International Journal Of Innovative Trends In Multi Disciplinary Scientific Research
ISSN (Online): 3139 – 2687
(www.ijtmsr.co.in) Volume 9, Issue 6, 2026

Advance Modelling and performance optimization of Solar photovoltaic system with MPPT Using Hybrid Algorithms

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Abstract

The increasing deployment of solar photovoltaic (PV) systems has created a growing need for efficient Maximum Power Point Tracking (MPPT) techniques to maximize energy extraction under varying environmental conditions. Conventional MPPT algorithms such as Perturb and Observe (P&O) and Incremental Conductance (IC) are widely used; however, their performance is often limited by slow convergence, steady-state oscillations, and reduced tracking efficiency during rapid changes in solar irradiance and temperature. To address these challenges, this study proposes a hybrid Genetic Algorithm-Particle Swarm Optimization-Incremental Conductance (GA-PSO-IC) MPPT technique for photovoltaic power optimization. Environmental parameters including solar irradiance, ambient temperature, relative humidity, and wind speed were obtained from the NASA POWER database and utilized for photovoltaic system modeling and simulation. A solar PV array integrated with a DC-DC boost converter was developed in Python, and the proposed MPPT controller was implemented to optimize power extraction under different operating conditions. The performance of the proposed algorithm was compared with conventional MPPT methods (P&O and IC) and existing hybrid approaches (GA+P&O, GA+IC, PSO+P&O, and PSO+IC). Simulation results demonstrated that the proposed GA-PSO-IC algorithm achieved superior performance with an output power of 2918 W, tracking efficiency of 99.2%, tracking time of 0.026 s, and settling time of 8.9 ms. The controller also exhibited reduced oscillations and maintained stable operation under varying irradiance and temperature conditions. The findings confirm that the proposed hybrid optimization approach significantly enhances photovoltaic system performance and offers an effective solution for practical solar energy applications operating in dynamic environments.

Keywords: *Solar Photovoltaic System; Maximum Power Point Tracking (MPPT); Hybrid Optimization Algorithms; Genetic Algorithm; Particle Swarm Optimization; Incremental Conductance; Energy Optimization.*

1. INTRODUCTION

1.1 Background

The increasing demand for clean and sustainable energy has led to rapid expansion of solar photovoltaic (PV) systems worldwide [1]. Solar energy is widely recognized for its environmental benefits, as it reduces dependence on fossil fuels and lowers carbon emissions [2]. With continuous advancements in technology and decreasing installation costs, solar PV systems are being increasingly adopted in residential, commercial, and industrial sectors [3]. Despite these advantages, a key challenge in solar PV systems is ensuring efficient energy extraction, since the power generated by a PV panel depends on environmental conditions such as sunlight intensity and temperature, which continuously change throughout the day, making it difficult for the system to always operate at maximum efficiency [4]. The concept of the Maximum Power Point (MPP) - the operating point at which the PV system generates the highest possible power [5] - is central to addressing this issue, and Maximum Power Point Tracking (MPPT) techniques are used to continuously adjust system parameters so that the PV array operates as close as possible to this optimal condition.

1.2 Problem Statement

Although MPPT techniques are widely used, conventional methods face several limitations. Solar power generation is highly dependent on irradiance and temperature, both of which vary unpredictably, causing frequent shifts in the maximum power point. Common MPPT methods such as Perturb and Observe (P&O) and Incremental Conductance are simple and easy to implement, but they often suffer from slow response times; in rapidly changing conditions, they may take longer to reach the optimal point, resulting in energy loss. They also tend to oscillate around the MPP rather than stabilizing exactly at it, which further reduces efficiency, and their tracking accuracy deteriorates when weather conditions change quickly. These issues highlight the need for more advanced techniques capable of handling the nonlinear, time-varying nature of PV systems.

1.3 Need for Hybrid Optimization Algorithms

To overcome the limitations of conventional methods, hybrid optimization algorithms that combine the strengths of two or more techniques have gained attention in recent years [6]. By integrating different approaches, hybrid methods can provide improved tracking speed, higher accuracy, and better stability [7], and are particularly effective in dealing with the nonlinear current-voltage behaviour that PV panels exhibit under varying environmental conditions [8]. Where traditional algorithms may struggle to adapt to rapid changes, hybrid methods can dynamically adjust and provide more reliable results, while also reducing oscillations around the maximum power point through intelligent control, leading to better energy utilization and improved system efficiency.

1.4 Objectives of the Study

The main objective of this study is to develop an advanced solar PV system model and enhance its performance using a hybrid MPPT algorithm capable of accurately tracking the maximum power point under varying environmental conditions. Specific objectives include: (i) acquiring and preprocessing environmental data from the NASA POWER database; (ii) developing a mathematical model of the PV array and DC-DC boost converter; (iii) implementing conventional MPPT algorithms (P&O and IC) as performance benchmarks; (iv) designing a hybrid Genetic Algorithm-Particle Swarm Optimization-Incremental Conductance (GA-PSO-IC) MPPT controller; and (v) conducting a comparative analysis between the proposed and existing methods using efficiency, tracking time, settling time, and output power as key performance indicators.

2. LITERATURE REVIEW

Accurate modeling of solar PV systems is essential for analyzing performance and developing effective control strategies. PV modeling is generally based on electrical equivalent circuits, with the single-diode model widely preferred for its simplicity and reasonable accuracy, while the double-diode model offers higher accuracy at the cost of additional computational complexity [3], [4]. Among conventional MPPT techniques, Perturb and Observe (P&O) and Incremental Conductance (IC) remain the most widely used [5]; P&O periodically perturbs the operating voltage and observes the resulting change in power, while IC uses the relationship between incremental and instantaneous conductance to more accurately locate the maximum power point. Both methods, however, tend to oscillate around the MPP and struggle under rapidly changing irradiance.

To overcome these limitations, advanced MPPT techniques based on artificial intelligence and optimization have been developed. Fuzzy-logic-based MPPT systems use linguistic rules to handle uncertainty and adapt to varying conditions, while artificial neural networks can learn complex patterns and respond quickly once trained [7], [8]. Genetic Algorithms, inspired by natural selection, search iteratively for the optimal operating point [8]. Hybrid algorithms that combine two or more of these techniques - for example PSO with ANN, GA with fuzzy logic, or PSO with fuzzy logic - achieve faster convergence and improved stability by exploiting the complementary strengths of each component technique [10], [11].

Diab et al. [11] proposed a hybrid optimization approach combining whale optimization and salp swarm algorithms for MPPT under partial shading, reporting faster convergence and higher tracking efficiency than either algorithm alone. Katche et al. [12] presented a comprehensive review of conventional, intelligent, optimization, and hybrid MPPT techniques, noting that hybrid approaches deliver better efficiency and tracking performance at the cost of higher design complexity. Mohamed et al. [13] developed an arithmetic-optimization-algorithm-tuned incremental conductance controller for grid-connected PV systems, demonstrating significant reductions in rise time and settling time compared with GA, PSO, and GWO-based approaches. Villegas-Mier et al. [14] reviewed ANN-based MPPT techniques and reported that ANN-based controllers achieve approximately 98% tracking efficiency under uniform environmental conditions, while Sulthan et al. [15] developed a two-stage hybrid MPPT algorithm that improved both convergence speed and steady-state accuracy relative to single-stage methods.

Research Gap

Despite this progress, several challenges remain. Many existing methods focus on either simplicity or accuracy but rarely achieve both simultaneously, and there is a noticeable lack of hybrid MPPT methods that combine global search, fast convergence, and precise local tracking within a single, unified controller. Most current approaches are evaluated only under standard test conditions and may not perform as effectively across a wide range of irradiance and temperature scenarios. This work addresses that gap through a three-stage hybrid GA-PSO-IC MPPT algorithm, in which Genetic Algorithm performs global exploration, Particle Swarm Optimization accelerates convergence, and Incremental Conductance provides precise local refinement, as detailed in Section 3.

3. RESEARCH METHODOLOGY

This section presents the methodology adopted for developing an advanced solar PV system integrated with the proposed hybrid GA-PSO-IC MPPT technique, covering the overall research framework, dataset acquisition and preprocessing, PV and converter modeling, conventional MPPT benchmarks, the proposed hybrid algorithm, and the simulation and evaluation framework.

3.1 Overall Research Framework

The research framework adopted in this study provides a systematic approach for developing and evaluating the proposed MPPT technique. Environmental data are first collected from the NASA POWER database and preprocessed to ensure data quality. A mathematical model of the PV array and DC-DC boost converter is then developed, followed by implementation of conventional MPPT algorithms (P&O, IC) as benchmarks and the proposed hybrid GA-PSO-IC controller. The complete system is simulated under varying environmental conditions, and performance is evaluated using tracking efficiency, output power, tracking time, and settling time, culminating in a comparative analysis against existing methods. The complete workflow is illustrated in Figure 1.

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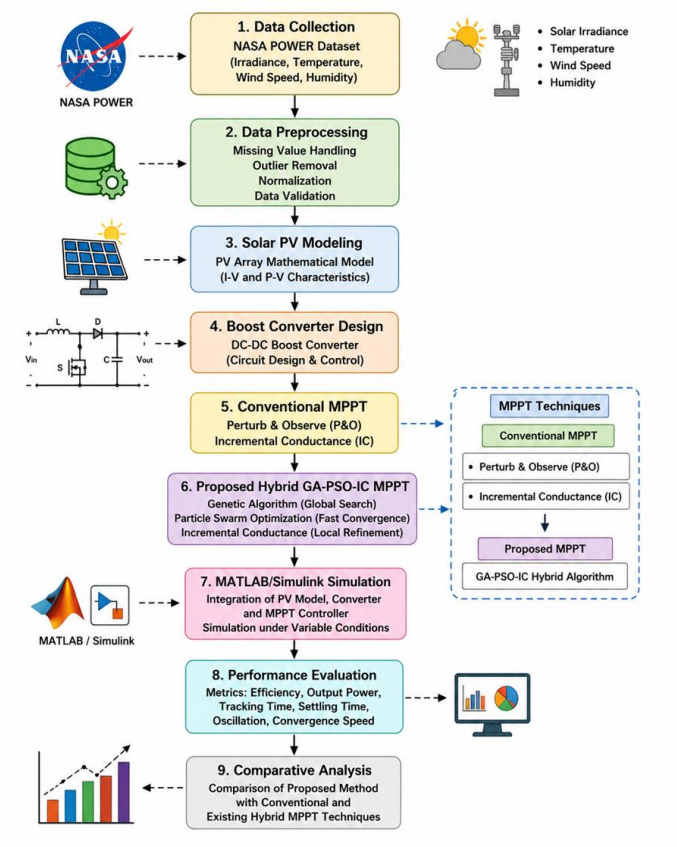


Figure 1: Overall Research Framework for the Proposed GA-PSO-IC Based Solar PV System

3.2 Dataset Acquisition and Preprocessing

Environmental parameters used for photovoltaic modeling and simulation were obtained from the NASA Prediction of Worldwide Energy Resources (POWER) database, a freely accessible source of satellite-derived meteorological data widely used in renewable energy research. The environmental parameters selected for this study, along with their units, are listed in Table 1. Prior to simulation, the collected dataset underwent a comprehensive preprocessing procedure comprising missing-value handling, outlier detection and removal, min-max normalization, feature selection, and dataset validation, ensuring that only high-quality environmental data were used for photovoltaic modeling, MPPT implementation, and performance analysis. The complete preprocessing workflow is illustrated in Figure 2.

Table 1: NASA POWER Environmental Dataset Parameters

Parameter	Unit
Solar Irradiance	W/m²
Ambient Temperature	°C
Relative Humidity	%
Wind Speed	m/s

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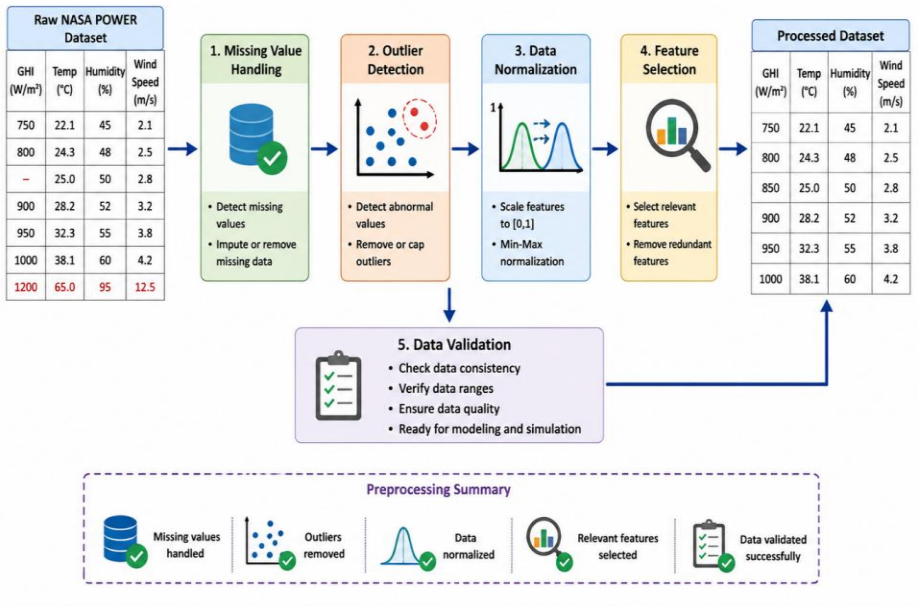


Figure 2: Data Preprocessing Workflow

3.3 Solar Photovoltaic System Modeling

A photovoltaic cell converts solar energy directly into electrical energy through the photovoltaic effect. The single-diode equivalent circuit model, comprising a photocurrent source, a diode, a series resistance, and a shunt resistance, is adopted in this study due to its simplicity and satisfactory accuracy in representing the nonlinear current-voltage behaviour of PV cells. Multiple cells and modules are interconnected in series and parallel arrangements to form the PV array used in this work; the electrical specifications of this array, adapted from the benchmark study and used throughout the simulation, are summarized in Table 2. The array is capable of producing a maximum power output of 2940 W under standard test conditions, with a maximum-power-point voltage and current of 243 V and 12.1 A respectively.

Table 2: Electrical Specifications of the Photovoltaic Array

Parameter	Symbol	Value
Maximum Power	P_max	2940 W
Voltage at Maximum Power Point	V_MPP	243 V
Current at Maximum Power Point	I_MPP	12.1 A
Open Circuit Voltage	V_OC	292.8 V
Short Circuit Current	I_SC	12.86 A
PV Module Configuration	-	6 Series × 2 Parallel
Number of PV Modules	-	12 Modules
Rated Power per Module	P_m	245 W

The PV array exhibits characteristic nonlinear Current-Voltage (I-V) and Power-Voltage (P-V) behaviour: at low voltage the output current remains close to the short-circuit current before falling to zero at the open-circuit voltage, while the P-V curve exhibits a single, distinct peak corresponding to the maximum power point. As solar irradiance and ambient temperature vary, the location of this peak continuously shifts along the voltage axis, making fixed operating strategies ineffective and motivating the need for a continuously adaptive MPPT controller such as the one proposed in Section 3.6.

3.4 DC-DC Boost Converter Design

A DC-DC boost converter is used to interface the PV array with the load and to regulate the array operating voltage according to the MPPT controller's requirements. The converter is selected for its simple structure, high efficiency, and ease of control, and consists of an inductor, a MOSFET switch, a diode, an output capacitor, and the load. The inductor stores energy while the switch is on and releases it when the switch is off; the MOSFET acts as a high-speed switching device controlled by the MPPT algorithm; and the output capacitor smooths voltage fluctuations. The converter is controlled through duty-cycle adjustment - the ratio of switch-on time to the total switching period - which the MPPT controller continuously updates to maintain operation at the maximum power point as irradiance and temperature change.

3.5 Conventional MPPT Algorithms

Two widely used conventional MPPT techniques, Perturb and Observe (P&O) and Incremental Conductance (IC), are implemented as benchmark methods. The P&O algorithm periodically perturbs the PV operating voltage and observes the resulting change in output power, continuing in the same direction if power increases and reversing direction otherwise. The output power of the PV array is given by Equation (1), and at the maximum power point the slope of the power-voltage curve is zero, as expressed in Equation (2):

$$P = I \times V \quad ...(1)$$

$$dP/dV = I + V(dI/dV) = 0 \quad ...(2)$$

Rearranging Equation (2) gives the Incremental Conductance MPPT criterion in Equation (3), which forms the fundamental operating principle of the IC algorithm: when the incremental conductance (dI/dV) equals the negative instantaneous conductance (-I/V), the array is operating at the maximum power point.

$$dI/dV = -I/V \quad ...(3)$$

Compared with P&O, the IC algorithm provides faster convergence and better tracking accuracy under varying irradiance, though at the cost of increased computational and control complexity. Both algorithms serve as the baseline against which the proposed hybrid controller is evaluated.

3.6 Proposed Hybrid GA-PSO-IC MPPT Algorithm

The proposed MPPT algorithm is implemented in Python to improve photovoltaic power extraction under dynamic environmental conditions. It combines the global optimization capability of a Genetic Algorithm (GA), the fast convergence characteristics of Particle Swarm Optimization (PSO), and the accurate local tracking ability of Incremental Conductance (IC), using Python libraries including NumPy, SciPy, DEAP, and PySwarms for implementation and optimization.

In the first stage, the Genetic Algorithm treats the boost-converter duty cycle as the optimization variable and performs global exploration of the search space through population initialization, fitness evaluation (based on PV output power), selection, crossover, and mutation, producing a set of optimized duty-cycle candidates. In the second stage, Particle Swarm Optimization refines these candidates through particle initialization, velocity and position updates, and local/global best evaluation, yielding a refined optimal duty cycle with improved convergence characteristics. In the third stage, the Incremental Conductance algorithm performs fine local tuning around the maximum power point, reducing residual oscillations and producing the final optimal duty cycle used to control the boost converter. The complete algorithm flow - from voltage/current measurement through GA global search, PSO refinement, and IC fine tracking to final duty-cycle control - is illustrated in Figure 3.

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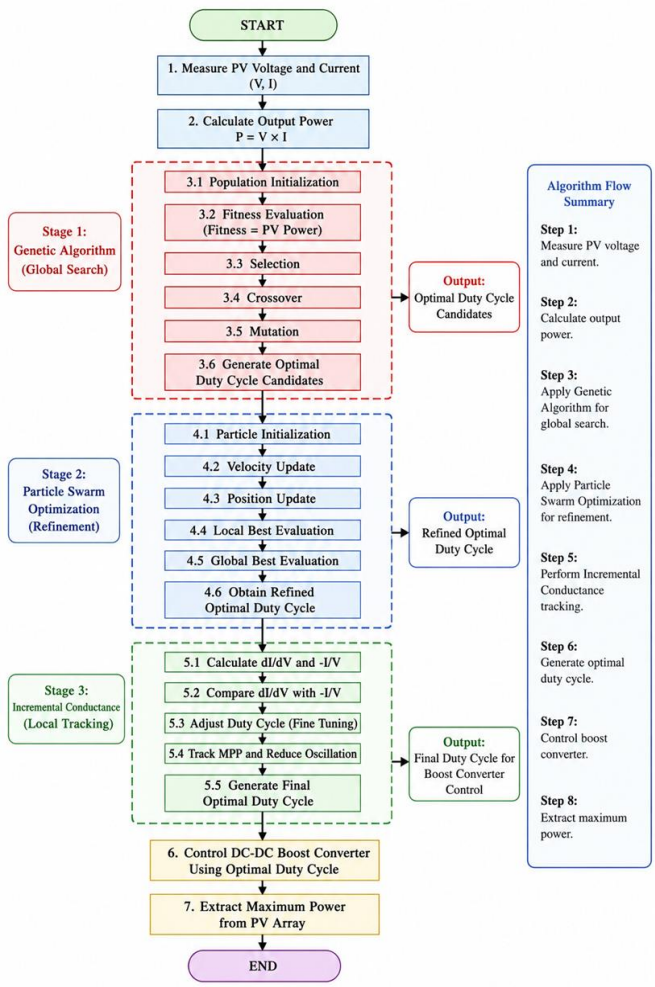


Figure 3: Proposed Hybrid GA-PSO-IC MPPT Algorithm Flowchart

3.7 Simulation Environment and Scenarios

The proposed photovoltaic system and hybrid MPPT controller were developed and executed in Python 3.11, using NumPy, Pandas, Matplotlib, SciPy, DEAP (Genetic Algorithm), and PySwarms (Particle Swarm Optimization) within a Jupyter Notebook/Google Colab environment. The simulation framework integrates the PV array model, the boost-converter model, the hybrid GA-PSO-IC MPPT controller, and the NASA POWER environmental dataset. Three simulation scenarios were considered: standard test conditions (irradiance = 1000 W/m², temperature = 25°C); variable irradiance conditions (750-1000 W/m² at constant 25°C); and variable temperature conditions (22-38°C at constant 1000 W/m²).

3.8 Performance Evaluation Metrics

The effectiveness of the proposed controller is evaluated using tracking efficiency (the percentage of extracted power relative to the theoretical maximum available power), output power, tracking time (the time required to locate the maximum power point after an environmental change), settling time (the time required for output power to stabilize after convergence), and oscillation magnitude (the extent of power fluctuation around the MPP during steady-state operation). These metrics provide the basis for the comparative analysis between the proposed GA-PSO-IC controller, the conventional P&O and IC algorithms, and the existing hybrid GA+P&O, GA+IC, PSO+P&O, and PSO+IC approaches, presented in Section 4.

4. RESULTS AND DISCUSSION

4.1 Dataset Description and Preprocessing Results

Environmental parameters used for simulation - solar irradiance, ambient temperature, relative humidity, and wind speed - were obtained from the NASA POWER database, as summarized earlier in Table 1. Solar irradiance exhibited significant fluctuation across the dataset and, since photovoltaic output is directly proportional to irradiance, these variations translated directly into changes in simulated output power; ambient temperature also played an important role, since increased temperature generally reduces photovoltaic conversion efficiency by lowering module output voltage. Prior to simulation, all preprocessing operations described in Section 3.2 - missing-value removal, outlier detection, normalization, feature selection, and dataset validation - were successfully completed, as illustrated in Figure 2, providing a reliable foundation for the photovoltaic modeling, MPPT implementation, and performance analysis presented in the remainder of this section.

4.2 Solar PV System Characteristics

The photovoltaic array, whose electrical specifications are listed in Table 2, exhibits the expected nonlinear Current-Voltage and Power-Voltage behaviour of a solar PV system: output current remains nearly constant near the short-circuit value at low voltage before falling to zero at the open-circuit voltage of 292.8 V, while output power rises to a single peak at the maximum power point (243 V, 12.1 A, 2940 W) before falling away as voltage increases further. Because this operating point shifts continuously with irradiance and temperature, an MPPT controller capable of tracking it in real time is essential for efficient energy extraction, motivating the conventional and hybrid MPPT evaluations that follow.

4.3 Performance of Conventional and Existing Hybrid MPPT Algorithms

The conventional P&O algorithm achieved an output power of 2832 W with a tracking efficiency of 96.3%, a tracking time of 0.038 s, and a settling time of 12.4 ms, while the Incremental Conductance algorithm improved on this slightly, reaching 2848 W, 96.9% efficiency, 0.036 s tracking time, and 12.2 ms settling time; both methods, however, exhibited noticeable oscillations around the maximum power point during steady-state operation. The introduction of optimization-based hybridization produced clear improvements: GA+P&O achieved 98.7% efficiency (2903 W, 0.032 s, 10.3 ms), GA+IC achieved the best efficiency among the existing hybrid methods at 98.8% (2904 W, 0.030 s, 10.3 ms), while PSO+P&O and PSO+IC achieved 98.3% (2890 W) and 98.6% (2900 W) respectively. These results, summarized in Table 3, confirm that all optimization-based hybrid algorithms outperform the conventional P&O and IC controllers, though minor oscillations and tracking delays remain under dynamic conditions.

4.4 Performance of Proposed GA-PSO-IC MPPT Algorithm

The proposed hybrid GA-PSO-IC controller achieved the best overall performance among all evaluated methods, reaching an output power of 2918 W with a tracking efficiency of 99.2%, a tracking time of only 0.026 s, and a settling time of 8.9 ms, with an oscillation magnitude limited to ±1.2%. Figure 4 illustrates the corresponding power-tracking response: the controller converges rapidly during the transient region and settles into a steady-state region with very low oscillation, confirming that the combination of GA's global search, PSO's fast convergence, and IC's precise local tracking enables the proposed controller to identify and maintain the maximum power point more effectively than any of the conventional or existing hybrid approaches.

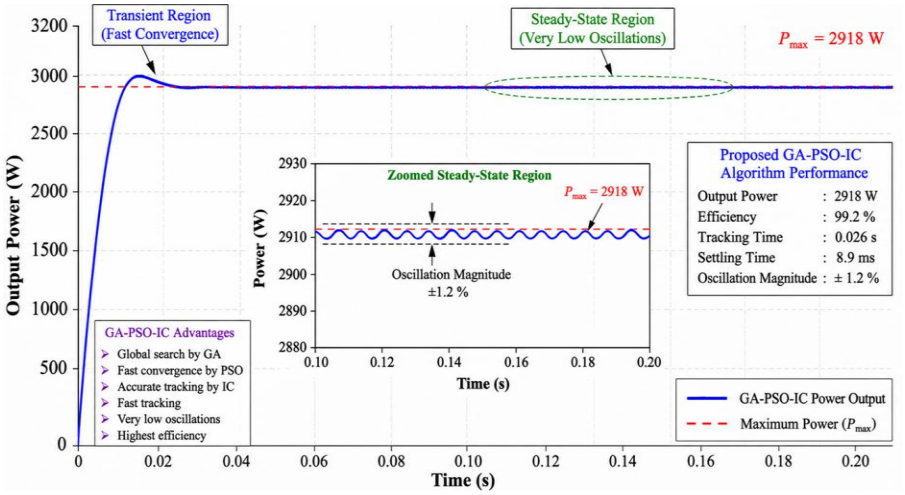


Figure 4: Power Tracking Response of the Proposed GA-PSO-IC MPPT Algorithm

Table 3: Overall Performance Comparison of MPPT Algorithms

Method	Output Power (W)	Efficiency (%)	Tracking Time (s) / Settling Time (ms)
P&O	2832	96.3	0.038 / 12.4
IC	2848	96.9	0.036 / 12.2
GA+P&O	2903	98.7	0.032 / 10.3
GA+IC	2904	98.8	0.030 / 10.3
PSO+P&O	2890	98.3	0.033 / 11.5
PSO+IC	2900	98.6	0.032 / 11.4
Proposed GA-PSO-IC	2918	99.2	0.026 / 8.9

4.5 Performance Under Variable Irradiance and Temperature Conditions

To evaluate robustness, simulations were performed under irradiance levels ranging from 750 to 1000 W/m² at a constant 25°C, and under temperatures ranging from 22°C to 38°C at a constant 1000 W/m². As shown in Table 4, output power increased with irradiance for all algorithms, and the proposed GA-PSO-IC controller consistently extracted the most power at every level - for example, 1801 W at 750 W/m² compared with 1656 W for P&O, 1673 W for IC, 1783 W for GA+IC, and 1757 W for PSO+IC, rising to 2918 W at 1000 W/m². Under temperature variation, output power decreased for all algorithms as temperature increased, reflecting the reduction in cell voltage at higher temperatures; nevertheless, the proposed controller again consistently outperformed all benchmark methods, generating 2941 W at 22°C and maintaining 2804 W even at the highest tested temperature of 38°C, exhibiting the smallest relative power reduction among all evaluated algorithms and confirming its superior robustness under both irradiance and thermal variation.

Table 4: Output Power Under Variable Irradiance Conditions

Irradiance (W/m²)	P&O (W)	IC (W)	GA+IC (W)	PSO+IC (W)	Proposed (W)
750	1656	1673	1783	1757	1801
800	1877	1897	2032	1971	2052
850	2111	2132	2294	2223	2320
900	2354	2377	2534	2487	2565

Irradiance (W/m²)	P&O (W)	IC (W)	GA+IC (W)	PSO+IC (W)	Proposed (W)
1000	2832	2848	2904	2900	2918

4.6 Comparative Analysis

The overall comparative analysis, summarized in Table 3 and illustrated in Figures 5 and 6, confirms that the proposed GA-PSO-IC algorithm consistently outperforms conventional and existing hybrid MPPT methods across all evaluation metrics. Figure 5 shows the efficiency achieved by each algorithm under standard test conditions, with efficiency rising from 96.3% (P&O) and 96.9% (IC) through 98.3-98.8% for the existing hybrid methods to 99.2% for the proposed controller - the highest among all seven methods evaluated.

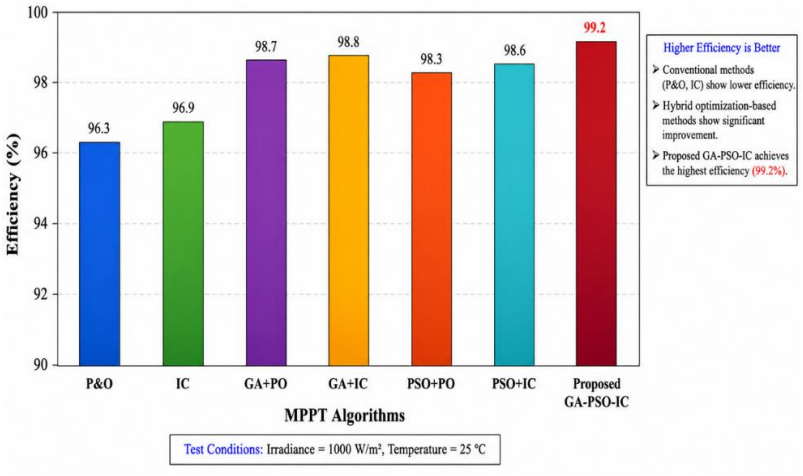


Figure 5: Efficiency Comparison of MPPT Algorithms

Figure 6 presents the corresponding settling-time comparison, in which the proposed controller again achieves the best result at 8.9 ms, compared with 12.4 ms and 12.2 ms for the conventional P&O and IC methods and 10.3-11.5 ms for the existing hybrid approaches. Taken together with the tracking-time results in Table 3, these comparisons demonstrate that the proposed GA-PSO-IC algorithm not only extracts the most power but does so with the fastest convergence and the most stable steady-state behaviour of any method considered in this study.

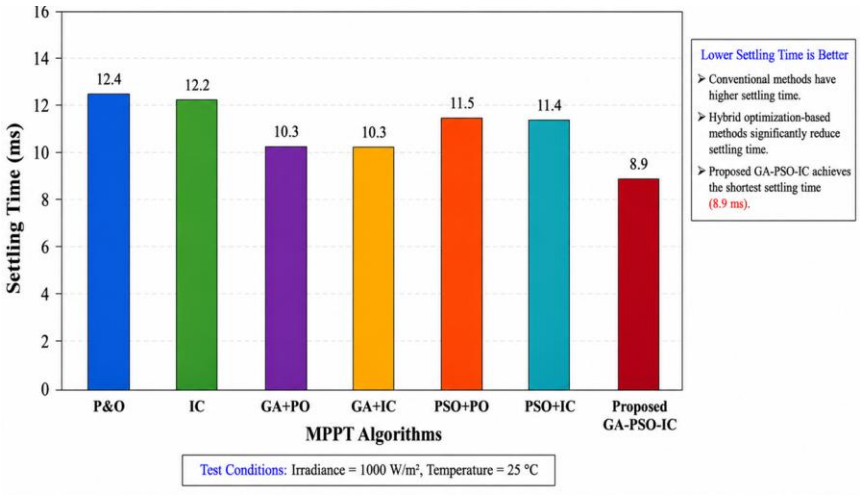


Figure 6: Settling Time Comparison of MPPT Algorithms

4.7 Discussion of Results

The results obtained under standard test conditions, variable irradiance, and variable temperature consistently show that the proposed hybrid GA-PSO-IC MPPT algorithm outperforms both conventional and existing hybrid MPPT approaches. This performance advantage arises from the complementary roles of its three stages: the Genetic Algorithm performs global exploration and prevents the optimization process from becoming trapped in local optima; Particle Swarm Optimization accelerates convergence toward the optimal operating point; and Incremental Conductance performs precise local tracking that minimizes residual oscillation around the maximum power point. The proposed controller achieved the highest tracking efficiency (99.2%), the shortest tracking time (0.026 s), and the lowest settling time (8.9 ms) among all seven algorithms evaluated, while also extracting more power than every benchmark method at all tested irradiance and temperature levels, confirming its suitability for practical photovoltaic applications operating under dynamic environmental conditions.

5. CONCLUSION

This work presented the development and performance evaluation of a hybrid Genetic Algorithm-Particle Swarm Optimization-Incremental Conductance (GA-PSO-IC) Maximum Power Point Tracking technique for solar photovoltaic systems. Environmental data comprising solar irradiance, ambient temperature, relative humidity, and wind speed were obtained from the NASA POWER database and used for photovoltaic system modeling and simulation. A solar PV array integrated with a DC-DC boost converter was developed in Python, and conventional (P&O, IC), existing hybrid (GA+P&O, GA+IC, PSO+P&O, PSO+IC), and the proposed GA-PSO-IC MPPT algorithms were implemented and evaluated under standard test conditions and under variable irradiance and temperature conditions.

The proposed controller achieved an output power of 2918 W, a tracking efficiency of 99.2%, a tracking time of 0.026 s, a settling time of 8.9 ms, and an oscillation magnitude of only ±1.2%, outperforming all conventional and existing hybrid benchmark methods across every evaluation metric and at every irradiance and temperature level tested. These findings confirm that integrating evolutionary optimization, swarm intelligence, and conductance-based local tracking within a unified MPPT framework significantly improves photovoltaic power extraction, tracking speed, and operating stability, making the proposed GA-PSO-IC technique an effective and reliable solution for enhancing energy-harvesting efficiency in modern solar photovoltaic applications operating under dynamic real-world conditions.

FUTURE SCOPE

Although the proposed GA-PSO-IC MPPT algorithm demonstrated excellent performance under simulated conditions, several directions remain open for future work: (i) real-time hardware implementation and experimental validation using embedded platforms such as Arduino, Raspberry Pi, DSP, FPGA, or dSPACE with a physical PV test bench; (ii) extending the approach to partial-shading conditions, where multiple local maxima make global MPP identification particularly challenging; (iii) integrating machine learning and AI techniques such as ANN, Deep Learning, Reinforcement Learning, or Adaptive Neuro-Fuzzy Inference Systems (ANFIS) to improve prediction and adaptive control capability; (iv) applying the framework to grid-connected PV systems, microgrids, smart grids, and hybrid renewable energy systems incorporating wind, battery storage, and electric-vehicle integration; (v) exploring multi-objective optimization to jointly optimize power extraction, converter efficiency, thermal performance, and system reliability, potentially using additional metaheuristics such as Grey Wolf Optimization, Whale Optimization, Harris Hawks Optimization, or Ant Colony Optimization; and (vi) integrating IoT-based monitoring and cloud platforms to enable intelligent, autonomous photovoltaic energy management.

ACKNOWLEDGMENT

I am greatly obligated forever to my guide Prof. Uddhav Takle Sir and to all teaching and non-teaching staff who supported me directly and indirectly to complete my work. I am sincerely thankful to my principal Dr.S.K Biradar for their continued encouragement and active interest in my progress throughout the work I am grateful to be an M.Tech Electrical Power System student at Matsyodari Shikshan Sanstha's College of Engineering and Technology, Jalna, Maharashtra

REFERENCES

[1] M. G. Hasan, M. A. Uddin, A. H. M. I. Ferdous, and M. G. Sadeque, "Enhanced maximum power point tracking using hybrid GA and PSO algorithms for solar PV systems," Results Eng., vol. 28, 2025, doi: 10.1016/j.rineng.2025.107708.

[2] G. B. A. Kumar and Shivashankar, "Optimal power point tracking of solar and wind energy in a hybrid wind solar energy system," Int. J. Energy Environ. Eng., vol. 13, no. 1, pp. 77-103, 2022, doi: 10.1007/s40095-021-00399-9.

[3] S. Chandra, P. Gaur, and Srishti, "Maximum Power Point Tracking Approaches for Wind-Solar Hybrid Renewable Energy System - A Review," in Advances in Energy and Power Systems, S. N. Singh, F. Wen, and M. Jain, Eds., Singapore: Springer Singapore, 2018, pp. 3-12.

[4] M. H. Moradi and A. R. Reisi, "A hybrid maximum power point tracking method for photovoltaic systems," Sol. Energy, vol. 85, no. 11, pp. 2965-2976, 2011, doi: 10.1016/j.solener.2011.08.036.

[5] M. T. Hussain, A. Sarwar, M. Tariq, S. Urooj, A. BaQais, and M. A. Hossain, "An Evaluation of ANN Algorithm Performance for MPPT Energy Harvesting in Solar PV Systems," Sustainability, 2023, doi: 10.3390/su151411144.

[6] A. Demirci, I. Dagal, S. M. Tercan, H. Gundogdu, M. Terkes, and U. Cali, "Enhanced ANN-Based MPPT for Photovoltaic Systems: Integrating Metaheuristic and Analytical Algorithms for Optimal Performance Under Partial Shading," IEEE Access, vol. 13, pp. 92783-92799, 2025, doi: 10.1109/ACCESS.2025.3572554.

[7] S. J. Yaqoob et al., "Advanced Maximum Power Point Tracking in Photovoltaic Systems: A Comprehensive Review of Classical, AI-Based, and Metaheuristic Optimization Techniques," Eng. Reports, vol. 7, no. 9, p. e70404, 2025, doi: 10.1002/eng2.70404.

[8] R. B. Bollipo, S. Mikkili, and P. K. Bonthagorla, "Critical Review on PV MPPT Techniques: Classical, Intelligent and Optimisation," IET Renew. Power Gener., vol. 14, no. 9, pp. 1433-1452, 2020, doi: 10.1049/iet-rpg.2019.1163.

[9] J. Águila-León, C. Vargas-Salgado, D. Díaz-Bello, and C. Montagud-Montalvá, "Optimizing photovoltaic systems: A meta-optimization approach with GWO-Enhanced PSO algorithm for improving MPPT controllers," Renew. Energy, vol. 230, p. 120892, 2024, doi: 10.1016/j.renene.2024.120892.

[10] H. Alhusseini, L. M. Abdali, H. A. Issa, and V. I. Velkin, "Adaptive particle swarm optimization based model predictive control MPPT algorithm for PV systems under partial shading conditions," Results Eng., vol. 28, p. 107419, 2025, doi: 10.1016/j.rineng.2025.107419.

[11] A. A. Z. Diab, M. A. Mohamed, A. Al-Sumaiti, H. Sultan, and M. Mossa, "A Novel Hybrid Optimization Algorithm for Maximum Power Point Tracking of Partially Shaded Photovoltaic Systems," in Advanced Technologies for Solar Photovoltaics Energy Systems, S. Motahhir and A. M. Eltamaly, Eds., Cham: Springer International Publishing, 2021, pp. 201-230, doi: 10.1007/978-3-030-64565-6_7.

[12] M. L. Katche, A. B. Makokha, S. O. Zachary, and M. S. Adaramola, "A Comprehensive Review of Maximum Power Point Tracking (MPPT) Techniques Used in Solar PV Systems," Energies, 2023, doi: 10.3390/en16052206.

[13] M. A. E. Mohamed, S. Nasser Ahmed, and M. Eladly Metwally, "Arithmetic optimization algorithm based maximum power point tracking for grid-connected photovoltaic system," Sci. Rep., vol. 13, no. 1, p. 5961, 2023, doi: 10.1038/s41598-023-32793-0.

[14] C. G. Villegas-Mier, J. Rodriguez-Resendiz, J. M. Álvarez-Alvarado, H. Rodriguez-Resendiz, A. M. Herrera-Navarro, and O. Rodríguez-Abreo, "Artificial Neural Networks in MPPT Algorithms for Optimization of Photovoltaic Power Systems: A Review," Micromachines, 2021, doi: 10.3390/mi12101260.

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

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