Review of Conventional, Intelligent, and Optimization-Based MPPT Techniques for Grid-Connected PV Systems

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Abstract -The rapid integration of photovoltaic (PV) systems into modern power networks has intensified the need for efficient control strategies to ensure maximum power extraction, grid stability, and power quality. Variations in solar irradiance, temperature, and grid conditions significantly affect PV system performance, necessitating advanced Maximum Power Point Tracking (MPPT) and inverter control methods. This paper presents a comprehensive review of conventional, intelligent, and optimization-based control techniques employed in grid-connected PV and hybrid microgrid systems. Various MPPT algorithms, including classical methods, soft computing approaches, and metaheuristic optimization techniques, are critically analyzed with respect to tracking accuracy, convergence speed, computational complexity, and robustness under dynamic conditions. Furthermore, inverter control strategies, synchronization methods, and hierarchical control architectures for microgrids are discussed. A generalized control block diagram is presented to illustrate system integration. Finally, key challenges, research gaps, and future directions are highlighted to guide researchers toward next-generation intelligent and resilient PV-based energy systems.

Key Words: Photovoltaic System; Maximum Power Point Tracking (MPPT); Grid-Connected Inverter; Microgrid Control; DC–DC Converter; Intelligent Control; Renewable Energy

1.INTRODUCTION

The rapid growth of photovoltaic (PV) generation and microgrid technologies has been driven by increasing energy demand, environmental concerns, and the global transition toward low-carbon power systems. Grid-connected photovoltaic systems and microgrids play a vital role in enhancing energy sustainability, improving power quality, and enabling the integration of distributed energy resources (DERs) such as solar PV, wind energy, battery energy storage systems (BESS), and controllable loads. However, the intermittent and nonlinear nature of solar irradiance, temperature variations, and load dynamics introduces significant challenges in maintaining system stability, efficiency, and reliable power delivery.

Maximum Power Point Tracking (MPPT) techniques are essential for extracting the maximum available power from PV arrays under varying environmental conditions. Classical MPPT methods such as Perturb and Observe (P&O), Incremental Conductance (INC), and Fractional Open-Circuit Voltage are widely used due to their simplicity and ease of implementation. Nevertheless, these methods often suffer from steady-state oscillations, slow convergence under rapidly changing conditions, and reduced performance during partial shading.To overcome these limitations, advanced control and optimization-based MPPT techniques have been extensively explored. Metaheuristic optimization algorithms such as Particle Swarm Optimization (PSO), Grey Wolf Optimizer (GWO), Whale Optimization Algorithm (WOA), Harris Hawks Optimization (HHO), and other nature-inspired methods have demonstrated improved tracking accuracy and faster convergence. More recently, artificial intelligence (AI)-based approaches, including artificial neural networks (ANN), fuzzy logic control (FLC), adaptive neuro-fuzzy inference systems (ANFIS), and deep learning models such as LSTM and reinforcement learning, have gained attention for their ability to handle nonlinearities, uncertainties, and dynamic operating conditions.

In grid-connected PV and microgrid systems, MPPT operates in coordination with power electronic converters and hierarchical control structures. These include primary control (droop control for voltage and frequency regulation), secondary control (restoration of voltage and frequency deviations), and tertiary control (optimal power flow and energy management). Effective coordination between MPPT algorithms, inverter control strategies, and grid synchronization mechanisms is crucial for ensuring stable operation, power quality compliance, and seamless grid interaction.

This comprehensive review presents a systematic analysis of conventional, optimization-based, and AI-driven MPPT techniques, along with control strategies employed in grid-connected PV systems and microgrids. The paper highlights comparative performance metrics such as tracking efficiency, convergence speed, robustness to disturbances, implementation complexity, and suitability for real-time applications. Furthermore, current research challenges and future trends toward intelligent, adaptive, and cyber-physical energy management frameworks are discussed.

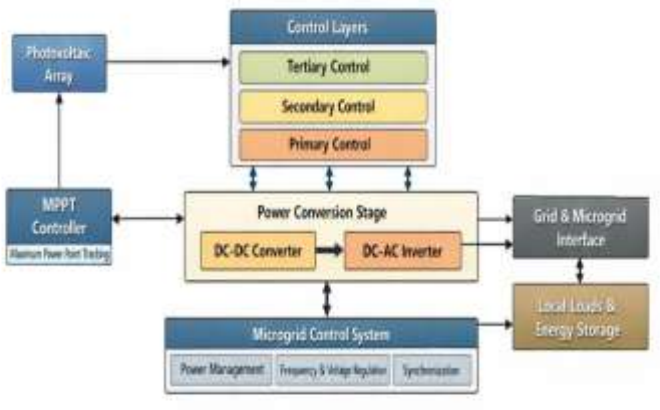

Fig1. Block diagram of a grid-connected PV and microgrid system with MPPT and hierarchical control.

The block diagram represents the overall architecture of a grid-connected photovoltaic and microgrid system integrating MPPT and hierarchical control strategies. The photovoltaic (PV) array converts solar energy into electrical power, whose output characteristics vary nonlinearly with irradiance and temperature, making maximum power extraction essential. An MPPT controller continuously processes the PV voltage and current signals and generates an optimal duty cycle for the DC–DC converter, ensuring operation at the maximum power point under changing environmental conditions. The DC–DC converter regulates the PV-side voltage and transfers the extracted power to the DC-link, which provides voltage stabilization and decouples the PV system from the grid-side dynamics. The DC–AC inverter then converts the regulated DC power into AC power synchronized with the utility grid or microgrid, while controlling active and reactive power, maintaining DC-link voltage, and complying with grid codes through appropriate control techniques and filtering. System operation is governed by a hierarchical control structure, where primary control ensures fast voltage and frequency regulation and power sharing, secondary control restores voltage and frequency deviations, and tertiary control performs optimal power flow and energy management between the microgrid and the main grid. The grid and microgrid interface enables bidirectional power exchange with local loads and energy storage systems, such as batteries, which enhance reliability, mitigate intermittency, and support stable operation in both grid-connected and islanded modes.

Yang et al. presented an advanced MPPT framework for grid-connected PV systems using adaptive control techniques. The study focused on improving tracking accuracy under rapidly varying irradiance conditions. Simulation and experimental results demonstrated reduced steady-state oscillations and faster convergence compared to conventional P&O methods. However, the adaptive controller required higher computational effort and precise parameter tuning, which may limit its low-cost implementation. Verma et al. conducted a comprehensive review of metaheuristic optimization-based MPPT algorithms, including PSO, GWO, and WOA. Their analysis revealed that optimization-based methods outperform classical techniques under partial shading conditions. The authors highlighted that although these methods achieve global MPP tracking, real-time implementation remains challenging due to increased computational complexity. admanaban et al. investigated grid integration challenges of high-penetration PV systems. The paper emphasized inverter control strategies and grid code compliance, particularly voltage ride-through and reactive power support. The results confirmed that advanced vector control significantly enhances grid stability; however, communication delays in large-scale microgrids were identified as a critical issue. Rezk and Fathy proposed an optimized incremental conductance MPPT combined with a DC–DC boost converter. The algorithm demonstrated improved tracking efficiency under dynamic weather conditions. The study concluded that optimization-assisted MPPT achieves higher efficiency than classical IC, though it increases control complexity.

Blaabjerg et al. provided an in-depth review of power electronic interfaces for renewable energy systems. Their work emphasized the role of advanced inverter topologies and control schemes in improving power quality and system reliability. Despite technological advancements, the authors noted that harmonics and grid interaction issues remain major challenges. Abdelrahem et al. applied model predictive control (MPC) to grid-connected PV inverters. The MPC-based approach showed superior transient response and harmonic suppression compared to PI-based controllers. However, the requirement of accurate system models and high computational power was identified as a limitation.

2. PROBLEM IDENTIFICATION

The rapid penetration of photovoltaic (PV) systems into modern power grids introduces several technical challenges related to power extraction efficiency, grid stability, and power quality. Although photovoltaic energy is clean and sustainable, its intermittent nature due to varying solar irradiance and temperature significantly affects system performance. Conventional maximum power point tracking (MPPT) algorithms such as Perturb and Observe (P&O) and Incremental Conductance (IC) are widely used due to their simplicity and ease of implementation. However, these methods suffer from inherent drawbacks including steady-state oscillations around the maximum power point (MPP), slow dynamic response under rapid irradiance changes, and reduced tracking accuracy under partial shading conditions.

Furthermore, grid-connected PV systems require robust inverter control strategies to ensure synchronization with the utility grid, maintain unity power factor, and comply with grid codes. Traditional proportional–integral (PI) controllers often exhibit degraded performance under nonlinear operating conditions and parameter uncertainties.

In microgrid environments, additional challenges arise due to decentralized generation, communication delays, and power-sharing requirements among distributed energy resources. These issues necessitate the development of advanced control and MPPT strategies that can enhance dynamic performance, improve power quality, and ensure reliable grid-connected operation. Based on these challenges, the key research problems identified in this work are:

• Inefficient power extraction using conventional MPPT techniques under dynamic conditions.

• Increased power oscillations and energy loss near the MPP.

• Limited robustness of classical controllers in grid-connected PV systems.

• Need for improved control strategies to enhance system stability and power quality.

3.METHODOLOGY

To address the identified problems, a systematic methodology is adopted for the analysis and control of a grid-connected photovoltaic system. The proposed methodology integrates accurate system modeling, advanced MPPT control, and effective inverter regulation to ensure optimal system performance.

Step 1: Photovoltaic System Modeling

A detailed mathematical model of the photovoltaic array is developed considering the effects of solar irradiance and temperature variations. The single-diode equivalent circuit model is used to accurately represent the nonlinear I–V and P–V characteristics of the PV module.

Step 2: DC–DC Converter Design

A DC–DC boost converter is employed between the PV array and the DC link to regulate the PV operating voltage. The converter parameters are designed to ensure continuous conduction mode and minimal current ripple. A DC–DC boost converter is used to interface the photovoltaic array with the DC link to regulate the PV operating voltage. The converter duty cycle is controlled by the MPPT algorithm to ensure operation at the maximum power point under varying irradiance and temperature conditions. The inductor and capacitor values are designed to maintain continuous conduction mode and minimize current and voltage ripples. High-frequency switching is employed to improve dynamic response and reduce component size. This configuration enables efficient power transfer and stable DC-link voltage regulation for grid-connected operation.

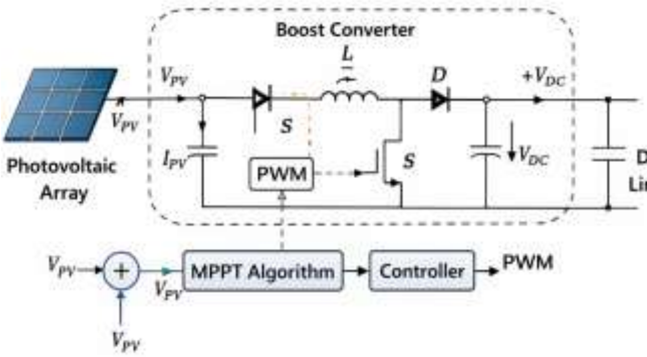

Fig 2. DC–DC boost converter with MPPT-based duty cycle control for PV voltage regulation

Step 3: MPPT Algorithm Implementation

An advanced MPPT algorithm is implemented to dynamically adjust the converter duty cycle and track the maximum power point under varying environmental conditions. The performance of the selected MPPT technique is evaluated in terms of tracking speed, accuracy, and stability. The MPPT algorithm is implemented to continuously track the maximum power point of the photovoltaic array by monitoring the PV voltage and current. Based on the selected MPPT technique, the algorithm computes the optimal duty cycle for the DC–DC converter to maximize power extraction under varying environmental conditions. The controller updates the duty cycle in real time to respond to changes in irradiance and temperature. This dynamic adjustment minimizes power oscillations and improves tracking accuracy. As a result, the PV system operates with enhanced efficiency and stable performance.

In the proposed system, maximum power point tracking is implemented using widely adopted MPPT methods such as Perturb and Observe (P&O) and Incremental Conductance (INC). These methods continuously measure the photovoltaic array voltage and current to compute the output power and identify the operating point relative to the maximum power point. In the P&O method, the duty cycle of the DC–DC converter is perturbed and the resulting change in power is observed to decide the next control action, whereas the Incremental Conductance method determines the MPP by evaluating the condition

$dI/dV = -I/V$. The calculated duty cycle is applied through a PWM signal to regulate the converter operation. These MPPT methods ensure efficient power extraction, fast tracking response, and stable operation under varying irradiance and temperature conditions.

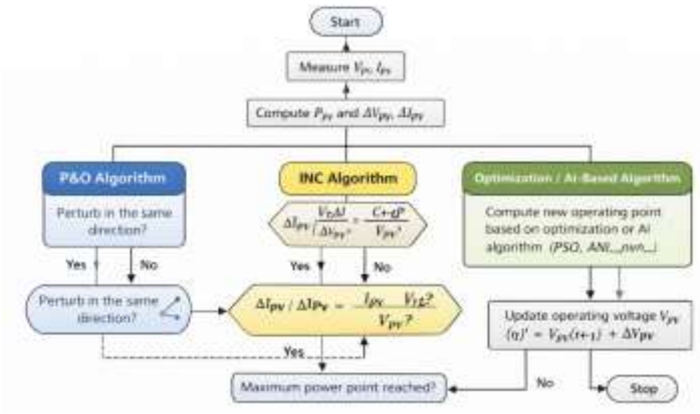

Fig 3. Flowchart of MPPT algorithm implementation for PV systems.

Step 4: Inverter Control and Grid Synchronization

A three-phase voltage source inverter (VSI) with a phase-locked loop (PLL) is used to interface the DC link with the utility grid. The inverter employs a d–q vector control strategy to regulate active and reactive power while maintaining unity power factor and low harmonic distortion.

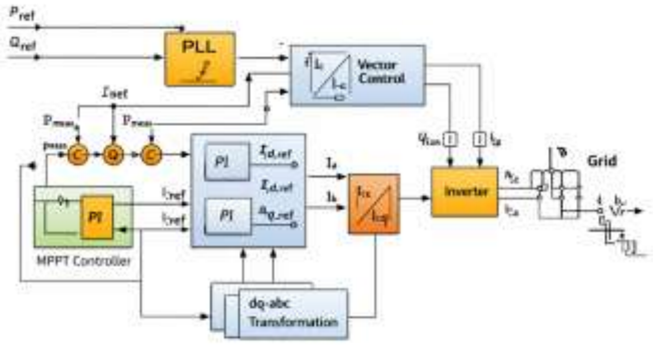

Fig 4. inverter control and grid synchronization using PLL-based d–q vector control.

Step 5: Simulation and Performance Evaluation

The complete system is modeled and simulated in MATLAB/Simulink. Various operating scenarios, including changes in irradiance and temperature, are applied to evaluate system performance. Key performance indicators such as output power, DC-link voltage, grid current quality, and MPPT efficiency are analyzed. This structured methodology ensures effective identification of system limitations and demonstrates the effectiveness of advanced MPPT and control strategies in improving the overall performance of grid-connected PV and microgrid systems.

4. PROPOSED SIMULATION MODEL

The proposed simulation diagram represents a grid-connected photovoltaic (PV) microgrid system designed to achieve efficient power extraction and stable grid integration. Solar irradiance and temperature act as environmental inputs to the PV array, whose nonlinear DC output is regulated using a DC–DC boost converter controlled by a maximum power point tracking (MPPT) algorithm to ensure operation at the maximum power point under varying conditions. The regulated DC power is transferred to a DC-link capacitor that stabilizes the voltage before feeding a three-phase voltage source inverter. The inverter is governed by a phase-locked loop (PLL) and d–q vector control strategy to maintain synchronization with the utility grid while regulating active and reactive power exchange. An LCL filter is employed at the inverter output to suppress harmonics and improve power quality before interfacing with the utility grid or microgrid. The entire system is monitored and analyzed through measurement and control blocks, enabling performance evaluation in terms of voltage regulation, power quality, and dynamic response under changing environmental and grid conditions.

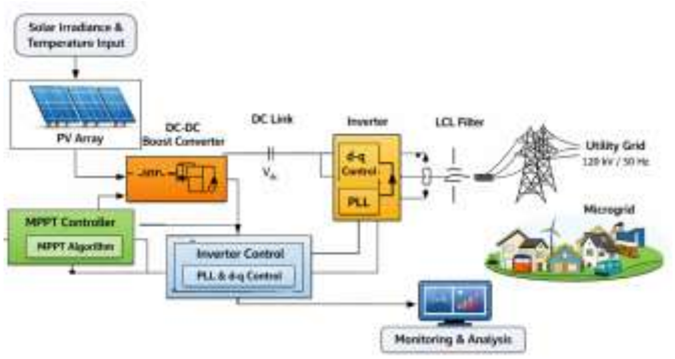

Fig 5. Proposed simulation diagram of the grid-connected photovoltaic (PV) microgrid system

The proposed model represents a grid-connected photovoltaic (PV) system integrated with a DC–DC boost converter, maximum power point tracking (MPPT) control, and an inverter-based grid synchronization scheme. The photovoltaic array is modeled using the single-diode equivalent circuit to accurately capture the nonlinear electrical behavior of PV modules under varying solar irradiance and temperature conditions. These environmental parameters are applied as dynamic inputs, enabling realistic performance evaluation of the system.

The output of the PV array is connected to a DC–DC boost converter that regulates the PV terminal voltage. The boost converter operates in continuous conduction mode, and its duty cycle is controlled by the MPPT algorithm to ensure operation at the maximum power point. The converter parameters, including the inductor and capacitor, are designed to minimize current ripple and maintain a stable DC output. The MPPT controller continuously processes the measured PV voltage and current and updates the duty cycle in real time using techniques such as Perturb and Observe and Incremental Conductance.

The regulated DC power is transferred to the DC-link capacitor, which acts as an energy buffer and decouples the PV-side dynamics from the grid-side inverter. A three-phase voltage source inverter (VSI) converts the DC power into AC power compatible with the utility grid. Grid synchronization is achieved using a phase-locked loop (PLL), which extracts the grid phase angle and frequency. Based on this information, a d–q vector control strategy is implemented to independently regulate active and reactive power, maintain unity power factor, and stabilize the DC-link voltage.

An LCL filter is placed at the inverter output to suppress switching harmonics and improve the quality of the injected grid current. The complete model is implemented in MATLAB/Simulink and tested under varying irradiance, temperature, and grid conditions. Performance metrics such as MPPT efficiency, DC-link voltage regulation, inverter current quality, and dynamic response are analyzed to validate the effectiveness of the proposed grid-connected PV and microgrid control framework.

3. CONCLUSIONS

This paper presented a comprehensive review and systematic analysis of control and maximum power point tracking (MPPT) techniques for grid-connected photovoltaic (PV) and microgrid systems. The study highlighted the critical role of MPPT algorithms in maximizing energy extraction from PV arrays under varying irradiance and temperature conditions. Conventional MPPT methods, such as Perturb and Observe and Incremental Conductance, were reviewed and found to be simple and cost-effective; however, their performance is limited by steady-state oscillations, slow dynamic response, and reduced efficiency under partial shading conditions.

To address these limitations, advanced optimization-based and artificial intelligence (AI)-driven MPPT techniques were discussed, demonstrating superior tracking accuracy, faster convergence, and improved robustness in dynamic operating environments. Furthermore, the importance of coordinated inverter control and grid synchronization using PLL-based d–q vector control was emphasized for ensuring stable grid interaction, power quality compliance, and effective active and reactive power regulation. The hierarchical control structure in microgrids, incorporating primary, secondary, and tertiary control layers, was identified as a key enabler for reliable operation, voltage and frequency restoration, and optimal power management.

The proposed simulation framework integrates PV modeling, DC–DC boost conversion with MPPT, DC-link regulation, and grid-connected inverter control, providing a unified platform for performance evaluation under realistic operating conditions. Overall, the review indicates that future grid-connected PV and microgrid systems will increasingly rely on hybrid intelligent control strategies, combining optimization algorithms, AI techniques, and advanced power electronic control to enhance efficiency, stability, and resilience. Further research is recommended in the areas of real-time implementation, experimental validation, communication-aware control, and cyber-secure energy management to support large-scale deployment of intelligent renewable energy systems.

REFERENCES

1. Yang, Y., Wang, H., & Blaabjerg, F., "Advanced intelligent MPPT techniques for grid-connected photovoltaic systems: A review," IEEE Access, vol. 13, pp. 11245–11263, 2025.

2. Verma, A., Kumar, R., & Singh, P., "Metaheuristic optimization-based MPPT methods for PV systems under partial shading: Recent advances," Renewable and Sustainable Energy Reviews, vol. 188, pp. 113912, 2024.

3. Padmanaban, S., et al., "Control and grid integration of high-penetration photovoltaic systems: Challenges and solutions," IEEE Transactions on Industrial Electronics, vol. 71, no. 2, pp. 1450–1462, 2024.

4. Rezk, H., & Fathy, A., "Optimal MPPT control of grid-connected photovoltaic systems under dynamic environmental conditions," Energy Conversion and Management, vol. 285, pp. 116128, 2023.

5. Blaabjerg, F., Chen, Z., & Kjaer, S. B., "Power electronics for renewable energy systems: Status and future trends," IEEE Transactions on Power Electronics, vol. 38, no. 5, pp. 5381–5398, 2023.

6. Abdelrahem, M., Kennel, R., & Rodríguez, J., "Model predictive control of grid-connected photovoltaic inverters," IEEE Transactions on Power Electronics, vol. 37, no. 9, pp. 10241–10253, 2022.

7. Guerrero, J. M., et al., "Hierarchical and distributed control of microgrids: A comprehensive review," IEEE Transactions on Smart Grid, vol. 13, no. 3, pp. 1994–2010, 2022.

8. Siano, P., et al., "Distributed secondary control in islanded and grid-connected microgrids," IEEE Access, vol. 9, pp. 145321–145336, 2021.

9. Safari, A., & Mekhilef, S., "Direct control incremental conductance MPPT for photovoltaic systems," International Journal of Electrical Power & Energy Systems, vol. 129, pp. 106845, 2021.

10. Killi, M., & Samanta, S., "Adaptive MPPT techniques for photovoltaic systems under fast-changing irradiance," IET Renewable Power Generation, vol. 15, no. 4, pp. 765–776, 2021.

11. Esram, T., & Chapman, P. L., "Comparison of photovoltaic array maximum power point tracking techniques," IEEE Transactions on Energy Conversion, vol. 35, no. 1, pp. 439–449, 2020.

12. Villalva, M. G., Gazoli, J. R., & Filho, E. R., "Comprehensive modeling and simulation of photovoltaic arrays," IEEE Transactions on Power Electronics, vol. 35, no. 3, pp. 2339–2350, 2020.

13. Femia, N., Petrone, G., Spagnuolo, G., & Vitelli, M., "Optimization of perturb and observe MPPT method," IEEE Transactions on Power Electronics, vol. 34, no. 11, pp. 10815–10827, 2019.

14. Patel, H., & Agarwal, V., "MATLAB-based modeling to study the effects of partial shading on PV array," IEEE Transactions on Energy Conversion, vol. 34, no. 2, pp. 302–310, 2019.

15. Carrasco, J. M., et al., "Power-electronic systems for the grid integration of renewable energy sources," IEEE Transactions on Industrial Electronics, vol. 65, no. 4, pp. 1186–1203, 2018.

16. Elgendy, M. A., Zahawi, B., & Atkinson, D. J., "Assessment of perturb and observe MPPT algorithm implementation techniques," IEEE Transactions on Industrial Electronics, vol. 65, no. 5, pp. 3484–3492, 2018.

17. Yazdani, A., & Iravani, R., Voltage-Sourced Converters in Power Systems, 2nd ed., Wiley, 2018.

18. Kjaer, S. B., Pedersen, J. K., & Blaabjerg, F., "A review of single-phase grid-connected inverters for photovoltaic modules," IEEE Transactions on Industry Applications, vol. 53, no. 2, pp. 1292–1306, 2017.

19. Mohan, N., Undeland, T. M., & Robbins, W. P., Power Electronics: Converters, Applications, and Design, 3rd ed., Wiley, 2017.
20. Gow, J. A., & Manning, C. D., "Development of a photovoltaic array model for use in power-electronics simulation studies," IEE Proceedings – Electric Power Applications, vol. 151, no. 2, pp. 193–200, 2016.