OPTIMIZING SOLAR ENERGY HARVESTING: A REVIEW OF CLASSICAL AND MODERN MPPT STRATEGIES

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Abstract

Photovoltaic (PV) systems typically convert only 30–40% of incident solar energy into electrical output, necessitating Maximum Power Point Tracking (MPPT) techniques to optimize efficiency. This review paper presents a comprehensive analysis of classical and advanced MPPT strategies under varying environmental conditions. Initially, traditional methods like Perturb and Observe (P&O) and Incremental Conductance (INC) are discussed, highlighting their operational principles and limitations such as steady-state oscillations and sensitivity to rapidly changing irradiance. The survey then explores recent advancements including intelligent controllers like fuzzy logic, hybrid MPPT techniques, and global optimization approaches. Statistical evaluations, dynamic performance improvements, hybridization trends, shading mitigation strategies, and climate-specific adaptations are emphasized based on recent literature. Key findings demonstrate that no universal MPPT method suits all scenarios, and the integration of intelligent control with adaptive and hybrid strategies is crucial for achieving high efficiency, fast dynamic response, and robustness under partial shading. This review provides valuable insights for researchers and designers aiming to enhance PV system performance with optimized MPPT strategies.

Keywords: MPPT techniques, P&O, FLC, Neural network

1. INTRODUCTION

A typical solar panel converts only 30 to 40 percent of the incident solar irradiation into electrical energy. Maximum power point tracking technique is used to improve the efficiency of the solar panel[1]. The highest produced power from PV system at different weather conditions is called a maximum power point (MPP) [2]. This happens at maximum voltage and maximum current. To achieve this, an electronic system called maximum power point tracking (MPPT) has been invented and developed [3].

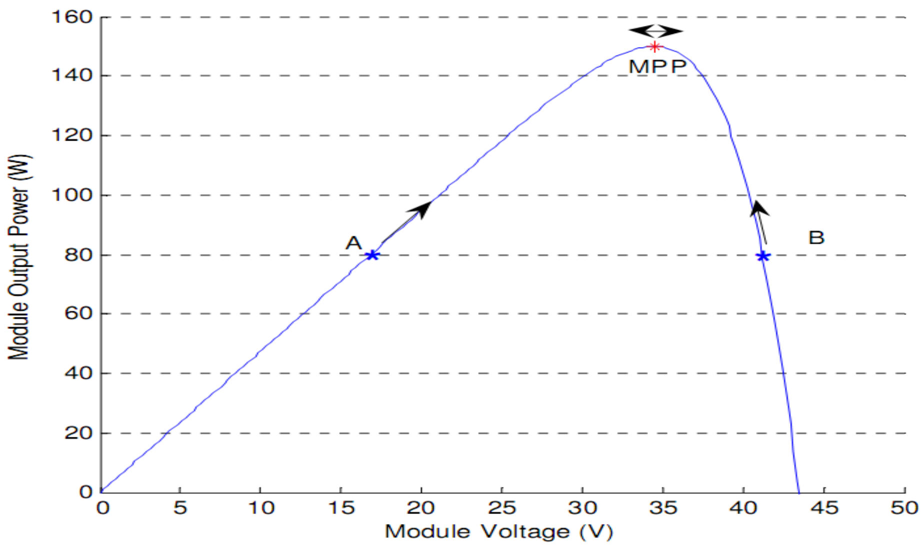

Figure 1: PV characteristics of a solar PV

Figure 1 shows the plot of module output power versus module voltage for a solar panel at a given irradiation [4].

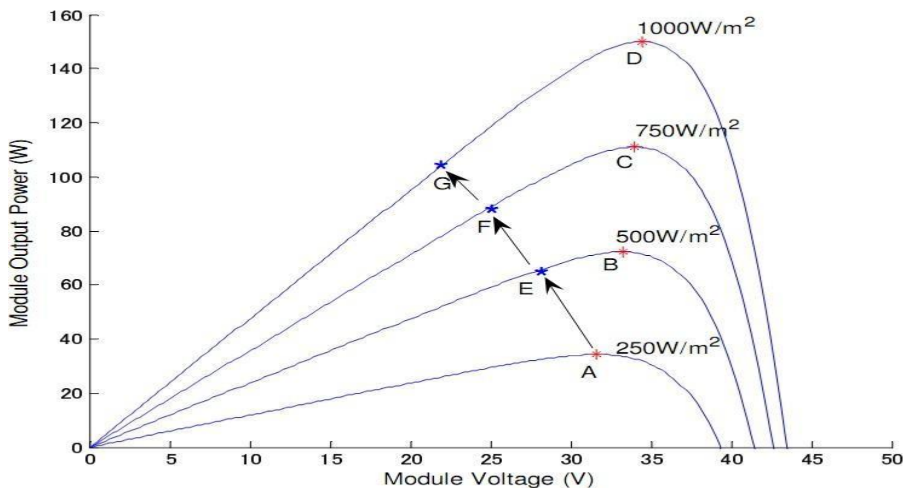

Figure 2: wrong tracking of MPP by P&O algorithm under rapidly varying irradiance

The point marked as MPP is the Maximum Power Point, Consider A and B as two operating points, the point A is on the left-hand side of the MPP. Therefore, to move towards the MPP a positive perturbation to the voltage is provided on the other hand, point B is on the right- hand side of the MPP, on giving positive perturbation, the value of ΔP becomes negative, thus it is imperative to change the direction of perturbation to achieve MPP, this is done from the most popular Perturb & Observe algorithm (P&O) [1], [5]. In a situation where the irradiance changes rapidly, the MPP also moves on the right-hand side of the curve [1]. The algorithm takes it as a change due to perturbation and in the next iteration it changes the direction of perturbation and hence goes away from the MPP as shown in the Figure 2. Taking into account the limitations of P&O, the INC method was introduced in order to overcome these problems [6]. A fundamental comparison between instantaneous conductance and incremental conductance is used to develop the INC technique. The values of conductance and incremental conductance at the MPP are equal; nevertheless, they are in opposite directions. As compared to P&O, this technique has a medium level of complexity when it comes to implementation. These MPPT techniques have problems such as slow response and steady-state oscillations; therefore, they might not be able to track the MPP properly, especially when there are variable environmental conditions. Another approach that can be used for MPPT applications is the FLC. In comparison to traditional MPPT controllers, the FLC has a high response and less oscillation, making it one of the most powerful intelligent controllers for PV systems. Furthermore, it has been regarded as a powerful tool to deal with nonlinearities and uncertainties in a system. Nevertheless, one major disadvantage of this method is the drift phenomenon caused by changing irradiation levels or temperatures. The reason behind this is FLC's dependency on PV systems knowledge, which can cause membership functions to be inaccurate. Table 1 presents the comparative features of the MPPT techniques explored in previous researches.

Table 1 : features in MPPT techniques

Reference	**Discussed MPPT technique**	**Convergence speed**	**Implementation complexity**	**Periodic tuning**	**Sensed parameters**
[7]	Perturb & observe	Varies	Low	No	**Voltage**
[8]	Incremental conductance	Varies	Medium	No	**Voltage, current**
[9]	Fractional V_{oc}	Medium	Low	Yes	**Voltage**
[10]	Fractional I_{sc}	Medium	Medium	Yes	**Current**
[11]	Fuzzy logic control	Fast	High	Yes	**Varies**
[12]	**Neural network**	**Fast**	**High**	**Yes**	**Varies**

2. RECENT LITERATURE SURVEY

In recent years, a wide spectrum of advanced Maximum Power Point Tracking (MPPT) techniques has been explored to enhance the energy extraction efficiency of photovoltaic (PV) systems, particularly under partial shading and variable environmental conditions. Rezk et al. [10]conducted a comprehensive statistical analysis of 20 global optimization- based MPPT algorithms, providing a solid foundation for selecting effective strategies under non-uniform irradiance. Complementing this, Alik and Jusoh [13] enhanced the traditional P&O algorithm with a novel checking mechanism that accurately identifies the global MPP, achieving high efficiency in both simulation and hardware testing. To improve dynamic response, Alaas et al. [8] introduced a fuzzy gain-scheduled PID controller optimized using a modified fluid search algorithm, combining intelligent control with classical PID for fast and accurate MPPT. Similarly, Manna et al.[14] proposed a two-stage hybrid MPPT method using P&O

and an enhanced MRAC (EMRAC), ensuring rapid convergence (0.11 s) and high efficiency under changing irradiance. Further, their follow-up study [11] on adaptive MRAC MPPT demonstrated even faster tracking (3.6 ms) with superior accuracy over conventional methods. Mohanty et al [15] provided a modeling-based comparison of various MPPT techniques under multiple scenarios, highlighting the importance of context-specific method selection. Expanding this approach, Sulthana et al. [16]developed a hybrid MPPT algorithm combining P&O and a look-up table (LUT), achieving 99.31% efficiency and emphasizing the growing trend of hybridization for better performance under rapidly changing conditions. Addressing shading effects, Badea et al. [9] applied the Levenberg- Marquardt algorithm and curve fitting to analyze MPPT under diverse shading patterns, stressing the need for adaptive approaches to mitigate shading-induced losses and potential hotspots. Intelligent and soft computing-based methods were thoroughly reviewed by Saxena et al [12], who compared ANN, PSO, FLC, and FDDL techniques. Their analysis showed ANN's strength in varying irradiance, PSO's efficiency in minimizing switching losses, and FDDL's ability to reduce THD—suggesting that hybrid or tailored solutions are often most effective. Returning to simplicity, Alik and Jusoh [7] proposed a low-cost microcontroller-compatible modified P&O algorithm with a peak-checking mechanism that achieved 100% tracking efficiency, ideal for resource-limited environments. Focusing on low-power applications, Raj et al. [17]integrated MPPT with ZETA and SEPIC DC–DC converters using soft switching and demonstrated notable efficiency gains (up to 7.23%), underscoring the importance of aligning MPPT strategies with converter hardware. Lastly, Gusev et al. [18] introduced a Fuzzy Particle Swarm Optimization (FPSO) algorithm designed for temperate climates, validated through experimental data in Russia. Their results confirmed strong predictive accuracy (correlation coefficient 0.933), demonstrating the role of climate-aware MPPT strategies. The following outcome can be set from the review

- **Global Optimization Improves Selection:**
  Statistical analysis of 20 global optimization-based MPPT algorithms (Rezk et al.) provides a strong foundation for selecting effective strategies under non-uniform irradiance.
- **Enhanced P&O Achieves High Efficiency:**
  Modifications to the traditional Perturb and Observe (P&O) algorithm (Alik and Jusoh) with novel peak-checking mechanisms lead to high simulation and hardware efficiency.
- **Intelligent Controllers Improve Dynamic Response:**
  Fuzzy gain-scheduled PID controllers optimized with a modified fluid search algorithm (Alaas et al.) significantly enhance tracking speed and accuracy.
- **Hybrid MPPT Techniques Ensure Faster Convergence:**
  Two-stage hybrid approaches like P&O combined with enhanced MRAC (Manna et al.) achieve very fast convergence times (as low as 3.6 ms) and high efficiency.
- **Context-Specific Method Selection is Crucial:**
  Modeling-based comparisons (Mohanty et al.) show that no single MPPT technique is universally best; performance depends on specific conditions (shading, temperature, irradiance).
- **Hybridization Becomes a Strong Trend:**
  Hybrid MPPT methods (e.g., P&O + LUT by Sulthana et al.) achieve very high efficiencies (~99.31%), indicating that hybrid algorithms outperform single methods under dynamic conditions.

- **Advanced Techniques Mitigate Shading Effects:**
  Adaptive techniques like curve fitting and Levenberg-Marquardt algorithms (Badea et al.) help address power losses and hotspots due to partial shading.
- **Soft Computing Methods are Effective but Situation-Dependent**: Techniques like ANN, PSO, FLC, and FDDL (reviewed by Saxena et al.) offer advantages such as:
  i. ANN: Best for rapidly changing irradiance.
  ii. PSO: Good for minimizing switching losses
  iii. FDDL: Effective for reducing Total Harmonic Distortion (THD).
- **Simplified Low-Cost Methods Remain Valuable**
  For resource-limited environments, low-cost modified P&O algorithms with peak- checking (Alik and Jusoh) can achieve 100% tracking efficiency.

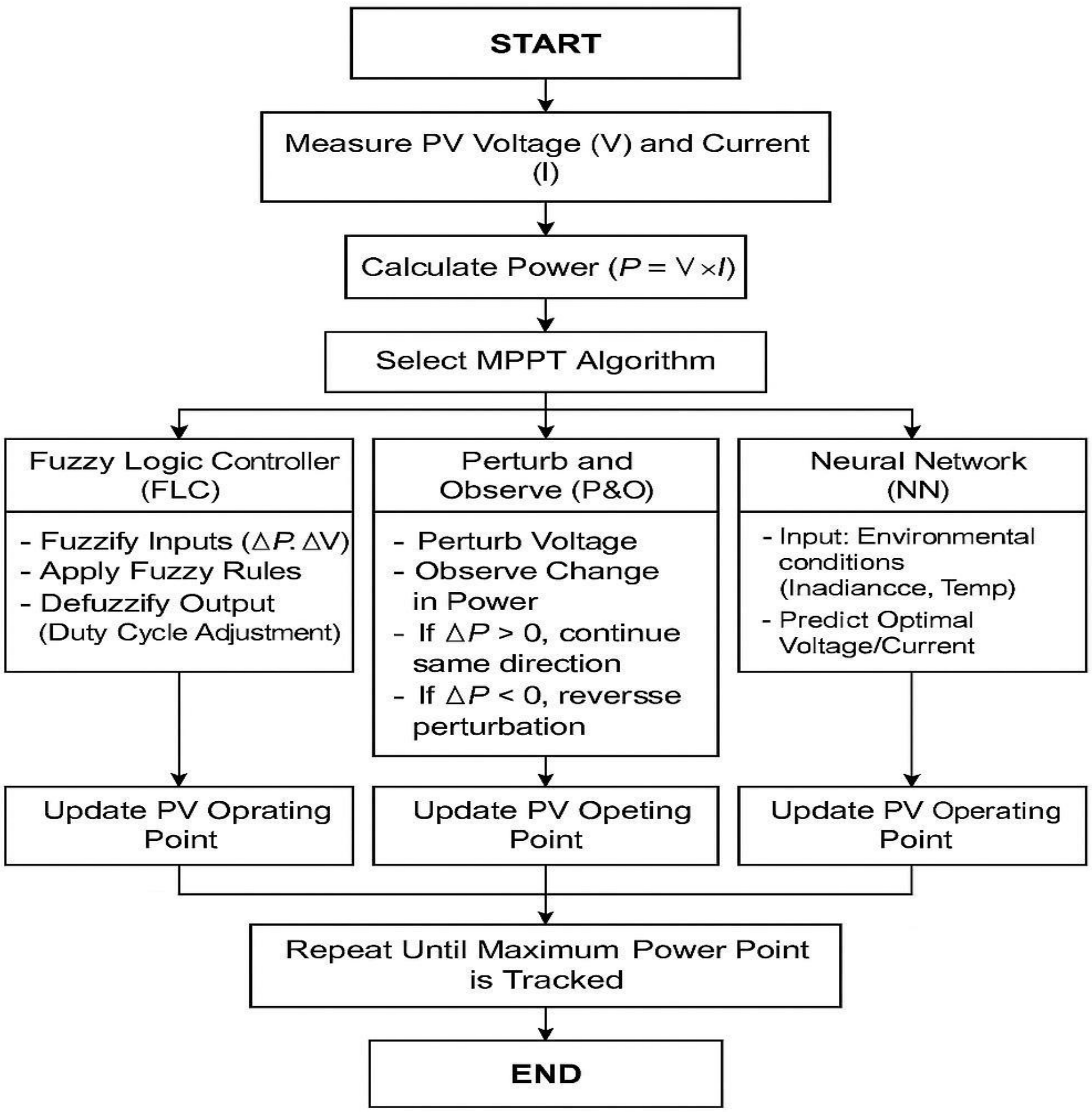

Figure 3: Combined flowchart of conventional and intelligent MPPT techniques

- **Integration with Converter Design Boosts Efficiency:**

Integrating MPPT with converters like ZETA and SEPIC (Raj et al.) improves system efficiency by up to 7.23%, showing the importance of matching MPPT control with hardware.

- **Climate-Specific MPPT Strategies are Beneficial:**
  Climate-adapted MPPT algorithms (Gusev et al.) such as Fuzzy PSO demonstrate strong predictive performance (correlation coefficient 0.933), highlighting the importance of regionally tailored MPPT designs.

To implement the MPPT algorithms a common approach can be followed with all the different MPPT techniques, based on the literature survey figure 3 presents a flowchart which helps in understanding the working principle and control steps involved in different MPPT techniques, providing a comparative view of how traditional methods (like P&O and HC), optimization-based methods (like INC), and intelligent methods (FLC and Neural Networks) operate to track the maximum power point in a photovoltaic (PV) system.

3. CONCLUSION

The efficiency of photovoltaic systems can be significantly improved through effective Maximum Power Point Tracking (MPPT) techniques. Traditional methods such as Perturb and Observe (P&O) and Incremental Conductance (INC) provide foundational approaches but suffer from challenges like oscillations and reduced performance under dynamic environmental conditions. Recent advancements have demonstrated that intelligent controllers, hybrid MPPT strategies, and global optimization algorithms offer superior performance by combining the strengths of multiple methods. Key trends include the adoption of fuzzy logic control, the hybridization of algorithms for faster convergence and improved tracking, and the development of climate-specific MPPT solutions. Moreover, integrating MPPT design with converter hardware further enhances system efficiency. However, the choice of an MPPT technique must be context-specific, as no single method universally outperforms others under all conditions. This review underscores the growing importance of adaptive, intelligent, and hybrid MPPT strategies to meet the evolving challenges of modern PV systems, especially under partial shading and rapidly changing irradiance.

References

[1] D. Mathew and R. C. Naidu, “A review on single-phase boost inverter technology for low power grid integrated solar PV applications,” *Ain Shams Engineering Journal*, vol. 15, no. 2, p. 102365, Feb. 2024, doi: 10.1016/J.ASEJ.2023.102365.

[2] V. Sumathi, R. Jayapragash, A. Bakshi, and P. Kumar Akella, “Solar tracking methods to maximize PV system output – A review of the methods adopted in recent decade,” *Renewable and Sustainable Energy Reviews*, vol. 74, pp. 130–138, Jul. 2017, doi: 10.1016/J.RSER.2017.02.013.

[3] R. K. Kharb, S. L. Shimi, S. Chatterji, and M. F. Ansari, “Modeling of solar PV module and maximum power point tracking using ANFIS,” *Renewable and Sustainable Energy Reviews*, vol. 33, pp. 602–612, May 2014, doi: 10.1016/J.RSER.2014.02.014.

[4] M. Mao, L. Cui, Q. Zhang, K. Guo, L. Zhou, and H. Huang, "Classification and summarization of solar photovoltaic MPPT techniques: A review based on traditional and intelligent control strategies," *Energy Reports*, vol. 6, pp. 1312–1327, Nov. 2020, doi: 10.1016/J.EGYR.2020.05.013.

[5] A. Z. Arsad, A. W. M. Zuhdi, A. D. Azhar, C. F. Chau, and A. Ghazali, "Advancements in maximum power point tracking for solar charge controllers," *Renewable and Sustainable Energy Reviews*, vol. 210, p. 115208, Mar. 2025, doi: 10.1016/J.RSER.2024.115208.

[6] S. Manna, D. K. Singh, M. H. Alsharif, and M. K. Kim, "Enhanced MPPT approach for grid- integrated solar PV system: Simulation and experimental study," *Energy Reports*, vol. 12, pp. 3323–3340, Dec. 2024, doi: 10.1016/J.EGYR.2024.09.029.

[7] R. Alik and A. Jusoh, "An enhanced P&O checking algorithm MPPT for high tracking efficiency of partially shaded PV module," *Solar Energy*, vol. 163, no. November 2017, pp. 570–580, 2018, doi: 10.1016/j.solener.2017.12.050.

[8] Z. Alaas, Z. M. S. Elbarbary, A. Rezvani, B. N. Le, and M. khaki, "Analysis and enhancement of MPPT technique to increase accuracy and speed in photovoltaic systems under different conditions," *Optik (Stuttg)*, vol. 289, no. July, pp. 1–20, 2023, doi: 10.1016/j.ijleo.2023.171208.

[9] A. M. Badea, D. Manaila-Maximean, L. Fara, and D. Craciunescu, "Maximizing solar photovoltaic energy efficiency: MPPT techniques investigation based on shading effects," *Solar Energy*, vol. 285, no. October 2024, 2025, doi: 10.1016/j.solener.2024.113082.

[10] H. Rezk *et al.*, "A novel statistical performance evaluation of most modern optimization- based global MPPT techniques for partially shaded PV system," *Renewable and Sustainable Energy Reviews*, vol. 115, no. August, 2019, doi: 10.1016/j.rser.2019.109372.

[11] S. Manna *et al.*, "Design and implementation of a new adaptive MPPT controller for solar PV systems," *Energy Reports*, vol. 9, pp. 1818–1829, 2023, doi: 10.1016/j.egyr.2022.12.152.

[12] A. Saxena, R. Kumar, M. Amir, and S. M. Muyeen, "Maximum power extraction from solar PV systems using intelligent based soft computing strategies: A critical review and comprehensive performance analysis," *Heliyon*, vol. 10, no. 2, 2024, doi: 10.1016/j.heliyon.2023.e22417.

[13] R. Alik and A. Jusoh, "Modified Perturb and Observe (P&O) with checking algorithm under various solar irradiation," *Solar Energy*, vol. 148, pp. 128–139, 2017, doi: 10.1016/j.solener.2017.03.064.

[14] S. Manna, D. K. Singh, M. H. Alsharif, and M. K. Kim, "Enhanced MPPT approach for grid- integrated solar PV system: Simulation and experimental study," *Energy Reports*, vol. 12, no. July, pp. 3323–3340, 2024, doi: 10.1016/j.egyr.2024.09.029.

[15] P. Mohanty, G. Bhuvaneswari, R. Balasubramanian, and N. K. Dhaliwal, "MATLAB based modeling to study the performance of different MPPT techniques used for solar PV system under various operating conditions," *Renewable and Sustainable Energy Reviews*, vol. 38, pp. 581–593, 2014, doi: 10.1016/j.rser.2014.06.001.

[16] S. M. Sulthan, D. Devaraj, S. R. B., M. M. O., and V. Raj, "Development and analysis of a Two stage Hybrid MPPT algorithm for solar PV systems," *Energy Reports*, vol. 9, pp. 1502– 1512, 2023, doi: 10.1016/j.egyr.2023.07.006.

[17] A. Raj, S. R. Arya, and J. Gupta, "Solar PV array-based DC–DC converter with MPPT for low power applications," *Renewable Energy Focus* , vol. 34, no. September, pp. 109–119, 2020, doi: 10.1016/j.ref.2020.05.003.

[18] G. N. Gusev, O. V. Zhdaneev, M. E. Gainullin, A. Y. Argastsev, and D. N. Lapkin, "Solar PV system with maximum power tracking," *Int J Hydrogen Energy*, vol. 87, no. March, pp. 258–267, 2024, doi: 10.1016/j.ijhydene.2024.08.441.