Review on AI Based Global Maximum Power Point Tracking MPPT for Grid Connected Photovoltaic System Under Partial Shading Condition

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ABSTRACT

The photovoltaic system is one of the renewable energy devices, which directly converts solar radiation into electricity. The I-V characteristics of PV system are nonlinear in nature and under variable Irradiance and temperature, PV system has a single operating point where the power output is maximum, known as Maximum Power Point (MPP) and the point varies on changes in atmospheric conditions and electrical load. Maximum Power Point Tracker (MPPT) is used to track MPP of solar PV system for maximum efficiency operation. The various MPPT techniques together with implementation are reported in literature. In order to choose the best technique based upon the requirements, comprehensive and comparative study should be available. The aim of this paper is to present a comprehensive review of various MPPT techniques for uniform insolation and partial shading conditions. Furthermore, the comparison of practically accepted and widely used techniques has been made based on features, such as control strategy, type of circuitry, number of control variables and cost. This review work provides a quick analysis and design help for PV systems.

Keywords: Renewable Energy System, Solar Photovoltaic, Solar Power Conversion, Maximum Power Point Tracking, Partial Shading, Global MPPT

I INTRODUCTION

Electrical energy is the backbone of modern industry and an essential tool for modern life. Because of the growing demand for energy and the stress on conventional energy resources with undesirable impact on environment, the industry has been urged to accelerate the researches on alternative energy resources. Among the available alternative energies, Photovoltaic (PV) energy is one of the most promising renewable energies. PV energy is freely available and environment friendly. PV equipment generates electricity without any gas emissions and its operation is virtually silent. Moreover, its is simple in design and requires few maintenances [1], [2]. Its construction as a stand-alone system can provide a large power supply for remote areas, whereas grid-connected PV systems are still quite expensive. PV power systems are now widely being installed around the world and the demand of such power is increasing every year.

As of the end of 2014, the worldwide installed photovoltaic capacity reached 178 gigawatts (GW) and in 2014 it is expected to reach 327 GW at the end of 2015 and at least 400 GW within the next four years. In this context, Algeria has launched an ambitious program to develop renewable energies (REn) in order to diversify energy sources and engage in sustainable energy use [3]. The Algerian energy strategy is mainly based on solar energy development; this choice is motivated by the huge solar potential in the country. PV power should achieve by 2030 more than 37% of national electricity production. However, the realization of PV systems remains a great challenge due to the high installation cost for PV arrays and the related equipment. Furthermore, Photovoltaic energy lack's reliability due to the direct dependence on weather conditions.

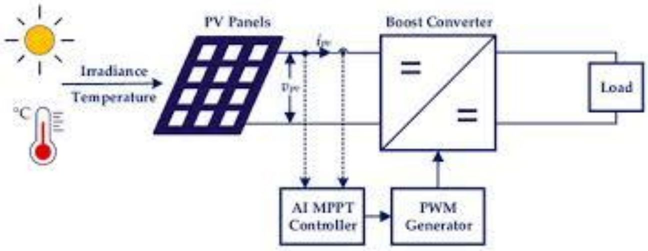

Fig.1. MPPT

Photovoltaic energy comes from conversion of a part of the solar irradiance into electrical energy. This conversion is based on the photovoltaic effect. The PV modules are composed of the series and parallel association of many PV cells. The maximum power point of the PV module changes with the variations of solar irradiance and temperature levels. Because of the high cost of PV modules and their low efficiency (between 10 and 23%) [4], [5], the integration of a robust MPPT controller is necessary; maximum power point tracking (MPPT) consists of extracting the maximum power from the PV generator.

II RESEARCH MOTIVATION

The increasing global demand for clean and sustainable energy has accelerated the deployment of photovoltaic (PV) systems in modern power networks. However, the efficiency of grid-connected PV systems is significantly affected by environmental conditions such as cloud movement, dust accumulation, nearby buildings, and tree shadows, which create partial shading conditions (PSC). Under PSC, conventional Maximum Power Point Tracking (MPPT) techniques often fail to identify the global maximum power point because multiple local peaks appear in the power-voltage characteristics of the PV array. This leads to reduced energy harvesting, lower system efficiency, power losses, and instability in grid-connected operation. Therefore, there is a strong need for intelligent and adaptive MPPT techniques capable of accurately tracking the global maximum power point under dynamic shading conditions. Artificial Intelligence (AI) methods such as Artificial Neural Networks (ANN), Fuzzy Logic, Genetic Algorithms, Particle Swarm Optimization, and Deep Learning provide advanced optimization and prediction capabilities that overcome the limitations of traditional MPPT methods. The motivation behind this research is to develop an AI-based Global MPPT technique that improves power extraction efficiency, enhances tracking speed, minimizes oscillations, and ensures reliable grid integration of photovoltaic systems under partial shading conditions. This research contributes toward improving renewable energy utilization, increasing grid stability, and supporting the transition toward smart and sustainable power systems.

III GLOBAL MAXIMUM POWER POINT TRACKING (GMPPT)

Global Maximum Power Point Tracking (GMPPT) is an advanced control technique used in photovoltaic (PV) systems to extract the highest possible power from solar panels, especially under partial shading conditions. In a PV array, changes in solar irradiance and temperature can create multiple peaks in the power-voltage (P–V) characteristic curve. Conventional MPPT methods may become trapped at a local maximum power point, resulting in reduced energy output. GMPPT techniques are specifically designed to identify and track the global maximum power point, which represents the absolute highest power available from the PV system. These methods continuously monitor PV parameters such as voltage and current and apply intelligent optimization algorithms to ensure maximum energy harvesting. AI-based GMPPT approaches, including Artificial Neural Networks, Fuzzy Logic, Particle Swarm Optimization, and Genetic Algorithms, provide faster convergence, higher tracking accuracy, reduced oscillations, and improved efficiency compared to traditional techniques. Therefore, GMPPT plays a vital role in enhancing the performance, reliability, and power generation capability of grid-connected photovoltaic systems operating under dynamic environmental and partial shading conditions.

IV PHOTOVOLTAIC SYSTEM UNDER PARTIAL SHADING CONDITION

A Photovoltaic (PV) System under Partial Shading Condition refers to a solar power generation system in which some solar panels or cells receive reduced sunlight while others continue to operate under normal irradiance. Partial shading can occur due to clouds, nearby buildings, trees, dust accumulation, poles, or other obstacles that block sunlight from reaching certain sections of the PV array. Under these conditions, the electrical characteristics of the PV system become non-uniform, causing mismatch losses and the formation of multiple peaks in the power-voltage (P–V) curve. This significantly reduces the overall power output and efficiency of the solar system.

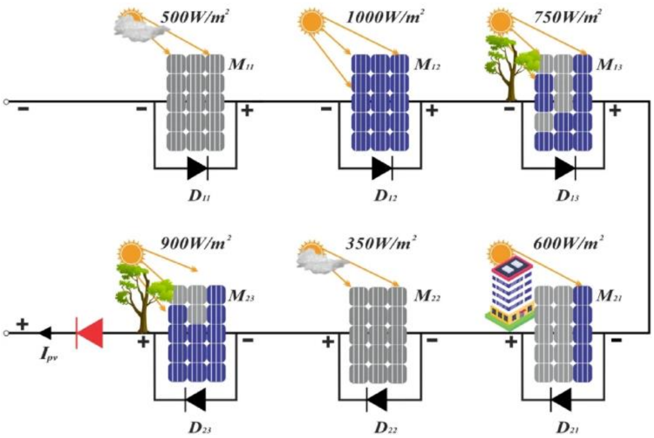

Fig.2. Series configuration of PV array

In grid-connected photovoltaic systems, partial shading may also create instability, overheating, and reduced reliability if not properly managed. Therefore, advanced control and optimization techniques such as Global Maximum Power Point Tracking (GMPPT) and Artificial Intelligence (AI)-based algorithms are widely used to detect the optimal operating point and maximize energy extraction under varying shading conditions. Managing partial shading is an important challenge in modern photovoltaic systems to ensure efficient, stable, and reliable renewable energy generation.

V OBJECTIVES

1. To develop an AI-based Global Maximum Power Point Tracking (GMPPT) technique for grid-connected photovoltaic systems operating under partial shading conditions.

2.To improve the power extraction efficiency and tracking accuracy of the photovoltaic system by identifying the global maximum power point under varying irradiance conditions.

3. To minimize power losses, oscillations, and tracking time in the MPPT process using intelligent optimization algorithms such as Artificial Neural Networks (ANN) or other AI techniques.

4. To evaluate and compare the performance of the proposed AI-based GMPPT method with conventional MPPT techniques in terms of efficiency, response speed, stability, and reliability under partial shading conditions.

VI LITERATURE REVIEW

Karam Khairullah Mohammed et al. [1] Maximizing the power output from photovoltaic (PV) panels is a critical concern in PV system operation, particularly in partial shading conditions (PSCs). While the global maximum power point (GMPP) might not be captured by conventional methods. Consequently, several optimization techniques have been presented for following the GMPP. On the other hand, partial shading cannot be distinguished from uniform shading using optimization techniques. A new hybrid MPPT approach is presented in this paper to overcome this limitation and prevent an unneeded search area of the entire P-V curve via the USCs. If the system is subjected to uniform shading conditions (USCs), an ANFIS technique is suggested for finding the best power point while the irradiance sensor is eliminated in order to reduce costs. Moreover, a modified hybrid levy rat swarm optimization technique (LRSO) has been applied to mitigate the partial shading in order to enhance the convergence speed. Using dSPACE and Micro Lab Box with a sampling time of 0.05 s, the proposed strategy was implemented experimentally. The results illustrated that the suggested strategy had been successfully applied, with uniform and PSCs having a high efficiency of 99.7 % and an average tracking time of 0.34 s. The effectiveness of the suggested approach has been evaluated by contrasting it with the most significant approaches in this domain. Additionally, the suggested approach has been verified with a grid connected to demonstrate the tracking ability under different shading patterns with lower oscillation and fast tracking efficiency.

Rambabu Motamarri et al. [2] Shadowing in photovoltaic (PV) systems often causes significant reductions in power generation. Traditional maximum power point tracking (MPPT) techniques, such as Perturb and Observe and Incremental Conductance, struggle to identify the global peak in the power-voltage (P-V) curve, particularly under partial shading, due to limitations such as longer tracking times and steady-state oscillations. To address these challenges, optimization-based algorithms have been employed for more accurate MPPT. While Particle Swarm Optimization (PSO) has demonstrated effectiveness in this domain, it suffers from high transient fluctuations, poor convergence, and excessive computational time due to intensive parameter involvement and randomness. This study introduces the Magnificent Frigatebird Optimization (MFO) technique, designed to enhance MPPT performance and to reduce the computational effort. The magnificent frigatebird is known for its remarkable soaring ability, quick maneuverability, and energy-efficient hunting techniques, enabling it to fly long distances with minimal effort. Extracting these features, the proposed method is tested on solar PV systems rated at 240 W and 480 W under dynamic irradiance conditions. Extensive numerical simulations and PV emulator investigations are conducted under various shadowing scenarios. A detailed comparative analysis shows that the proposed MFO method achieves faster settling times—40% better than Grey Wolf Optimization, 30% better than Particle Swarm Optimization, 10% better than the Bat Algorithm, and 30% better than Improved Water Cycle Optimization. Computational times per iteration are also evaluated, demonstrating a significantly lower time of 151 μs compared to all other relevant methods discussed in this article.

Panneerselvam Priya et al. [3] Ongoing improvements in MPPT methods are essential for boosting the energy production and cost-effectiveness of solar photovoltaic (PV) systems. This review explores foundational PV modelling approaches, including single-diode, double-diode, and three-diode models that accurately reflect the solar cells' nonlinear properties in different environmental settings. Photovoltaic characteristics are analyzed through P–V and I–V curves across different scenarios, including standard irradiance, partial shading, and dusty environments. MPPT techniques are categorized into single- and multiple-MPPT methods, the latter being essential for distributed systems with multiple local maxima. The study classifies MPPT algorithms into four categories: conventional (P&O, HC, IncCond, etc.), intelligent (FL, ANN, GNT, etc.), optimization-based (PSO, GA, CS, etc.), and hybrid methods (AN-FIS, F-PSO, GWO-P&O, etc.). Each technique is evaluated for accuracy, convergence speed, computational demand, sensors, tracking performance, cost, and environmental adaptability. While conventional methods are simple and cost-effective, they suffer under dynamic conditions. Intelligent and optimization-based methods offer enhanced performance but require significant computational resources and precise data. Hybrid approaches balance speed, robustness, and implementation complexity, making them suitable for real-time systems. The review further explores machine learning-based MPPT methods (SVMs, RL, and

CNNs), hardware constraints, and cost considerations. Special focus is placed on MPPT strategies for emerging technologies like PSCs, which demand tailored control due to unique electrical characteristics. The impact of MPPT algorithms on power quality, especially THD, is also discussed alongside the role of multilevel inverters. Furthermore, the review outlines recent advancements in MPPT research and discusses the gaps in this field. Finally, future directions include the integration of IoT, edge computing, and AI for predictive, adaptive, and high-efficiency MPPT.

Saeed Danyali et al. [4] Today, renewable energy systems like photovoltaic system are widely used in various applications. Among the different types of microgrids, hybrid microgrids are the most used type, therefore, inverters should be used to exchange power between DC and AC sides. According to the existing economic issues, extracting the maximum possible power from these systems are an important issue. This paper presents a new neuro-fuzzy controller for achieving maximum power point tracking (MPPT) in a grid-connected PV system under partially shaded conditions. This controller uses the Gravity Search Algorithm (GSA) to track the global maximum power point (GMPP) of the presented grid-connected PV system. The method controls the grid-connected inverter at the desired voltage to achieve maximum power after receiving its required specifications from the system. The Matlab/Simulink software is used to evaluate the performance of the proposed method. The results show that the proposed method can track the maximum power point under uniform and partial shading conditions with high speed and accuracy. Specifically, the proposed algorithm improves the tracking speed and increases the power output compared to traditional methods. The neuro-fuzzy controller's adaptive capabilities allow it to respond efficiently to dynamic changes in shading, ensuring stable and optimal power output. These advantages make the proposed method a significant improvement over existing MPPT techniques.

Madavena Kumaraswamy et al. [5] Photovoltaic (PV) array reconfiguration is an effective method for enhancing the global maximum power (GMP) and, therefore, improving the array performance. This is attained by alleviating the fluctuations between the rows, resulting in reduced load on Maximum Power Point Tracking (MPPT) devices. However, several current reconfiguration approaches have limitations, such as scalability challenges, inadequate shade distribution, multiple power peaks, increasing mismatch, and other issues, etc. Addressing these issues, this paper presents a static PV array reconfiguration technique based on the Fibonacci-Lucas transform (FLT), which is extensively used in the image encryption concept. The proposed methodology is tested with 9 × 9, 5 × 5 and 4 × 6 PV arrays under twelve distinct shading conditions, and its performance is compared with seven existing techniques. The proposed approach outperforms other methods by minimizing shade dispersion, resulting in significant GMP enhancements of 33.15 %, 14.52 %, 10.65 %, and 4.05 % for 9 × 9 arrays, 32.94 %, 32.73 %, 12.64 %, and 10.98 % for 5 × 5 arrays, and 22.60 %, 22.07 %, and 16.57 % for 4 × 6 arrays across different shading conditions. Additionally, wiring losses associated with the reconfiguration patterns are analysed to ensure practical deployment feasibility. An adaptive neuro-fuzzy inference system (ANFIS)-based MPPT controller for a 250Wp standalone PV system tracks maximum power quickly and with low steady-state oscillations. Integrating reconfiguration with an ANFIS-based MPPT method optimizes PV arrays with rapid and precise MPPT tracking. Hardware set-up a Chroma 62100H-600S programmable solar array simulator is employed for experimental results. ANFIS-based MPPT integrated static reconfiguration requires only two sensors regardless of array size and converges in 0.07s.

Jun Yang et al. [6] Flexible power point tracking (FPPT) enables photovoltaic (PV) systems to provide essential grid support services. However, under partial shading conditions (PSC), the resulting multi-peak power characteristics create a technical bottleneck, where scanning methods ensure robustness but suffer from slow dynamic response; numerical iteration methods are fast but have limited stability. Direct calculation methods offer response speed, but are prone to significant errors due to parameter mismatch. To resolve this conflict, this paper proposes a novel model-free global FPPT method based on I-V curve reconstruction (CR-GFPPT). Unlike traditional black-box AI approaches, this method introduces a physically constrained data-driven gray-box framework. A multichannel neural network (MCNN) is employed to predict the coordinates of key knots, the geometric feature points strictly located on the I-V curve, which are then used to reconstruct the global characteristic curve with high fidelity via shape-preserving interpolation. Furthermore, a step-by-step voltage extraction strategy is developed to address the non-measurability of sub-module voltages, enabling the analytical calculation of the reference voltage without iterative searching. Comprehensive hardware-in-the-loop (HIL) experiments and simulations were conducted to validate the proposed method against state-of-the-art FPPT. The results demonstrate that CR-GFPPT achieves superior steady-state accuracy (error < 0.5%) and realizes fast, non-iterative dynamic response under varying commands, significantly enhancing the reliability of PV systems in active grid support.

SeyedJalal SeyedShenava et al. [7] The declining viability of fossil fuels and their adverse environmental impacts are accelerating the global transition to Renewable Energy Sources (RESs), with solar energy emerging as a key pillar due to its versatility and scalability. Photovoltaic (PV) systems enable direct solar-to-electric conversion but face challenges such as nonlinear behavior and multiple Local Maximum Power Points (LMPPs) under Complex Partial Shading Conditions (CPSCs). This study introduces an enhanced Maximum Power Point Tracking (MPPT) method based on a hybrid Artificial Neural Network–Improved Incremental Conductance (ANN-IINC) model. The ANN is trained using representative datasets capturing diverse shading patterns to estimate optimal reference voltages dynamically, while the IINC module accelerates convergence with reduced oscillations. To validate the proposed method, three CPSC scenarios are simulated and compared with traditional perturb and observe and INC techniques, as well as recent metaheuristic optimization algorithms. Sensitivity and descriptive statistical analyses confirm that the ANN-IINC approach not only achieves faster convergence (81.9 ms) and higher tracking accuracy (up to 99.9096 %) but also reduces standard deviation in power output by 11.3 %–14.8 % compared to classical methods. Furthermore, confidence intervals for efficiency are narrowed by over 20 %, demonstrating improved robustness and statistical significance. The method's computational complexity is optimized, maintaining real-time applicability without sacrificing precision. A comprehensive adaptive analysis and hyperparameter sensitivity study further reinforce the superiority and practical relevance of the hybrid architecture. The study offers a scalable, stable, and efficient solution to the MPPT problem under dynamic environmental conditions. These results highlight the ANN-IINC technique's capacity to outperform both classical and metaheuristic MPPT strategies, contributing meaningfully to the advancement of intelligent PV control under CPSCs.

YuYao Li et al. [8] Solar photovoltaic (PV) system efficiency is highly dependent on Maximum Power Point Tracking (MPPT) technology. Currently, MPPT technology achieves performance optimization mainly through two core approaches: hardware-level reconfiguration strategy and software-level algorithm strategy, whose coordination is key to enhancing PV efficiency. First, this paper constructs a dual-core classification system for topology reconfiguration and control algorithms, dividing 36 topology reconfiguration strategies into 2 major categories and 5 subcategories; 105 control algorithm strategies are classified into 4 types, among which intelligent algorithms are further subdivided into 8 subcategories. Second, conduct a quantitative and qualitative comparative analysis focusing on core indicators such as tracking accuracy, dynamic response speed, local shading adaptability, computational complexity, and hardware cost. For example, results show that under local shading conditions, static topology reconfiguration strategies can reduce mismatch loss by up to 76.3%; compared with conventional algorithms, intelligent algorithms improve tracking efficiency by 10%-47%; hybrid strategies can achieve optimal balance of multiple performance indicators.

Jia Shun Koh et al. [9] In photovoltaic (PV) systems, the inherent non-linear relationship between duty cycle and PV voltage poses a major challenge for effective Maximum Power Point Tracking (MPPT) remains underexplored in existing literature, leading to suboptimal tracking algorithms. This paper introduces the Double-Exponential (DEx) MPPT algorithm to mitigate this non-linearity. The proposed DEx MPPT algorithm reduces tracking points by 77 %, lowering GMPP tracking time while maintaining comprehensive coverage of the entire tracking region.

Renganathan Rani Hemamalini et al. [10] Photovoltaic Systems (PV), while extracting maximum power from PV remains a critical concern. As PV relies on various environmental factors like temperature and solar irradiance, many different Maximum Power Point Tracking (MPPT) techniques are employed and most of the conventional techniques struggle with slow responses and poor performance. Hence, to address these limitations a novel Hybrid Puma Radial - Twin Delayed Incremental Stochastic MPPT Controller (PR-TDISC) is proposed. Instead of functioning continuously, the controller processes and updates the control signal only at discrete sampling intervals. This is mainly due to transient errors and temporary power loss, which cause a major reduction in energy harvesting. To overcome these issues, a novel Puma Optimized Twin Delayed Deterministic Gradient (PO-TDG) is proposed to reduce the Ephemeral Power Dip (EPD), thereby controlling oscillations and stability issues. Further, as tuning of controller faces challenges with Broad Flat regions of local surface, a novel Incremental Stochastic Variational Encoder (IS-VE) is employed, which significantly lowers the complexities with Local Plateau Ceiling (LPC), while reaching the optimal condition. The implementation results illustrate that, when compared to other conventional models, the defined model possesses better MPPT tracking efficiency, reduced convergence time and error rates.

Wulfran Fendzi Mbasso et al. [11] Utility-scale PV plants increasingly operate under partial shading, soiling, temperature swings, and rapid irradiance ramps that depress yield and challenge stability on weak grids. This critical review addresses those conditions by (i) unifying a stressor-to-method taxonomy that links field stressors to global intelligent MPPT (metaheuristics and learning-based trackers) and to advanced inverter controls (adaptive/MPC and grid-forming), (ii) standardizing metrics and reporting aligned with IEC 61724-1 and IEEE 1547/1547.1 to enable fair, reproducible comparisons, and (iii) framing MPPT and grid support as a co-design problem with a DT→HIL→Field validation pathway and seedable scenarios. We identify persistent gaps—fragmented partial-shading benchmarks, limited low-SCR testing, and scarce field-grade validation—and compile a quantitative synthesis: global soiling typically reduces annual production by ≈3%–5%, and hybrid/learning MPPT frequently report ≈99% tracking efficiency under PSC in simulation/HIL studies.

Moazameh Sadeghi et al. [12] Photovoltaic systems experience voltage and power fluctuations under varying irradiance, temperature, and load conditions, which lead to control challenges. To stabilize the output voltage and improve efficiency, a DC–DC boost converter is employed in this study. For fast and accurate maximum power point tracking (MPPT), the Incremental Conductance (IC) algorithm is combined with an adaptive control structure. The proposed framework is based on a Model Reference Adaptive PID Controller (MRAC-PID), which automatically adjusts the controller parameters and guarantees system stability analytically through the Lyapunov function. The control design approach treats the PV-converter system as having structured parametric uncertainty. This means that while the system's general structure (second-order) and the sign of its high-frequency gain are assumed known, its actual parameter values are considered unknown and subject to wide operational variations. This approach eliminates the need for a precise, parameterized mathematical model of the system, which reduces computational complexity and simplifies implementation.

Anci Manon Mary A (Scholar) et al. [13] The rising global electricity demand for green energy has enhanced the integration of non-conventional energy sources with modern power grid. Among various renewable sources, photovoltaic (PV) technology has developed as one of the most assuring solutions because of environmental effectiveness compared to non-renewable power generation. However, the PV systems are extremely sensitive to irradiance changing condition due to nonlinear behaviour. This can be rectified by strong maximum power point tracking (MPPT) methodology to confirm greater power extraction. A various Conventional technique like Perturb and Observe (P&O) and Incremental Conductance (INC) are easy to implement due to steady-state oscillations, slower response and lower accuracy under fast varying circumstances. To overcome these shortcomings, this paper proposed novel Grey Wolf Optimizer (GWO) with Adaptive Learning Deep Neural Network (GWO-AL-DNN) based optimized MPPT controller designed to enrich the performance.

Abdulbari Talib Naser et al. [14] Weather variations present a major challenge for photovoltaic (PV) systems in obtaining the optimal output during maximum power point tracking (MPPT), particularly under partial shadowing conditions (PSCs). Bypass diodes are typically installed across the series-connected PV modules to avoid the occurrence of the hotspots. Consequently, the power curve exhibits several local peaks (LPs) and one global peak (GP). The conventional MPPTs typically become stuck in one of these LPs, presenting a significant decrease in both the power output and overall efficiency of the PV system. A major constraint of several optimization techniques is their inability to differentiate between the irradiance fluctuations and load alterations. In this study, we analyze seven different methods for MPPT.

Naveen Bhati et al. [15] The present state of Maximum Power Point Tracking (MPPT) techniques face challenges in accurately tracking the Global Maximum Power Point (GMPP) under non-uniform conditions. Swift transitions between operational points, significant transient fluctuations, and imprecise tracking contribute to notable power losses. To address these issues, a novel modified Perturb and Observe (P&O) algorithm is proposed. It mitigates persistent oscillations and enhances tracking accuracy in photovoltaic (PV) systems. Compared to traditional P&O and incremental conductance methods, the proposed algorithm achieves approximately 9.52 % higher average MPPT efficiency. Even under challenging conditions like partial shading, it maintains superior performance with faster tracking and less complexity.

VII CONCLUSION

In conclusion, the review of AI-based Global Maximum Power Point Tracking (GMPPT) techniques for grid-connected photovoltaic systems under partial shading conditions demonstrates that conventional MPPT methods are unable to consistently achieve maximum power extraction due to the presence of multiple local peaks in the PV characteristics. Partial shading significantly affects the efficiency, stability, and reliability of photovoltaic systems, making intelligent optimization methods essential for modern solar energy applications. The literature review highlights that Artificial Intelligence techniques such as Artificial Neural Networks (ANN), Fuzzy Logic, Genetic Algorithms, Particle Swarm Optimization, and Deep Learning provide superior tracking accuracy, faster convergence speed, reduced oscillations, and improved adaptability under dynamic environmental conditions. These AI-based approaches effectively identify the global maximum power point and enhance overall system performance compared to traditional methods. Furthermore, recent research trends focus on hybrid optimization techniques, real-time implementation, and smart grid integration to improve renewable energy utilization. Therefore, AI-based GMPPT techniques represent a promising solution for increasing the efficiency and reliability of grid-connected photovoltaic systems operating under partial shading conditions and contribute significantly toward sustainable and intelligent energy systems.

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