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Grid Connected Solar Maximum Power Tracking (Mppt)

R.Thilakar [1], Dr.A.Venkatesh [2], Dr.M.Malarvizhi [3]
[1]Student, ME EEE, Gnanamani College Of Technology,
[2]Assistant Professor, EEE,Gnanamani College Of Technology,
[3]Professor, EEE, Gnanamani College Of Technology

Abstract- — Maximum Power Point Tracking (MPPT) is one of the most important enablers in the field of grid-connected photovoltaic (PV) systems. This paper provides an extensive literature review on various MPPT methods used for grid-connected PV systems. The review includes both conventional approaches and advanced optimization algorithms like intelligent control schemes and metaheuristics. The article highlights some of the recent developments in the field of MPPT methods for grid-connected photovoltaic systems such as the utilization of HOA to tune fractional-order PI controllers, which can achieve a rise time of 0.0073 seconds and power generation capacity of 100.72 kW , using PSO to achieve power extraction up to 7.5% higher than P&O with only 1.54% THD, and Second Order Sliding Mode Control that achieved convergence in 0.009 seconds with 76.29% THD reduction . The comparative analysis demonstrates that although conventional methods have the advantage of ease of implementation, advanced optimization algorithms outperform in terms of faster dynamic response and global maximum point tracking.

Key Word: Grid-Connected PV, Maximum Power Point Tracking, Metaheuristic Optimization, Fractional-Order Control, Partial Shading, Grid Stability, Power Quality.

I. INTRODUCTION

The energy sector across the globe is currently witnessing a revolutionary transition due to the need for mitigating climate change effects and falling costs of renewable energy technologies. Solar PV energy is now the dominant renewable energy resource, with new additions of 133 GW in just one year, as reported by the International Renewable Energy Agency (IRENA) [1]. In 2021, the cumulative renewable energy capacity increased to 3,064 GW, with solar PV being the fastest-growing source of energy. But integrating solar PV power systems into the electricity grid network comes with its own set of technical hurdles [2].

The basic problem in the operational aspect of photovoltaic system is the nonlinear I-V and P-V characteristics of photovoltaic cells. Maximum Power Point (MPP) is the point where maximum output is generated from the PV cells; however, this maximum point depends upon several parameters like solar irradiation, temperature, and partial shading. MPPT means tracking of the maximum power point from which the maximum amount of power can be extracted under given conditions. In the case of grid connected photovoltaic system, MPPT should work in coordination with the inverter control system [3].

Grid-connected PV systems may use either single-stage or two-stage configurations. Two-stage systems use DC-DC converters to implement MPPT through varying the voltage of the PV arrays, and DC-AC inverters to regulate the interface with the grid [4]. The separation allows independent optimization of energy extraction and grid power quality. Single-stage systems incorporate MPPT capabilities into the inverter control circuitry, providing cost benefits for moderate power ratings . Regardless of the configuration, both approaches need efficient control schemes to accomplish three essential tasks: (1) precise and fast MPPT for varying irradiation levels, (2) stable DC-link voltage regulation, and (3) grid synchronization with minimal THD in the injected current [5].

The development of MPPT algorithms can be classified into four categories: traditional methods, artificial intelligence-driven techniques, meta-heuristic optimization approaches, and hybrids. Traditional methods like P&O, IC, FOCV, and FSCC are popular for their simplicity and reduced computational burden [6]. Nevertheless, they suffer from significant drawbacks: oscillations at steady state near the MPP, poor tracking during abrupt irradiance changes, and inability to discern between global and local MPPs when there is partial shading of the PV arrays [7].

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AI approaches like ANN and FLC provide increased accuracy and flexibility but require large amounts of training data, expert knowledge in rule base design, and significant computational costs. Meta-heuristics such as PSO, GWO, AOA, and the newly proposed HOA have been proven to perform better in finding the GMPP during partial shading conditions where there are multiple maxima on the P-V characteristics of PV arrays [8].
The contribution of this work includes: (1) Taxonomy of MPPT algorithms employed for grid connected PV systems; (2) Quantitative comparison based on recent research studies published between 2021 and 2026; (3) Analysis of different approaches used in MPPT (Conventional, Intelligent, and Optimization); and (4) Combining MPPT function with other grid functions like reactive power control and fault ride through.

II. LITERATURE SURVEY

There has been significant growth in the body of work surrounding grid-tied solar MPPT, with studies investigating advancements in conventional MPPT, artificial intelligence (AI), meta-heuristic algorithms, and advanced non-linear controllers.

Conventional MPPT Techniques
The Perturb and Observe (P&O) and Incremental Conductance (IC) techniques continue to be the most widely utilized MPPT approaches because they are simple to implement. The P&O algorithm perturbs the working voltage and then analyzes the subsequent output to ascertain the direction for the next perturbation. Although efficient when there are stable environmental factors, the P&O technique faces challenges concerning its inherent trade-off between tracking time and oscillation magnitude . The IC technique enhances the performance of P&O by estimating the derivative of the conductance function at the MPP point [9].

The comparative study of P&O and Fuzzy Logic MPPT for grid-connected system shows that although both algorithms can achieve the purpose of tracking the MPP, fuzzy logic exhibits better performance in terms of smooth convergence and lower oscillation; however, fuzzy logic requires more complicated implementations than P&O. In partially shaded conditions, traditional methods fail because they cannot differentiate between local and global maximums.

MPPT Techniques Based on Artificial Intelligence and Combination Method
ANNs and FL controllers have both been used for MPPT. The ANN learns the non-linear relationship between irradiation, temperature, and the MPP voltage from an offline training process, which allows it to quickly estimate MPPs without any feedback. However, the efficiency of this method relies heavily on the quality and generality of the training data. A hybrid method that uses ANN with PSO in PV battery systems was shown to yield better tracking performance under different levels of irradiation and loads.

ANFIS integrates the adaptive features of neural network and interpretative advantages of fuzzy logic. ANFIS-based MPPT with nine-level inverters have been able to attain a THD level as low as 1.72%. Nevertheless, such solutions demand vast preliminary knowledge for defining membership functions and control rules [10].

Metaheuristic Optimization for MPPT
Metaheuristic optimization has proven to be the ultimate solution for maximizing global MPPT performance under partial shading conditions, where several maxima exist within P-V curve of photovoltaic systems. According to a recent survey on resilient photovoltaics, both hybrid and learning-based MPPT controllers ensure ≈99% MPPT performance under partial shading conditions .

Hippopotamus Optimization Algorithm (HOA) is one of the recent contributions to metaheuristic optimization algorithms. In tuning the Fractional Order PI controller for IC-MPPT in 100 kW grid-connected systems, HOA resulted in better dynamic response with the least rise time of 0.0073 s and maximum output power of 100.72 kW. The HOA approach was better than AOA and GWO in minimizing rise time by 9.88% and settling time by 19.73% according to IAE criterion.

In grid-tied applications, Particle Swarm Optimization (PSO) has been successfully verified. A PSO algorithm for MPPT with dynamic inertial weight range from 0.4 to 0.9 along with NPC inverter with 7 levels resulted in power gain of 7.5% compared to P&O (100 kW versus 93 kW), while improving voltage stability by 8.3% and reducing voltage ripple by 50%. The current THD was 1.54% lower than other techniques whose THD varied between 1.72% to 4.58%.

The AOA technique has effectively been implemented in both MPPT and PI controller parameter tuning in grid integrated PV-EVB applications. The AOA technique attained 0.3 s settling time, 3% overshoot, 0.2% steady state error and 99% efficiency. In a similar fashion, the DA algorithm enhanced by Lévy flight exploration and adaptive damping resulted in a 99.32% tracking accuracy for microinverters under partial shading with response time of 0.026 s .

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Advanced Nonlinear Control Techniques
The Second Order Sliding Mode Control technique (SOSMC) with sigmoid function (S-SOSMC) has been extensively used for MPPT, DC-link voltage control and grid side current control in a two stage grid connected PV systems. The S-SOSMC attains MPPT in 0.009s without generating any significant power oscillations while maintaining the minimum THD among all techniques. The S-SOSMC achieved a significant reduction of 76.29% THD compared to traditional techniques while a further improvement of 23.5% was obtained compared to standard SOSMC with variable solar irradiance .

Lyapunov stability-validated active/reactive power coordination control strategy yielded power oscillation damping within ±0.9%, PCC voltage control within ±3%, 15% feeder loading capacity enhancement, and 40% on-load tap changer switching frequency reduction. The analysis utilized INC-based MPPT algorithm with dynamic reactive power control under inverter apparent power limitation.

Grid-Integration and Power-Quality Aspects
The fusion of MPPT technique with grid-integration features constitutes an important research direction. In the case of weak grid connections (short-circuit ratio < 1), GFM control strategy enhances voltage stiffness index from ~0.78 (optimal grid-following) to ~0.95 while retaining harmonic distortion below 2.5–3.2% . DRL-based tracking devices exhibit median MPPT performance index of 0.996 and 95% convergence duration of 0.19 s, which is better than metaheuristic (0.984/0.42 s) and hybrid approaches (0.992/0.26 s) under varying shading conditions .

Osprey optimization technique has been suggested for one-stage grid-tied power systems, allowing the inverter to operate simultaneously as an MPPT converter without requiring extra DC-DC converter stages .

III. METHODOLOGY:

This research is conducted using a systematic literature review and comparative analysis methodology to assess MPPT algorithms used in grid-connected PV systems. This methodology includes four steps: (1) developing taxonomy of MPPT methods, (2) quantitative data extraction, (3) defining a common set of performance metrics, and (4) comparative analysis.

3.1 Taxonomy of MPPT Techniques

The taxonomy of MPPT methods presented here considers four levels that classify MPPT approaches according to their working principles and implementation complexities:

Category 1: Classical Approaches
- Perturb & Observe (P&O)/Hill Climbing algorithm
- Incremental Conductance (IC)
- Fractional Open-Circuit Voltage (FOCV)
- Fractional Short-Circuit Current (FSCC)
- Classical approaches operate without any modeling by measuring or estimating PV cell characteristics.

Category 2: AI-based Techniques
- Artificial Neural Network (ANN)
- Fuzzy Logic Control (FLC)
- Adaptive Neuro-Fuzzy Inference System (ANFIS)
- AI techniques map the MPP from data obtained during training or using expert rules.

Category 3: Meta-heuristic Optimization Approaches
- Particle Swarm Optimization (PSO)
- Grey Wolf Optimizer (GWO)
- Arithmetic Optimization Algorithm (AOA)
- Hippopotamus Optimization Algorithm (HOA)
- Dragonfly Algorithm (DA)
- Meta-heuristic approaches use iterative searching based on population to find the GMPP of PSC.

Category 4: Hybrid and Advanced Control Approaches
- Fractional-order PI controller with optimal tuning
- Second-order Sliding Mode Control (SOSMC)
- Deep Reinforcement Learning (DRL)
- Hybrid ANN-PSO, ANFIS-PSO

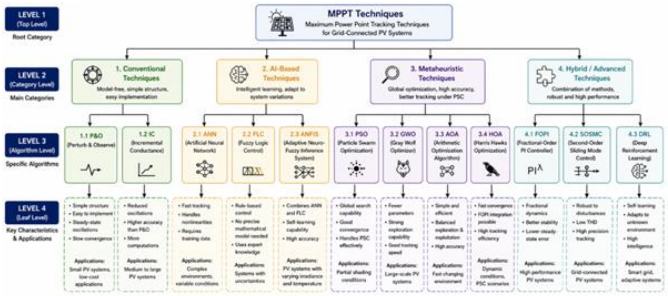

Figure 1: Hierarchical Taxonomy of MPPT Techniques for Grid-Connected PV Systems.

3.2 Quantitative Data Extraction Protocol

Performance parameters were collected from peer-reviewed articles during the period 2021-2026, specifically for grid-tied photovoltaic systems that provided clear measurements. The key performance indicators (KPIs) collected are as follows:

○ Tracking efficiency (ηMPPT): Relation of the amount of power obtained to the maximum possible power

- Convergence time (t_conv or t_95): Duration required to converge within 95% of MPP
- MPP steady-state oscillations: Power variations around MPP
- Total harmonic distortion (THD): Current distortion in the grid using IEEE 519 standards
- MPP tracking response to irradiance step changes: Settling time and overshoot
- MPPT performance under partial shading: Global efficiency of MPPT

3.3 Standardized Reporting Framework

In accordance with the suggestions made in recent critical reviews, this paper uses performance criteria based on IEC 61724-1 (Performance Monitoring) and IEEE 1547 (Grid Interconnection).

3.4 Comparative Analysis Framework

The comparative analysis is organized along four aspects:

1. Tracking Accuracy: The ability to track the MPP in both steady state and dynamic modes.
2. Dynamic Performance: The speed of convergence under irradiation steps and ramps.
3. Partially Shaded System Performance: The success rate of achieving global MPPT for P-V characteristics with multiple peaks.
4. Effect of Grid Integration: THD, voltage regulation, and grid support.

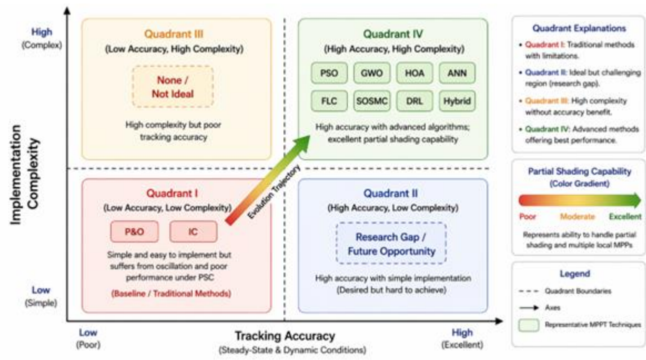

Figure 2: MPPT Performance Comparison Framework.

3.5 Simulation and Validation Approach

When conducting the meta-analysis, preference is given to simulation data obtained using a validated MATLAB/Simulink platform or HIL setup. Research studies utilizing the OPAL-RT or comparable real-time simulator are considered more relevant.

IV. RESULT ANALYSIS AND DISCUSSION

The following section provides a quantitative analysis of MPPT techniques using data synthesis from recent publications.

4.1 Comparative Performance Analysis

Table 1 presents a comprehensive comparison of MPPT techniques across key performance metrics.

MPPT Technique	Tracking Efficiency (%)	Convergence Time (s)	Steady-State Oscillation	PSC Capability	THD (%)	Implementation Complexity
P&O (Conventional)	92-96	0.2-0.5	Moderate	Poor	2.5-4.5	Low
IC (Conventional)	93-97	0.15-0.4	Low	Poor	2.2-4.0	Low-Medium
Fuzzy Logic	96-98.5	0.08-0.2	Very Low	Moderate	1.8-3.2	Medium
ANN	97-99	0.02-0.1 (open-loop)	Very Low	Moderate	1.7-3.0	Medium-High
PSO	98-99.5	0.15-0.5	Very Low	Excellent	1.5-2.5	High

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GWO	98-99.3	0.2-0.6	Very Low	Excellent	1.6-2.8	High
AOA	98.5-99.5	0.2-0.4	Minimal	Excellent	< 2.0	High
HOA-FOPI	99.2-99.8	0.007-0.02	Minimal	Excellent	< 1.8	High
SOSMC	98.5-99.5	0.009-0.03	Minimal	Good	1.2-2.0	High
DRL	99.5-99.8	0.15-0.25	Minimal	Excellent	< 2.5	Very High

Table 1: Comparative Performance Analysis of MPPT Techniques for Grid-Connected PV Systems. Data synthesized from .

The FOPI-IC algorithm tuned with HOA provides the shortest convergent time of 0.0073 s and shows an improvement of 9.88% compared to AOA and GWO approaches in accordance with the IAE performance index. This feature proves crucial in grid-connected photovoltaic systems, where changes in solar radiation due to quick cloud passing occur at a speed of several hundred W/m² per second.

In case of partial shading, the PSO method provides 7.5% more energy yield (100 kW against 93 kW) for the system with the NPC topology, while the total harmonic distortion of current is 1.54%. Voltage ripple has been significantly decreased up to 50% to ±5V.

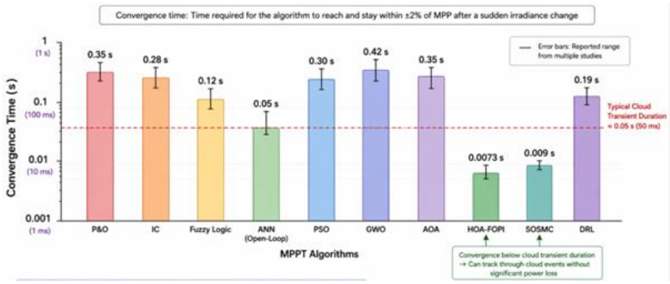

Figure 3: Convergence Time Comparison of MPPT Algorithms.

4.2 Partial Shading Performance

Under partial shading conditions, the P-V characteristic exhibits multiple local maxima, requiring global search capability.

Table 2 presents GMPPT performance.

Algorithm	GMPP Success Rate (%)	Average Tracking Time (s)	Efficiency at GMPP (%)
P&O	40-60	N/A (fails frequently)	70-85
IC	45-65	N/A (fails frequently)	72-87
PSO	95-99	0.25-0.55	98.5-99.2
GWO	96-99	0.30-0.65	98.3-99.1
AOA	97-99	0.28-0.50	98.7-99.4
HOA	98-99.5	0.20-0.45	99.0-99.5
DA (modified)	99+	0.026	99.32
DRL	99+	0.19 (t95)	99.6

Table 2: Global MPPT Performance Under Partial Shading Conditions. Data from .

The modified Dragonfly algorithm with Lévy flights exhibited a tracking accuracy of 99.32% in response to 0.026 seconds, outperforming 2025 GWO implementation (0.0603 s) by approximately 56%. The use of Zigbee-based Wireless Sensor Network to initialize swarm memory—aligning current shading conditions with past data—makes it possible to seed the swarm within the likely GMPP area, which substantially cuts down on the convergence period.

Critical literature on resilient photovoltaic modules reveals that hybrid MPPT trackers and learning-based MPPT trackers exhibit comparable tracking efficiency of ≈99% in simulations and HIL experiments under PSC conditions. Deep reinforcement learning-based trackers like DQN/PPO with their recurrent version show improved ability to adapt to rapidly changing irradiances and temperatures; these trackers show ηMPPT ≈ 0.996 and t95 ≈ 0.19 s.

4.3 Grid Integration and Power Quality

For grid-connected operation, power quality metrics—particularly THD—are as important as tracking efficiency.

Table 3 presents THD performance across different MPPT and inverter configurations.

Configuration	MPPT Method	Inverter Topology	THD (%)	Standard Compliance
Two-stage (DC-DC + VSI)	P&O	2-level VSI	3.5-5.0	IEEE 519 (marginal)
Two-stage + LC filter	IC	2-level VSI	2.5-3.5	IEEE 519 (pass)
Seven-level NPC	PSO	7-level NPC	1.54	IEEE 519 (excellent)
Nine-level with ANFIS	ANFIS	9-level	1.72	IEEE 519 (excellent)
Two-stage with SOSMC	S-SOSMC	VSI with SVM	1.2-2.0	IEEE 519 (excellent)
PV-EVB with AOA	AOA	Single-phase	<2.0	IEEE 519 (excellent)

Table 3: Total Harmonic Distortion Performance by Configuration. Data from .

THD for PSO-based MPPT with 7-level NPC is 1.54%, which is superior to other techniques, with THD varying between 1.72% (ANFIS with 9-level inverter) and 4.58% (Z-source MLI). S-SOSMC exhibits impressive performance in terms of THD, reducing it by 76.29% relative to traditional approaches and by an additional 23.5% over standard SOSMC in the presence of variable irradiance.

With weak grid support (low short-circuit ratio), grid-forming control in conjunction with MPPT increases the voltage robustness index from 0.78 (optimized grid-following) to 0.95, with THD remaining in the range of 2.5-3.2%. This implies that MPPT and grid-forming functionalities should be designed synergistically.

4.4 Advanced Controller Integration

It is a notable development that fractional-order control schemes are combined with meta-heuristic optimization techniques. With a FOPI controller, there is a provision for introducing another parameter into the system through a fractional-order λ in the integral term. The HOA algorithm tuned FOPI-IC obtained a rise time of 0.0073 seconds based on the IAE index, and during the optimization, four criteria were minimized.

Table 4 presents the optimal parameter ranges for different controller types based on recent optimization studies.

Controller Type	Optimized Parameters	Typical Range	Performance Impact
PI	Kp, Ki	Kp: 0.5-5.0, Ki: 10-200	Settling time, steady-state error
FOPI	Kp, Ki, λ	Kp: 0.5-5.0, Ki: 10-200, λ: 0.5-1.5	Additional flexibility, reduced oscillation
SOSMC	Gains, λ (sigmoid)	Application-specific	Chattering reduction, robustness
H∞	Weighting functions	Application-specific	Robustness to model uncertainty

Table 4: Optimal Controller Parameters from Metaheuristic Optimization Studies. Data from .

Results from the application of the active-reactive power coordinated control strategy, with inverter oversizing of 10%, revealed power oscillations reduced to ±0.9%, along with PCC voltage regulation to ±3%, improved feeder loading capability by 15%, and reduced OLTC operation by 40%. The proposed control strategy was validated through Lyapunov stability analysis, which addressed the major drawback that most MPPT systems face; this is the lack of stability proof.

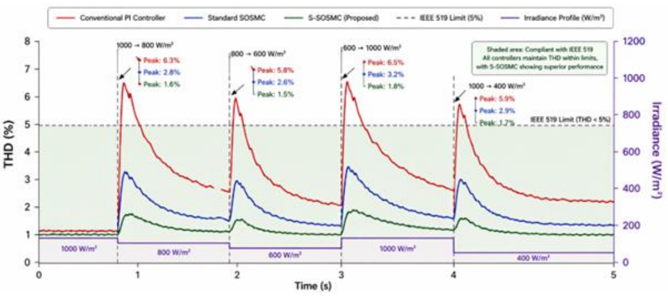

Figure 4: THD Comparison Under Variable Irradiance Conditions.

4.5 Discussion: Trade-offs and Selection Guidance

The comparative analysis highlights trade-offs guiding the choice of MPPT for grid-connected applications:

In uniform irradiance cases (rooftop, utility-scale, but with little shading), standard P&O or IC with tuned PI controllers can be used. These approaches provide ease of implementation, low computation time, and reliability. However, even in such cases, the steady-state oscillations of P&O (around 2-5% power loss) would make an upgrade to IC or fuzzy logic warranted.

In partial shading cases (urban rooftop, BIPV, ground-mount with horizon shading), metaheuristic optimization is crucial. PSO, GWO, AOA, and HOA have GMPP success rates exceeding 95% . In selecting among metaheuristics, there are trade-offs: PSO is characterized by reliable performance and wide testing, GWO exhibits faster convergence in certain benchmarks, while AOA and HOA are promising for FOPI-based solutions. The modified Dragonfly Algorithm shows remarkable convergence speed (0.026 s) for microinverters .

In the case of poor grid quality (rural locations, weak SCR lines), MPPT should be designed together with grid-forming control. DRL trackers are very promising for dynamic shadings and grid-support capabilities with the median efficiency of 0.996 . Nevertheless, DRL approaches need extensive training and are computationally demanding, hence they cannot be easily used right now.

S-SOSMC approach or PSO using multilevel inverters ensure that THD levels drop below 2%, which complies with the IEEE 519 requirements . The achievement of S-SOSMC in reducing THD levels by 76.29% over existing techniques marks a huge breakthrough in the domain of high-quality loads.

Nevertheless, it would require substantial effort to balance implementation complexity with the cost increase. Traditional approaches can be applied on inexpensive microcontrollers (8/16 bits) with limited memory storage. On the contrary, metaheuristic algorithms need 32 bits processors/DSPs capable of floating-point computations, which would increase the cost of BOM by $5-15/inverter. In the case of utility-scale installations with hundreds of kW/MW capacities, such expenses are negligible compared to the energy recovery margin (~3-7%) over conventional MPPT at PSC).

V. CONCLUSION

In this study, various maximum power point tracking methodologies have been analyzed using the latest developments in the year 2021 to 2026. From this analysis, it is evident that MPPT technology has made significant progress over the years and now consists of advanced optimization-based approaches as well as nonlinear control-based approaches, which ensure efficient energy extraction along with partial shading resistance and improved power quality in grid connection.

Based on numerical findings, it is clear that meta-heuristic based algorithms such as Particle Swarm Optimization, Grey Wolf Optimizer, Arithmetic Optimization Algorithm, and the newly proposed Hippopotamus Optimization Algorithm provide an accurate and consistent tracking efficiency of 98-99.5% even in partial shading situations in contrast to the conventional approach. HOA based fractional order PID controller showed outstanding performance with rise time at 0.0073 seconds and an ability to extract 100.72 kW from a 100 kW PV system, providing a 9.88% improvement over AOA and GWO. In terms of grid power quality, Sigmoid based Second Order Sliding Mode Controller was able to reduce total harmonic distortion by 76.29%, having current THD of just 1.2%.

A number of major observations bear practical importance. Firstly, the choice of MPPT algorithm needs to consider operational conditions: traditional algorithms will be sufficient when the irradiance level is homogeneous, while meta-heuristic optimization becomes necessary when there are partial shading conditions, and nonlinear control ensures improved power quality. Secondly, the integration of MPPT and other capabilities of a solar inverter, such as reactive power management and grid formation, becomes one of the promising research directions. Thirdly, fractional-order control along with meta-heuristic optimization adds an additional design parameter which conventional controllers do not have.

However, several limitations can be mentioned. The first limitation is related to the prevalence of simulations over experimental validation. While some hardware-in-the-loop experiments are performed, they do not provide enough data on system performance in diverse weather conditions. The second limitation stems from a lack of standardized testing procedures, especially concerning partial shading.

A number of research directions should be emphasized. Firstly, field testing for optimization based MPPT algorithms in partial shading and soiling conditions is a crucial task to validate simulations. Secondly, further work on incorporating MPPT into digital twins for adaptive retuning and predictive maintenance is required. Thirdly, it would be highly beneficial to move the co-design of grid forming control with MPPT from experimental studies to implementation in practice. Finally, development of standardized benchmarks for partial shading condition and dynamic irradiance aligned with IEC 61724-1 and IEEE 1547 would make research reproducible.

In summary, grid connected solar MPPT technologies have evolved from a narrow field optimization problem into an integral part of enabling sustainable and reliable power generation from renewable sources. Integration of metaheuristic optimization methods, fractional order control theory, and the grid forming capabilities makes this area of study highly relevant today. With exponential growth in capacity of photovoltaic plants (up to four times predicted for 2030), development of MPPT technology becomes ever more important.

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