IAES Journal of Electrical and Electronics Engineering
Vol. 5, No. 1, June 2018, pp. 1~5
ISSN: 2338-7432, DOI: 10.11591/jeee.v5i1.pp1-5

Beyond conventional MPPT: intelligent optimization techniques for high-efficiency solar photovoltaic energy harvesting

Tole Sutikno[1], Tri Wahono[2], Anggit Pamungkas[2]
[1]Faculty of Industrial Technology, Universitas Ahmad Dahlan, Yogyakarta, Indonesia
[2]Embedded Systems and Power Electronics Research Group, Yogyakarta, Indonesia

Article Info

Article history:

Received Mar 6, 2017
Revised Oct 27, 2017
Accepted Jan 4, 2018

Keywords:

Artificial intelligence
Differential evolution
Maximum power point tracking
Partial shading
Particle swarm optimization
Photovoltaic systems
Soft computing

ABSTRACT

Maximum power point tracking (MPPT) is essential to photovoltaic (PV) energy harvesting because the operating point of a solar array changes with irradiance, temperature, and load conditions. Conventional methods such as perturb and observe (P&O) and incremental conductance are attractive because of their simplicity, but they can exhibit steady-state oscillations, sluggish response, or incorrect tracking when partial shading produces multiple power peaks. This review examines how intelligent optimization techniques address these limitations, with emphasis on fuzzy logic, artificial neural networks (ANNs), particle swarm optimization (PSO), ant colony optimization (ACO), cuckoo search, differential evolution, and grey wolf optimization (GWO). The review follows a problem-oriented narrative approach, drawing on studies published no later than 2016 and considering algorithm behavior, operating conditions, implementation complexity, and experimental validation. The literature indicates that intelligent methods can improve global-peak detection and adaptability, particularly under nonuniform irradiance, while hybrid approaches can combine global exploration with local refinement. Their practical value, however, depends on sensing, parameter tuning, computational burden, converter dynamics, and fair testing procedures. The review concludes that no single optimizer is universally superior; effective MPPT design requires matching algorithm architecture and converter implementation to the expected PV operating environment.

This is an open access article under the CC BY-SA license.

1. INTRODUCTION

Solar photovoltaic (PV) systems are increasingly used in distributed generation, standalone electricity supplies, and grid-connected installations. However, the electrical power available from a PV array is not constant because its operating characteristics depend on solar irradiance, cell temperature, and electrical loading. Maximum power point tracking (MPPT) addresses this problem by adjusting the operating point of the array so that the available power can be extracted efficiently. Consequently, MPPT performance directly influences the energy yield and overall effectiveness of a PV installation [1], [2].

Conventional MPPT algorithms, particularly perturb and observe (P&O) and incremental conductance (INC), are widely adopted because they are relatively simple and require limited computational resources. Nevertheless, these methods may oscillate around the MPP, respond inadequately to rapid environmental changes, or converge toward a local rather than global maximum under partial shading. Partial shading is especially challenging because bypass-diode operation can produce several peaks in the array power–voltage characteristic. These limitations motivate the investigation of intelligent optimization methods that can improve global-peak detection and adapt to complex operating conditions [3], [4].

This review examines the development of intelligent optimization techniques for PV MPPT, focusing on their operating principles, strengths, limitations, and practical implementation requirements. The review uses a narrative and comparative approach based on peer-reviewed literature published up to 31 December 2016. It covers fuzzy logic and neural-network methods, population-based optimization

algorithms, and hybrid approaches that combine global search with conventional tracking. The discussion proceeds from the underlying tracking problem to algorithmic solutions, implementation considerations, and research directions.

2. MPPT FUNDAMENTALS AND LIMITATIONS OF CONVENTIONAL METHODS

The central objective of MPPT is to maintain the PV array near its instantaneous maximum-power operating point despite changes in environmental and electrical conditions. Under relatively uniform irradiance, the power–voltage characteristic generally exhibits one dominant maximum, making conventional tracking comparatively straightforward. P&O modifies the operating voltage or duty cycle and observes whether the resulting power increases or decreases. INC uses the relationship between instantaneous and INC to determine the direction of movement toward the MPP [1], [3].

Although conventional methods are attractive for low-cost applications, their performance involves important trade-offs. A small perturbation step can reduce steady-state oscillations but may slow the tracking response, whereas a large step can accelerate convergence while increasing power fluctuations around the MPP. Rapid irradiance changes can also confuse the decision process because a power variation may result from changing sunlight rather than the controller's own perturbation. These limitations have been documented in comparative assessments of MPPT methods and motivate the use of adaptive or intelligent control strategies [2], [3], [5].

Partial shading introduces a more demanding optimization problem because the PV array can exhibit multiple local maxima. A conventional local search may stop at a nearby peak without identifying the global maximum, thereby reducing the energy harvested from the array. Reviews by Ishaque and Salam [3], Liu *et al.* [6], and Seyedmahmoudian *et al.* [7] identify global MPP tracking under nonuniform irradiance as a major reason for adopting intelligent and metaheuristic methods. The challenge is therefore to achieve reliable global exploration without imposing excessive computational effort or introducing unacceptable delays into the control loop.

3. INTELLIGENT OPTIMIZATION TECHNIQUES

3.1. Fuzzy logic and artificial neural networks

Fuzzy logic control (FLC) provides a means of representing nonlinear control behavior through linguistic rules rather than relying exclusively on an exact mathematical model. A typical fuzzy MPPT controller uses variables associated with changes in PV power and voltage to determine an appropriate adjustment to the operating point. Its membership functions and rule base can be designed to provide different responses according to the distance and direction of movement from the MPP. However, controller performance depends on the selection of membership functions, rule definitions, scaling factors, and the operating conditions used during design [4], [8].

Artificial neural networks (ANNs) offer a different approach by learning relationships between environmental inputs and the desired PV operating point. Depending on the architecture, an ANN can use irradiance, temperature, voltage, or current measurements to estimate the MPP or generate a control reference. This approach can reduce dependence on repeated online searching when representative training data are available. Nevertheless, its accuracy depends on training-data coverage, network architecture, and the extent to which actual operating conditions resemble those represented during training [7], [8].

The combination of intelligent control with optimization can improve the design of fuzzy and neural controllers. Messai *et al.* [9] used a genetic algorithm to optimize fuzzy-controller membership functions and control rules, then implemented the controller on an FPGA platform. This work illustrates that intelligent optimization can contribute not only to online MPP tracking but also to offline controller design and hardware realization. The approach is promising, although the computational cost of optimization and the verification of the resulting controller remain important engineering considerations.

3.2. Population-based and nature-inspired optimization

Particle swarm optimization (PSO) searches for promising operating points through the coordinated movement of candidate solutions. Each particle updates its search behavior using information about its own best result and the best result identified by the swarm. This collective search can examine several regions of the PV power curve and is therefore suitable for global MPP tracking under partial shading. Liu *et al.* [10] demonstrated a PSO-based MPPT algorithm for partially shaded PV systems, highlighting its potential to locate the global peak where conventional tracking may become trapped at a local maximum.

Ant colony optimization (ACO) uses a collective search mechanism inspired by the behavior of ants exploring alternative paths. In PV applications, the method can be adapted to search for promising operating

regions on a multimodal power curve. Jiang *et al.* [11] proposed an ACO-based MPPT method for PV systems under partial shading and addressed the difficulty of finding the global MPP when several local peaks are present. Its practical performance depends on the search representation, parameter selection, and the balance between exploration and convergence.

Other nature-inspired methods extend the range of available optimization strategies. Ahmed and Salam applied cuckoo search to MPPT under partial shading and reported its ability to identify the global peak with favorable tracking behavior [12]. Ramli *et al.* [13] developed a modified differential evolution approach for partially shaded PV systems, using evolutionary search to improve global tracking performance. Mohanty *et al.* [14] investigated grey wolf optimization (GWO), comparing its performance with conventional P&O and an improved PSO approach and including experimental validation.

These algorithms should not be regarded as interchangeable solutions because their search mechanisms and implementation requirements differ. PSO uses particle movement and shared search information, while ACO relies on collective path selection and differential evolution uses mutation and recombination of candidate solutions. Cuckoo search and GWO introduce other population-based strategies for exploring complex search spaces. Their suitability depends on convergence behavior, parameter sensitivity, robustness to changing irradiance, and the computational resources available in the controller [7], [10]-[14].

3.3. Hybrid and adaptive strategies

Hybrid MPPT methods seek to combine the global-search capability of an intelligent optimizer with the simplicity or rapid local response of a conventional algorithm. A population-based optimizer can first identify a promising global operating region, after which P&O or INC can refine the operating point. This arrangement can reduce the need for continuous global optimization once the controller has located a suitable peak. However, the transition between global and local search must be designed carefully to prevent unnecessary oscillations or premature switching [6], [7].

Adaptive approaches also seek to change tracking behavior according to the operating environment. For example, a controller may use larger search steps during substantial changes in irradiance and smaller adjustments near the identified MPP. A hybrid strategy can also activate global search when shading or mismatch is detected, while retaining a conventional algorithm during relatively stable conditions. These strategies can improve practical efficiency, but their performance must be assessed under multiple irradiance profiles rather than a single favorable test case [6], [7].

4. COMPARATIVE ASSESSMENT

Selecting an intelligent MPPT technique requires consideration of more than its ability to locate a global maximum. Relevant criteria include tracking speed, steady-state oscillation, sensitivity to environmental changes, computational complexity, and hardware requirements. Table 1 summarizes the principal characteristics of the techniques discussed in this review. The comparison is qualitative because reported performance values depend on PV array configuration, shading patterns, converter design, sampling frequency, and experimental conditions.

Table 1. Qualitative Comparison of MPPT Techniques

MPPT technique	Main advantage	Principal limitation	Typical suitability
P&O	Simple and inexpensive	Oscillation and possible drift under rapid irradiance changes	Uniform irradiance and low-cost systems
Incremental conductance	Uses MPP slope information	Higher computational and sensing requirements than basic P&O	Conventional digital MPPT
Fuzzy logic	Handles nonlinear behavior without an exact model	Membership functions and rules require tuning	Variable operating conditions
Artificial neural network	Can estimate MPP from learned relationships	Requires representative training data	Predictive and adaptive tracking
Particle swarm optimization	Searches multiple candidate operating points	Parameter tuning and convergence-time concerns	Partial shading
Ant colony optimization	Population-based exploration of multiple peaks	Search design and computational overhead	Global MPP search
Cuckoo search	Global search with relatively few control parameters	Search behavior depends on algorithm settings	Partial shading
Differential evolution	Effective population-based global optimization	Requires suitable mutation and control settings	Complex multimodal characteristics
Grey wolf optimization	Collective exploration and exploitation	Embedded implementation and tuning require attention	Global peak identification

As Table 1 indicates, conventional algorithms remain attractive when cost, simplicity, and predictable implementation are the dominant requirements. Intelligent methods offer additional capabilities for complex power curves, but they introduce design choices that may increase development and computational effort. Their advantages should therefore be evaluated against the complete PV conversion system rather than in isolation. The reviews by Salam *et al.* [4], Mellit and Kalogirou [5], and El-Khozondar *et al.* [8] similarly emphasize the importance of considering implementation complexity and practical requirements alongside tracking performance.

A further concern is the comparability of published performance results. Different studies may use different module ratings, array configurations, irradiance profiles, temperature assumptions, converter topologies, and definitions of tracking efficiency. Simulation-based comparisons may also omit switching losses, sensor noise, measurement delays, and hardware constraints. Consequently, a reported high tracking efficiency in one study should not be interpreted as proof that the same algorithm will outperform alternatives in every PV installation [2], [6], [7].

5. IMPLEMENTATION CHALLENGES AND RESEARCH DIRECTIONS

The practical implementation of intelligent MPPT depends on the interaction between the optimization algorithm and its DC–DC converter. The MPPT controller generally determines a voltage, current, or duty-cycle reference, while the converter regulates energy transfer between the PV array and the load or DC link. Converter dynamics, switching frequency, component ratings, and control-loop bandwidth can therefore influence the observed tracking response. A sophisticated optimizer cannot compensate for an inadequately designed power stage or poorly selected measurement and control parameters [2], [8] [5].

Computational complexity is another important consideration, particularly for embedded controllers with limited processing capacity. Population-based algorithms may require multiple power evaluations during each search cycle, which can increase execution time and delay the response to environmental changes. Digital signal processors and microcontrollers provide practical platforms for many MPPT algorithms, while FPGA implementation can support parallel processing and deterministic execution for suitable architectures. Mellit and Kalogirou reviewed the implementation of intelligent MPPT methods on FPGA devices, and Messai *et al.* demonstrated an FPGA-based realization of a GA-optimized fuzzy controller [8], [9].

Future research should place greater emphasis on standardized experimental comparisons and reproducible evaluation procedures. Studies should report array configuration, shading patterns, irradiance transition profiles, converter parameters, sampling frequency, tracking time, steady-state oscillation, and energy harvested over a defined period. Hardware-in-the-loop testing and long-duration experiments would provide stronger evidence of practical robustness than isolated simulation scenarios. Researchers should also examine whether hybrid algorithms provide measurable energy benefits that justify their additional implementation complexity.

6. CONCLUSION

Intelligent optimization techniques provide useful alternatives to conventional MPPT methods, particularly when PV arrays operate under partial shading and rapidly changing environmental conditions. Fuzzy logic and neural networks offer adaptive or learned control behavior, while population-based methods such as PSO, ACO, cuckoo search, differential evolution, and GWO provide mechanisms for searching complex multimodal power curves. Hybrid strategies can further combine global exploration with local refinement, although their effectiveness depends on the design of the transition and the characteristics of the power converter. No single algorithm is universally optimal because performance is influenced by environmental conditions, sensing, computational resources, and implementation quality. High-efficiency PV energy harvesting therefore requires a system-level approach that evaluates the optimizer, converter, and experimental operating conditions together.

REFERENCES

[1] T. Esram and P. L. Chapman, "Comparison of photovoltaic array maximum power point tracking techniques," *IEEE Transactions on Energy Conversion*, vol. 22, no. 2, pp. 439–449, 2007, doi: 10.1109/TEC.2006.874230.

[2] M. A. G. De Brito, L. Galotto, L. P. Sampaio, G. De Azevedo Melo, and C. A. Canesin, "Evaluation of the main MPPT techniques for photovoltaic applications," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 3, pp. 1156–1167, 2013, doi: 10.1109/TIE.2012.2198036.

[3] K. Ishaque and Z. Salam, "A review of maximum power point tracking techniques of PV system for uniform insolation and partial shading condition," *Renewable and Sustainable Energy Reviews*, vol. 19, pp. 475–488, 2013, doi: 10.1016/j.rser.2012.11.032.

[4] Z. Salam, J. Ahmed, and B. S. Merugu, "The application of soft computing methods for MPPT of PV system: A technological and status review," *Applied Energy*, vol. 107, pp. 135–148, 2013, doi: 10.1016/j.apenergy.2013.02.008.
[5] H. J. El-Khozondar, R. J. El-Khozondar, K. Matter, and T. Suntio, "A review study of photovoltaic array maximum power tracking algorithms," *Renewables: Wind, Water, and Solar*, vol. 3, no. 1, 2016, doi: 10.1186/s40807-016-0022-8.
[6] L. Liu, X. Meng, and C. Liu, "A review of maximum power point tracking methods of PV power system at uniform and partial shading," *Renewable and Sustainable Energy Reviews*, vol. 53, pp. 1500–1507, 2016, doi: 10.1016/j.rser.2015.09.065.
[7] M. Seyedmahmoudian *et al.*, "State of the art artificial intelligence-based MPPT techniques for mitigating partial shading effects on PV systems – A review," *Renewable and Sustainable Energy Reviews*, vol. 64, pp. 435–455, 2016, doi: 10.1016/j.rser.2016.06.053.
[8] A. Mellit and S. A. Kalogirou, "MPPT-based artificial intelligence techniques for photovoltaic systems and its implementation into field programmable gate array chips: Review of current status and future perspectives," *Energy*, vol. 70, pp. 1–21, 2014, doi: 10.1016/j.energy.2014.03.102.
[9] A. Messai, A. Mellit, A. Guessoum, and S. A. Kalogirou, "Maximum power point tracking using a GA optimized fuzzy logic controller and its FPGA implementation," *Solar Energy*, vol. 85, no. 2, pp. 265–277, 2011, doi: 10.1016/j.solener.2010.12.004.
[10] Y. H. Liu, S. C. Huang, J. W. Huang, and W. C. Liang, "A particle swarm optimization-based maximum power point tracking algorithm for PV systems operating under partially shaded conditions," *IEEE Transactions on Energy Conversion*, vol. 27, no. 4, pp. 1027–1035, 2012, doi: 10.1109/TEC.2012.2219533.
[11] L. L. Jiang, D. L. Maskell, and J. C. Patra, "A novel ant colony optimization-based maximum power point tracking for photovoltaic systems under partially shaded conditions," *Energy and Buildings*, vol. 58, pp. 227–236, Mar. 2013, doi: 10.1016/j.enbuild.2012.12.001.
[12] J. Ahmed and Z. Salam, "A maximum power point tracking (MPPT) for PV system using Cuckoo Search with partial shading capability," *Applied Energy*, vol. 119, pp. 118–130, 2014, doi: 10.1016/j.apenergy.2013.12.062.
[13] M. A. M. Ramli, K. Ishaque, F. Jawaid, Y. A. Al-Turki, and Z. Salam, "A modified differential evolution based maximum power point tracker for photovoltaic system under partial shading condition," *Energy and Buildings*, vol. 103, pp. 175–184, 2015, doi: 10.1016/j.enbuild.2015.06.058.
[14] S. Mohanty, B. Subudhi, and P. K. Ray, "A new MPPT design using grey Wolf optimization technique for photovoltaic system under partial shading conditions," *IEEE Transactions on Sustainable Energy*, vol. 7, no. 1, pp. 181–188, 2016, doi: 10.1109/TSTE.2015.2482120.