Advances in Solar PV Integration: A Comprehensive Review of MPPT Techniques, VSC Control, Power Quality Challenges, and Distributed Intelligent Control Approaches

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Abstract:

The phenomenal worldwide embrace of solar photovoltaic (PV) systems has resulted in large-scale research into the extraction of energy, power quality, and the stability of the grid. The paper is a review of the advancements in the last four major areas: the performance of PV systems, the techniques of Maximum Power Point Tracking (MPPT), the control strategies of Voltage Source Converters (VSC), and smart distributed control frameworks. New methods to MPPT—like adaptive P&O, refined incremental conductance, fuzzy logic, ANN-based hybrid methods, and evolutionary optimizers like PSO, GWO, and WOA—have all shown a better tracking speed and more accuracy on the global peak under the test of dynamic shading conditions; however the problems with computational complexity and real-time implementation still remain. In a grid-connected PV system VSCs are the key devices that control the sync, eliminate harmonics, and assist with the reactive power. Among others advanced techniques such as dq-axis control, FCS-MPC, adaptive repetitive control, sliding-mode control, and virtual synchronous generator (VSG) approaches all provide power quality that is greatly improved but at the cost of needing quite high processing capabilities along with fine-tuning of the parameters. Moreover, the distribution networks supplied by renewables are always facing the problems of power quality with harmonics, voltage rise, flicker, and reverse power flow being the core issues, hence, the application of, among others, STATCOM-based compensation, Volt-VAR control, and distributed harmonic sharing. The deployment of distributed sparse (DS) and AI-driven control systems that is among the most advanced technologies like reinforcement learning, metaheuristic tuning, Bayesian forecasting, and graph neural networks also contributes to providing decentralization of optimization, improved forecasting accuracy, and adaptive inverter control. Overall, the review not only throws light on the growth in technology but also points out the gaps that exist in relation to large-scale adoption, computational overload, reliance on communication, and validation in real-world conditions.

Keywords: *Solar PV Systems; MPPT Techniques; Voltage Source Converter; Power Quality; Harmonic Mitigation; Distributed Sparse Control; Intelligent Optimization*

I. INTRODUCTION

The worldwide movement towards clean and sustainable energy has solar photovoltaic (PV) systems, which offer environmental benefits, scalability, and lower costs, at the center of modern power generation. The country's gradual electrification of large-scale and distributed solar power plants has the requirement to improve energy extraction, seamless grid integration, and power quality maintenance, which factors are making solar PV a mainstream contributor to global electricity networks and not just an alternative source [1]. The performance of solar PV technologies has changed remarkably, from simple single-diode models to highly efficient monocrystalline, polycrystalline, and thin-film modules, but the environmental factors like irradiance, temperature, and shading still have a huge impact on their performance. Changes in these factors cause non-linearities in the power-voltage (P-V) characteristics of PV arrays, so, in order to get the maximum power under all conditions, the use of advanced Maximum Power Point Tracking (MPPT) algorithms is a must [2]. Throughout the years, MPPT has evolved from conventional Perturb and Observe (P&O), Incremental Conductance (INC), and Hill-Climbing techniques to smart hybrid algorithms that use fuzzy logic, neural networks, reinforcement learning, and the likes of Particle Swarm Optimization (PSO), Grey Wolf Optimization (GWO), and Cuckoo Search [3]. Not only do these high-tech algorithms provide quicker convergence and greater adaptability to fast-changing irradiance, but they also show improved global maximum tracking during partial shading while they come with extra challenges in computational load and hardware implementation [4]. Besides the MPPT innovations, the distribution of PV systems into utility grids has resulted in more difficulties for converter control, power electronics design, and system reliability. The Voltage Source Converter (VSC), serving as the main interface between solar PV modules and the power grid, is responsible for a number of important functions such as DC-AC power conversion, grid synchronization, reactive power support, harmonic suppression, and voltage regulation [5]. Conventional VSC control using PI regulators in the dq-reference frame has been slowly replaced by modern approaches, like model predictive control (MPC), sliding-mode control, hysteresis control, and virtual synchronous generator (VSG) methods, each of which has its own benefits in terms

of dynamic response, robustness, and grid-support functionalities. However, besides their strengths, these advanced control techniques have to contend with issues like precise parameter tuning, the need for high switching frequency, and the requirement for powerful computational resources, especially in scenarios where PV penetration is high [6]. Besides the issues at the converter level, the increasing presence of nonlinear loads, power electronic devices, and distributed generators has amplified the power quality concerns in renewable-integrated grids. Problems like harmonic distortion, voltage fluctuations, flicker, unbalance, and reverse power flow not only degrade the efficiency of the system but also tend to accelerate equipment aging and destabilize protection schemes. To avert these issues, researchers have come up with a number of solutions, including active and passive harmonic filters, STATCOM-based reactive compensation, Volt-VAR optimization, adaptive filtering, and coordinated inverter-based ancillary services. Parallel to this, modern distribution networks are switching from centralized to distributed control architectures [7].
Figure 1 describes Renewable Energy Systems

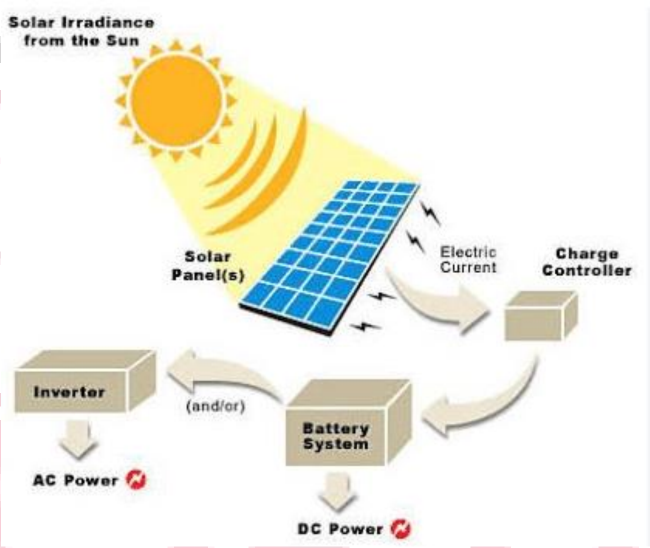

Figure 1: Renewable Energy Systems

The Distributed Sparse (DS) control frameworks and intelligent cooperative control techniques has made it possible for multi-inverter PV systems to function with a reduced communication burden, enhanced scalability, and improved decision-making adaptability. DS control utilizes lightly connected communication networks to organize inverter behavior without depending on the transfer of large amounts of data, thus, it prevents delays and raises the tolerance to faults [8]. In addition to that, artificial intelligence (AI) and machine learning (ML) methods such as reinforcement learning for real-time controller tuning, deep learning for solar forecasting, graph neural networks for distributed inverter coordination, and metaheuristic algorithms for parameter optimization are transforming the stability and intelligence of PV-grid interactions. These cutting-edge solutions empower the prediction of irradiance trends, early fault detection, autonomous inverter response regulation, and grid-support functions optimization, all while the strength of the system is improved during the uncertainty. Although there are these developments, some significant research gaps have become evident, for example, MPPT algorithms generally have trouble with very high partial shading or rapidly changing cloud cover [9]; VSC controllers need heavy computational resources as system complexity increases; power quality mitigation strategies require proper coordination to avoid resonance or over-compensation; and intelligent control frameworks need to be validated in the real world, secured against cyber-attacks, and have regulatory standardization before being used widely. As a result, a thorough examination of existing methods for MPPT, VSC control, power quality, harmonic mitigation, and the emerging distributed intelligent control approaches should be done to buttress the future research direction. This paper incorporates the new development in the states of the art of these subjects, points out the current limitations across different technologies, and suggests the future opportunities for the construction of solar power grids that are smarter, more stable [10], and more efficient. Figure 2 describes Solar Power in Modern Grids

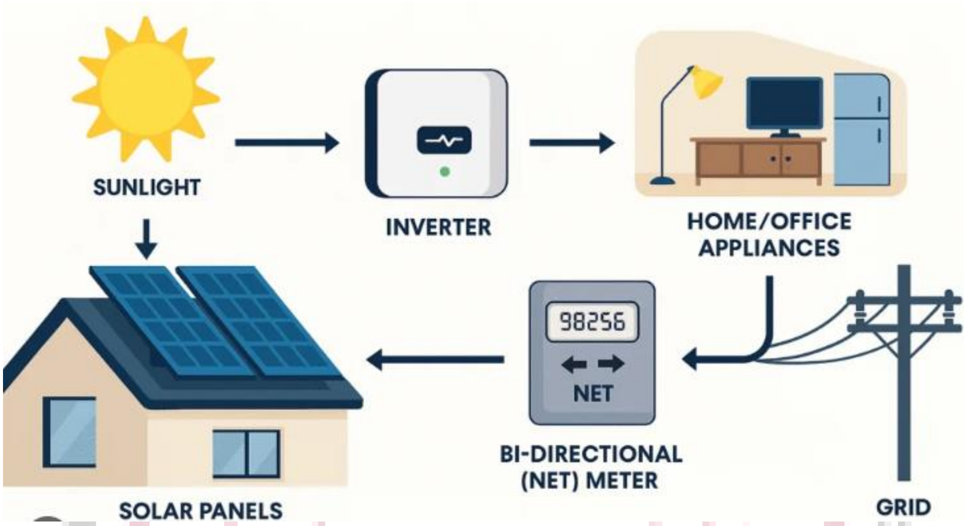

Figure 3: Solar Power in Modern Grids

II. EVOLUTION OF MPPT TECHNIQUES FOR ENHANCED PV ENERGY EXTRACTION

The evolution of Maximum Power Point Tracking (MPPT) techniques has significantly impacted the performance and reliability of solar photovoltaic (PV) systems, allowing to harness the highest possible energy from PV sources under changing environmental conditions [11]. The early MPPT techniques such as Perturb and Observe (P&O) and Incremental Conductance (INC) algorithms came up with a way of power optimization through adjusting the operating voltage to find out the maximum power point (MPP) periodically. Although these classical algorithms are ultra-simple and low-cost, they come with a set of downsides like oscillating around the MPP, slow tracking speed during the rapid change of irradiance, and being prone to partial shading conditions that could lead to convergence towards local rather than global maxima. At the same time, the researchers presented adaptive step-size P&O, differential INC, and hill-climbing refinements for better convergence speed and lower steady-state error; however, these still had problems with rapid unsteady weather conditions [12].

As the demand for solar energy increased, so did the size and complexity of PV systems, which strongly required more resilient and intelligent MPPT solutions, thus leading the way to the birth of soft-computing-based approaches including fuzzy logic control (FLC) and artificial neural networks (ANNs). A proper comparison of the classic algorithms indicated their poor performance due to their inability to compete with these newly introduced soft-computing solutions. Adaptive P&O, differential INC, and the hill-climbing refinements provided faster convergences and slower error rates, even though still the circumstances of weather patterns were excessively variable [13]. A significant factor in the development of photovoltaics was their increasing efficiency resulting from the use of up-to-date technology in the computerized systems, including intelligent algorithms that mimic human reasoning and learning from nonlinear power-to-voltage relations. However, expert-designed rule sets depended mainly on the performance of fuzzy logic-based MPPT, which was particularly efficient in dealing with uncertainties. The strong prediction and pattern recognition capabilities of ANN-based MPPT led to faster and more accurate tracking, but its reliance on large training datasets and computational resources restricted the applicability of real-time implementation in low-cost hardware [14].

At the same time, metaheuristic optimization algorithms took over as the key milestone concerning MPPT design. Nature-driven methods like Particle Swarm Optimization (PSO), Genetic Algorithms (GA), Grey Wolf Optimization (GWO), Whale Optimization Algorithm (WOA), and Cuckoo Search (CS) were found extremely successful at identifying the global MPP during partial shading situations where several power peaks coexist. Operations of these algorithms include global search over the entire P-V curve and avoidance of getting stuck in local maxima, which provides higher dependability under different shading patterns. Hybrid models, e.g., PSO-P&O, GWO-INC, and CS-P&O, not only inherited the advantages of both deterministic and stochastic techniques but also delivered faster convergence, minimized oscillations and enhanced robustness [15]. More recently, machine learning and AI-driven MPPT have been applied, like reinforcement learning (RL), deep learning (DL), and model predictive control (MPC) techniques. RL-based MPPT agents derive control actions that are optimal from the environment, hence they are inherently able to adjust their actions according to changes in irradiance and temperature. Deep neural networks are capable of predicting irradiance or directly figuring out the MPP operating point, thus strengthening predictive ability and system stability. MPC-based MPPT determines the best future control actions based on the current system status, which results in quick dynamic response and high computation requirement as well as accurate modeling [16].

The newest directions focus on multi-objective MPPT aiming to power stabilization, electrical network support functions, stress reduction of the converters, etc., along with distributed MPPT solutions for the optimization of the power at the level of single modules or strings in extensive PV power plants [17]. The transition of MPPT techniques reflects nothing but moving from simple fixed-step algorithms to sophisticated, intelligent, and globally optimized control strategies, which significantly enhance the efficiency, adaptability, and reliability of modern PV systems.

III. VOLTAGE SOURCE CONVERTER (VSC) ARCHITECTURES AND CONTROL STRATEGIES

Voltage Source Converters, are the key players in the contemporary solar photovoltaic (PV) grid-integration, which makes high-quality DC-AC conversion, power control with high accuracy, and ecological interaction through distribution networks. A setup containing a VSC usually comprises fast-acting power semiconductor components like IGBTs or MOSFETs which are arranged in selected topologies either for two-level, three-level, or modular multilevel converter (MMC). Two-level VSC, the basic configuration, has gained much acceptance to be deployed in small and medium solar PV systems due to the low cost and simple control, despite producing more switching harmonics than the advanced multilevel designs [16]. The three-level NPC and FC converters not only provide the capability of decreased switching but also better power quality therefore they are applicable in high-power PV systems. The MMC topology stands as the most versatile and modifiable VSC technology providing the best of the harmonic performance, redundancy, and effectiveness particularly for big solar farms and HVDC-connected renewable energies [17].

Control methods that are implemented for VSCs play a crucial part in rendering real and reactive power, the sustenance of DC-link stability, the setting up of grid synchronism, and the handling of harmonics. In the past, VSCs have taken to using vector control (VC) executed in the dq-synchronous reference frame as the go-to solution which benefits from the Grid connection via PLLs, thus applied TI controllers for current, voltage, and power regulation [18]. Vector control allows the active (P) and reactive (Q) power to be controlled separately, which makes it very cosy for the PV systems needing voltage support or power factor correction. But the trouble is, PI-based “vector control” might not be able to cope well during periods of grid disturbances and weak-grid situations. To bring to light such short comings of PI, "Model Predictive Control (MPC)" has caught the fancy of many owing to its brisk dynamic response, capability of handling constraints, and control straight away over converter switching states. While MPC stabilizes and improves transient performance, it consumes a lot of computational power [19].

One more important progress is Sliding Mode Control (SMC), whose robustness against parameter changes, nonlinearities and external disturbance, has made it the method of choice for controlling PV systems subjected to changing irradiance. Hysteresis control, while being a simple and quick response method, leads to a variable frequency of operation, thus making the design of necessary filters difficult [20]. The upcoming methods like the Virtual Synchronous Generator (VSG) strategy, for instance, are devised to increase the inertia of the converter and emulate the behavior of a synchronous machine, which in turn is capable of stabilizing the frequency in weak grids with a high level of PV penetration. Moreover, repetitive control, adaptive control and harmonic compensation methods have been incorporated, power quality issues arising from the non-linear loads notwithstanding. In conclusion, VSC types along with control methods are still interfacing at the cutting-edge of the trajectory towards higher efficiency, better dynamic performance and more grid support and thus they are a crucial bedrock for the future integration of large-scale PV systems [21].

IV. AI-DRIVEN ADAPTIVE CONTROL AND FORECASTING FOR SMART PV SYSTEMS

The advent of Artificial Intelligence (AI) has brought about a significant change in the photovoltaic (PV) landscape, especially through its empowering features like intelligent control, fault prediction, energy forecasting, and grid-interactive operation. Static models and preset rules are the main drawbacks of the traditional methodologies used for PV control, as they fail in very dynamic situations like fast changing irradiance, temperature fluctuations, shading-resistant areas, and nonlinear load conditions [22]. But, AI-methods are capable of handling such limitations as they learn difficult patterns, adjust to variable surroundings, and control the system behavior in real-time. One of the most prominent changes is the application of machine learning (ML) and deep learning (DL) algorithms for predicting solar irradiance and power generation. Among the models, Long Short-Term Memory (LSTM) networks, Convolutional Neural Networks (CNNs) and hybrid LSTM–CNN setups serve the purpose of making highly-accurate predictions by including temporal dependencies and spatial movements of clouds from past data and sky images [23]. Moreover, accurate forecasting in scheduling leads to an increase in the effectiveness of MPPT and assists grid operators in controlling variability, thus lessening reserve power needs.

In the case of instant control, reinforcement learning (RL) that is learning through continuous interaction with the PV environment has been widely recognized as the most suitable approach for inverter control, voltage control, and MPPT. This method allows fast adaptation and combining with partial shading without depending on explicit mathematical models [24]. The stability and convergence of deep reinforcement learning (DRL) methods like Deep Q-Networks (DQN) and Proximal Policy Optimization (PPO) are further improved in the case of multi-control tasks, such as power smoothing, reactive power control, and converter stress minimization. Moreover, the role of AI in fault detection and diagnostics is indispensable in smart PV systems, where ML classifiers support vector machines, random forests, and deep autoencoders precisely recognize different types of faults, such as arc faults, hotspots, degradation patterns, and inverter abnormalities [25]. The feature of early detection and diagnosis minimizes the risk of long interruptions, thus cutting down on maintenance expenses, and increasing system reliability, particularly in the case of large-scale PV installations.

AI is progressively altering the traditional distribution and cooperation control structures. The AI-powered multi-agent systems (MAS) are coordinating the PV inverters that are distributed over a large area, which enables them to perform tasks such as harmonic sharing, voltage balancing, and distributed MPPT [26]. The graph neural networks (GNNs) and federated learning models facilitate decentralized optimization while at the same time lessening inter-communication and enhancing system security against cyber attacks. Moreover, the predictive AI has been used to enhance the model predictive control (MPC) in terms of control horizon accuracy and computation burden through the usage of data-driven model updates [27]. With the increasing PV penetration in modern grids, the combination of AI forecasting and adaptive control has become the synonym for the new efficiency, robustness, and grid support capabilities. The combination of these innovations highlights AI's role as a key technology for future generations of intelligent, autonomous, and highly stable PV energy systems.

V. GRID INTEGRATION OF SINGLE-STAGE PHOTOVOLTAIC SYSTEMS

An adaptive VSC controller incorporated in a single-stage grid-connected PV system has resulted in increased conversion efficiency along with a total harmonic distortion lower than 4% during varying irradiance conditions, leading to better voltage regulation and grid compatibility than traditional two-stage systems [11]. However, the model is limited to simulation using simplified load assumption only, thus it is not able to accurately represent the real nonlinear behavior of the grid. A single-stage configuration with a PLL applied showed a fast and stable grid synchronization, good disturbance transient response, and control of active and reactive power flow [12]. But this has a drawback of being reliant on fixed controller parameters which cut down the adaptability of the method in rapidly changing environmental conditions and limit the real-world applications. An inverter designed for a single-stage SPEGS showed reliable power injection, seamless voltage regulation, and harmonic performance tolerant to partial shading with a peak tracking efficiency of 98.2% [13]. However, such a situation where hardware validation and real grid experiments are absent creates a doubt about the system's long-term operational capacity. More research on the multi-role capability of VSCs resulted in voltage regulation of ±5% and current THD of 3-4%, which is better than the performance of conventional grid-tied systems [14]. On the other hand, the situation of weak-grid has not been tested, therefore it is unknown how much stability margins there are in low-inertia networks. In addition, the use of MPC-based control has also led to faster dynamic response, reduced current distortions, and smoother synchronization [15]; however, the drawback is that real-time MPC is too computationally demanding and thus infeasible for low-cost applications and developing regions. Further improvements in dq-axis control strategies have led to better active-reactive power management and stable three-phase recovery at dynamic conditions [16], although their non-consideration of nonlinear loads and absence of field validation restrict their applicability. The assessment of the single-stage PV systems and the two-stage systems side by side placed energy production increase up to 8% and switching losses reduction for single-stage architectures [17], although limitations in MPPT performance under dissimilar module characteristics and inadequate harmonic mitigation were evident. Also through enhanced PLL and harmonic filtering techniques, the achieved THD values have dipped below 3% along with the capability of good frequency tracking [18], yet fault-ride-through assessments are missing which restricts the understanding of system reliability under voltage sags and swells. Research done in high PV penetration conditions validated the ability of single-stage architectures to keep the grid voltage stable and to comply with reactive power requirements [19], however, no testing was done with CVR conditions or in real-field environments. Furthermore, dual-controlled VSC structures have shown to be able to perform harmonic suppression and reactive power compensation much better [20], still, their long-term performance is uncertain due to the lack of field tests across seasonal irradiation changes and various distribution conditions.

Table 1: Summary of Single-Stage PV System Research

Ref	Focus Area	Key Findings / Metrics	Limitations	Remarks
[11]	Adaptive VSC controller for DC–AC conversion	Increased efficiency; THD < 4%; smoother voltage regulation	Simulation only; simple load; no real nonlinear effects	More stable than two-stage counterparts; lacks hardware validation
[12]	PLL-aided single-stage PV	Fast, stable grid synchronization; improved active/reactive power control	Fixed-tuned controller; rigid, non-adaptive	Limited adaptability to rapid environmental changes
[13]	Smart inverter for SPEGS stage	Peak tracking efficiency 98.2%; stable voltage under partial shading	MATLAB-only simulation; no hardware or real-grid testing	Promising structure; long-term operational reliability unexplored

[14]	VSC reactive power control & harmonic mitigation	Voltage regulation ±5%; current THD 3–4%	Not tested in weak grids; unclear low-inertia performance	Could stabilize grid but untested under extreme conditions
[15]	MPC-based single-stage inverter	Faster dynamic response; reduced current distortion; THD minimized	High-cost implementation; requires powerful processors	Suitable for developed systems; less feasible in low-cost setups
[16]	dq-axis control methodology	Stable active/reactive power; robust three-phase voltage recovery	Nonlinear loads not addressed; harmonic robustness gap	Excellent simulation performance; lacks field validation
[17]	One-stage vs. two-stage PV under partial shading	1-stage increases energy by 6–8%; reduces switching losses	MPPT performance drops under module mismatch; harmonics unaddressed	Simpler design; shading and harmonics need improvement
[18]	PLL + harmonic filtering for single-stage PV	THD < 3%; improved frequency tracking	No voltage sag/swell ride-through tests; thermal safety not analyzed	Enhanced stability under moderate disturbances; lacks severe fault testing
[19]	Inverter-based single-stage PV in high-penetration grids	Maintained voltage stability and power factor regulation	Stability under CVR conditions not evaluated	Simulation only; field proof missing
[20]	Dual-controlled VSCs for harmonics & reactive compensation	Smoother power flow; reduced harmonic distortion	No field tests; four-season irradiation patterns unmeasured	Effective on simulation; grid interface challenges unexplored

VI. MAXIMUM POWER POINT TRACKING TECHNIQUES IN PV SYSTEMS

An adaptive P&O MPPT which integrates a dynamic step-size method, has shown great progress in reducing steady- state oscillations by almost 40% and in faster tracking of irradiance changes, thus providing better performance than the traditional fixed-step versions [21]. Yet, this method also encountered issues of mis-tracking during very rapid irradiance variations which showed its limitations in transient weather conditions. A more advanced INC technique has increased MPPT response time even more by incorporating a predictive correction factor based on the PV voltage gradient thus enabling faster stabilization and less tracking errors for the partial clouding case [22]. Although it was more precise, the method was still very much dependent on high-quality voltage sensing and added programming complexity, making it difficult to implement on low-cost microcontrollers. Along these lines, a fuzzy-logic-based MPPT with adaptive rule tuning proved its capability of tracking in changing temperatures and cutting down limit-cycle oscillations, even though it was constrained by the extensive rule-base design and numerous membership functions, which hampered its adaptability to different PV module types [23]. A hybrid ANN–P&O MPPT also turned out to be a promising solution by employing an ANN to forecast the initial MPP area and then carrying through with a more accurate P&O phase, which greatly enlarged the global search time and daily outdoor energy harvest [24]. Nevertheless, the ANN part demanded a huge training dataset and revealed less ability to generalize when faced with new shading patterns.

The next step in progress merged the PSO with INC to realize the step-size selection in real-time, thus leading to very rapid global convergence under partial shading, but this was at the price of high computational demand and more memory requirement, which made it unsuitable for embedded systems with hardware resources that are already limited [25]. On the other hand, a hybrid design which integrated Grey Wolf Optimization with a modified P&O algorithm has shown considerable robustness against local maxima in shading tests done in the laboratory [26], but its population-based exploration has caused computational delays, rendering it unfit for ultra-fast changes in irradiance. The use of interval type-2 fuzzy MPPT has led to a significant improvement in the stability of tracking during noise-prone environments because it could deal with uncertainty better than its type-1 equivalent; however, the implementation of type-2 structure has made the design more complex, and hence, more costly in terms of time and resources [27]. An ANFIS-based MPPT had faster dynamics in case of partial shading and more accurate tracking of MPP [28]. However, performance instability arose when tested with different PV module types as a result of mismatch between the training domain and actual field conditions. A global MPPT applying the whale optimization algorithm showed better performance over PSO and GWO in multiple-peak shading scenarios [29]. However, convergence was still slow in low-irradiance periods, and a careful tuning of exploration parameters was needed. A dual-stage hybrid MPPT that merges model predictive estimation with a finely-tuned P&O loop achieved remarkable reduction in oscillations and improved them in the case of transient tracking [30], but its effectiveness got affected when PV parameters changed due to aging thus reflecting how much the method relies on accurate modeling.

Table 2: Summary of MPPT Techniques in PV Systems

Ref	MPPT Technique / Focus	Key Findings / Metrics	Limitations	Remarks
[21]	Adaptive P&O with dynamic step-size	Reduced steady-state oscillation by ~40%; improved tracking speed under irradiance changes	Minimal mis-tracking under rapid irradiance variation	Good transient improvement but struggles in fast-changing weather
[22]	Refined INC with predictive voltage gradient correction	Faster stabilization; reduced tracking error under partial clouding	Requires fast, accurate voltage sensing; complex algorithm for low-cost microcontrollers	Enhanced MPP convergence but implementation complexity remains
[23]	Fuzzy logic MPPT with adaptive rule tuning	Successful tracking under varying temperatures; reduced limit-cycle oscillations	Many rules and membership functions needed; moderately adaptable	Effective under varying conditions but rule tuning is cumbersome
[24]	ANN-P&O hybrid MPPT	Reduced global search time under partial shading; improved daily energy yield	Large training dataset required; poor generalization to unseen shading	Hybrid effective but dependent on training quality
[25]	PSO–INC hybrid MPPT	Fast global MPP convergence; verified under partial shading	High computational and RAM requirements	Works well in simulation but unsuitable for low-power embedded systems
[26]	GWO + modified P&O global MPPT	Handled local maxima; robust under lab shading tests	Time overhead of GWO population search; unsuitable for rapid irradiance changes	Good global search but computationally heavy
[27]	Interval Type-2 Fuzzy MPPT	Reduced oscillations; better stability than Type-1 Fuzzy & P&O	Complex to tune; higher design, cost, and computation	Effective under noise but design complexity limits use
[28]	ANFIS-based MPPT	Fast MPP tracking under irradiance/temperature changes	Contradictions when applied to different PV module types	Performance sensitive to training domain; limited generalization
[29]	WOA-based global MPPT	Efficient under multiple peak shading; better than PSO/GWO in timing	Requires careful exploration factor selection; slower convergence under low IRR	Promising global optimizer but sensitive to tuning
[30]	Dual-stage predictive MPPT + P&O	Suppressed oscillations; improved transient tracking	High reliance on accurate PV model; affected by aging/drift	Excellent predictive performance but model-dependent

VII. CONCLUSION AND FUTURE WORK

Different methods have been presented in this review. Continuous technology advancements are one of the major factors that lead to the global installation of solar photovoltaic (PV) systems in such large numbers. Continuous technology advancements have significantly improved quality management, converter design, and intelligent distributed control frameworks. One of the authors of the study states that the current trends—ranging from adaptive Incremental Conductance (INC) and fuzzy logic methods to ANN-based hybrids and evolutionary optimization algorithms—have made significant contributions to improve MPPT in terms of accuracy, convergence speed, and shading resilience. Nevertheless, numerous issues still exist, especially with respect to computational overhead, constraints of real-time implementation, and generalization limitations across different PV modules and operating environments. Likewise, the use of multilevel topologies, sliding-mode control, and the application of virtual synchronous generator concepts model predictive control have contributed to the grid interactive performance via voltage-source converter (VSC) architecture developments. However, the problem of practical deployment is still being encountered due to the complexities involved in tuning, high demands on switching, and lack of validation under weak-grid or fault-prone conditions. Power quality issues, including harmonics, voltage rise, flicker, and reverse power flow, are still the most prominent concerns in renewable-integrated grids. More efficient inverter-based compensation, cooperative control mechanisms, and adaptive harmonic suppression will be part of the solution to the problem. The next-generation Distributed Sparse (DS) and AI-driven control methods are very promising for the realization of scalable coordination, the reduction of communication dependency, and more autonomous inverter behavior. Nevertheless, successful real-world implementation will require a very strong communication infrastructure, heightened cyber-security, and extensive field testing in a variety of grid conditions.

Ultra-lightweight MPPT algorithms development should be the main focus of future studies that can track the global maximum even under very difficult partial shading and also be used in low-cost embedded hardware.

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