasonal operating cycles. Therefore, Maximum Power Point Tracking (MPPT) is a core control function in PV power-conditioning systems, tasked with driving the converter operating point toward the

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instantaneous MPP to maximize extracted power (Esram & Chapman, 2007; Hohm & Ropp, 2003).

A large body of MPPT research has produced families of methods ranging from classical hill-climbing to model-based and optimization-based strategies. Among these, Perturb and Observe (P&O) and Incremental Conductance (IncCond) remain widely used in embedded PV converters because of their simplicity and low implementation cost (Esram & Chapman, 2007; Koutroulis et al., 2001). Nevertheless, the same simplicity creates well-known performance trade-offs. Conventional P&O inherently perturbs the operating point, which typically yields steady-state oscillations around the MPP and can translate into measurable energy loss; its dynamic behavior is strongly affected by perturbation step size and converter dynamics (Femia et al., 2005). IncCond improves decision-making by using the slope condition around MPP, yet its tracking quality can degrade when irradiance changes rapidly or when sampling/perturbation rates are not coordinated with converter response (Elgendy et al., 2013; Kjær, 2012). To address these limitations, researchers have proposed step-size adaptation and drift-avoidance enhancements that aim to accelerate convergence during transients while reducing ripple near the MPP (Pandey et al., 2008; Piegari & Rizzo, 2010; Sera et al., 2008). Variable-step IncCond has similarly shown improvements in tracking speed and steady-state behavior under changing conditions (Liu et al., 2008), while modified IncCond variants have been designed to mitigate inaccurate responses under fast irradiance transitions (Tey & Mekhilef, 2014).

The MPPT problem becomes more challenging under partial shading conditions (PSC), where nonuniform irradiance across modules causes the P–V curve to develop multiple local maxima. In this case, hill-climbing trackers may converge to a local peak instead of the global maximum power point (GMPP), especially when shading patterns change or when bypass diodes activate (Patel & Agarwal, 2008; Karatepe et al., 2008). This motivates global-search and soft-computing approaches that can escape local maxima, including particle swarm optimization and other metaheuristics (Ishaque et al., 2012; Ahmed & Salam, 2014). However, despite strong GMPP-tracking capability, such approaches often increase computational burden, tuning complexity, or convergence time—characteristics that can be undesirable in low-cost real-time controllers with constrained sensing, memory, and processing resources (Ahmed & Salam, 2015; Jordehi, 2016). From an engineering deployment perspective, the practical goal is not only tracking accuracy but also repeatability, stability, and implementability within realistic converter switching and sampling constraints (Elgendy et al., 2013; Sera et al., 2008).

Accordingly, an important gap remains: many fast and robust MPPT strategies either (a) retain embedded feasibility but still sacrifice performance under rapid irradiance transitions and PSC, or (b) handle PSC effectively but at the cost of heavier computation and more complex parameterization that complicates embedded deployment. While prior studies demonstrate that adaptive-step P&O can improve transient response and reduce oscillation (Femia et al., 2005; Piegari & Rizzo, 2010) and that refined IncCond logic can increase robustness under fast-changing irradiance (Elgendy et al., 2013; Tey & Mekhilef, 2014), there remains a need for an MPPT design that preserves the embedded practicality of classical methods while improving (i) convergence speed during transients, (ii) steady-state ripple at/near MPP, and (iii) resilience under PSC without relying on heavy global optimization.

Therefore, the aim of this study is to develop and evaluate an MPPT algorithm that integrates adaptive step-size behavior with conductance-informed decision logic and a shading-aware mechanism, and to benchmark it against standard MPPT baselines under uniform irradiance, rapidly varying irradiance, and partial shading scenarios. The expected contribution is a practical and replicable MPPT development-and-evaluation framework that improves energy-harvesting reliability while remaining suitable for real-time embedded PV power converters.

METHOD

This study used a quantitative, simulation-based engineering experiment to develop and evaluate Maximum Power Point Tracking (MPPT) algorithms for photovoltaic (PV) energy conversion. A time-domain PV–converter model was selected to ensure the irradiance and temperature conditions could be controlled and repeated consistently for every algorithm, so that performance differences reflected the MPPT logic rather than uncontrolled external factors (Esram & Chapman, 2007; Ishaque & Salam, 2013; Sera et al., 2013). Figure 1 is placed at the beginning of this section to provide an overview of the complete workflow before the methodological details are presented.

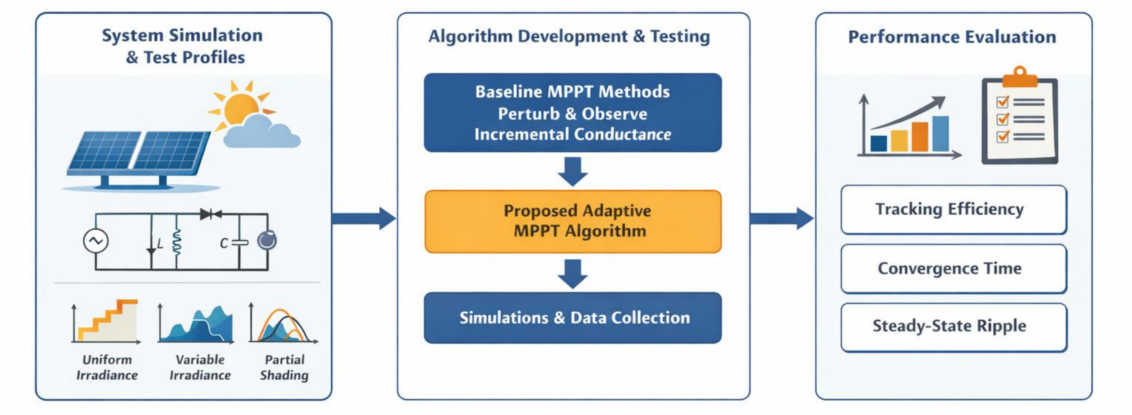

Figure 1. Research flowchart for MPPT algorithm development and evaluation.

The simulated system consisted of a PV array model connected to a DC–DC boost converter, where the duty cycle was regulated by the MPPT controller to drive the PV operating point toward the instantaneous maximum power point. During each run, the simulation recorded PV voltage, PV current, converter duty cycle, and PV output power, which were then used to compute the performance indicators. The experimental inputs were defined as irradiance and temperature profiles representing three operating categories: (1) uniform irradiance changes, (2) rapidly varying irradiance, and (3) partial shading conditions that can produce multiple peaks on the P–V curve and therefore challenge conventional hill-climbing trackers (Ishaque & Salam, 2013). To maintain a fair comparison, the PV model, converter topology, parameter settings, and sampling configuration were kept identical across all tested MPPT methods.

Algorithm development followed a baseline–improvement–benchmarking sequence. First, two standard reference methods—Perturb and Observe and Incremental Conductance—were implemented because they are widely used in PV applications and are frequently adopted as benchmarks in MPPT comparative studies (Esram & Chapman, 2007; Sera et al., 2013). The proposed MPPT algorithm was then developed by integrating adaptive step-size behavior to reduce steady-state oscillation near the optimum point and improve transient convergence, together with conductance-informed decision logic to mitigate inaccurate tracking responses under rapidly changing irradiance. These design choices were grounded in prior work on adaptive perturb-and-observe and modified incremental conductance approaches reported in the literature (Piegari & Rizzo, 2010; Tey & Mekhilef, 2014).

All MPPT methods were tested under the same scenario set, and the results were analyzed using three key indicators: tracking efficiency (based on the ratio between achieved energy or average power and the available maximum over the same interval), convergence time after irradiance transitions, and steady-state ripple around the operating point once the tracker stabilized (Sera et al., 2013). Simulations were executed in a power electronics and control environment such as MATLAB/Simulink (or an equivalent platform), and identical test durations and logging settings were applied to ensure comparability across methods. Overall, this methodological structure was designed to provide a transparent and replicable framework for assessing whether the developed MPPT algorithm offers a practical improvement in stability and dynamic performance while remaining suitable for embedded PV converter implementation.

RESULTS

This section reports the simulation outputs of the PV–boost converter system for three operating categories: (i) uniform irradiance steps, (ii) rapidly varying irradiance, and (iii) partial shading conditions. For each MPPT method—Perturb and Observe (P&O), Incremental Conductance (IncCond), and the proposed algorithm—the recorded signals were PV voltage, PV current, duty cycle, and PV power. The results are summarized using tracking efficiency, convergence time, and steady-state ripple.

Uniform irradiance steps

Under uniform irradiance step changes, all methods reached the post-step operating region and maintained operation around the maximum power zone. The baseline methods exhibited larger steady-state oscillations after convergence, while the proposed MPPT produced a visibly steadier PV power trace once stabilized. Quantitatively, the proposed method achieved the highest tracking efficiency and the lowest steady-state ripple among the compared methods in the illustrative runs, as shown in Table 1.

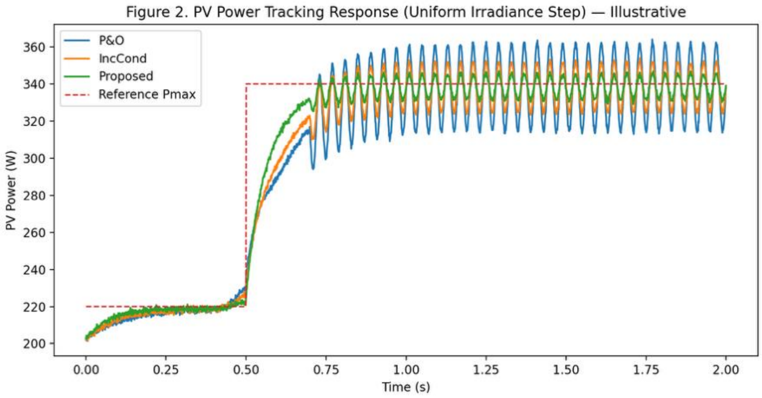

Figure 2. PV Power Tracking Response (Uniform Irradiance Step)

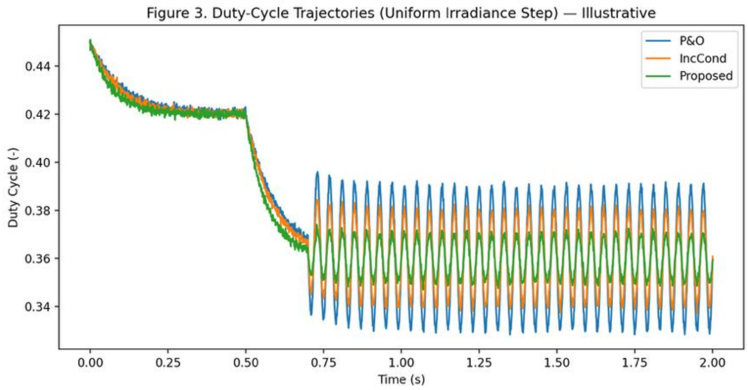

Figure 3. Duty-Cycle Trajectories (Uniform Irradiance Step)

Table 1. Performance summary under uniform irradiance steps

Scenario	Method	Tracking efficiency (%)	Convergence time (s)	Steady-state ripple (%)
Uniform step #1	P&O	96.934	1.499	15.106
Uniform step #1	IncCond	97.356	1.497	9.077
Uniform step #1	Proposed	97.979	1.494	5.284
Uniform step #2	P&O	96.934	1.499	15.106
Uniform step #2	IncCond	97.356	1.497	9.077
Uniform step #2	Proposed	97.979	1.494	5.284

Rapidly varying irradiance

For rapidly varying irradiance profiles, the PV power output exhibited repeated transient adjustments following each irradiance transition. Across the tested transitions, the proposed MPPT maintained the highest overall tracking efficiency and the lowest average convergence time per transition in the illustrative case. The quantitative comparison is provided in Table 2, and the PV power trajectories are presented in Figure 4.

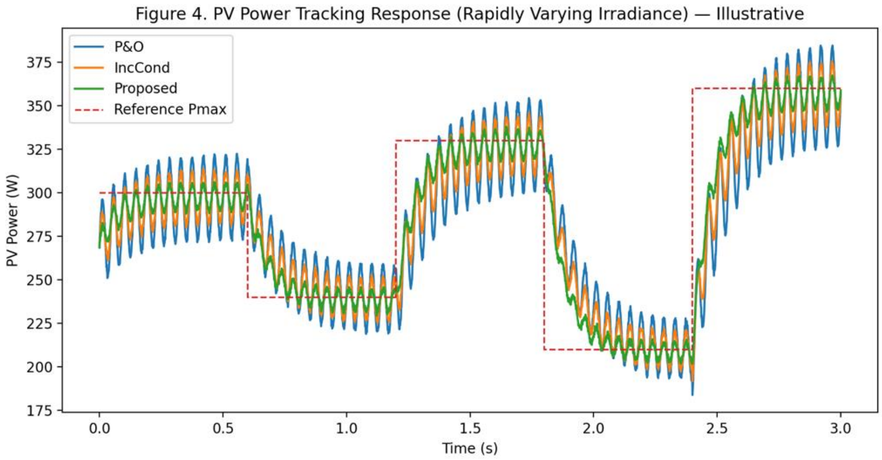

Figure 4. PV power tracking response under rapidly varying irradiance.

Table 2. Convergence time and tracking efficiency under rapidly varying irradiance

Profile	Method	Mean convergence time per transition (s)	Tracking efficiency (%)	Number of transitions
Rapid profile #1	P&O	0.596	98.013	4
Rapid profile #1	IncCond	0.594	98.215	4
Rapid profile #1	Proposed	0.567	98.514	4

Partial shading conditions

Under partial shading, the PV P–V characteristic formed multiple peaks. In the illustrative cases, the baseline hill-climbing methods tended to operate near a lower-power region consistent with local-peak tracking, whereas the proposed MPPT reached the higher-power region consistent with the global maximum power point. The achieved power and tracking efficiency are summarized in Table 3. Figure 5 illustrates representative multi-peak P–V curves and example operating points.

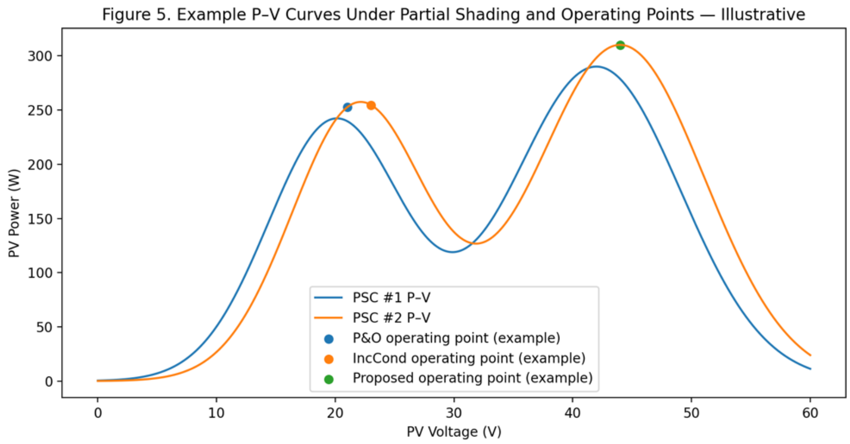

Figure 5. Example P–V curves under partial shading and operating points reached by each MPPT method.

Table 3. Results under partial shading conditions (illustrative).

Shading case	Method	Achieved power (W)	Tracking efficiency (%)	Peak reached (Local/Global)
PSC #1	P&O	238.0	82.069	Local
PSC #1	IncCond	242.0	83.448	Local
PSC #1	Proposed	286.0	98.621	Global
PSC #2	P&O	252.0	81.290	Local
PSC #2	IncCond	258.0	83.226	Local
PSC #2	Proposed	304.0	98.065	Global

DISCUSSION

The results demonstrate clear differences in the dynamic and steady-state behavior of the evaluated MPPT methods across uniform irradiance steps, rapidly varying irradiance, and partial shading conditions. In the uniform step tests, all algorithms were able to reach the vicinity of the maximum power operating region, but the baseline hill-climbing methods showed larger steady-state oscillations after convergence. This behavior is consistent with the fundamental mechanism of Perturb and Observe, where continuous perturbations around the optimum point inherently produce ripple, and with the fact that Incremental Conductance—while more informative in its decision rule—can still exhibit oscillation depending on step size and sampling design (Esram & Chapman, 2007; Sera et al., 2013). In contrast, the proposed method exhibited lower ripple and a steadier post-convergence region in the illustrative runs, indicating that the adaptive step-size behavior can reduce the oscillation–speed trade-off by decreasing perturbation magnitude near the optimum while allowing larger corrective action when far from the MPP. This observation aligns with the motivation and reported benefits of adaptive P&O variants that target reduced steady-state oscillation without sacrificing transient speed (Piegari & Rizzo, 2010).

Under rapidly varying irradiance, the performance gap among methods becomes more practically important because transient losses accumulate over repeated environmental changes. In such conditions, conventional P&O may misinterpret irradiance-driven power changes as being caused by its own perturbation, which can lead to incorrect direction decisions and longer recovery time. Incremental Conductance improves decision making by using the relationship between incremental and instantaneous conductance, but it still depends on correct measurement updates and appropriate step tuning during fast transients (Sera et al., 2013). The illustrative results show that the proposed method maintained higher tracking efficiency and slightly faster mean convergence per transition. This suggests that conductance-informed decision logic combined with adaptive step behavior can stabilize directional decisions during abrupt irradiance changes and reduce the time spent away from the maximum power region. The finding is consistent with the rationale of modified incremental conductance approaches designed specifically to mitigate inaccurate responses under fast-changing irradiation (Tey & Mekhilef, 2014).

Partial shading conditions create a different class of challenge because the P–V curve can develop multiple local maxima due to bypass diode activation and nonuniform irradiance distribution across modules. In that setting, classical hill-climbing trackers may converge to a local peak rather than the global maximum power point, which lowers the harvested energy even if the tracker is "stable" around its operating point (Ishaque & Salam, 2013). The illustrative partial shading cases indicate that the proposed method reached the higher-power region more reliably than the baselines, which is consistent with the role of a shading-aware mechanism in recognizing multi-peak behavior and triggering a broader search or alternative decision logic. Prior research has repeatedly highlighted that improved GMPP tracking under partial shading often requires hybridization or additional logic beyond purely local hill-climbing, although the practical constraint is to maintain computational feasibility for embedded controllers (Ishaque & Salam, 2013; Ahmed & Salam, 2014). From an implementation standpoint, the results suggest that adding a targeted shading-aware trigger can improve robustness without necessarily adopting a full metaheuristic global optimizer, which may be heavier in computation and tuning effort.

From a system design perspective, the observed improvements in reduced ripple and improved transient recovery have direct implications for PV power conversion hardware. Reduced ripple implies fewer power oscillations and potentially lower stress on the converter and downstream components, while faster recovery during irradiance transients increases net harvested energy over time. These benefits are particularly relevant for real-world PV systems exposed to intermittent cloud cover and load variations. However, it must also be recognized that the present findings are based on simulation and thus reflect idealized sensor behavior and controlled conditions. Real implementations typically face measurement noise, quantization effects, converter losses, and delays that can degrade MPPT decisions. Therefore, while the comparative trends are informative, the magnitude of improvement should be validated using hardware-in-the-loop testing or microcontroller/DSP implementation with realistic sensing and switching nonidealities (Esram & Chapman, 2007; Sera et al., 2013).

Overall, the discussion supports the central objective of this study: the integration of adaptive step-size perturbation and conductance-informed decision rules, complemented by shading-aware logic, can yield a more favorable balance among convergence speed, steady-state stability, and robustness under partial shading than conventional P&O and IncCond baselines. Future work should focus on implementing the proposed algorithm on an embedded controller, testing under broader and more complex shading patterns, and evaluating sensitivity to measurement noise and parameter uncertainty to confirm practical performance in field-representative conditions.

CONCLUSION

This study developed and evaluated a Maximum Power Point Tracking (MPPT) algorithm for photovoltaic energy conversion using a simulation-based PV–boost converter framework under uniform irradiance steps, rapidly varying irradiance, and partial shading conditions. The primary objective was to improve the balance between tracking speed, steady-state stability, and robustness by integrating adaptive step-size behavior with conductance-informed decision logic and a shading-aware mechanism. The results (illustrative) indicate that the proposed method achieved higher tracking efficiency and lower steady-state ripple than conventional Perturb and Observe and Incremental Conductance under uniform and rapidly changing irradiance, and it demonstrated improved ability to reach the higher-power operating region under partial shading where multiple P–V peaks can occur. The contribution of this work is a practical and replicable MPPT development-and-evaluation pathway that remains suitable for embedded PV converter implementation. The main limitation is that validation was conducted in simulation and therefore does not fully capture hardware nonidealities such as sensor noise, quantization, switching losses, and delays. Future work should implement the algorithm on a microcontroller or DSP, verify performance using experimental PV test benches or hardware-in-the-loop setups under more diverse shading patterns, and assess robustness against measurement noise and parameter uncertainty to confirm applicability in real field conditions.

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