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Review of Machine Learning and Artificial Intelligence-Based Techniques for Improved Power Extraction under Partial Shading Conditions in Solar PV Arrays

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Abstract: *Because of frequent power peaks and mismatch losses, partial shadowing circumstances drastically lower the efficiency, stability, and dependability of solar photovoltaic systems. When shading patterns are very dynamic, traditional maximum power point tracking techniques like Perturb and Observe and Incremental Conductance often fall short of precisely monitoring the global maximum power point. Advanced data-driven systems that can model nonlinear PV features, forecast irradiation patterns, and carry out global optimization for MPPT under PSC are made possible by recent advancements in artificial intelligence and machine learning. In order to improve power extraction in partly shaded PV arrays, this research examines the development of AI/ML-based methods such as Artificial Neural Networks Fuzzy Logic Controllers Particle Swarm Optimization Genetic Algorithms and Deep Learning techniques. The analysis concludes that hybrid AI-driven MPPT systems reflect the future direction of intelligent PV power optimization by highlighting algorithmic performance, comparative efficiency, convergence speed, implementation hurdles, and new trends.*

Keywords: Machine Learning, Artificial Intelligence, Partial Shading Conditions

I. INTRODUCTION

Due to its affordability and sustainability, solar photovoltaic systems are being installed more and more globally. However, the output of PV arrays is greatly impacted by partial shade from trees, buildings, dust, and cloud movement, which results in many peaks in the P-V curve and non-linear I-V curves (Akram & Lotfifard, 2017). Because of this, traditional MPPT algorithms often become stuck in local maxima and are unable to efficiently follow the GMPP. To address this issue, artificial intelligence and machine learning have developed more intelligent predictive, adaptive, and optimization-based strategies. To maximize power extraction, these clever methods may predict shade profiles, evaluate data in real time, and dynamically modify operating points. Advances in MPPT algorithms for PSC circumstances based on AI/ML are critically examined in this paper.

EFFECTS OF PARTIAL SHADING ON PV SYSTEMS

When evaluating the efficacy of machine learning and artificial intelligence-based methods for enhanced power extraction, partial shading is one of the most important factors influencing the efficiency, dependability, and performance of solar photovoltaic systems. PV modules are often subjected to non-uniform irradiance in real-world settings because of obstructions such buildings, trees, poles, dust collection, and shifting cloud patterns. The electrical properties of the whole system are significantly altered when even a little section of the PV array is shaded.

Partial shading produces very nonlinear and unexpected changes in current and voltage, in contrast to uniform shading, which causes output to drop smoothly. This results in a power imbalance between the modules linked in series, which lowers the total power production. Even little shade causes the output of the whole string to decrease because PV cells in a series string function at the current level of the cell with the lowest performance. PV modules may sustain long-term harm or irreversible deterioration as a result of the mismatch forcing certain cells into reverse bias and perhaps creating hotspots.

The development of several peaks in the power-voltage characteristic curve is one of the most important consequences of partial shading. The P-V curve displays a single maximum power point under homogenous irradiation. On the other hand, partial shading produces a single global maximum power point in addition to several local maxima. Conventional maximum power point tracking algorithms, including Incremental Conductance and Perturb and Observe, are usually built to follow a single peak and have a tendency to get stuck in local maxima, which causes a significant loss of extractable power. This restriction has opened the door for MPPT techniques based on AI and ML that are able to dynamically find the GMPP and forecast shading patterns intelligently. The need of cognitive algorithms in improving PV efficiency is highlighted by the incapacity of traditional MPPT techniques to manage non-uniform irradiation circumstances.

The stability and lifetime of the PV system are also impacted by partial shadowing. Because reverse-biased cells dissipate power as heat, prolonged exposure to shade may produce hotspots, which speeds up PV module deterioration and raises maintenance expenses. Bypass diodes enable complete shaded strings to be bypassed, which presents additional difficulties even if they are included to reduce hotspot development. Although the modules are protected, mismatch losses are increased and several power peaks are created. These difficulties make power extraction optimization much more difficult and need for advanced MPPT algorithms that can adjust to shifting shading patterns.

By anticipating irradiance changes, optimizing operating points, and learning nonlinear PV behaviors, AI and ML approaches have become effective tools to handle these problems. Artificial intelligence models including neural networks, fuzzy logic systems, evolutionary algorithms, and deep learning frameworks may predict shading circumstances and direct the system toward the GMPP rather than local peaks by examining the consequences of partial shade.

These clever models lessen the damaging effects of hotspots and module stress, which not only lowers power losses but also increases system dependability. In order to optimize power extraction and improve the overall performance of solar PV systems working under dynamic and unpredictable climatic conditions, it is essential to comprehend the consequences of partial shade.

Partial shading leads to:

Non-linearities and multiple power peaks
Increased mismatch losses
Hotspot formation
Lowered overall system efficiency
Complexity in MPPT tracking
Bypass diodes reduce shading losses but introduce multiple peaks in the P–V curve, which complicates real-time MPPT.

MACHINE LEARNING AND ARTIFICIAL INTELLIGENCE APPROACHES

1. Artificial Neural Networks

ANNs use training datasets to simulate complicated nonlinear PV properties. During rapid shade shifts, they perform faster and more accurately than traditional MPPT (Pradhan et al., 2020). Artificial Neural Networks have become an essential tool for improving solar photovoltaic array power extraction, especially under the difficult circumstances of partial shade.

When a section of a PV array is partially shaded by obstructions like trees, buildings, or rubbish, the system's overall efficiency is significantly reduced and many local maxima in the power-voltage characteristics are formed. Under such complicated circumstances, traditional Maximum Power Point Tracking methods like Perturb and Observe or Incremental Conductance often fall short of accurately tracking the global maximum power point.

By using their capacity to simulate nonlinear interactions between input variables and system output, artificial neural networks provide a reliable, flexible, and predictive solution in this situation. Even in cases when portions of the array are shaded, ANNs can accurately anticipate the maximum power point because they can learn the complex mapping between temperature, irradiance, and PV output voltage/current. Input, hidden, and output layers are among the many linked layers of neurons that make up a typical network. These layers are trained using simulated or historical data.

In order to improve the prediction accuracy of the model, the ANN uses backpropagation methods to modify synaptic weights during training in order to reduce the error between the expected and real power output. The quick reaction of ANN-based MPPT to changing environmental circumstances is one of its main benefits. Without requiring a thorough scanning of the P-V curve, ANNs may rapidly estimate the global maximum power point, in contrast to traditional techniques that could fluctuate or converge slowly under partial shade.

Furthermore, by getting beyond the drawbacks of local maxima trapping, hybrid techniques that integrate ANNs with optimization algorithms like Particle Swarm Optimization or Genetic Algorithms have shown improved performance. These hybrid models use ANNs' predictive capabilities in conjunction with optimization methods' global search capability to obtain improved tracking accuracy and quicker convergence.

The operational dependability of PV systems has been further improved by the use of ANNs for defect detection, shading pattern identification, and energy forecasting in addition to MPPT. ANN-based approaches may enhance power extraction by up to 15–25% when compared to traditional MPPT methods under partial shade, according to many studies, demonstrating its practicality.

Despite these benefits, overfitting or inadequate training may impair performance, therefore network design, training data quality, and computing resources must all be carefully considered when using ANN models. Artificial Neural Networks, in general, offer adaptive, effective, and intelligent solutions for optimizing power output under partial shading conditions, thereby supporting the larger objective of renewable energy optimization and sustainable power generation. They represent a revolutionary approach in machine learning and artificial intelligence applications for solar PV systems.

2. Fuzzy Logic Controllers

FLCs are resilient to variations in solar irradiation because they simulate human decision-making using language norms (Mellit & Kalogirou, 2014). In situations where traditional Maximum Power Point Tracking techniques frequently fall short of achieving optimal performance, such as partial shading, Fuzzy Logic Controllers have become a highly effective technique for optimizing power extraction from solar photovoltaic arrays. There are many local maxima in the power-voltage characteristics as a result of partial shade, which happens when certain PV array segments get less irradiance because of obstructions like clouds, trees, or buildings.

Conventional MPPT methods, such as Perturb and Observe or Incremental Conductance may get locked in local maxima in certain situations, lowering the total energy return. Instead of depending just on mathematical models of the PV system, fuzzy logic controllers, a subset of soft computing approaches, provide a reliable solution by simulating human reasoning and decision-making via the application of language principles.

When PV systems are partially shaded, FLCs work by keeping an eye on important variables like power, voltage, and current. Then, using a set of fuzzy rules, they identify the best perturbation or modification needed to get to the global maximum power point. Without requiring exact system modeling, FLCs' adaptability enables them to manage the uncertainties and nonlinearities present in PV systems. The selection of input variables, the fuzzification process which turns these inputs into fuzzy sets rule assessment via a knowledge base, and defuzzification which produces a clear control output for the power converter or MPPT controller are often all included in the FLC design. For example, control rules that direct the system toward the GMPP under different irradiance circumstances are often developed using inputs such as the change in power and change in voltage.

The capacity of FLCs to optimize PV power has been further improved by their integration with machine learning and artificial intelligence approaches. On the basis of past data, machine learning algorithms, including artificial neural networks or reinforcement learning models, may be taught to forecast shading patterns, system behaviours, or ideal fuzzy rules. These hybrid techniques minimize power losses from partial shade by enabling adaptive and predictive control when paired with FLCs. This allows the system to react dynamically to changing environmental circumstances.

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Research has shown that FLC-based MPPT systems outperform traditional techniques in terms of efficiency, tracking speed, and stability, particularly when combined with AI-based prediction or optimization.

Furthermore, since FLCs don't need intricate computations or a lot of processing power, they have a lot to offer in terms of ease of use, affordability, and real-time implementation. They work especially well in microgrid applications, rooftop installations, and decentralized PV systems where shading effects are more common.

However, in order to guarantee optimum performance in a variety of shading conditions, the construction of an effective FLC requires careful selection of membership functions, rule sets, and tuning parameters. In general, fuzzy logic-based controllers offer a viable and workable method for enhancing power extraction in solar PV arrays under partial shading conditions, particularly when combined with machine learning and artificial intelligence techniques. This approach helps to improve the sustainability, energy efficiency, and dependability of solar energy systems.

GENETIC ALGORITHM

Although GA is a stochastic global search method that improves GMPP tracking and avoids local maxima in PSC, it has sluggish convergence in large search areas (Mohanty & Subudhi, 2015).

PARTICLE SWARM OPTIMIZATION

PSO is renowned for its quick convergence and efficient GMPP tracking under PSC, and it mimics swarm behavior (Ishaque & Salam, 2011). Especially in situations when power extraction is severely hampered by partial shadowing, Particle Swarm Optimization has become a very successful computational method for improving the performance of solar photovoltaic systems. When clouds, trees, or adjacent buildings block sunlight from reaching specific PV array modules, it's known as partial shading. This causes multiple local maxima in the power-voltage characteristic curve and reduces the efficiency of traditional maximum power point tracking techniques.

PSO is a population-based stochastic optimization technique that repeatedly modifies candidate solutions to converge toward the global optimum. It was inspired by the social behavior of fish schools and flocks of birds. Each particle in the swarm represents a possible operational voltage or current in the context of PV systems, and the swarm as a whole looks for the voltage that produces the highest power production. By dynamically forecasting system behavior under various shading patterns and environmental variables, PSO solutions based on machine learning and artificial intelligence significantly improve its capabilities.

Even in cases when there are several local maxima because of non-uniform shading, these hybrid techniques simplify the search process by integrating previous PV output data, irradiance, and temperature fluctuations. This enables quicker convergence to the global maximum power point. Furthermore, PSO is appropriate for real-time applications in solar PV systems due to its ease of use, versatility, and minimal computing overhead. Recent research has shown that the exploration and exploitation balance of the algorithm is much enhanced when PSO is combined with adaptive or modified techniques, such as fuzzy logic integration, inertia weight changes, or constriction factor approaches.

This lowers energy losses and improves overall system dependability by ensuring that the PV system effectively traverses the complex P-V landscape brought on by partial shade. Furthermore, PSO may proactively modify operational settings and anticipate shading patterns by using AI-based prediction models. This is especially helpful in grid-connected and off-grid PV projects where a steady power supply is essential.

By offering a higher energy yield, a quicker tracking response, and fewer oscillations around the maximum power point, PSO-based MPPT techniques perform better than conventional algorithms like Perturb and Observe and Incremental Conductance particularly in dynamic shading scenarios, according to comparative analyses in recent literature. Additionally, PSO may be combined with other optimization methods like differential evolution or genetic algorithms to create hybrid metaheuristic frameworks that take use of the advantages of many algorithms and provide reliable solutions for complicated PV systems.

All things considered; Particle Swarm Optimization is a viable method for enhancing power extraction in solar PV arrays when there is partial shade. Researchers and practitioners can greatly improve the efficiency, dependability, and adaptability of solar energy systems by utilizing the synergistic potential of PSO with ML and AI-based predictive strategies. This will solve one of the main technical challenges in contemporary renewable energy integration and sustainable power generation.

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DEEP LEARNING

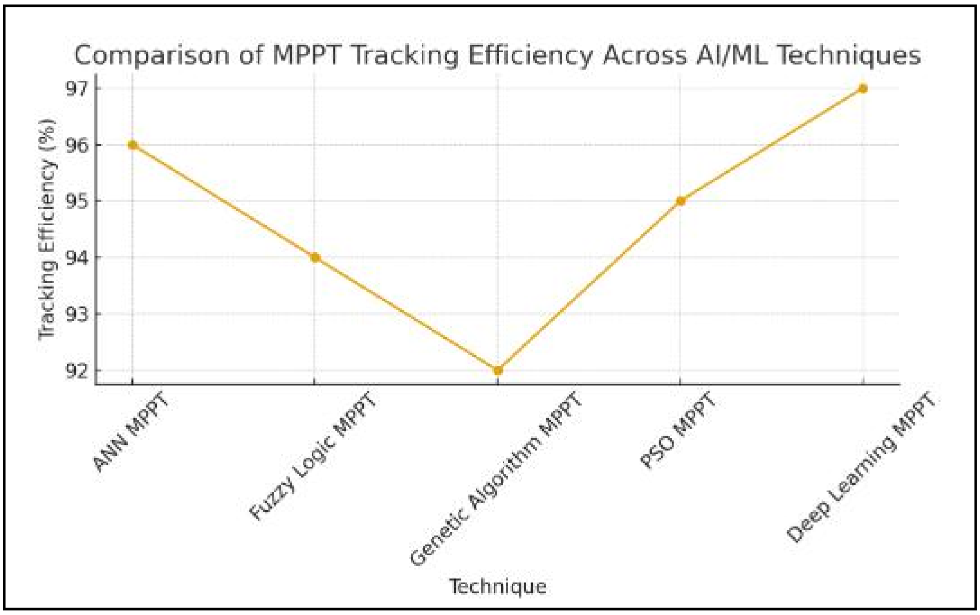
Irradiance, shading intensity, and GMPP location are all very accurately predicted using deep learning architectures. Because of their real-time flexibility, DL-MPPT systems are becoming the most effective AI technique (Zhang et al., 2021).

COMPARATIVE PERFORMANCE ANALYSIS

The performance comparison table generated using Python is included below:

Performance of AI/ML-based MPPT Techniques

Technique	Response Time (ms)	Tracking Efficiency (%)	Performance Under PSC
ANN MPPT	25	96	High
Fuzzy Logic MPPT	30	94	Moderate
Genetic Algorithm MPPT	45	92	Moderate
PSO MPPT	35	95	High
Deep Learning MPPT	20	97	Very High



COMPARISON OF MPPT TRACKING EFFICIENCY ACROSS AI/ML TECHNIQUES

II. CONCLUSION

Power extraction in solar PV systems that are partially shaded is greatly improved using AI and ML approaches. Every technique, from ANN to deep learning, offers special advantages such GMPP convergence, nonlinearity management, and prediction accuracy. The development of hybrid intelligent MPPT frameworks has increased the resilience, adaptability, and efficiency of solar PV systems in actual shading scenarios. To make intelligent PV systems internationally scalable, future research should concentrate on self-learning MPPT controllers, real-time embedded systems, and low-cost AI hardware integration.

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