Frontiers in Artificial Intelligence Research **Volume 3 Issue 2, 2026**

ISSN: 3079-6342

Recent Advances in Intelligent MPPT Algorithms for Photovoltaic Systems: Performance Comparison and Application Analysis

Xia Wei[1] ,Tadiwa Elisha Nyamasvisva[1]

[1]Kuala Lumpur University of Science and Technology, School of Information Technology

Block 11, De Centrum City, Jalan Ikram-Uniten, 43000 Kajang, Selangor Darul Ehsan, Malaysia

Email: 242924688@klust.edu.my; xw_mickey@163.com

Abstract

Maximum power point tracking (MPPT) plays a vital role in improving the energy conversion efficiency of photovoltaic systems. In recent years, intelligent MPPT algorithms have advanced rapidly; however, existing studies still lack a sufficiently integrated comparison of their performance characteristics, application suitability, and engineering practicality. This paper reviews recent advances in intelligent MPPT algorithms for photovoltaic systems and classifies them into four categories: rule-based control, prediction-learning, search-optimization, and hybrid-collaborative methods. These methods are comparatively analyzed in terms of tracking speed, tracking accuracy, tracking stability, computational complexity, and application adaptability, with further discussion of typical operating scenarios such as dynamic irradiance variation, partial shading, and resource-constrained control platforms. The review indicates that rule-based methods are generally easier to implement in real-time environments, prediction-learning methods show advantages under dynamic conditions, search-optimization methods are more suitable for multi-peak conditions such as partial shading, and hybrid-collaborative methods offer stronger overall potential under complex operating conditions. Overall, the selection of an MPPT method should be made in accordance with specific operating conditions, control objectives, and engineering constraints

Keywords

photovoltaic systems; maximum power point tracking; intelligent MPPT; performance comparison; application analysis; partial shading; engineering applicability

1. Introduction

With the development of new energy technologies, solar photovoltaic (PV) power generation has attracted extensive attention because of its cleanliness and renewability. In PV systems, the output power of PV modules is strongly influenced by solar irradiance, ambient temperature, and partial shading, causing the maximum power point (MPP) to shift continuously with external operating conditions. Therefore, maximum power point tracking (MPPT) plays an important role in improving the energy conversion efficiency and operational performance of PV systems[1-2]. Conventional MPPT methods, such as perturb and observe (P&O) and incremental conductance (INC), have been widely adopted because of their simple structure and ease of implementation. However, under complex conditions such as dynamic irradiance variation and partial shading, these methods are prone to insufficient tracking speed, relatively large steady-state oscillations, and convergence to local optima. To overcome these limitations, intelligent techniques, including fuzzy logic, neural networks, swarm-based optimization, and multi-method integration, have gradually been introduced into MPPT control, thereby promoting the continuous development of intelligent MPPT algorithms[1-4]. In recent years, intelligent MPPT algorithms have evolved into several technical routes, including rule-based control, prediction-learning, search-optimization, and hybrid-collaborative methods. Existing review studies have mainly focused on method classification and principle description, whereas a comprehensive comparison of different algorithms in terms of performance characteristics, adaptability to application scenarios, and development trends still deserves further summarization[2-4]. Accordingly, this paper reviews recent advances in intelligent MPPT methods for photovoltaic systems from the perspectives of algorithm classification, performance comparison, and application analysis, and further summarizes their future development trends.

2 Classification and Basic Principles of Intelligent MPPT Algorithms

2.1 Rule-Based Control MPPT Methods

Rule-based control MPPT methods regulate the operating point of photovoltaic systems according to predefined control rules and are characterized by explicit control logic, simple structure, and relatively low implementation difficulty[3-4]. Among them, fuzzy logic control is a representative approach. This type of method does not rely on an accurate mathematical model and exhibits a certain level of adaptability to system nonlinearity and parameter uncertainty; therefore, it is often used to improve dynamic response and reduce steady-state oscillations[3][5-6]. Overall, rule-based control methods are structurally simple and relatively easy to implement in real time, although their adaptability under complex operating conditions is usually limited[3-6].

2.2 Prediction-Learning MPPT Methods

Prediction-learning MPPT methods establish a mapping between operating states and the maximum power point based on sample data, thereby enabling rapid estimation of the target operating point[7-8][26]. Artificial neural networks (ANNs) are among the earliest methods applied in this category, while RNN-, LSTM-, and GRU-based methods further enhance the utilization of temporal information and therefore usually show promising dynamic response capability under rapidly varying irradiance and temperature conditions[9][11-12][28]. The main advantage of this category lies in its ability to learn complex nonlinear relationships and reduce energy loss caused by repeated perturbations. Its limitations are that performance depends strongly on the quality of training data and model structure, and the complexity of model training and deployment is relatively high[7][11-12].

2.3 Search-Optimization MPPT Methods

Search-optimization MPPT methods mainly rely on swarm intelligence optimization or heuristic search strategies to perform global optimization over candidate operating points, so as to obtain the optimal control variable corresponding to the maximum power point [13-14][29]. Under partial shading conditions, the P-V curve of a photovoltaic array usually exhibits multiple peaks, which requires stronger global search capability. To illustrate this issue more intuitively, Figure 2-1 presents a schematic of the multi-peak P-V curve and the global search process under partial shading.

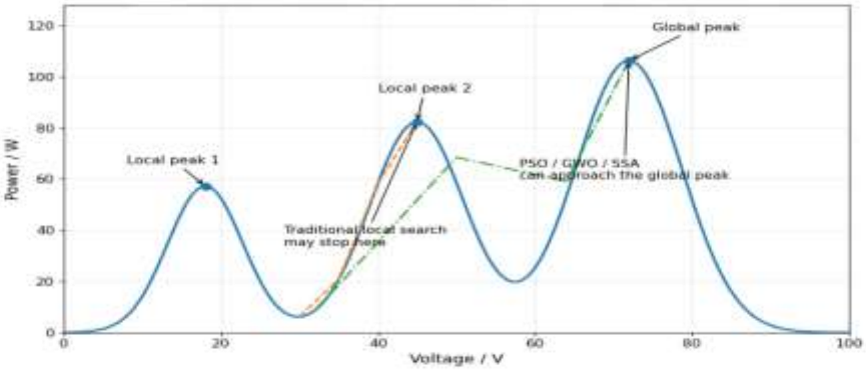


Figure 1:Schematic illustration of the multi-peak P-V curve and global search under partial shading conditions

(The curve and search trajectory in the figure are schematic only and are used to illustrate the difference between local search and global search under partial shading conditions.) As indicated in Figure 2-1, methods such as PSO, GWO, and SSA gradually approach the optimal solution through population updating and usually show clear advantages under partial shading and multi-peak power curve conditions[14-18][31]. However, they also generally require more iterative computation, which imposes higher demands on controller resources and parameter tuning.

2.4 Hybrid-Collaborative MPPT Methods

Hybrid-collaborative MPPT methods combine two or more methods with different principles in order to exploit their respective strengths and compensate for the shortcomings of a single algorithm[19][20-25][32-33]. Their basic idea is usually to employ one method for rapid localization or coarse search and then use another method for fine adjustment or local optimization, so as to achieve a better balance among tracking speed, tracking accuracy, and operational stability. The main advantage of this category lies in its superior overall performance and stronger adaptability under complex operating conditions, whereas its limitation is higher structural complexity and greater difficulty in parameter design and engineering implementation[19-25][32-33].

2.5 Comparison of the Characteristics of Different Methods

Overall, the four types of intelligent MPPT methods differ significantly in terms of underlying principles, control strategies, and implementation pathways, and therefore exhibit different characteristics in tracking speed, tracking accuracy, operational stability, implementation complexity, and application adaptability. Rule-based control methods are structurally simple and relatively easy to implement in real time[3-6]. Prediction-learning methods usually show good predictive and responsive potential in dynamic environments[7-12]. Search-optimization methods possess strong global search capability and are particularly suitable for complex multi-peak operating conditions such as partial shading[13-18]. Hybrid-collaborative methods, through complementary mechanisms, offer greater potential in overall performance, but also introduce higher structural complexity and engineering implementation difficulty[19][22-25]. Therefore, no single type of method is absolutely superior regardless of application context; its suitability depends on specific operating conditions, control objectives, and implementation constraints.

Table 2-1 further summarizes the main characteristics, advantages, limitations, and applicable scenarios of different types of methods.

Table 1:Comparison of the characteristics of different intelligent MPPT methods

Method type	Summary
Rule-based control	FLC and expert-rule methods. Simple structure and good real-time capability, but limited adaptability under complex conditions.
Prediction-learning	ANN, RNN/LSTM/GRU, and RL methods. Good dynamic response and nonlinear mapping capability, but strong dependence on training data and deployment conditions.
Search-optimization	PSO, GWO, and SSA methods. Strong global search capability under multi-peak conditions, but relatively high computational burden.
Hybrid-collaborative	FLC-ANN, FLC-PSO, and P&O-PSO methods. Better overall performance through complementary mechanisms, but higher implementation complexity.

3 Performance Comparison of Intelligent MPPT Algorithms

Because differences exist among published studies in terms of test platforms, operating conditions, and the definitions of evaluation metrics, this paper does not attempt to make simple horizontal comparisons of specific numerical results reported in different works. Instead, different types of intelligent MPPT methods are compared from the perspectives of tracking speed, tracking accuracy, tracking stability, computational complexity, and application adaptability. Specifically, tracking speed focuses on the response rate after operating conditions change; tracking accuracy reflects the degree of convergence to the maximum power point; tracking stability characterizes the smoothness of operation near the maximum power point; and computational complexity and application adaptability further indicate the engineering feasibility of an algorithm under different hardware conditions and operating scenarios.

3.1 Comparison of Tracking Speed

Tracking speed reflects how fast an MPPT algorithm approaches a new maximum power point after operating conditions change and is an important indicator of dynamic performance. Overall, rule-based control methods usually exhibit fast initial responses; prediction-learning methods, relying on data-driven estimation, often show strong potential for rapid tracking in dynamic environments; search-optimization methods usually respond more slowly under rapidly changing conditions because they require iterative optimization; and hybrid-collaborative methods place greater emphasis on balancing rapid localization with subsequent adjustment[3][5-6][7-12][13-18][19][22-25]. Among these methods, temporal modeling approaches such as RNN, LSTM, and GRU are generally more suitable for dynamic irradiance scenarios[9][11-12][28]. In contrast, although search-optimization methods such as PSO, GWO, and SSA tend to have relatively slower initial responses under multi-peak conditions, they still offer advantages from the perspective of effectively reaching the target maximum power point[14-18][30-31].

3.2 Comparison of Tracking Accuracy

Tracking accuracy mainly reflects the degree to which an algorithm converges to the maximum power point and is usually associated with metrics such as steady-state error, MPPT efficiency, and target-point deviation. The accuracy of rule-based control methods mainly depends on control rules and parameter settings, whereas prediction-learning methods can usually achieve better target-point estimation accuracy when training data are sufficient and the model is well matched to the operating conditions[3-4][7-12]. The advantage of search-optimization methods in terms of accuracy is mainly reflected in their ability to identify the global maximum power point under complex operating conditions, especially under partial shading, where they are less likely than local-search methods to remain trapped at local peaks[13-18]. Hybrid-collaborative methods, through the complementarity of different algorithms, usually demonstrate relatively good overall accuracy under complex conditions such as dynamic irradiance and partial shading, although their performance depends on the design of the hybrid structure and the quality of parameter coordination[19][22-25].

3.3 Comparison of Tracking Stability

Tracking stability mainly reflects the fluctuation level and sustained holding capability of an algorithm when operating near the maximum power point. Rule-based control methods usually show relatively good local steady-state smoothness, while prediction-learning methods can also effectively reduce output fluctuations when the model is well adapted, because they reduce the need for continuous perturbation[3][5-6][7-12]. Search-optimization methods may introduce some fluctuations under single-peak conditions because of iterative search, but under multi-peak operating conditions such as partial shading, they usually exhibit better global stability in terms of overall output performance because they are more capable of identifying the true global maximum power point[14-18]. Hybrid-collaborative methods place greater emphasis on balancing dynamic and steady-state performance in complex environments, and can reduce oscillations and improve sustained stable operation through rapid localization followed by fine adjustment[19][22-25].

3.4 Comparison of Complexity and Application Adaptability

Computational complexity and application adaptability are also important aspects in evaluating intelligent MPPT methods. Rule-based control methods usually have clear structures and relatively simple computational procedures, and therefore require fewer controller resources and show good feasibility in engineering implementation[3-6]. Prediction-learning methods usually provide fast outputs during online operation, but require substantial effort in offline training, parameter optimization, and model deployment[7-12]. Search-optimization methods generally require population-based iterations and therefore have relatively high computational complexity, although they show clear advantages under partial shading and multi-peak power curve conditions[13-18]. Hybrid-collaborative methods, because they combine two or more classes of algorithms, usually have the highest complexity, but they also exhibit better overall adaptability under complex operating conditions such as dynamic irradiance, partial shading, and parameter uncertainty[19][22-25][32-33]. Different types of intelligent MPPT methods place emphasis on different aspects of performance and engineering applicability, and the choice of method should therefore be made by jointly considering operating conditions, control objectives, and controller resource constraints. To

ISSN: 3079-6342

provide an overall view of these differences, Table 3-1 summarizes the key performance dimensions and typical application scenarios of different types of methods.

Table 2:Performance comparison of different types of intelligent MPPT methods

Method type	Speed	Accuracy	Stability	Complexity	Typical scenarios
Rule-based control	Fast	Moderate	Good	Low	Resource-constrained systems
Prediction-learning	Fast	High	Good	Medium-High	Dynamic irradiance conditions
Search-optimization	Moderate*	High*	Good*	High	Partial shading conditions
Hybrid-collaborative	Fast	High	Good	High	High-performance complex scenarios

Note: Particularly under complex multi-peak operating conditions.

As shown in Table 3-1, no type of intelligent MPPT method is absolutely superior regardless of scenario. Its suitability depends on a comprehensive trade-off between performance requirements and engineering constraints.

4 Application Analysis of Intelligent MPPT Algorithms

4.1 Common Sources of Differences in the Literature

In studies on intelligent MPPT algorithms, differences in experimental results and performance conclusions are frequently observed. Such differences arise not only from the algorithms themselves, but also from factors such as photovoltaic system models, validation platforms, test conditions, and the definitions of evaluation metrics. Variations in system scale, device parameters, control periods, and simulation or experimental platforms may lead to different performances of the same algorithm across studies. Meanwhile, test conditions can also significantly affect comparative results. In particular, under partial shading conditions, different studies often adopt different shading patterns and irradiance distributions[29], and algorithm performance therefore tends to be highly scenario-dependent. In addition, the definitions and statistical criteria for tracking time, MPPT efficiency, steady-state error, and power fluctuation are not always consistent across studies. For these reasons, the results reported in the literature are more suitable for trend identification and characteristic summarization than for direct horizontal ranking without considering the specific context.

4.2 Performance Under Dynamic Irradiance Conditions

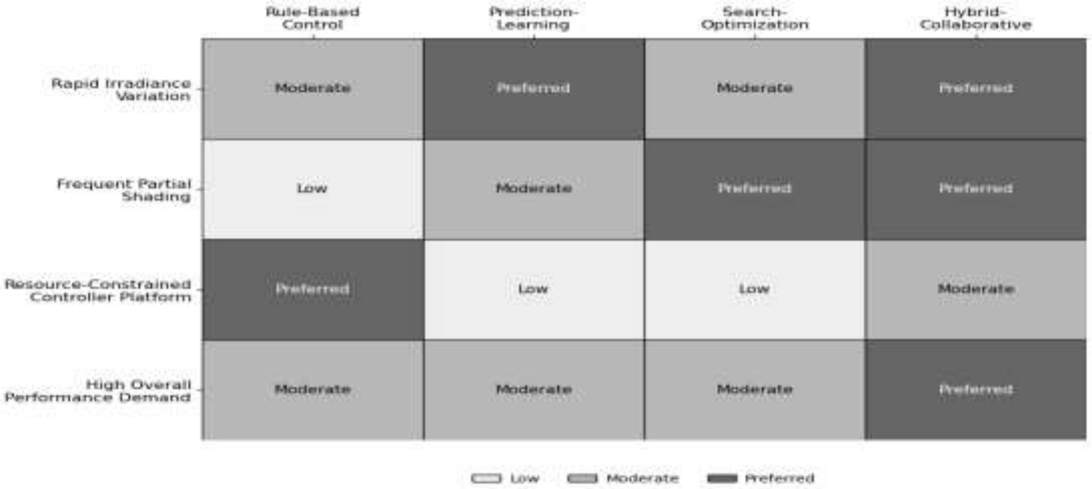
Dynamic irradiance conditions constitute an important scenario for evaluating the practical applicability of MPPT algorithms. When solar irradiance changes rapidly, the maximum power point shifts accordingly, and this scenario therefore mainly concerns response speed, tracking accuracy, and operational stability. Overall, rule-based control methods usually exhibit fast initial responses; fuzzy logic control, for example, often shows better dynamic response than conventional fixed-step methods under abrupt irradiance changes[3][5-6], although its performance depends strongly on control rules and parameter settings. Prediction-learning methods are generally more suitable for this scenario, because they can estimate a new target operating point rapidly through data-driven learning[7-12]. In particular, temporal modeling methods such as RNN, LSTM, and GRU often demonstrate good response capability and tracking accuracy under rapidly fluctuating irradiance conditions[9][11-12], although their effectiveness still depends on training data quality and model generalization capability. By contrast, search-optimization methods usually require multiple iterations to update candidate solutions and therefore are more likely to suffer from response lag under rapid irradiance changes[13-18]. Hybrid-collaborative methods, on the other hand, can balance response speed and stability through a “fast localization + subsequent adjustment” strategy[19][22-25]. Therefore, under dynamic irradiance conditions, prediction-learning and hybrid-collaborative methods generally show stronger application potential, whereas rule-based control methods still retain practical value in resource-constrained systems.

4.3 Performance of Different Algorithms Under Partial Shading Conditions

Partial shading is a typical complex operating condition in photovoltaic systems. When PV modules are subjected to non-uniform irradiance, the array P-V curve usually exhibits multiple peaks[29]. Under such conditions, an algorithm must not only track the operating point but also avoid being trapped at local optima, making global search capability particularly important. In this scenario, rule-based control methods remain essentially local regulation approaches. When multiple peaks appear on the power curve, these methods often have difficulty distinguishing between local maximum power points and the global maximum power point, and are therefore more likely to remain trapped in a locally optimal region[3-4]. The performance of prediction-learning methods depends strongly on the coverage of the training data. If the samples adequately cover different shading patterns and irradiance distributions, these methods can improve tracking capability under multi-peak conditions to some extent[7-12]; however, when actual operating conditions deviate from the range represented in the training data, their ability to identify the global maximum power point may deteriorate. In contrast, search-optimization methods perform iterative population-based search over the entire candidate space and are therefore less likely to remain trapped near local peaks, usually making them more capable of approaching the global maximum power point[13-18]. Hybrid-collaborative methods further enhance overall performance under complex operating conditions by combining prediction, local adjustment, and global search mechanisms, thereby balancing global optimization with subsequent regulation[19][22-25]. Therefore, under frequent partial shading and highly variable operating conditions, search-optimization and hybrid-collaborative methods generally demonstrate greater application potential.

4.4 Method Selection Recommendations for Typical Scenarios

The above analysis indicates that different intelligent MPPT methods exhibit distinct applicability across typical operating scenarios, and practical method selection should therefore be based on a comprehensive consideration of operating conditions, control objectives, and hardware resource constraints. For scenarios with significant dynamic irradiance variation, system performance is mainly determined by response speed, dynamic tracking capability, and recovery performance; in such cases, prediction-learning methods usually show good potential, while hybrid-collaborative methods are more advantageous in balancing dynamic performance and subsequent steady-state performance[28][32]. For scenarios with frequent partial shading, MPPT must deal with multi-peak P-V curves and the risk of local optima, making global search capability the key consideration in method selection. Under such conditions, search-optimization methods are generally more suitable for global maximum power point tracking, while hybrid-collaborative methods often provide better overall potential when both dynamic response and steady-state performance are required[29][31][33]. By contrast, resource-constrained control platforms place greater emphasis on computational burden, real-time implementation difficulty, and implementation cost. In such cases, rule-based control methods are generally more feasible from an engineering perspective, whereas systems with some degree of data support and lightweight model capability may also consider relatively simple prediction-learning methods. In addition, for complex engineering scenarios requiring high tracking speed, tracking accuracy, and operational stability simultaneously, a single method is often insufficient to satisfy all performance requirements. Hybrid-collaborative methods are usually more favorable for achieving overall performance optimization, especially in scenarios where dynamic irradiance variation and partial shading may occur alternately and where high overall performance is required[32-33]. Therefore, method selection should not be made in an absolute manner without considering the specific application background, but rather through targeted decisions based on scenario characteristics and engineering constraints. The adaptation of different intelligent MPPT methods under typical application scenarios is illustrated in Figure 4-1.



	Rule-Based Control	Prediction-Learning	Search-Optimization	Hybrid-Collaborative
Rapid Irradiance Variation	Moderate	Preferred	Moderate	Preferred
Frequent Partial Shading	Low	Moderate	Preferred	Preferred
Resource-Constrained Controller Platform	Preferred	Low	Low	Moderate
High Overall Performance Demand	Moderate	Moderate	Moderate	Preferred

Figure 2:Schematic illustration of the adaptation of intelligent MPPT methods under different application scenarios

It should be noted that the adaptation relationship shown in Figure 4-1 is qualitative rather than absolute, and the final method selection should still be comprehensively determined according to system scale, control objectives, operating conditions, and hardware resource constraints.

5 Research Challenges and Development Trends

5.1 Main Challenges Faced by Current Intelligent MPPT Algorithms

Although intelligent MPPT algorithms have shown considerable application potential in photovoltaic systems, current research still faces several common challenges. First, a single algorithm usually cannot simultaneously balance tracking speed, tracking accuracy, operational stability, and implementation complexity, and each type of method exhibits both clear advantages and evident limitations. Second, under the combined influence of dynamic irradiance, partial shading, temperature fluctuation, and load variation, the stability and adaptability of existing methods still need further improvement, and problems such as response lag, mistracking, or increased output fluctuation may still occur[29][31][33]. In addition, engineering implementation remains an important constraint on practical deployment. Although some methods perform well in simulations or experiments, they often face challenges such as high computational burden, complex parameter tuning, and insufficient real-time capability when implemented on resource-constrained controller platforms[28][33].

5.2 Development Trends and Research Implications of Intelligent MPPT Algorithms

According to current research progress, the development of intelligent MPPT algorithms is mainly reflected in hybrid collaboration, lightweight and real-time implementation, enhanced scenario adaptability, and deeper integration of data-driven and control-based methods. Hybrid collaboration will remain an important direction[32-33]. Since a single algorithm can hardly achieve a comprehensive balance among speed, accuracy, stability, and complexity, a reasonable combination of prediction, search, rule-based control, and local adjustment mechanisms is expected to achieve better overall performance under complex operating conditions[30][32-33]. At the same time, lightweight and real-time implementation will become key requirements for the engineering application of intelligent MPPT algorithms. Future research should focus not only on performance improvement, but also on model size, computational burden, parameter tuning difficulty, and online implementation capability. As application scenarios continue to expand, the adaptability of algorithms to complex operating environments, such as dynamic irradiance variation, partial shading, temperature fluctuation, and load variation, will also need to be continuously enhanced [29]. In addition, the integration of data-driven and control-based methods will continue to deepen[26-28][32]. Prediction-learning methods are advantageous in state estimation and trend prediction, whereas conventional control and optimization-based search methods are effective in local adjustment and global optimization. Their combination is expected to further improve the overall performance of MPPT algorithms. Future studies should also pay greater attention to consistency in algorithm evaluation and application-oriented analysis, and should strengthen the unified description of typical operating conditions and evaluation criteria so as to improve the comparability and reference value of research results[29]. Overall, the development of intelligent MPPT algorithms should not be limited to improving a single performance index, but should place greater emphasis on balancing overall performance with engineering feasibility.

6 Conclusions

This paper reviews recent advances in intelligent MPPT algorithms for photovoltaic systems. The related methods are categorized into four types, namely rule-based control, prediction-learning, search-optimization, and hybrid-collaborative methods, and are analyzed from the perspectives of performance comparison and application scenarios. Overall, different types of intelligent MPPT methods have their own strengths and limitations, and their applicability depends on specific operating conditions, control objectives, and hardware constraints. Rule-based control methods are simple to implement, prediction-learning methods are more suitable for dynamic environments, search-optimization methods are more appropriate for complex multi-peak operating conditions, and hybrid-collaborative methods show greater potential in overall performance. Future research may further focus on hybrid collaboration, lightweight implementation, real-time capability, and enhanced scenario adaptability, while placing greater emphasis on engineering feasibility and application reliability of intelligent MPPT algorithms.

References

[1] Ram JP, Babu TS, Rajasekar N. A comprehensive review on solar PV maximum power point tracking techniques. Renew Sustain Energy Rev, 2017, 67: 826-847. https://doi.org/10.1016/j.rser.2016.09.076

[2] Ramli MAM, Twaha S, Ishaque K, et al. A review on maximum power point tracking for photovoltaic systems with and without shading conditions. Renew Sustain Energy Rev, 2017, 67: 144-159. https://doi.org/10.1016/j.rser.2016.09.013

[3] Mellit A, Kalogirou SA. 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, 2014, 70: 1-21. https://doi.org/10.1016/j.energy.2014.03.102

[4] Kermadi M, Berkouk EM. Artificial intelligence-based maximum power point tracking controllers for photovoltaic systems: Comparative study. Renew Sustain Energy Rev, 2017, 69: 369-386. https://doi.org/10.1016/j.rser.2016.11.125

[5] Guenounou O, Dahhou B, Chabour F. Adaptive fuzzy controller based MPPT for photovoltaic systems. Energy Convers Manag, 2014, 78: 843-850. https://doi.org/10.1016/j.enconman.2013.07.093

[6] Napole C, Derbeli M, Barambones O. Fuzzy logic approach for maximum power point tracking implemented in a real time photovoltaic system. Appl Sci, 2021, 11(13): 5927. https://doi.org/10.3390/app11135927

[7] Villegas-Mier CG, Rodriguez-Resendiz J, Álvarez-Alvarado JM, et al. Artificial neural networks in MPPT algorithms for optimization of photovoltaic power systems: A review. Micromachines, 2021, 12(10): 1260. https://doi.org/10.3390/mi12101260

[8] Ourici A, Abderaouf B. Maximum power point tracking in a photovoltaic system based on artificial neurons. Indian J Sci Technol, 2023, 16(23): 1760-1767. https://doi.org/10.17485/IJST/v16i23.648

[9] Robles Algarín C, Sevilla Hernández D, Restrepo Leal D. A low-cost maximum power point tracking system based on neural network inverse model controller. Electronics, 2018, 7(1): 4. https://doi.org/10.3390/electronics7010004

[10] Tsai MF, Tseng CS, Hung KT, et al. A novel DSP-based MPPT control design for photovoltaic systems using neural network compensator. Energies, 2021, 14(11): 3260. https://doi.org/10.3390/en14113260

[11] Bandara A, Ratnayake K, Dissanayake R, et al. LSTM-based MPPT algorithm for efficient energy

harvesting of a solar PV system under different operating conditions. Electronics, 2024, 13(24): 4875. https://doi.org/10.3390/electronics13244875

[12] Salman D, Elmi YK, Mohamed AS, et al. Forecasting maximum power point in solar panels using CNN-GRU. SSRG Int J Electr Electron Eng, 2024, 11(7): 215-227. https://doi.org/10.14445/23488379/IJEEE-V11I7P119

[13] Rezk H, Fathy A, Abdelaziz AY. A comparison of different global MPPT techniques based on meta-heuristic algorithms for photovoltaic system subjected to partial shading conditions. Renew Sustain Energy Rev, 2017, 74: 377-386. https://doi.org/10.1016/j.rser.2017.02.051

[14] Ishaque K, Salam Z, Shamsudin A, et al. A direct control based maximum power point tracking method for photovoltaic system under partial shading conditions using particle swarm optimization algorithm. Appl Energy, 2012, 99: 414-422. https://doi.org/10.1016/j.apenergy.2012.05.026

[15] Cherukuri SK, Rayapudi SR. Enhanced grey wolf optimizer based MPPT algorithm of PV system under partial shaded condition. Int J Renew Energy Dev, 2017, 6(3): 203-212. https://doi.org/10.14710/ijred.6.3.203-212

[16] Silaa MY, Derouich A, El Ghzizal A, et al. A new MPPT-based extended grey wolf optimizer for stand-alone PV system: A performance evaluation versus four smart MPPT techniques in diverse scenarios. Designs, 2023, 8(6): 142. https://doi.org/10.3390/designs8060142

[17] Zafar MH, Khan UA, Khan NM. A sparrow search optimization algorithm based MPPT control of PV system to harvest energy under uniform and non-uniform irradiance. In: 2021 International Conference on Emerging Power Technologies (ICEPT); 2021; Piscataway, NJ: IEEE. p. 1-6. https://doi.org/10.1109/ICEPT51706.2021.9435504

[18] Wan Y, Mao M, Zhou L, et al. A novel nature-inspired maximum power point tracking controller based on SSA-GWO algorithm for partially shaded photovoltaic systems. Electronics, 2019, 8(6): 680. https://doi.org/10.3390/electronics8060680

[19] Batarseh MG, Za'ter ME, Harb AM. Hybrid maximum power point tracking techniques: A comparative survey, suggested classification and uninvestigated combinations. Sol Energy, 2018, 169: 535-555. https://doi.org/10.1016/j.solener.2018.05.014

[20] Liu H, Hu H, Wang H, et al. Hybrid maximum power extraction methods for photovoltaic systems under partial shading condition: A review. Energies, 2023, 16(15): 5665. https://doi.org/10.3390/en16155665

[21] Rezvani A, Gandomkar M, Izadbakhsh M, et al. Modeling and control of grid connected intelligent hybrid photovoltaic system using GA and ANFIS. Sol Energy, 2016, 139: 232-247. https://doi.org/10.1016/j.solener.2016.09.027

[22] Li Y, Yang W, Xu D, et al. Analysis and enhancement of PV efficiency with hybrid fuzzy logic controller and modified shuffled frog leaping algorithm under partial shading conditions. J Clean Prod, 2020, 262: 121241. https://doi.org/10.1016/j.jclepro.2020.121241

[23] Kumar D, Chauhan YK, Pandey AS, et al. A novel hybrid MPPT approach for solar PV systems using particle-swarm-optimization-trained machine learning and flying squirrel search optimization. Sustainability, 2023, 15(6): 5575. https://doi.org/10.3390/su15065575

[24] Timur O, Aydemir MT. Design and analysis of a hybrid MPPT method for PV systems based on P&O and PSO. Appl Sci, 2025, 15(13): 7386. https://doi.org/10.3390/app15137386

[25] Zhang X, Zhao B, Cui H, et al. A hybrid global maximum power point tracking control method based on particle swarm optimization and perturbation and observation. Electr Power Syst Res, 2025, 241: 111967. https://doi.org/10.1016/j.epsr.2025.111967

[26] Kofinas P, Doltsinis S, Dounis AI, et al. A reinforcement learning approach for MPPT control method of photovoltaic sources. Renew Energy, 2017, 108: 461-473. https://doi.org/10.1016/j.renene.2017.03.008

ISSN: 3079-6342

[27] Phan BC, Lai YC, Lin CE. A deep reinforcement learning-based MPPT control for PV systems under partial shading condition. Sensors, 2020, 20(11): 3039. https://doi.org/10.3390/s20113039

[28] Roy B, Adhikari S, Datta S, et al. Harnessing deep learning for enhanced MPPT in solar PV systems: An LSTM approach using real-world data. Electricity, 2024, 5(4): 843-860. https://doi.org/10.3390/electricity5040042

[29] Eltamaly AM. A novel benchmark shading pattern for PV maximum power point trackers evaluation. Sol Energy, 2023, 263: 111897. https://doi.org/10.1016/j.solener.2023.111897

[30] Wang H, Li L, Ye H, et al. Enhancing MPPT efficiency in PV systems under partial shading: A hybrid POA&PO approach for rapid and accurate energy harvesting. Int J Electr Power Energy Syst, 2024, 162: 110260. https://doi.org/10.1016/j.ijepes.2024.110260

[31] Mohamed RG, Hasanien HM, Ebrahim MA. Global MPPT controllers for enhancing dynamic performance of photovoltaic systems under partial shading condition. Prime, 2024: 100638. https://doi.org/10.1016/j.prime.2024.100638

[32] Bisht R, Sikander A, Sharma A, et al. A new hybrid framework for the MPPT of solar PV systems under partial shaded scenarios. Sustainability, 2025, 17(12): 5285. https://doi.org/10.3390/su17125285

[33] Siddique MAB, Zhao D, Rehman AU, et al. An adapted model predictive control MPPT for validation of optimum GMPP tracking under partial shading conditions. Sci Rep, 2024, 14: 9462. https://doi.org/10.1038/s41598-024-59304-z