A Comprehensive Review of Maximum Power Point Tracking Techniques in Solar Photovoltaic Systems: Historical Evolution and Contemporary Approaches

Sanjay Rane, N.B. Bankhele, G.U Kharat

***Abstract*— the efficiency of photovoltaic (PV) systems is inherently limited by their nonlinear current-voltage characteristics and susceptibility to environmental variations such as irradiance and temperature. Maximum Power Point Tracking (MPPT) techniques are essential for optimizing the energy harvest from PV systems by continuously adjusting the operating point to extract maximum power. This paper presents a comprehensive review of MPPT techniques, tracing their historical development from the inception of PV technology to contemporary intelligent and hybrid methods. The review categorizes MPPT strategies into classical, intelligent, and optimization-based approaches, analyzing their operational principles, advantages, limitations, and suitability for various applications. Emphasis is placed on the performance of these techniques under partial shading conditions and dynamic environmental scenarios. The paper concludes by identifying emerging trends and potential areas for future research in MPPT technologies.**

***Index Terms*—MPPT,PV system, PSC.**

I. Introduction

The global shift towards renewable energy sources has intensified research and development in photovoltaic (PV) technologies. Despite advancements in PV cell efficiencies, the actual power output is significantly influenced by environmental factors such as solar irradiance and temperature. These factors cause the Maximum Power Point (MPP) of a PV system to vary, necessitating the implementation of Maximum Power Point Tracking (MPPT) techniques to ensure optimal energy extraction. MPPT algorithms dynamically adjust the operating point of the PV system to align with the MPP, thereby enhancing overall efficiency.

II. Historical Evolution of MPPT Techniques

The concept of MPPT emerged alongside the development of the first practical silicon solar cells in 1954 by Bell Laboratories, which had an efficiency of approximately 6% [1]. Early MPPT methods were rudimentary, often involving manual adjustments to the load to approximate the MPP. The 1980s saw the introduction of more systematic approaches, such as the Constant Voltage (CV) and Constant Current (CC) methods, which relied on maintaining the PV system at a fixed voltage or current presumed to be near the MPP [2]. In 1984, Hart et al. conducted experimental tests on open-loop MPPT techniques, highlighting the need for more adaptive methods [3]. The late 1980s and early 1990s introduced the Perturb and Observe (P&O) and Incremental Conductance (InC) methods, which became foundational due to their simplicity and ease of implementation [4][5]. The advent of digital controllers in the 1990s facilitated the development of more sophisticated algorithms, including those based on artificial intelligence (AI) and optimization techniques.

III. Classification of MPPT Techniques

3.1 Classical Techniques

Perturb and Observe (P&O): This method involves perturbing the operating voltage and observing the resulting change in power. If the power increases, the perturbation continues in the same direction; otherwise, it reverses. While simple, P&O can oscillate around the MPP and may fail under rapidly changing conditions [6].
Incremental Conductance (InC): InC calculates the derivative of power with respect to voltage and compares it to the instantaneous conductance. It offers better performance under varying irradiance but is more complex than P&O [7].
Constant Voltage (CV): CV maintains the PV voltage at a fixed percentage (typically 76%) of the open-circuit voltage. It is easy to implement but less accurate, especially under varying environmental conditions [8].
Constant Current (CC): Similar to CV, CC maintains the current at a fixed value, usually a percentage of the short-circuit current. It suffers from similar limitations as CV [9].

3.2 Intelligent Techniques

Fuzzy Logic Control (FLC): FLC uses linguistic rules and fuzzy sets to handle uncertainties and nonlinearities in PV systems. It does not require an exact mathematical model, making it robust under varying conditions [10].
Artificial Neural Networks (ANN): ANNs are trained with historical data to predict the MPP under different conditions. They can adapt to changing environments but require substantial training data and computational resources [11].

Sliding Mode Control (SMC): SMC is a robust control method that forces the system state to "slide" along a predetermined surface towards the MPP, offering fast response and stability [12].

3.3 Optimization-Based Techniques

Particle Swarm Optimization (PSO): PSO simulates the social behavior of birds flocking or fish schooling to find the optimal solution. It is effective in locating the global MPP, especially under partial shading [13].
Genetic Algorithms (GA): GA mimics natural selection processes to evolve solutions towards the MPP. It is suitable for complex optimization problems but may converge slowly [14].
Ant Colony Optimization (ACO): ACO is inspired by the foraging behavior of ants and is used to find optimal paths, including the MPP in PV systems [15].
Hybrid Methods: Combining different algorithms, such as ANN with PSO, can leverage the strengths of each to improve tracking performance and adaptability [16].

IV. Performance Under Partial Shading Conditions

Partial shading introduces multiple local maxima in the power-voltage (P-V) curve, challenging traditional MPPT methods. Optimization-based and intelligent algorithms have shown superior performance in navigating these complex landscapes to locate the global MPP [17]. Techniques like PSO and hybrid methods are particularly effective in such scenarios due to their global search capabilities.

V. Comparative Analysis

A comparative analysis of various MPPT techniques is presented in Table 1, highlighting their key characteristics.

Technique	Complexity	Stability	Performance
P&O	Low	Moderate	Low
InC	Moderate	High	Moderate
CV	Low	Low	Poor
FLC	High	High	High
ANN	High	Moderate	High
PSO	High	High	High
GA	High	High	Moderate

VI. Conclusion

MPPT techniques have evolved significantly since the inception of PV technology, transitioning from simple manual adjustments to sophisticated intelligent algorithms. While classical methods remain relevant for their simplicity and low cost, intelligent and optimization-based techniques offer superior performance,

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