ISSN: 2583-5637 (Online)

International journal of Inventive Research in Science and Technology

Volume 4 Issue 10 October 2025

Review Paper 2

Advancements in Maximum Power Point Tracking: A Review of Hybrid Genetic Algorithm-ANFIS Approaches for Photovoltaic Systems

Geetanjali sen[1], Devendra Sharma[2], M.S. Dash[3], Vasant Acharya[4]

Geetsen1825@gmail.com[1], devendrasharma798@gmail.com[2]
malaya_rec@rediffmail.com[2],vasantacharyatitc@gmail.com[3]

[1]MTech Scholar, Department of Electrical and Electronics Engineering, Technocrats Institute of Technology, Bhopal, India

[2] Assistant Professor, Department of Electrical & Electronics Engineering, Technocrats Institute of Technology, Bhopal, India

[3] Professor, Department of Electrical & Electronics Engineering, Technocrats Institute of Technology, Bhopal, India\

[4] Assistant Professor, Department of Electrical & Electronics Engineering, Technocrats Institute of Technology, Bhopal, India

Abstract

This paper provides a comprehensive analysis of the hybrid Genetic Algorithm (GA) and Adaptive Neuro-Fuzzy Inference System (ANFIS) approach for Maximum Power Point Tracking (MPPT) in photovoltaic (PV) systems. The inherent non-linear power-voltage (P−V) characteristics of PV modules, exacerbated by fluctuating environmental conditions and partial shading, necessitate advanced control strategies to maximize energy extraction. While traditional methods like Perturb and Observe (P&O) and Incremental Conductance (INC) are simple and widely used, they exhibit significant performance limitations, including slow tracking, power oscillations, and susceptibility to local maxima. This review demonstrates that hybrid AI-based controllers, particularly the GA-ANFIS method, offer a superior solution by combining the learning and adaptive capabilities of ANFIS with the robust global optimization power of GA. This synergistic approach demonstrably enhances energy harvesting efficiency, tracking speed, and system stability. The paper discusses the core methodology, key performance advantages, current implementation challenges, and outlines critical future research directions, positioning GA-ANFIS as a cornerstone for next-generation smart PV systems and microgrids.

Keywords: Photovoltaic Systems, Maximum Power Point Tracking (MPPT), Genetic Algorithm (GA), Adaptive Neuro-Fuzzy Inference System (ANFIS), Hybrid Control, Partial Shading.

I. Introduction

1.1. The Critical Role of MPPT in PV Systems

Photovoltaic (PV) systems are becoming an increasingly popular choice for decentralized power generation due to their high efficiency and environmental friendliness. However, the output power of a PV module is highly dependent on environmental factors, specifically solar irradiance and ambient temperature. This dependency results in a non-linear relationship between the module's voltage, current, and power, which means there is a unique operating point—the Maximum Power Point (MPP)—at which the module can deliver its peak power. Under ideal, uniform irradiance, the power-voltage curve has a single peak. In contrast, under partial shading conditions (PSC) caused by clouds, trees, or buildings, the curve can have multiple local maxima, making the identification of the true Global Maximum Power Point (GMPP) a complex task.

Maximum Power Point Tracking (MPPT) is an essential control technique employed in PV systems to continuously adjust the operating parameters, typically through a DC-DC converter, to ensure that the PV array consistently operates at its MPP. Without an effective MPPT algorithm, PV systems would experience substantial energy loss and operate at suboptimal efficiency, undermining their economic viability and overall performance.

1.2. Evolution of MPPT Algorithms: From Heuristics to Intelligence

The evolution of MPPT algorithms reflects a progression from simple, heuristic approaches to complex, intelligent solutions aimed at overcoming the limitations of their predecessors. Early and conventional methods, such as Perturb and Observe (P&O) and Incremental Conductance (INC), are favored for their ease of design and implementation and their low hardware cost. However, these algorithms are based on local search strategies, and their performance is compromised in dynamic environments. The need for more robust and efficient solutions, particularly under the complex conditions of partial shading, has driven the development of intelligent and metaheuristic algorithms. These include those based on Artificial Neural Networks (ANN), Fuzzy Logic (FL), Particle Swarm Optimization (PSO), and Genetic Algorithms (GA), which leverage computational intelligence to adapt to uncertain and rapidly changing conditions. This progression highlights a fundamental causal relationship: as PV system deployment has expanded into real-world settings with highly variable conditions, the limitations of simple, local-search algorithms have become apparent, creating a clear demand for intelligent, global-search-capable solutions.

1.3. Objective of the Review Paper

This paper provides an in-depth review of the hybrid GA-ANFIS approach, a cutting-edge solution that addresses the key limitations of both conventional and single-approach AI-based MPPT methods. We will dissect the core methodology, analyze its proven advantages, discuss the challenges of its implementation, and identify critical areas for future research. This analysis aims to serve as a definitive resource for researchers and engineers in the field, providing a comprehensive understanding of how this hybrid control strategy advances the performance and reliability of modern PV systems.

II. Literature Review: A Comparative Analysis of MPPT Techniques

2.1. Conventional MPPT Methods and Their Limitations

The most prevalent conventional MPPT algorithms are P&O and INC. The P&O method operates by periodically perturbing the PV array's operating voltage and observing the effect on power output. If the perturbation leads to an increase in power, the algorithm continues in that direction; otherwise, it reverses. While simple to implement, P&O is known for its oscillations

ISSN: 2583-5637 (Online)

International journal of Inventive Research in Science and Technology

Volume 4 Issue 10 October 2025

around the MPP in steady-state conditions, which results in energy loss. Furthermore, it exhibits slow tracking under rapidly changing irradiance, often failing to keep up with dynamic weather patterns.

The INC algorithm improves upon P&O by using the derivative of power with respect to voltage (dP/dV) to determine the MPP. When dP/dV is zero, the MPP has been reached. This method offers a more accurate and reliable performance, especially under changing conditions, and a faster response time than P&O. However, both P&O and INC, being local-search algorithms, are susceptible to getting trapped in local maxima under partial shading, leading to significant energy yield degradation.

2.2. Single-Approach AI Methods: Advantages and Inherent Flaws

The limitations of traditional MPPT methods motivated the exploration of intelligent algorithms. Artificial Neural Networks (ANNs) have shown superior dynamic adaptability, particularly under rapid environmental changes, compared to conventional techniques. However, the performance of an ANN is highly dependent on its training method and requires a large amount of training data to ensure accuracy. A notable drawback is that an ANN trained for a specific PV system is often not reusable for another, and periodic re-tuning is required as the system ages.

Fuzzy Logic (FL) controllers also demonstrate better performance than traditional methods in a variety of weather conditions. A primary challenge, however, is the complex and time-consuming manual design of the membership functions and fuzzy rules. The precision of the entire system is highly dependent on the quality of this design, and any manual flaw can negatively affect the output.

2.3. Hybrid AI-Based Controllers: The Rise of Synergy

The limitations of single-approach AI methods spurred the development of hybrid systems that combine the strengths of multiple algorithms. The Adaptive Neuro-Fuzzy Inference System (ANFIS) is a powerful hybrid framework that merges the adaptive learning capabilities of neural

ISSN: 2583-5637 (Online)
International journal of Inventive Research in Science and Technology
Volume 4 Issue 10 October 2025

networks with the rule-based logic of fuzzy systems. This combination allows ANFIS to automatically learn and design its membership functions and rules from data, eliminating the complex manual process of traditional fuzzy controllers.

To further enhance performance and address the complexity of global optimization, metaheuristic algorithms like Particle Swarm Optimization (PSO) and Genetic Algorithms (GA) are used to train and fine-tune the ANFIS parameters offline. This synergy results in a controller that is not only intelligent and self-adaptive but also capable of robust global search, allowing it to efficiently identify the GMPP under complex shading scenarios. The ability of these hybrid algorithms to perform an offline global search for the optimal operating parameters is the fundamental reason for their superiority over traditional algorithms, which rely on reactive, local-search strategies.

Table 1: Comparative Performance of MPPT Algorithms

Algorithm	Key Advantage	Key Disadvantage	Tracking Speed	Oscillation at MPP	Handling of Partial Shading	Computational Complexity	Implementation Cost
P&O	Simple, easy to implement	Oscillations, susceptible to local maxima	Low to Medium	High	Poor	Low	Low
INC	More accurate than P&O	More complex than P&O, susceptible to local maxima	Medium to High	Low	Poor	Medium	Medium
ANN	Highly adaptive,	Requires extensive	High	Low	Limited	High	High

Algorithm	Key Advantage	Key Disadvantage	Tracking Speed	Oscillation at MPP	Handling of Partial Shading	Computational Complexity	Implementation Cost
	fast response	training data, not reusable					
Fuzzy Logic	Good performance in varying conditions	Complex manual rule design, prone to human error	High	Low	Limited	Medium	Medium
GA-ANFIS	High efficiency, minimal oscillation, GMPP tracking	Computationally complex, costly	Very High	Very Low	Excellent	Very High	Very High
PSO-ANFIS	High efficiency, minimal oscillation, GMPP tracking	Computationally complex, costly	Very High	Very Low	Excellent	Very High	Very High

ISSN: 2583-5637 (Online)
International journal of Inventive Research in Science and Technology
Volume 4 Issue 10 October 2025

III. The GA-ANFIS Methodology for MPPT

3.1. The Architecture of ANFIS

The Adaptive Neuro-Fuzzy Inference System (ANFIS) is a data-driven approach that combines the learning capabilities of a neural network with the reasoning power of a fuzzy inference system. It is an implementation of Takagi-Sugeno "if-then" rules within a network structure that consists of five layers: an input layer, a fuzzyfication layer, a normalization layer, an adaptive fuzzy layer, and an output layer. The key advantage of ANFIS is its ability to automatically design and tune its membership functions and rules based on training data, thus eliminating the complex and often imprecise process of manual design that plagues traditional fuzzy controllers. The inputs for the ANFIS MPPT controller are typically environmental parameters such as solar irradiance and temperature, or electrical parameters like PV panel voltage and current.

3.2. Role of the Genetic Algorithm in Offline Optimization

The core of the hybrid GA-ANFIS methodology is the use of a Genetic Algorithm (GA) as an offline training tool. In this two-phase approach, the GA's primary function is to optimize the antecedent and consequent parameters of the ANFIS model. This process circumvents the need for complex, manual tuning and leverages the GA's robust capability for global search to find the optimal set of parameters for the ANFIS.

The GA-based optimization process involves several steps: an objective function is defined, which aims to minimize the error between the ANFIS output and the ideal MPP. An initial population of ANFIS parameter sets is then created, and this population is evolved over multiple generations using genetic operators such as selection, crossover, and mutation. This powerful search mechanism allows the GA to explore the vast parameter space and converge on a highly effective solution. Once the training is complete, the optimized ANFIS model is ready for deployment in the real-time control system.

ISSN: 2583-5637 (Online)

International journal of Inventive Research in Science and Technology

Volume 4 Issue 10 October 2025

3.3. System Implementation and Control Loop

The GA-ANFIS controller is integrated into the PV system via a DC-DC boost converter. The control loop operates in two distinct phases, as outlined in the table below. The offline phase involves the GA-based training, where the ANFIS model learns the optimal relationship between its inputs (e.g., irradiance and temperature) and the output (e.g., the duty cycle of the boost converter's Pulse Width Modulation, or PWM, signal). During the online phase, the trained ANFIS model is used for real-time MPPT operation. It takes live input data from the PV system and generates a precise duty cycle signal to drive the PWM generator, which in turn adjusts the operating point of the PV array to track the MPP. This two-phase approach creates a synergistic model where the global optimization power of GA is perfectly complemented by the fast-response, adaptive inference of ANFIS.

Table 2: GA-ANFIS MPPT: A Two-Phase Methodology

Phase	Objective	Key Steps	Algorithms Involved	Output	Purpose
1. Offline Optimization	To find the optimal parameters for the ANFIS model.	1. Define objective function. 2. Generate initial population of ANFIS parameters. 3. Use genetic operators (selection, crossover, mutation) to evolve population.	Genetic Algorithm (GA)	A trained and optimized ANFIS model.	To address the complexity of parameter tuning and provide a robust, globally optimized model before real-time operation.

Phase	Objective	Key Steps	Algorithms Involved	Output	Purpose
2. Online Operation	To track the MPP in real time under dynamic conditions.	1. Receive inputs (e.g., irradiance, temperature, V, I). 2. Process inputs through the trained ANFIS model. 3. Generate a control signal (e.g., PWM duty cycle).	Adaptive Neuro-Fuzzy Inference System (ANFIS)	A real-time control signal for the DC-DC converter.	To enable rapid, accurate, and adaptive tracking of the MPP with minimal oscillation.

IV. Key Advantages of the GA-ANFIS Approach

4.1. Superior Tracking Speed and Energy Extraction Efficiency

The hybrid GA-ANFIS controller's primary advantage lies in its ability to achieve significantly higher tracking speed and energy efficiency compared to conventional methods. The adaptive nature of the ANFIS model, refined through the GA's robust training, allows for a rapid response to abrupt changes in environmental conditions. The GA-ANFIS-MPPT P&O algorithm, for instance, can adaptively adjust the perturbation step size, enabling the power to quickly reach a new maximum value when ambient temperature and illuminance vary. Simulation results for a similar hybrid approach (ANFIS-PSO) demonstrate a remarkable MPPT efficiency of 99.2% under stable irradiance and 98.7% under dynamic conditions, a performance that substantially outperforms traditional algorithms. Similarly, a comparative assessment showed that a PSO-ANFIS controller consistently provided a higher power output at every measured interval than the P&O method, underscoring the effectiveness of the hybrid approach in maximizing energy extraction.

4.2. Reduced Oscillation and Enhanced Stability

A major drawback of traditional P&O and INC methods is their tendency to cause constant oscillations around the MPP in a steady state, which leads to energy loss and power quality issues. In contrast, the GA-ANFIS approach demonstrably reduces these oscillations across the entire working point of the MPPT. This leads to a smoother, more stable power output and significantly enhances the quality of the boost converter's output voltage. This improvement is particularly important for grid-connected PV systems, as it directly reduces the Total Harmonic Distortion (THD) and ensures compliance with grid standards. The reduction in harmonics and voltage deviations makes the PV system a more reliable and stable energy source, preventing it from driving the distribution system into a "risky operating zone".

4.3. Robustness Against Partial Shading Conditions (PSC)

Partial shading creates a complex, multi-peaked power-voltage curve where traditional algorithms, being local-search-based, are highly likely to get trapped at a sub-optimal local maximum, resulting in significant energy loss. The GA-ANFIS approach directly addresses this critical limitation. By using a GA in its offline training phase, the algorithm can perform a global search of the solution space, identifying the true Global Maximum Power Point (GMPP). This capability makes the hybrid GA-ANFIS controller exceptionally robust and reliable under complex shading scenarios, a fundamental advantage over conventional methods that are unable to find the global optimum. The algorithm’s ability to efficiently identify the GMPP is a key enabler for high energy harvesting capabilities in real-world, dynamic environments.

V. Recent Challenges and Future Directions

5.1. Implementation Challenges and Limitations

Despite their superior performance, hybrid algorithms like GA-ANFIS face several practical challenges. The most significant is computational complexity and cost. The metaheuristic optimization phase, in particular, can be computationally intensive and may require powerful hardware, which can increase the overall cost of the controller. The training process can also be time-consuming, necessitating offline optimization before deployment. Furthermore, while GA-ANFIS is a significant improvement over traditional methods, research suggests that other hybrid approaches, such as PSO-ANFIS, may offer even better performance with less error in some scenarios. This introduces a trade-off between performance, cost, and complexity that designers must consider. Additionally, AI-based controllers rely on robust data processing for training and continuous adaptation, and new challenges have been observed in managing the large datasets required and maintaining the models' performance as the system ages.

5.2. Integration into Smart Grids and Microgrids

The advanced capabilities of hybrid GA-ANFIS controllers make them a cornerstone for the future of distributed energy systems, including smart grids and microgrids. The superior performance and stability provided by these intelligent algorithms allow for seamless integration with advanced microgrid controllers, which are responsible for orchestrating the interaction between generation sources, storage, and loads. By ensuring maximum energy extraction and high power quality, GA-ANFIS contributes to the overall stability and efficiency of modern hybrid energy systems.

5.3. Research Frontiers

Future research in this field should focus on several key areas to further enhance the performance and viability of hybrid AI-based MPPT controllers. There is a need for the development of new, more efficient metaheuristic algorithms or novel hybrid combinations that could potentially outperform existing methods. Additionally, validating these complex algorithms through advanced simulation techniques like hardware-in-the-loop (HIL) testing is essential to bridge the gap between simulation and real-world deployment. The development of multi-objective optimization models is another important frontier, where the algorithm is designed to simultaneously optimize for multiple objectives, such as maximizing power, while minimizing

ISSN: 2583-5637 (Online)
International journal of Inventive Research in Science and Technology
Volume 4 Issue 10 October 2025

Total Harmonic Distortion (THD) and system cost. This multi-faceted approach will be critical for the widespread adoption of these advanced control systems.

Table 3: Summary of Challenges and Opportunities

Challenge	Description	Corresponding Research Opportunity
Computational Complexity	The algorithms, particularly the GA training phase, are computationally intensive and require significant processing power, which can increase cost.	Develop more lightweight and efficient metaheuristic algorithms or explore on-chip hardware implementations to reduce computational overhead.
Model Management	AI-based models require robust data processing for training and may need periodic re-tuning as the PV system ages.	Investigate self-learning and real-time model adaptation techniques to reduce the need for manual re-tuning.
Algorithm Selection	Other hybrid algorithms, such as PSO-ANFIS, may provide better performance with less error in certain scenarios compared to GA-ANFIS.	Conduct comprehensive comparative studies and develop clear guidelines for selecting the optimal algorithm based on system scale, cost, and application requirements.
Power Quality	While hybrid methods improve power quality, a complete solution requires simultaneous optimization of multiple parameters.	Develop multi-objective optimization models that can simultaneously maximize power extraction while minimizing THD and other grid disturbances.

VI. Conclusion

This review paper establishes that the hybrid GA-ANFIS approach represents a significant leap forward in MPPT technology for photovoltaic systems. By synergistically combining the global search capability of a Genetic Algorithm with the adaptive learning of an Adaptive Neuro-Fuzzy Inference System, this algorithm effectively addresses the critical weaknesses of both conventional and single-approach AI methods. The proven advantages of the GA-ANFIS approach in enhancing energy harvesting efficiency, reducing power oscillations, and ensuring stability under complex conditions like partial shading are substantial. Although challenges remain concerning computational complexity and implementation cost, the superior performance and reliability of this technology make it a cornerstone for the development of resilient, next-generation smart PV systems. By paving the way for advanced control strategies, the GA-ANFIS approach is poised to play a pivotal role in the efficient and reliable integration of solar energy into the future of power systems.

VII. References

[1] D. Mlakić, L. Majdandžić, and S. Nikolovski, "ANFIS Used as a Maximum Power Point Tracking Algorithm for a Photovoltaic System," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 8, no. 2, pp. 867–879, Apr. 2018. doi: 10.11591/ijece.v8i2.pp867-879.

[2] A. Rezvani, M. Izadbakhsh, and M. Gandomkar, "Implementing GA-ANFIS for maximum power point tracking in PV system," *Indian Journal of Science and Technology*, vol. 8, no. 10, pp. 982–991, Apr. 2015. doi: 10.17485/ijst/2015/v8i10/51832.

[3] T. H. Vo, "Design of the Adaptive Neuro-Fuzzy Inference System (ANFIS) and a Genetic Algorithm Controller for Solar Photovoltaic Systems Using the Boost Converter", *Journal of Technical Education Science*, no. 78A, Aug. 2023. doi: 10.54644/jte.78A.2023.1439.

[4] M. Y. Aldulaimi and M. Çevik, "AI-Enhanced MPPT Control for Grid-Connected Photovoltaic Systems Using ANFIS-PSO Optimization," *Electronics*, vol. 14, no. 13, p. 2649, 2025. doi: 10.3390/electronics14132649.

[5] D. M. Yassine, H. Tedjini, and A. Nasri, "Comparative Assessment of P&O, PSO Sliding Mode, and PSO-ANFIS Controller MPPT for Microgrid Dynamics," *Elektronika ir Elektrotechnika*, vol. 30, no. 3, pp. 54–61, Jul. 2024. doi: 10.5755/j02.eie.36335.