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When sunlight changes: MPPT strategies and DC–DC converter control under partial shading and dynamic conditions

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ABSTRACT

Photovoltaic (PV) systems rarely operate under constant environmental conditions, and variations in irradiance, temperature, and partial shading can substantially reduce their energy yield. These disturbances modify the electrical characteristics of PV arrays and may produce multiple local maxima on their power–voltage curves. Conventional maximum power point tracking (MPPT) methods, including perturb and observe (P&O) and incremental conductance (IncCond), are attractive because of their simplicity, but they may converge to local peaks or respond inaccurately during rapid environmental changes. This review examines MPPT strategies and DC–DC converter control approaches developed to address these challenges, using peer-reviewed literature published up to 2016. Conventional tracking methods, artificial intelligence techniques, population-based optimization, and hybrid strategies are discussed in relation to their global search capability, convergence behavior, and implementation requirements. Particular attention is given to the interaction between MPPT algorithms and converter dynamics, since duty-cycle limits, switching behavior, and transient response influence actual energy extraction. The review identifies the trade-offs between tracking accuracy, response speed, computational complexity, and hardware cost. It concludes that robust PV energy harvesting requires coordinated algorithm and converter design rather than the selection of an MPPT method in isolation.

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1. INTRODUCTION

Photovoltaic (PV) energy conversion is strongly influenced by environmental conditions, making the operating point of a PV array continuously variable. Changes in solar irradiance and cell temperature alter the current–voltage and power–voltage characteristics, while nearby buildings, trees, clouds, or other obstructions can create non-uniform illumination across modules. Under uniform irradiance, a PV array generally exhibits one dominant maximum power point, which conventional tracking methods can locate with reasonable simplicity. Under partial shading, however, bypass diode operation can produce several local maxima, making the identification of the global maximum substantially more difficult [1]–[3].

The central research problem is that an MPPT controller must distinguish between changes caused by its own control action and changes caused by the environment. A conventional controller may interpret an irradiance-induced power increase as evidence that its previous perturbation was correct, even when the operating point has moved away from the true maximum. Partial shading introduces a separate difficulty because a controller that follows the local slope of the power curve may settle at a local peak rather than the global one. These effects can cause energy losses even when the PV modules and power converter are operating within their electrical ratings [4], [5].

This review examines how MPPT algorithms and DC–DC converter control can be coordinated to improve PV energy extraction under partial shading and rapidly changing conditions. It considers conventional methods, intelligent and population-based optimization, hybrid approaches, and converter-level implementation issues. The discussion is based on peer-reviewed publications available up to December

2016, with emphasis on methods that explicitly address global tracking or dynamic environmental changes. The review follows a problem-to-solution structure, moving from PV array behavior to algorithmic approaches, converter interaction, comparative assessment, and research priorities.

2. PV ARRAY BEHAVIOR UNDER PARTIAL SHADING AND DYNAMIC CONDITIONS

Partial shading changes the electrical behavior of a PV array because series-connected cells or modules must carry a common current despite receiving different levels of irradiance. Bypass diodes reduce the risk of reverse-bias damage and hot spots, but their operation also changes the overall array voltage–current relationship. As different groups of cells become bypassed, the resulting power–voltage curve can contain several local peaks, with only one representing the global maximum. The location and magnitude of these peaks depend on the shading pattern, module interconnection, irradiance distribution, and temperature [1], [6].

Dynamic irradiance creates a different but related tracking problem because the power curve itself changes while the controller is searching. A sudden cloud passage or moving shadow may alter the PV current faster than a conventional MPPT algorithm can complete its perturbation cycle. Temperature changes generally occur more slowly than irradiance changes, but they also shift the voltage associated with maximum power and should not be ignored in long-term operation. Dadjé *et al.* [1] reviewed methods for both partially shaded and rapidly variable insolation conditions, emphasizing that the two operating scenarios require different detection and tracking considerations.

The interaction between environmental disturbances and converter dynamics makes the overall problem more complex. The MPPT algorithm normally changes a reference voltage or converter duty cycle, but the actual PV operating point responds according to the converter's electrical and control dynamics. If the measurement interval is too short, the algorithm may evaluate transient rather than steady-state power, leading to incorrect decisions. Conversely, an excessively long interval can delay tracking when irradiance changes rapidly, so sampling and converter settling time must be considered together [7], [8].

3. CONVENTIONAL MPPT METHODS AND THEIR LIMITATIONS

Perturb and observe (P&O) remains popular because it requires relatively few measurements and can be implemented using inexpensive digital controllers. The algorithm perturbs the PV operating voltage or converter duty cycle and observes whether the measured output power increases or decreases. Its main limitation is the persistent oscillation around the maximum power point, which creates a small but continuous loss under steady conditions. During rapid irradiance changes, the measured power variation may be dominated by the environmental disturbance rather than the controller perturbation, causing the algorithm to move in the wrong direction [4], [5].

Incremental conductance (IncCond) improves the decision process by using the relationship between instantaneous and IncCond to identify the maximum power point. Compared with basic P&O, it can reduce steady-state oscillation and provide more reliable tracking when irradiance changes. However, its performance depends on measurement accuracy, sampling frequency, and the selection of decision thresholds. More importantly, conventional IncCond does not inherently solve the multiple-peak problem under partial shading, because its local decision process can still converge to a local maximum [2], [3].

These limitations explain why conventional algorithms are often retained as local tracking controllers rather than treated as complete solutions for all operating conditions. A practical architecture can use a conventional method during uniform illumination and activate a global search when shading or a substantial power deviation is detected. Such a strategy avoids unnecessary global searches during stable operation while retaining the ability to recover from significant changes in the array characteristic. The challenge is to detect when global retracking is necessary without introducing excessive interruption or energy loss [1], [9].

4. INTELLIGENT AND GLOBAL MPPT STRATEGIES

Intelligent MPPT methods seek to overcome local convergence by exploring the power curve beyond the immediate neighborhood of the operating point. Particle swarm optimization (PSO) is among the widely studied approaches because multiple candidate solutions can search different regions of the duty-cycle or voltage range. Liu *et al.* [10] proposed a PSO-based MPPT algorithm for PV systems under partial shading, demonstrating its ability to identify the global maximum in conditions where conventional methods may become trapped at local peaks. Ishaque *et al.* [11] developed a direct-control PSO method that adjusts converter duty cycle without requiring an additional conventional PI control loop, and evaluated it experimentally using a PV array simulator.

Ant colony optimization (ACO) and artificial bee colony (ABC) algorithms provide alternative population-based search mechanisms. Jiang *et al.* [12] introduced an ACO-based MPPT method for partially shaded PV systems, using a cooperative search process to identify the global operating point. ABC-based tracking was investigated by Sundareswaran *et al.* [13] who combined algorithmic search with experimental validation under partial shading. These methods can explore multiple candidate regions, but their performance depends on search parameters, population size, measurement quality, and the time available for convergence.

Other approaches seek to improve global search while reducing computational overhead. Ahmed and Salam applied cuckoo search to PV MPPT under partial shading, demonstrating another bio-inspired approach to global peak identification [14]. Mohanty *et al.* [15] proposed a grey wolf optimization-based MPPT design for PV systems under partial shading, extending the use of population-based optimization to the same problem. Seyedmahmoudian *et al.* [16] reviewed artificial intelligence-based MPPT methods and emphasized the importance of comparing their tracking accuracy, convergence, and implementation complexity rather than relying solely on simulated peak-search results.

Extremum-seeking control offers a different route to global or improved tracking by using feedback from the system's measured output. Peng *et al.* [7] developed a sequential extremum-seeking approach for global MPPT under variable shading, while Heydari-doostabad *et al.* [8] proposed an extremum-seeking method designed to distinguish global and local maxima under uniform and non-uniform irradiance. These methods are attractive because they can adapt to system behavior without requiring a complete analytical model of the PV array. Their practical performance nevertheless depends on filter design, perturbation frequency, transient behavior, and the ability to distinguish genuine environmental changes from control-induced variations.

Hybrid methods combine the strengths of global search and local tracking to balance convergence speed with steady-state accuracy. A population-based algorithm can first identify a promising global region, after which P&O or IncCond can refine the operating point with smaller perturbations. This division reduces the need to run an expensive global search continuously, although the transition between the two control modes must be carefully managed. El-Khozondar *et al.* [2] and Sameeullah and Swarup [3] provide broader comparisons of MPPT algorithms and highlight the importance of selecting a method according to environmental conditions, hardware requirements, and application constraints.

5. DC–DC CONVERTER CONTROL AND MPPT INTEGRATION

The DC–DC converter is the physical actuator through which an MPPT algorithm changes the operating point of a PV array. A boost converter is commonly used when the PV voltage must be raised to a higher DC-link voltage, while buck–boost structures can accommodate a wider range of input and output voltages. The converter duty cycle may be adjusted directly by the MPPT algorithm or indirectly through a voltage or current reference and an inner feedback controller. The choice affects control complexity, transient response, and the interaction between the global search procedure and the converter's closed-loop dynamics [11], [17].

Direct duty-cycle control can reduce the number of control loops and simplify the path between the MPPT algorithm and the switching converter. However, the approach requires careful consideration of duty-cycle limits, measurement filtering, and converter stability because each search step directly changes the switching operating condition. In contrast, a cascaded structure with an MPPT-generated reference and an inner voltage or current controller can provide more explicit regulation of the converter response. The additional control loop may improve robustness, but it can also introduce delays that influence the speed and accuracy of global tracking [11], [17].

Converter dynamics are particularly important during global searches because candidate operating points must be evaluated after the electrical response has settled sufficiently. Chao *et al.* [18] demonstrated this issue in a distributed PV system using a dedicated buck converter for each module and a multicore PSO algorithm for global tracking. Their study reported that converter settling time and measurement intervals influenced the tracking process, illustrating that the algorithm cannot be designed independently of the power stage. Therefore, MPPT evaluation should include the converter's transient response, switching behavior, and power losses rather than considering only the mathematical convergence of the optimization routine.

6. COMPARATIVE ASSESSMENT

The reviewed approaches differ in their ability to track the global maximum, respond to rapid environmental changes, and operate within practical hardware constraints. Conventional algorithms are computationally economical, whereas intelligent search methods offer stronger global exploration at the cost of additional processing and tuning requirements. Hybrid and event-triggered approaches attempt to combine

these characteristics by activating global search only when necessary. Table 1 summarizes the principal differences and their implications for PV converter control.

Table 1. Comparison of MPPT Strategies Under Partial Shading and Dynamic Conditions

MPPT strategy	Global peak capability	Main strength	Main limitation
P&O	Generally limited	Simple and inexpensive	Oscillation and drift during rapid irradiance changes
Incremental conductance	Generally limited without additional search	Improved local tracking behavior	Measurement and threshold sensitivity
Particle swarm optimization	Yes, with suitable search configuration	Multiple candidate solutions explore the operating range	Parameter tuning and convergence time
Ant colony optimization	Yes, with suitable search configuration	Cooperative global exploration	Computational and parameter complexity
Artificial bee colony	Yes, with suitable search configuration	Flexible search with relatively few control parameters	Search-time and implementation requirements
Cuckoo search	Yes, with suitable search configuration	Global optimization capability	Algorithmic tuning and transient evaluation
Extremum-seeking control	Can be designed for global tracking	Feedback-based adaptation	Filter and perturbation design
Hybrid global–local methods	Yes, if global stage identifies the correct region	Combines global search and local refinement	Mode switching and coordination complexity

As summarized in Table 1, no algorithm is universally superior because the best choice depends on the shading pattern, environmental dynamics, converter response, and available controller hardware. Global optimization methods are especially relevant when the array exhibits several competing peaks, but their computational requirements can be excessive for low-cost controllers or large distributed systems. Conventional algorithms remain useful when the PV array is uniformly illuminated or when a global search is activated only after a significant disturbance. A fair comparison should therefore report not only tracking efficiency but also convergence time, steady-state oscillation, energy loss during retracking, and implementation cost [1]–[3], [16].

The distinction between simulated and experimental performance is also important when evaluating MPPT techniques. Simulation can provide repeatable irradiance patterns and allow detailed analysis of multiple local maxima, but it may not fully represent sensor noise, converter losses, switching delays, and component tolerances. Experimental validation using PV simulators or real modules is needed to establish whether the reported global tracking performance survives practical operating conditions. Chao *et al.* [11] and Ishaque *et al.* [18] provide examples of experimental evaluation that include the interaction between search algorithms and converter hardware.

7. RESEARCH CHALLENGES AND FUTURE DIRECTIONS

A major research challenge is developing reliable shading-detection and retracking mechanisms that avoid unnecessary global searches. Continuous global optimization can consume processing resources and disturb the operating point, while infrequent searches may allow the system to remain at a local maximum for too long. Event-triggered approaches offer a practical compromise by monitoring changes in power, voltage, or operating conditions before initiating a wider search. Further work should evaluate these mechanisms under complex shading patterns and rapidly moving shadows rather than relying only on a small set of predefined irradiance profiles [1], [9], [18].

Another priority is the coordinated design of MPPT algorithms and converter control loops. Algorithm comparisons should account for converter settling time, switching frequency, duty-cycle limits, sensor bandwidth, and the stability of the inner control loop. Distributed PV architectures also deserve attention because module-level converters can reduce mismatch losses, although they introduce additional hardware and coordination requirements. A consistent experimental framework would make it easier to compare global tracking performance, energy yield, converter efficiency, and system cost across different designs [16], [18].

8. CONCLUSION

Partial shading and dynamic environmental conditions create substantial challenges for extracting maximum energy from PV arrays. Conventional P&O and IncCond methods remain attractive for their simplicity, but their local search behavior and sensitivity to rapid irradiance changes limit their effectiveness

in complex conditions. Population-based optimization, extremum-seeking control, and hybrid methods provide stronger global search capabilities, although they introduce additional computational and implementation requirements. The reviewed literature also shows that MPPT performance depends on the dynamics of the DC–DC converter, including settling time, control-loop structure, and switching constraints. Reliable PV energy harvesting therefore requires integrated design of the tracking algorithm, converter, and measurement system, supported by realistic experimental validation.

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