

Maximum Power Point Tracking via a PSO-Enhanced Sliding Mode Technique—A Review

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Abstract

Maximum Power Point Tracking (MPPT) is crucial for optimizing energy extraction from photovoltaic (PV) systems, which inherently exhibit non-linear power characteristics influenced by environmental variations. The dynamic nature of solar irradiance and temperature, coupled with the complexities of partial shading, poses significant challenges to traditional MPPT methods. This review paper introduces the Particle Swarm Optimization (PSO)-enhanced Sliding Mode Control (SMC) technique as a robust hybrid solution. This approach aims to accelerate convergence to the maximum power point (MPP), enhance system robustness, and improve overall energy harvesting efficiency, thereby addressing the limitations prevalent in conventional and individual intelligent MPPT algorithms for real-world applications.

Keywords: Maximum Power Point Tracking (MPPT), Photovoltaic (PV) Systems, Particle Swarm Optimization (PSO), Sliding Mode Control (SMC), Hybrid Control, Renewable Energy.

I. Introduction

Photovoltaic (PV) systems are pivotal in the global transition towards sustainable energy sources, with their installed capacity experiencing rapid growth. To maximize the economic and environmental benefits of PV technology, efficient energy harvesting is paramount. PV panels exhibit non-linear current-voltage (I-V) and power-voltage (P-V) characteristics, featuring a

unique Maximum Power Point (MPP) that fluctuates with environmental factors such as solar irradiance and temperature. This inherent variability necessitates the deployment of Maximum Power Point Tracking (MPPT) techniques to continuously extract the maximum available power from the PV array.

Traditional MPPT algorithms often struggle under rapidly changing atmospheric conditions or partial shading scenarios. These limitations can lead to reduced efficiency, undesirable power oscillations around the MPP, or the system becoming trapped in local power maxima rather than the true global maximum. The need for more resilient and intelligent control strategies to overcome these shortcomings has driven research into advanced, hybrid approaches. The Particle Swarm Optimization (PSO)-enhanced Sliding Mode Control (SMC) technique has emerged as a promising hybrid solution designed to address these challenges, offering accelerated convergence and improved robustness. The increasing global installed capacity of PV power implies that even marginal improvements in MPPT efficiency, achieved through such advanced techniques, can translate into substantial absolute energy savings and economic advantages on a macro scale. This underscores the critical importance of developing highly effective MPPT solutions.

This paper provides a comprehensive review of the PSO-enhanced SMC technique for MPPT. Subsequent sections delve into a literature review of MPPT fundamentals and existing methods, detail the methodology of the PSO-enhanced SMC approach, highlight its advantages, discuss recent challenges, and explore future research directions.

II. Literature Review: Maximum Power Point Tracking (MPPT)

Maximum Power Point Tracking (MPPT) is a technique employed in PV systems to continuously adjust the load characteristics presented to the solar array, ensuring operation at the Maximum Power Point (MPP) for optimal energy extraction. This adjustment is typically facilitated by a DC-DC converter, which acts as an interface between the PV panels and the load.

Conventional MPPT Methods

Among the earliest and most widely adopted MPPT methods are Perturb and Observe (P&O) and Incremental Conductance (INC). The P&O algorithm is favored for its simplicity and ease of implementation. However, it suffers from inherent drawbacks, including oscillations around the MPP during steady-state conditions and slow tracking speed under rapidly changing environmental parameters, leading to power losses. Incremental Conductance (INC) offers an improvement over P&O by tracking changing conditions more rapidly and, ideally, without oscillations at the MPP. Despite its advantages, INC demands higher computational resources and can still exhibit erratic behavior under extremely rapid atmospheric changes. A significant limitation for both P&O and INC arises under partial shading conditions (PSCs). In such scenarios, the PV array's power-voltage (P-V) curve presents multiple local maxima, often causing these conventional algorithms to become trapped at a suboptimal local peak, resulting in substantial power loss. This deficiency in handling complex operating conditions has driven the evolution towards more sophisticated solutions.

Intelligent and Metaheuristic MPPT Algorithms

To overcome the limitations of conventional methods, particularly under PSCs, intelligent and metaheuristic algorithms have gained prominence. Particle Swarm Optimization (PSO) is a nature-inspired optimization algorithm that excels in solving non-linear problems and is less susceptible to local optima compared to traditional search methods. Its global search capability makes it particularly effective in identifying the true MPP under partial shading. Nevertheless, conventional PSO can still face challenges such as steady-state oscillations and slower convergence rates in certain dynamic scenarios, and its performance can be sensitive to initialization values.

Sliding Mode Control (SMC) is a robust non-linear control technique known for its fast dynamic response, inherent robustness against system disturbances and parameter variations, and relative simplicity in implementation. Historically, a challenge associated with SMC has been the

"chattering" phenomenon, which refers to high-frequency oscillations around the sliding surface. The progression from simple (P&O, INC) to intelligent (PSO, Fuzzy Logic Control, Artificial Neural Networks) and then to robust (SMC) and hybrid methods reflects a continuous research effort. This adaptive response aims to address the increasing complexity of PV operating conditions and the demand for improved performance in terms of speed, accuracy, and robustness. The inherent trade-offs in individual methods, such as PSO's global search capability versus its potential for oscillations, and SMC's robustness versus its chattering issues, form the fundamental rationale for their hybridization. This strategic combination seeks to leverage the strengths of each technique while mitigating their respective weaknesses.

III. PSO-Enhanced Sliding Mode Technique for MPPT

The PSO-enhanced Sliding Mode Control (SMC) technique represents a sophisticated hybrid approach to MPPT, designed to combine the global optimization capabilities of PSO with the robust control characteristics of SMC. The typical system architecture integrating this hybrid controller comprises PV panels, a DC-DC converter (commonly a boost converter), and the central PSO-SMC MPPT control block.

Methodology of Integration

The integration of PSO and SMC can manifest in several ways, each contributing to the "enhancement" of the MPPT process. One common approach involves PSO performing a global search across the P-V curve to identify the Global Maximum Power Point (GMPP, especially crucial under partial shading conditions), and subsequently generating an optimal voltage reference. This optimal reference voltage is then provided to the SMC, which robustly tracks it by adjusting the duty cycle of the DC-DC converter. Alternatively, PSO can be employed to dynamically tune the critical parameters of the SMC controller, such as the sliding surface coefficients or the reaching gain. This dynamic tuning is a direct result of PSO's ability to optimally select SMC parameters, thereby mitigating SMC's inherent sensitivity to parameter choice and reducing potential chattering, while SMC's robustness compensates for PSO's potential for steady-state oscillations.

SMC's role is to ensure the system operates precisely at the MPP by forming a dynamic sliding surface that represents the deviation between the actual operating point and the desired MPP. A discontinuous control law is then applied to drive the system states onto and along this surface, providing a fast and stable response. The synergistic operation of these two techniques means that PSO's global exploration capabilities are combined with SMC's robust local tracking, leading to accelerated convergence, reduced oscillations, and enhanced adaptability. The PSO block effectively optimizes the control signal generated by the sliding mode controller, creating a sophisticated integration where one algorithm directly improves the performance of the other. This dual approach, where PSO either sets a global reference or tunes SMC parameters, highlights a design space for hybrid algorithms, suggesting that the optimal integration strategy may vary depending on specific application requirements.

The mathematical basis of this methodology involves defining objective functions for PSO (primarily maximizing power output) and formulating the sliding surfaces and control laws for SMC, which are typically applied to regulate the duty cycle of the DC-DC converter.

IV. Advantages of the Hybrid Approach

The PSO-enhanced Sliding Mode Control (SMC) technique offers significant performance improvements over conventional and even individual intelligent MPPT methods, establishing itself as a highly effective solution for photovoltaic systems.

One of the primary benefits is accelerated convergence to the MPP. The hybrid approach demonstrates significantly faster tracking, particularly under dynamic conditions and partial shading, compared to traditional algorithms and standalone PSO or SMC. For example, convergence times as low as 63 milliseconds have been reported. This rapid response ensures that the PV system quickly adapts to changing environmental conditions, minimizing energy loss during transients.

Furthermore, the technique provides enhanced robustness. By leveraging SMC's inherent ability to withstand parameter variations, external disturbances, and modeling errors, the hybrid

controller ensures stable operation even in challenging and unpredictable environments. This resilience is critical for reliable long-term performance in real-world installations.

The combination also leads to improved accuracy and efficiency. PSO's global search capability is instrumental in accurately locating the Global Maximum Power Point (GMPP) under partial shading, effectively preventing the system from becoming trapped in suboptimal local maxima. This results in higher energy harvesting efficiency, with reported efficiencies ranging from 99.2% to 99.65% for PSO-SMC, a notable increase over conventional SMC. Such quantifiable improvements represent a significant leap in MPPT performance, directly translating to economic gains.

Moreover, the hybrid approach contributes to reduced oscillations in the power output. It effectively mitigates the steady-state oscillations commonly associated with P&O and conventional PSO, leading to a smoother and more stable power delivery. Finally, the dynamic tuning of SMC parameters by PSO enhances the system's adaptability to rapidly changing environmental conditions. This multi-faceted improvement indicates that the synergy between PSO and SMC creates a more resilient and versatile controller, offering a holistic enhancement in MPPT capability.

Table 1: Comparative Performance of MPPT Algorithms

Algorithm Type	Key Advantages	Key Disadvantages	Tracking Efficiency (%)	Convergence Speed	Handling Partial Shading
Perturb & Observe (P&O)	Simplicity, ease of implementation	Oscillations, slow tracking, power loss	-	-	Limited/Fails
Incremental Conductance (INC)	Faster than P&O, no oscillation at MPP	Higher computation, erratic under rapid changes	~95%	Moderate	Limited/Fails

Algorithm Type	Key Advantages	Key Disadvantages	Tracking Efficiency (%)	Convergence Speed	Handling Partial Shading
Conventional PSO	Global search, avoids local optima	Steady-state oscillations, slower convergence, initial-condition dependent	-	Moderate	Yes
Conventional SMC	Fast dynamic response, robustness	Chattering effect, parameter sensitivity	96.79%	-	-
PSO-SMC (Hybrid)	Accelerated convergence, enhanced robustness, high accuracy/efficiency, reduced oscillations, adaptability, GMPP tracking	Higher computational resources, parameter tuning sensitivity, residual chattering, extreme dynamic response	99.2% - 99.65%	63ms - 200ms	Yes (GMPP)

V. Recent Challenges

Despite the significant advancements offered by PSO-enhanced SMC techniques, several challenges persist in their practical implementation and optimization. The enhanced performance often comes at the cost of increased computational complexity and resource requirements compared to simpler MPPT methods. This can pose limitations for real-time implementation on low-cost, embedded hardware platforms.

Another critical aspect is the sensitivity to parameter tuning and initialization dependence. While PSO aids in optimizing SMC parameters, the performance of PSO itself is highly dependent on its initial conditions and the careful selection of its own parameters, such as swarm size, inertia weight, and acceleration coefficients. Suboptimal parameter choices can still lead to slower

convergence or suboptimal tracking, representing a potential vulnerability in the hybrid system if not properly initialized or tuned.

Although generally reduced, some hybrid PSO approaches may still exhibit residual steady-state oscillations or prematurely terminate the search process before reaching the absolute GMPP. Furthermore, despite PSO enhancement, the chattering effect inherent in the discontinuous nature of SMC can still occur, potentially causing wear and tear on power electronic switches and introducing undesirable high-frequency harmonics into the system. Finally, maintaining optimal performance under extremely rapid and unpredictable changes in irradiance or highly complex partial shading patterns remains a dynamic response challenge. These challenges highlight a trade-off: achieving high accuracy and fast convergence often requires increased algorithmic complexity and resource demands, necessitating a careful balance in design.

VI. Future Directions

The field of MPPT, particularly for hybrid control strategies like PSO-SMC, continues to evolve with several promising avenues for future research and development. A crucial step involves moving beyond simulation to real-time hardware implementation and validation on programmable boards such as Digital Signal Processors (DSPs) or Field-Programmable Gate Arrays (FPGAs). This will allow for rigorous testing and validation of performance under diverse and unpredictable real-world operating conditions.

Further research will focus on developing more sophisticated adaptive and self-tuning algorithms within the PSO-SMC framework. The aim is to enable dynamic adjustment of parameters (e.g., PSO coefficients, SMC sliding surface parameters) in real-time in response to environmental changes, thereby reducing the need for manual tuning and enhancing system autonomy. This represents a clear trend towards the convergence of control theory with advanced computing paradigms.

Another significant direction is the integration with Artificial Intelligence (AI) and Machine Learning (ML) techniques. Exploring the combination of advanced AI/ML methods (e.g., neural networks, fuzzy logic, deep learning) with PSO-SMC can enhance predictive capabilities,

improve decision-making, and enable the handling of more complex scenarios such as highly dynamic partial shading or fault detection. This suggests that MPPT is evolving towards intelligent, self-learning, and predictive systems, mirroring broader trends in engineering.

Research into multi-objective optimization strategies for MPPT is also gaining traction. Future solutions will likely optimize not only power extraction but also other critical factors such as power quality (e.g., Total Harmonic Distortion, THD), system stability, and component lifespan. This indicates a shift from component-level optimization to system-level optimization, where the quality of power and its interaction with the grid become equally important. Investigating PSO-SMC for distributed MPPT in large-scale PV arrays and its seamless integration with smart grids will address challenges related to grid stability and overall energy management. Finally, efforts to develop simplified or optimized versions of PSO-SMC are crucial to reduce computational complexity and resource requirements, making these advanced techniques more feasible for cost-sensitive embedded systems.

VII. Conclusion

Maximum Power Point Tracking (MPPT) is indispensable for maximizing energy yield from photovoltaic (PV) systems, which are inherently non-linear and subject to varying environmental conditions. While conventional MPPT methods offer simplicity, they often fall short in dynamic environments and under partial shading, leading to suboptimal power extraction and oscillations. The PSO-enhanced Sliding Mode Control (SMC) technique presents a robust and efficient hybrid solution that synergistically combines the global exploration capabilities of Particle Swarm Optimization with the inherent robustness and fast dynamic response of Sliding Mode Control.

This hybrid approach has demonstrated significant improvements, including accelerated convergence to the global maximum power point, enhanced robustness against disturbances and parameter variations, improved tracking accuracy and overall energy harvesting efficiency, and reduced steady-state oscillations. These advancements are critical for ensuring the reliable and optimal performance of PV systems in real-world applications, thereby contributing to more effective and sustainable renewable energy harvesting. Despite its advantages, challenges such as

computational complexity, sensitivity to parameter tuning, and residual chattering effects persist. Future research directions are poised to address these limitations through real-time hardware implementation, adaptive and self-tuning algorithms, integration with advanced AI/ML techniques, multi-objective optimization, and seamless grid integration, further solidifying the role of intelligent hybrid control in the future of solar energy.

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