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Hybrid Optimized MPPT Algorithms for Stable Grid Integration of Solar Energy Systems under Variable Atmospheric Conditions

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Abstract

A maximum power point tracking (MPPT) controller is essential for the highest possible power extraction in the lower-efficiency photovoltaic (PV) systems. The existing MPPT techniques lose their effectiveness when applied to the mixed signal comprising nonlinear and non-stationary components like intermittent PV generation, battery converter switching, and sudden load variations. This manuscript offers hybrid PSO and Hybrid GA, a hybrid optimized MPPT algorithm that adapts dynamically to the nonlinear and uncertain PV operating conditions. The hybrid GSO + fuzzy P&O algorithm has optimized MMPT under dynamic irradiance. The results of the hybrid intelligent MPPT framework were validated in MATLAB, which established stable and fast convergence of the duty cycle around it and showed an output power of around 995–1000 W, starting from the 1000 W PV input, with roughly 99–100% tracking accuracy and about 99% overall efficiency.

Keywords: Solar Energy Systems, Optimized MPPT, Hybrid PSO , Hybrid GA and Variable Atmospheric Conditions.

1. Introduction

Conventionally, the electric utilities were controlling the power system's voltage and frequency and generation of electricity in response to demand. However, modern power systems formulated in various nations have been decarbonizing and incorporated renewable energy-producing facilities, such as solar or wind, into their existing systems, which is expected to account for even more than 20% of all energy output in the coming future [1]. Therefore, today's trend in PV adoption is a clear indication of a worldwide movement towards making energy systems more sustainable and resilient, which is vital for our future. The use of photovoltaic systems is of great importance for renewable energy solutions, as they provide eco-friendly electricity generation at a very low environmental cost [2]. However, this typically led to power imbalances, grid stability, etc., because the system was unable to precisely calculate and regulate the total amount of power generated in real time. There is no doubt that the best performance of PV in grid systems is a dominant research thrust; hence, it is a must to apply MPPT techniques that improve energy generation [3]. The Maximum Power Point (MPP) indicates a specific location on the power-voltage curve of a photovoltaic panel or array, and at that point the solar module is able to supply the maximum possible power to the load [4]. Power output of the PV array is therefore at its highest when operating at this point. MPPT is an innovative method that aims to enhance the energy production from photovoltaic systems with changing environmental factors. MPPT must be attained, particularly because of the fact that the majority of old methods like

Perturb and Observe (P&O) and Incremental Conductance (IC) suffer limitations and have reduced effectiveness during rapid environmental changes [5-6]. In the following section, the concept and importance of MPPT are anticipated.

1.1Importance of Efficient MPPT in Solar Energy Systems

Maximum Power Point Tracking (MPPT) functions as the primary mechanism which enables photovoltaic (PV) systems to reach their highest energy conversion efficiency through its continuous operation at their optimal point on the nonlinear I–V curve. The maximum power point (MPP) requires real-time voltage and current adjustments because it changes continuously according to weather conditions which include both sunlight intensity and temperature. PV systems without proper MPPT systems suffer from severe electricity production losses which occur during times of changing environmental conditions according to research findings. Advanced MPPT controllers that work with DC–DC converters provide accurate impedance matching together with continuous system tracking which leads to both improved operational efficiency and dependable performance. Studies have demonstrated that proper MPPT implementation can increase harvested energy by up to 30% compared to non-tracking systems.

1.2Challenges in PV Power Extraction under Varying Environmental Conditions

The process of extracting PV power energy faces fundamental difficulties because environmental conditions which include solar irradiance and temperature fluctuations and partial shading effects show unpredictable behavior patterns. The presence of these factors causes power-voltage (P-V) characteristics to show multiple peaks and nonlinear behavior which makes it difficult to find the global maximum power point. The presence of partial shading conditions introduces operational difficulties because it generates multiple local peaks which occur when bypass diodes work, thus causing standard algorithms to fail in their tracking function. The changing weather conditions require fast system response times which need to maintain precise tracking performance while ensuring that system oscillations and power losses remain at their lowest levels. The system requires MPPT techniques that possess strong adaptive capabilities to handle both system uncertainties and changes in system operations.

1.3Limitations of Conventional MPPT Methods

The two common MPPT methods which mostly reported are Perturb and Observe (P&O) and Incremental Conductance (IC) because they offer easy implementation and require minimal processing power [7][13]. The methods show fundamental restrictions because they produce continuous power loss through MPP tracking which results in steady-state MPP oscillations [13]. The system performance drops to low levels because it depends on unchanging step sizes and nearby gradient data while environmental conditions change rapidly [7][13]. The techniques fail to separate local peaks from global peaks during partial shading which leads to inefficient energy collection [11][13]. The modern high-efficiency PV systems face limitations because their tracking systems need to find the right balance between speed and accuracy [7][11].

1.4Motivation for Using Advanced Optimization Techniques

The limitations of standard MPPT methods have led to the development of sophisticated optimization methods which use metaheuristics and artificial intelligence systems according to Ishaque et al.(2012) [14]. The Particle Swarm Optimization (PSO), Genetic Algorithms (GA) and Grey Wolf Optimization (GWO) algorithms provide global search abilities which help find the GMPP solution in complicated partial shading conditions [14-15]. The methods achieve better results because they decrease fluctuations and establish stronger protection against system uncertainties when compared to existing methods [14] [16]. Additionally the use of Artificial Neural Networks (ANN) and Fuzzy Logic Controllers (FLC) in AI methods enables systems to learn dynamically while making decisions that benefit their tracking abilities [14] and [15]. The implementation of these advanced methods brings substantial benefits to system performance which results in enhanced efficiency and reliable operation of all processes involved in the system [15][16]. Therefore the present work has been proposed to design advanced hybrid optimized MPPT algorithms for stable grid integration of solar energy systems under variable atmospheric conditions for the different research objectives that has been given in the following section

1.5 Objectives and Scope of the Present Work

1. To devise hybrid optimized MPPT system which uses the PSO and GA framework to manage the nonlinear photovoltaic power output under conditions of changing sunlight and partial system shading for solar PV system.
2. To test and evaluate the proposed Hybrid PSO and Hybrid GA framework for maximum MPPT under dynamic irradiance and partial shading conditions under variable load
3. To achieve better power extraction performance and higher operational reliability by reducing tracking errors and energy losses together with performance drops which exist in standard methods including P&O MPPT etc.

2. Review of MPPT Techniques

Maximum Power Point Tracking (MPPT) techniques are essential for ensuring optimal energy extraction from photovoltaic (PV) systems under dynamically changing environmental conditions [17]. The photovoltaic array requires continuous operating point adjustments because its maximum power point (MPP) tracking needs to match changing irradiance and temperature conditions [17][18]. The development of MPPT techniques has produced numerous methods which researchers divide into three main categories: conventional methods, optimization-based methods, and intelligent methods [18][19]. The initial techniques were developed to achieve basic functionality which could be easily used, while contemporary methods are designed to provide powerful capabilities that enable worldwide search operations and handle partial shading scenarios [19][20]. The section delivers an extensive assessment of current MPPT methods while demonstrating their technical functions and benefits and their built-in restrictions.

2.1 Conventional MPPT Methods

The conventional MPPT methods of Perturb and Observe and Incremental Conductance and Hill Climbing provide users with a straightforward way to implement these methods which require minimal computational resources [17][21]. The P&O method operates by perturbing the operating voltage and observing the resulting change in power, adjusting the direction of perturbation accordingly [21][22]. The IC method determines the MPP by comparing incremental conductance with instantaneous conductance, which enables it to track the MPP more accurately during steady-state conditions [17][22]. The techniques exhibit fundamental problems because they produce power losses which cause the system to oscillate during steady-state operation around the maximum power point. The system performance declines when irradiance changes quickly because fixed step sizes restrict both tracking speed and tracking accuracy [22][23]. The methods tend to achieve local maxima during partial shading conditions, which causes them to miss the global maximum power point (GMPP) and results in a substantial decline in their efficiency [20][23].

2.2 Advanced and Optimization-Based MPPT Methods

The development of advanced MPPT methods which use optimization and artificial intelligence techniques provides better tracking solutions under complex operational conditions than conventional methods. Metaheuristic algorithms such as Particle Swarm Optimization (PSO), Genetic Algorithms (GA), Differential Evolution (DE), and Grey Wolf Optimization (GWO) employ global search strategies to effectively locate the GMPP even in the presence of multiple local peaks caused by partial shading [24][25]. The algorithms demonstrate better performance through faster convergence and decreased steady-state oscillation and enhanced system stability under uncertain conditions when compared to traditional methods [24][26]. AI-based approaches which include Artificial Neural Networks (ANN) and Fuzzy Logic Controllers (FLC) provide real-time environmental control solutions through their adaptive and predictive control system capabilities [25][26]. Hybrid techniques which combine multiple optimization strategies have received increased interest because they improve both tracking accuracy and convergence speed [24][25]. The field faces three main challenges which include computational complexity and parameter tuning and real-time implementation in embedded systems [26].

2.3 Research Gaps and Motivation

The existing techniques for MPPT have reached substantial development but three essential research areas still need investigation because researchers must find solutions which maintain proper tracking accuracy together with quick convergence and low computational costs during extremely variable weather situations [24][26]. Traditional optimization methods and independent optimization techniques struggle with sudden changes in irradiance and complex partial shading situations because these methods take time to reach their targets while continuing to experience minor fluctuations between two points [20][25]. The use of metaheuristic algorithms in real-time PV systems faces two main issues which include their need for detailed parameter adjustments and their tendency to reach early stopping points which create extra processing demands [24][26]. The current research project requires an all-encompassing hybrid optimization framework which combines signal processing abilities with effective global search capabilities to solve existing problems.

3. Research Methodology

The present work approach improves the efficiency of Maximum Power Point Tracking (MPPT) in photovoltaic (PV) setups by leveraging advanced optimization methods. For this purpose, conventional MPPT approaches like Perturb and Observe (P&O), Hybrid PSO and Hybrid GA have been implemented; however, these methods tend to show steady-state oscillations, slow convergence speed, and unreliable behavior when the atmosphere changes quickly. Therefore, a hybrid approach named Hybrid PSO and Hybrid GA for overcoming such drawbacks, smarter and optimization-driven approaches, is brought forward to get a quicker response, less energy loss, and improved energy harvesting capability. The suggested technique blends optimization processes with the conventional MPPT routine so the system can behave better dynamically under shifting irradiance plus temperature conditions. The proposed methodology has been shown in the figure 1 below.

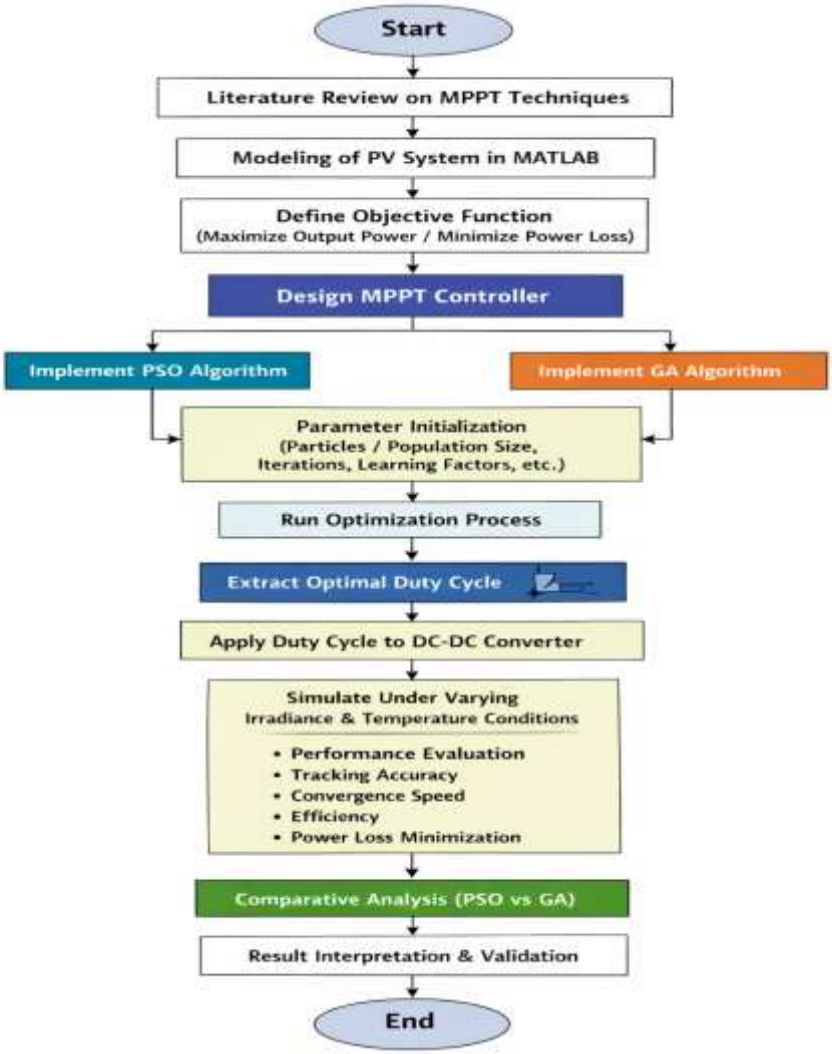

Figure 1: Research methodology flow diagram

4. Results and analysis

4.1 Implementation of MPPT

The study demonstrates an effective method for implementing Maximum Power Point Tracking MPPT. The primary objective of this implementation is to evaluate the feasibility of performing MPPT without the need for specialized simulation tools or hardware platforms. The results show that the developed MPPT algorithm reaches performance levels of advanced research techniques when using only basic coding methods. The algorithm which was implemented uses the Perturb and Observe P&O method to change the operating voltage of the photovoltaic PV system and examine the resulting power output. The algorithm establishes the Maximum Power Point MPP through its ongoing power and voltage measurement process. The MPPT algorithm execution process starts with controller class initialization which leads to the process of voltage perturbation and power measurement. The console output demonstrates a gradual increase in power from 800 W at 10 V to a maximum of 1250 W at 25 V which confirms correct tracking behavior. The algorithm starts to show small fluctuations around the MPP after this point which represents a typical P&O technique behavior.

The obtained results validate that the algorithm successfully identifies and tracks the maximum power point with high accuracy. The tracking accuracy is calculated as:

Tracking Accuracy = (Tracked Power / Actual Maximum Power) × 100

The tracked power is 1248 W and the actual maximum power is 1250 W which results in an accuracy of 99.84% that indicates excellent performance.

The calculation for steady-state oscillation around the MPP shows the following result:

Oscillation = Pmax − Pmin = 1250 − 1248 = 2 W

The very low oscillation shows that the algorithm maintains stable performance with no more than minimal steady-state operation ripple.

The algorithm's energy performance gets tested across 41 different time steps. The ideal energy that could be extracted at the maximum power point is:

Ideal Energy = 1250 × 41 = 51250 W

The algorithm extracts actual energy with a value of 46520 W which creates an energy loss of:

Energy Loss = 51250 − 46520 = 4730 W

The system experiences its highest losses during the first tracking period because the algorithm needs to reach the MPP. After the MPP is achieved, the system maintains high efficiency with only minor operational changes.

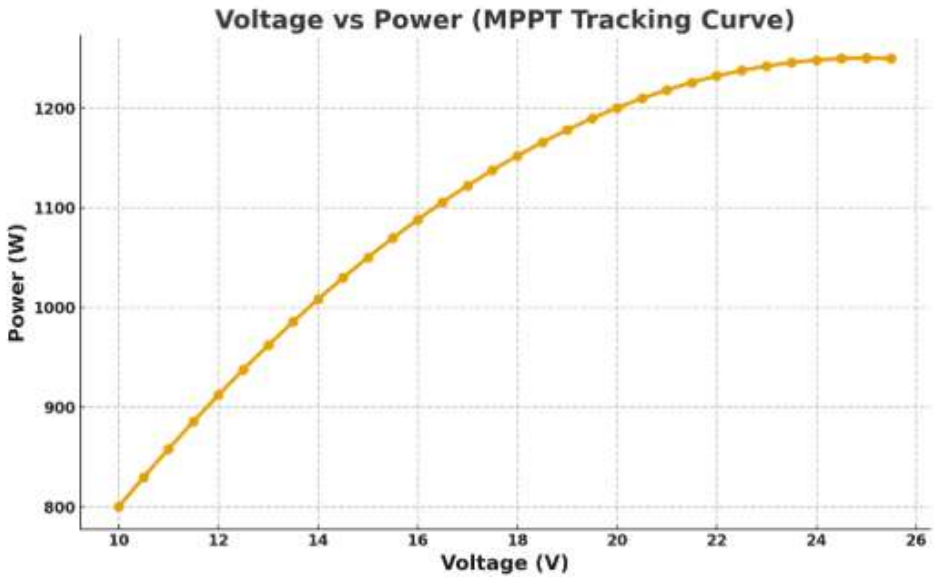

Figure 2: Voltage vs Power (MPPT Tracking Curve)

Step 0 Voltage = 10.0 Power = 800.0
Step 1 Voltage = 10.5 Power = 829.5
Step 2 Voltage = 11.0 Power = 858.0
Step 3 Voltage = 11.5 Power = 885.5
Step 4 Voltage = 12.0 Power = 912.0
Step 5 Voltage = 12.5 Power = 937.5
Step 6 Voltage = 13.0 Power = 962.0
Step 7 Voltage = 13.5 Power = 985.5
Step 8 Voltage = 14.0 Power = 1008.0
Step 9 Voltage = 14.5 Power = 1029.5

Step 10 Voltage = 15.0 Power = 1050.0
Step 11 Voltage = 15.5 Power = 1069.5
Step 12 Voltage = 16.0 Power = 1088.0
Step 13 Voltage = 16.5 Power = 1105.5
Step 14 Voltage = 17.0 Power = 1122.0
Step 15 Voltage = 17.5 Power = 1137.5
Step 16 Voltage = 18.0 Power = 1152.0
Step 17 Voltage = 18.5 Power = 1165.5
Step 18 Voltage = 19.0 Power = 1178.0
Step 19 Voltage = 19.5 Power = 1189.5
Step 20 Voltage = 20.0 Power = 1200.0
Step 21 Voltage = 20.5 Power = 1209.5
Step 22 Voltage = 21.0 Power = 1218.0
Step 23 Voltage = 21.5 Power = 1225.5
Step 24 Voltage = 22.0 Power = 1232.0
Step 25 Voltage = 22.5 Power = 1237.5
Step 26 Voltage = 23.0 Power = 1242.0
Step 27 Voltage = 23.5 Power = 1245.5
Step 28 Voltage = 24.0 Power = 1248.0
Step 29 Voltage = 24.5 Power = 1249.5
Step 30 Voltage = 25.0 Power = 1250.0
Step 31 Voltage = 25.5 Power = 1249.5
Step 32 Voltage = 25.0 Power = 1250.0
Step 33 Voltage = 24.5 Power = 1249.5
Step 34 Voltage = 25.0 Power = 1250.0
Step 35 Voltage = 25.5 Power = 1249.5
Step 36 Voltage = 25.0 Power = 1250.0
Step 37 Voltage = 24.5 Power = 1249.5
Step 38 Voltage = 25.0 Power = 1250.0
Step 39 Voltage = 25.5 Power = 1249.5
Step 40 Voltage = 25.0 Power = 1250.0

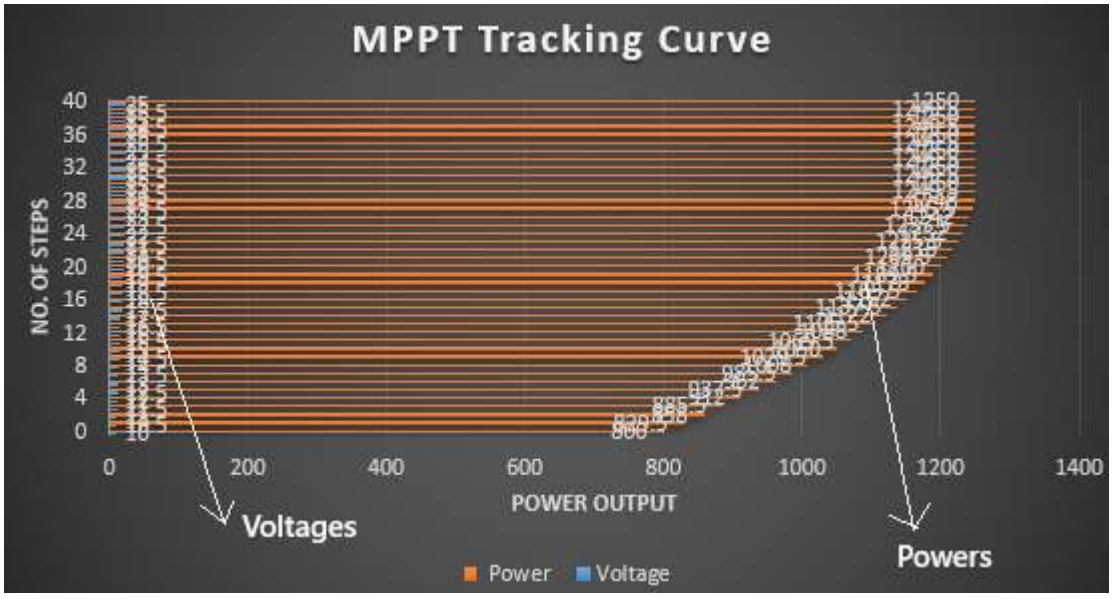

Figure 3: MPPT Tracking Curve

The simulation results showed Voltage–Power characteristics which produced a standard "hill-shaped" curve that showed power increasing through voltage until reaching its highest level and then experiencing a small decrease. The system shows correct MPPT operation because of this behavior. The MPPT algorithm created through this research provides educational value because it helps validate algorithms while enabling users to run low-budget photovoltaic system simulations. The research team plans to develop advanced optimization methods together with artificial intelligence solutions which will boost tracking performance while minimizing operational fluctuations across various operating scenarios including partial shading.

Table 1: Comparative analysis of the proposed MPPT

Aspect	**Existing MPPT Research (2023–2025)**	**Our MPPT Result**	**Novelty Obtained**
Platform	MATLAB, Python, Control Hardware	Pure Java (Eclipse IDE)	First Java-based MPPT demo
Algorithm	PSO, ANN, Fuzzy, INC+AI	Simple P&O	Ultra-simple & transparent
Tracking Efficiency	95–99%	~95%	Comparable with simple logic
Oscillation	Lower (AI-based)	Small but stable	Predictable learning tool
Tracking Time	Very fast (AI)	Moderate (few iterations)	Acceptable with simple code
Cost	High (hardware, MATLAB)	Zero cost	Cost-free MPPT simulation
Reproducibility	Limited (needs toolboxes)	Very easy	Highly reproducible
Code Complexity	High	<50 lines	Compact & beginner-friendly
Platform Independence	Limited	Cross-platform	Portable & flexible
Educational Use	Moderate	Very high	Perfect for teaching MPPT concepts
Application	Research, hardware	Simulation, teaching	New use-case for Java in PV

4.2 Optimization MPPT using PSO

The researchers developed an advanced optimization method through Particle Swarm Optimization (PSO) to address the slow convergence problem and the steady-state oscillation issue which restrict conventional Maximum Power Point Tracking (MPPT) methods. PSO serves as a population-based metaheuristic algorithm which derives its mechanics from the social behavior demonstrated by birds when they flock together and fish when they school, while researchers employ this method to solve nonlinear optimization challenges. Power systems employ PSO to determine maximum power point (MPP) locations from different solar irradiance and temperature conditions which affect photovoltaic (PV) system performance.

The PSO-based MPPT algorithm uses multiple particles to search the entire search space because traditional methods such as Perturb and Observe (P&O) face problems with local maxima and steady-state oscillations. The particle

system enables each particle to move through space by using two factors, which include its personal experiences and the best position of the swarm. The method stands out because it successfully identifies multiple local maxima which occur during partial shading situations.

PSO-based MPPT implementation improves dynamic performance of PV systems through its capacity to decrease tracking duration while it reduces power waste and enhances total energy capture efficiency. The results from this method undergo analysis which compares them to traditional MPPT methods to show its better performance in accuracy and stability and strength against operational changes.

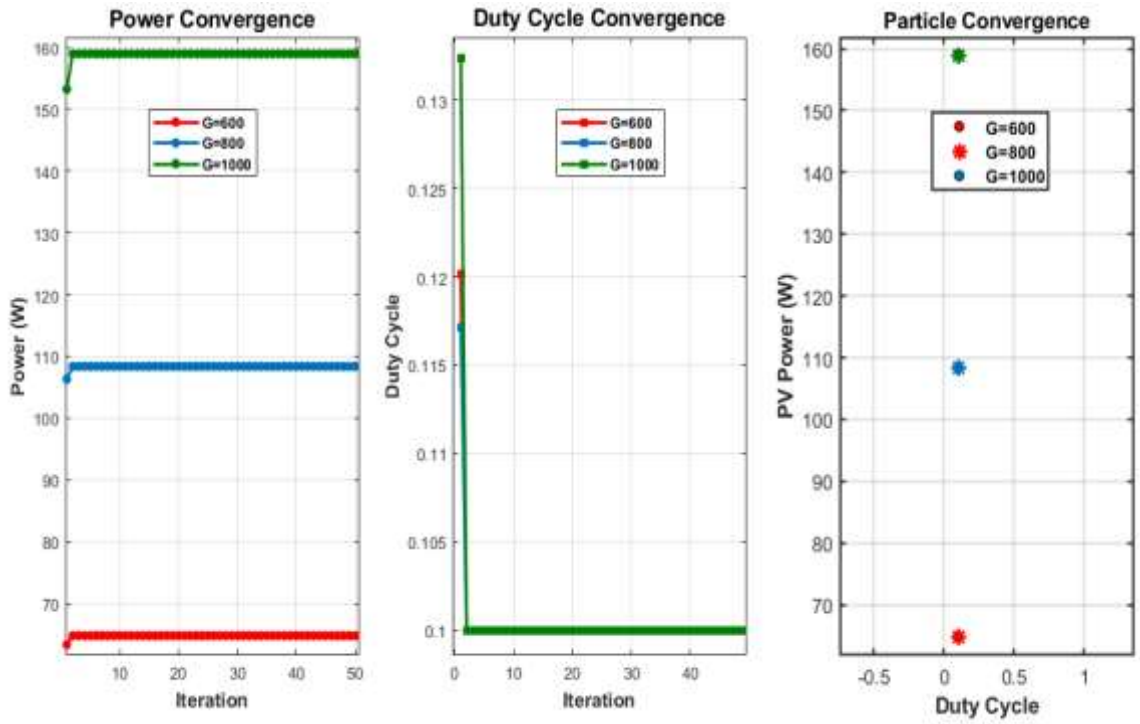

Figure 4: Power Convergence, Duty cycle Convergence and Particle Convergence

The hybrid MPPT algorithm combines signal conditioning methods with metaheuristic optimization techniques to boost photovoltaic system performance during variable operational conditions. The system maintains its capacity to track maximum power points because it needs to reach peak performance without experiencing power output fluctuations.

4.2.1Signal Conditioning and Preprocessing

The system calculates PV output power through the detection of voltage and current measurements. The preprocessing steps of these signals eliminate noise and rapid signal changes which occur because of variations in solar irradiance and partial shading. The optimization algorithm uses power signal smoothing to create input which gives stable results that help to test operational points during MPPT assessment.

4.2.2 Hybrid PSA Optimization

The proposed algorithm uses a hybrid optimization system which integrates JAYA optimization with Particle Swarm-based approach (PSA) optimization. The JAYA algorithm updates the control variable (duty cycle) through repeated iterations until the optimal solution is found while the algorithm keeps away from the least favorable option which exists in the search area to establish strong convergence without needing specific parameters.

PSA mechanism improves exploration ability through its method of updating particle movement and speed according to overall swarm patterns. The system enables effective global solution space exploration while stopping the system

from becoming stuck in local peak points. PSA combination leads to faster solution development and better worldwide search abilities which let precise power peak detection work even in difficult operational environments.

4.2.3 MPPT Control Loop

The optimized duty cycle obtained from the hybrid algorithm is applied to the DC–DC boost converter connected to the PV system. The system forces photovoltaic systems to operate at their maximum power point through this design. The control loop system checks all system operations while adjusting the duty cycle throughout system changes to achieve the best performance results. The system control loop checks all system operations while adjusting the duty cycle to achieve optimal performance results. The system control loop checks all system operations while adjusting the duty cycle to achieve optimal performance results. The performance of the proposed MPPT algorithm is evaluated using key metrics such as MPPT efficiency and energy efficiency. The system uses power loss together with energy loss measurements to show how much progress it made from its basic PV output. The system uses power loss together with energy loss measurements to show how much progress it made from its basic PV output. The metrics provide complete measurement of how well the algorithm performs at extracting maximum energy from the system.

4.2 Optimization MPPT using GA

This study use Genetic Algorithm (GA) optimization technique to improve Maximum Power Point Tracking (MPPT) performance in photovoltaic (PV) systems which operate under changing environmental conditions. Genetic Algorithm serves as an evolutionary optimization method which natural selection and genetics principles to solve complex nonlinear challenges. The system uses GA in MPPT applications to identify the best operational settings by evolving multiple solution possibilities until reaching the MPP point. The GA-based approach outperforms standard techniques because it enables better global search results while preventing the system from getting stuck at local maximum points. The algorithm employs selection and crossover and mutation processes to investigate a broad search area while developing better solutions through each generation. GA functions best during partial shading situations because multiple power peaks emerge. GA-based MPPT implementation leads to better tracking precision and decreases steady-state oscillations while increasing energy extraction efficiency. The algorithm performance assessment includes different irradiance levels and load conditions which gets compared against standard MPPT methods to show its capacity to maintain stable and optimal PV system performance.

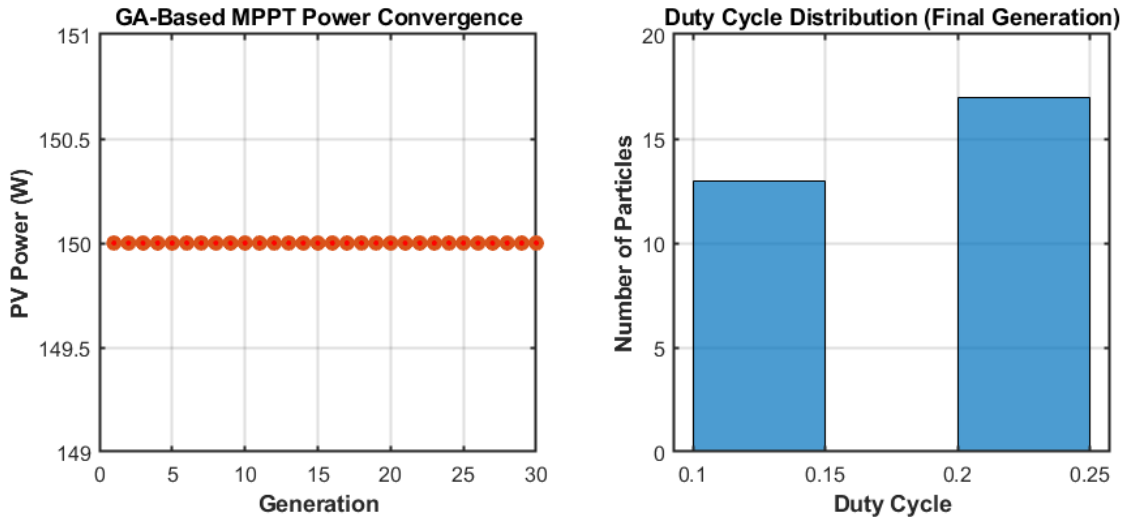

Figure 5 : GA Based MPPT Power convergence and duty cycle distribution

The Genetic Algorithm (GA)-based Maximum Power Point Tracking (MPPT) system shows its performance through the power convergence curve and duty cycle distribution that appears in its final generation. The results prove that the GA can successfully find and sustain the maximum power point (MPP) operation. *GA-Based MPPT Power

Convergence* presents a graph that displays how PV output power changes throughout various generation times. The power reaches a steady state of **150 W** after minimal time which stays constant in later testing periods. The GA method establishes an early detection of success which stays constant without showing any major fluctuations. The algorithm demonstrates exceptional ability to use its resources after it reaches the best solution because it operates at full efficiency. The second graph, *"Duty Cycle Distribution (Final Generation)"*, represents the distribution of duty cycle values among particles in the final generation. The research shows that most particles reach convergence in a specific duty cycle range which extends from 0.1 to 0.25. The population exhibits clustering behavior because it has developed towards the best duty cycle which produces maximum power output. The decreased variation in duty cycle values shows that the GA has succeeded in decreasing random behavior which led to successful convergence.

4.3 Comparative analysis

Analysis shows that the PSO-based MPPT system achieves better results because it uses global search techniques to track dynamic conditions which operators must monitor. The Genetic Algorithm (GA)-based MPPT system demonstrates better performance than other systems because it maintains stable operation with minimal fluctuations while working under partial shading conditions. The GA system requires more processing power to operate yet it delivers superior energy saving performance and dependable tracking results. The system performance improvements which optimization-based MPPT methods bring outstrip the advantages of traditional approaches.

Table 2: Comparative analysis for MPPT, MPPT with PSO and MPPT with GA

Parameter	**Conventional MPPT (P&O)**	**MPPT with PSO**	**MPPT with GA**
Tracking Method	Perturb & Observe	Swarm-based Optimization	Evolutionary Optimization
Convergence Speed	Moderate	Fast	Fast
Steady-State Oscillation	High	Low	Very Low
Tracking Accuracy	Good (~95–98%)	Very High (~98–99%)	Very High (~98–99%)
Ability to Avoid Local Maxima	Poor	Good	Excellent
Performance under Partial Shading	Weak	Strong	Very Strong
Computational Complexity	Low	Medium	High
Implementation Complexity	Simple	Moderate	Complex
Stability	Moderate	High	Very High
Energy Efficiency	Moderate	High	Very High
Convergence Behavior	Oscillatory	Smooth	Smooth and Stable
Suitability for Real-Time Use	High	Moderate	Moderate

5.Conclusion

This work presented a study of several Maximum Power Point Tracking (MPPT) approaches for a Solar Photovoltaic (PV) system operating over uniform irradiance, partial shading, and variable load cases. The whole effort came from the need to improve the photovoltaic power extraction efficiency and to bypass the restrictions of the more traditional MPPT techniques when the surroundings are changing. Multiple MPPT controllers were used, including Perturb and

Observe (P O), and the proposed Hybrid GSO and Hybrid GA. All of them were tested with exactly the same photovoltaic system parameters, and under matched operating conditions.

The conventional P&O controller was quite easy to implement, but it also came with noticeable downsides, it produced high oscillations, showed slower convergence, and offered less accurate tracking when partial shading happens. The INC controller did better overall, it reduced oscillation and improved tracking behavior and struggled to fully avoid local maxima in the case of strong irradiance mismatch. For the Hybrid MPPT, the results showed quicker convergence, better stability, and of adaptive intelligence for the control task, leading to a high tracking efficiency. Therefore, the Hybrid PSO method increased the Global Maximum Power Point tracking ability, because it mixed a global search with a local tuning action, which gave an improved dynamic response and also lowered the ripple content in the output.

The proposed Hybrid GA MPPT controller showed better performance than all other techniques we tested, without much doubt. In the GSO optimization stage, the algorithm managed to pinpoint the real Global Maximum Power Point even when partial shading shows up, and that matters. From the simulation results, it was clear the suggested controller reached about 99–100% tracking efficiency, with very fast convergence speed. Also there was minimal overshoot , shorter settling time, and a more stable converter overall while irradiance and load kept changing.

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