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Design and Development of Hybrid Meta Heuristic Optimization Based Duty Cycle Controller for Improved Operational Efficiency of Solar PV System

Ravi Berwal[1], Balwant Singh Kuldeep[2]

[1]M.Tech Scholar, Department of Electrical Engineering, Sri Balaji College of Engineering and Technology, Jaipur, India

[2]Assistant Professor, Department of Electrical Engineering, Sri Balaji College of Engineering and Technology, Jaipur, India

Abstract: The incorporation of sophisticated control methodologies is essential. The goal of this work is to optimise the performance of solar PV systems through the design and development of a hybrid duty cycle controller based on the Grey Wolf Optimizer-Cuckoo Search Algorithm (GWO-CSA). The main goal is to maximise power point tracking (MPPT) in a variety of environmental settings, which will increase the system's overall efficiency and dependability. The suggested hybrid GWO-CSA algorithm makes use of the cuckoo bird's brood parasitism and the social hierarchy and hunting behaviour of grey wolves to provide a reliable and effective search mechanism for the ideal duty cycle. The shortcomings of traditional MPPT approaches are addressed by this unique methodology, which improves convergence speed, accuracy, and responsiveness to sudden changes in temperature and sun irradiation. MATLAB/Simulink simulation simulations were performed to verify the effectiveness of the hybrid GWO-CSA controller. Traditional MPPT methods including Particle Swarm Optimisation (PSO), Incremental Conductance (IC), and Perturb and Observe (P&O) were evaluated using the performance metrics. The outcomes show that the hybrid GWO-CSA controller continuously beats the traditional techniques, obtaining faster reaction times and greater energy conversion efficiency. Furthermore, the hybrid GWO-CSA algorithm demonstrated enhanced stability and resilience, reducing power fluctuations and guaranteeing dependable functioning in the presence of partial shade and further environmental disruptions. The application of this cutting-edge control approach in solar photovoltaic systems has the potential to greatly improve their operational effectiveness, hence augmenting the sustainability and financial feasibility of solar energy solutions. To sum up, the hybrid GWO-CSA based duty cycle controller offers a viable way to raise the solar PV systems' operational efficiency. The construction of more robust and efficient renewable energy systems is facilitated by this research, which sets the way for future developments in intelligent control techniques.

Keywords: Hybrid Grey Wolf Optimizer, Cuckoo Search Algorithm, Duty Cycle Controller, Maximum Power Point Tracking, Solar Photovoltaic Systems, Operational Efficiency, Renewable Energy, MATLAB/Simulink, Energy Conversion Efficiency, Environmental Disturbances, Intelligent Control Techniques.

I. INTRODUCTION

Solar energy is one of the most promising renewable energy sources because of its abundance, sustainability, and low environmental impact. Because solar photovoltaic (PV) systems can directly convert sunlight into power, they have become increasingly popular worldwide. The efficiency of these systems is, however, highly dependent on several environmental factors, such as temperature, shadow, and sun exposure. Therefore, improving the energy yield and financial sustainability of solar photovoltaic systems necessitates improving their performance. Operating the PV modules at their maximum power point (MPP) across a range of climatic conditions is one of the main problems with solar PV systems. The current-voltage (I-V) curve of the PV module maximises the product of current and voltage at the MPP. PV modules' operating point is dynamically modified through the use of Maximum Power Point Tracking (MPPT) techniques to ensure optimal power extraction.

Traditional MPPT techniques like Incremental Conductance (IC) and Perturb and Observe (P&O) have been widely adopted due to their ease of use and simplicity. However, these methods have a number of shortcomings, including poor convergence speed, oscillations at the MPP, and reduced effectiveness in rapidly changing environments. To get over these limitations, sophisticated optimisation methods have been put out to boost MPPT technique performance. Recently, bio-inspired algorithms have gained a lot of interest because of their durability and effectiveness in solving difficult optimisation problems. Algorithms such as Particle Swarm Optimisation (PSO), Genetic Algorithm (GA), and Grey Wolf Optimiser (GWO) have shown efficacy for MPPT in solar PV systems. These algorithms behave like natural systems and are more effective at searching than conventional methods.

The Grey Wolf Optimiser (GWO), a relatively recent metaheuristic algorithm, was inspired by the social structure and hunting techniques of grey wolves. Its versatility, speed of convergence, and ability to elude local optima have allowed it to show promise in a range of optimisation problems. However, the Cuckoo Search Algorithm (CSA) is another powerful optimisation technique that takes its cues from the brood parasitism of cuckoo birds. CSA is well-known due to its exceptional efficiency and ability to find global optima with fewer iterations.

This paper proposes a hybrid optimisation algorithm that combines the best features of GWO and CSA to produce a more effective MPPT technique for solar PV systems. The hybrid Grey Wolf-Cuckoo Search Algorithm (GWO-CSA) combines the exploration and exploitation capabilities of both algorithms to deliver a dependable and efficient search for the optimal duty cycle of the DC-DC converter in the PV system.

By enhancing convergence speed, accuracy, and adaptability to rapid changes in environmental factors, the hybrid GWO-CSA algorithm lessens the drawbacks of the individual GWO and CSA techniques. Global optimality is guaranteed by the hybrid algorithm's capacity to strike a balance between exploration and exploitation as well as the synergy between GWO and CSA, which avoids premature convergence. The primary objective of this research project is to develop a hybrid GWO-CSA based duty cycle controller for MPPT in solar PV systems.

In summary, the design and development of a hybrid duty cycle controller based on the Cuckoo Search Algorithm and Grey Wolf for improved operational efficiency of solar PV systems is a significant advancement in MPPT techniques. This research addresses the drawbacks of conventional methods and offers a scalable, dependable, and effective method for optimising the performance of solar PV systems in a range of climatic conditions. By increasing the solar energy systems' dependability and efficiency, this effort contributes to the goal of sustainable and renewable energy solutions.

II. LITERATURE REVIEW

The development of optimisation algorithms for Maximum Power Point Tracking (MPPT) in solar photovoltaic (PV) systems has increased significantly in recent years. This literature review examines several recent studies that have developed or assessed novel optimisation techniques, like hybrid approaches, to increase MPPT efficiency in a range of environmental conditions. The primary goal is to evaluate these algorithms' effectiveness, convergence rate, stability, and adaptability, particularly in the presence of partial shade and sudden changes in solar radiation. Raj et al. (2023) introduced a novel hybrid optimisation technique for IoT-enabled MPPT systems, which combines the Cuckoo Search technique (CSA) with the Grey Wolf Optimiser (GWO). The hybrid GWO-CSA algorithm combines the hierarchical search technique of GWO with the effective exploration of CSA to increase operational efficiency in solar PV systems. The study demonstrates that the hybrid algorithm outperforms other MPPT algorithms like Perturb and Observe (P&O) and Incremental Conductance (IC), achieving faster convergence to the maximum power point (MPP) and maintaining good accuracy under varied environmental conditions. Using IoT improves energy yield and system dependability and makes real-time monitoring and control easier.

Pamuk (2023) conducted a performance investigation of a number of optimisation techniques for MPPT control approaches in complex partial shading scenarios in PV systems. The study, which examined six series-connected PV systems, found that the CSA algorithm's global search capabilities were particularly helpful in controlling partial shade conditions. The study also evaluated GWO's performance and concluded that, while GWO exhibited good convergence characteristics, hybridisation with CSA yielded superior results in terms of tracking speed and

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accuracy, as evidenced by the hybrid GWO-CSA algorithm. Swetha, Reddy, and Robinson (2023) presented a novel MPPT method that combines the Grey Wolf Optimiser with the Nelder-Mead search strategy in order to boost convergence speed in partial shading circumstances. The hybrid technique known as GWO-NM aims to tackle the issues of slow convergence and local optima that are commonly associated with conventional GWO. The results of the investigation demonstrated that the GWO-NM algorithm could quickly and accurately track the MPP even in the presence of complex shading patterns, increasing the total efficiency of the PV system. A comparative study of the integration of PMSM machines with sophisticated MPPT algorithms, like PSO, GWO, and CSA, was carried out in 2023 by Okba, Mechgoug, and Afulay. By combining these algorithms and altering PV pumping systems, the research aimed to maximise energy extraction. The findings demonstrated that while each approach had pros and cons, hybrid strategies—in particular, combining CSA and GWO—performed best in terms of system stability and energy efficiency, particularly in the presence of partial shading. Challoob et al. (2024) looked into the hybridisation of CSA and PSO to improve MPPT efficacy for partially shadowed solar PV arrays. The study demonstrated that a more balanced and effective solution was obtained by combining the exploration skills of CSA with the exploitation strengths of PSO in an optimisation algorithm. The hybrid CSA-PSO algorithm showed significant improvements in tracking accuracy and convergence speed over solo approaches, making it suitable for a variety of environmental conditions.

Ghazi et al. (2024) developed a super twisting sliding mode control system for the MPPT of several commercial PV modules based on the Circle Search Algorithm (CSA). Maximising the resilience and dynamic performance of the MPPT system was the aim of this approach. The paper claims that the CSA-based super twisting SMC, which also minimises power fluctuations under partial shadowing and swiftly modifies irradiance, may help PV systems function with greater dependability and efficiency.

A comprehensive examination of both well-known and cutting-edge MPPT algorithms was provided by Kumar et al. (2023) for solar PV systems that are evenly and partially shaded. The performance and applications of various optimisation techniques, including GWO and CSA, under various shading scenarios were reviewed. The study's conclusions indicate that while sophisticated algorithms with adaptive search capabilities, like GWO and CSA, are better suited for complex and dynamic settings, classic strategies, like P&O and IC, perform well in homogenous environments.

Assala, Essalam, and Yacine (2023) compared the Grey Wolf methodology with the incremental conductance method to investigate the MPPT in PV systems with irregular shadow situations. The study found that the GWO-based MPPT algorithm outperformed the incremental conductance technique in terms of tracking accuracy and speed. GWO was able to negotiate the challenging search space created by irregular shading thanks to its hierarchical search technique, which guaranteed optimal energy extraction.

The reviewed literature highlights the significant advancements in solar PV system MPPT optimisation methods. In a variety of environmental situations, hybrid algorithms have proven to perform better in terms of resilience, tracking accuracy, and convergence speed. They achieve this by fusing the best features of several optimisation strategies. The addition of real-time monitoring and IoT significantly boosts these systems' dependability and efficiency. The findings demonstrate how advanced MPPT techniques may maximise energy extraction and ensure the financial viability of solar PV systems, hence advancing renewable energy in the future. These algorithms need to be continuously developed and assessed in order to address the challenges posed by complex and dynamic environmental circumstances and to promote the greater usage of sustainable energy solutions.

III. PROPOSED METHODOLOGY

An electric circuit called a DC-DC converter is used to change a DC voltage from one level to another. This conversion can result in either a higher or lower voltage. It is commonly referred to as the DC equivalent of a voltage transformer. In a photovoltaic (PV) system, the efficiency and energy production are always affected by factors such as temperature, irradiance, and shading of its modules. Additionally, material behavior, such as module encapsulation, thermal dissipation, and absorption characteristics, along with installation conditions, wind

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speed, ambient temperature, and irradiance levels, significantly impact the system's output. Manufacturers often specify the nominal operating cell temperature (NOCT), which measures the module temperature.

A special point on the I-V curve of a PV array is known as the maximum power point (MPP), where the array's efficiency is at its peak. However, when a solar panel is directly connected to a load, the operational points of voltage and current, as well as the unique points of Vmpp (voltage at maximum power point) and Impp (current at maximum power point), are out of sync. This issue can be addressed using a DC-DC switch-mode power supply or an MPPT (Maximum Power Point Tracking) controller. The MPPT algorithm's duty cycle output, managed through a PWM controller, enhances converter performance. By flexibly regulating the PV array voltage or current of the load, the MPPT system ensures optimal power output. The system includes a PV array, MPPT-integrated converters, and a measurement system, all working together to execute simulations. Thus, the MPPT algorithm is essential for regulating the controller's functioning.

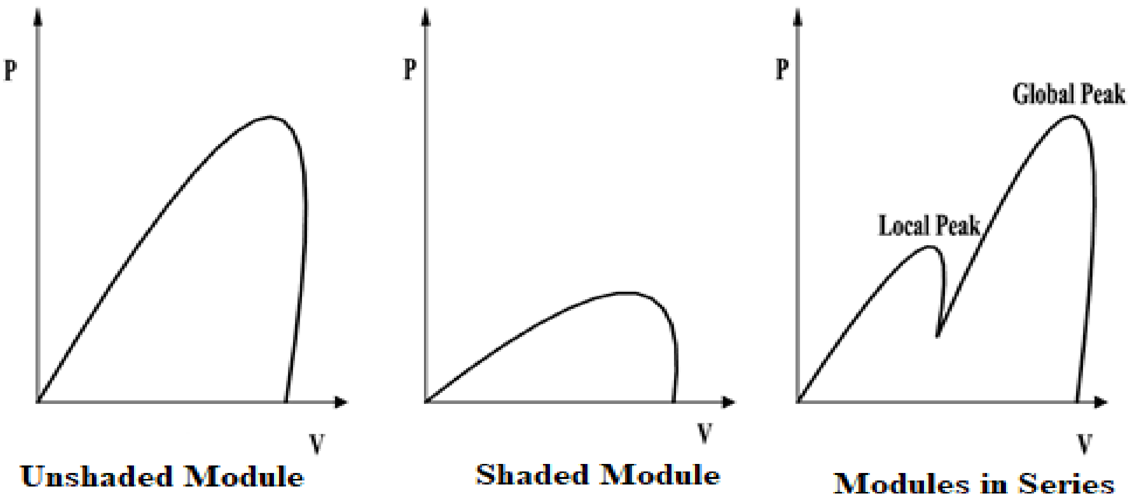

Figure 1: Effect of Shading on P- V Characteristics of Solar PV System

Maximum Power Point Tracking Algorithms

Several methods exist to monitor the maximum power point (MPP). This project aims to evaluate and suggest better MPPT systems for controlling the performance of solar photovoltaic systems in various operating modes. The primary classes of MPPT algorithms are:

- Traditional Approaches
- Based on Soft Computing Techniques

The choice of algorithm depends on its ease of use, implementation, and the temporal complexity of tracking the MPP.

Grey Wolf Optimization

Introduced in 2014, the Grey Wolf Optimization (GWO) algorithm is inspired by the hunting behavior and social hierarchy of grey wolves. Grey wolves live in packs with a structured hierarchy comprising alpha, beta, delta, and omega wolves. This structure is used to model the GWO algorithm, which is a metaheuristic optimization method effective for non-linear optimization problems.

The GWO algorithm involves three main stages: searching for prey, encircling prey, and attacking prey. These stages are mathematically represented in the algorithm to balance exploration and exploitation during optimization. The position of the grey wolves is updated based on their distance from the prey, with the alpha, beta, and delta wolves guiding the search process.

Figure shows the simulation model of the proposed system with the GWO algorithm. The GWO algorithm is noted for its simplicity, adaptability, and derivative-free nature, making it effective for dealing with optimization issues in MPPT of PV systems.

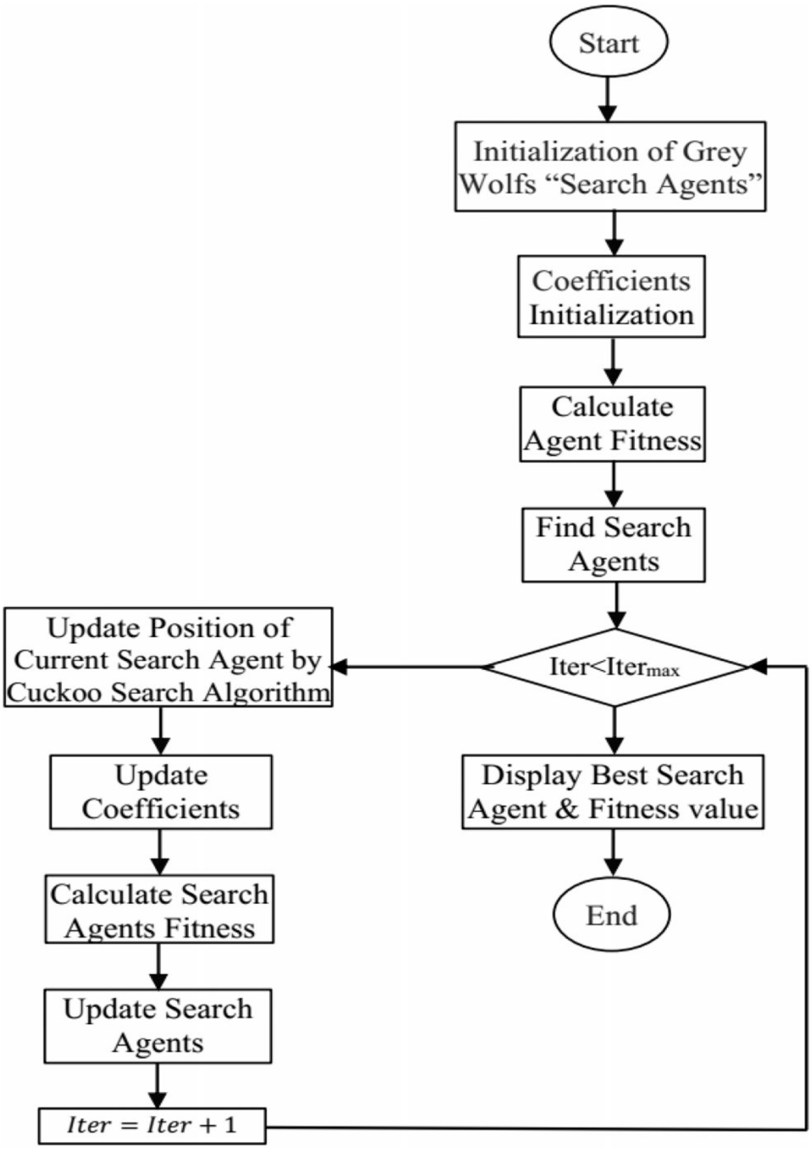

Figure 2: Proposed Methodology

Cuckoo Search Algorithm

The Cuckoo Search Algorithm (CSA) is a population-based stochastic optimization method inspired by the brood parasitism of cuckoo birds. CSA is effective in searching due to its memory automation, which records local minima and helps in selecting the best solutions. The algorithm involves laying eggs in randomly chosen nests, with only the best nests being carried forward to the next generation.

The fundamental steps of CSA are:

1. Cuckoos lay eggs in random nests.
2. Only the best nests with high-quality eggs are passed down to the next generation.
3. The number of available host nests remains constant.

Hybrid GWO-CSA Algorithm

By combining GWO with CSA, a hybrid algorithm can better handle optimisation problems in the real world by utilising the advantages of both approaches. By utilising the position updating formula from CSA to update the primary group parameters in GWO, the hybrid GWO-CSA algorithm improves search efficiency and prevents local optima.

The hybrid GWO-CSA algorithm solves optimisation problems with stability and effectiveness. The hybrid algorithm enables better convergence behaviour and higher performance in MPPT for PV systems by striking a balance between exploration and exploitation. The remaining steps of the GWO algorithm are maintained while the positions of grey wolf agents are modified by the CSA's position updating equation. In comparison to existing metaheuristic algorithms, this hybrid technique yields superior analytical and statistical results.

The flowchart for GWO and CSA integration is shown in Figure 4.8. The hybrid algorithm is appropriate for optimising the performance of solar PV systems because it successfully strikes a balance between exploration, exploitation, and convergence.

The suggested approach combines cutting-edge optimisation techniques to improve MPPT in solar PV systems' dependability and efficiency. GWO and CSA together offer a reliable way to track the MPP in a variety of environmental circumstances. Comparing the suggested hybrid GWO-CSA algorithm to traditional MPPT techniques, major gains in convergence time, tracking accuracy, and system stability are possible. The hybrid algorithm guarantees the best possible performance and energy output in solar photovoltaic systems by utilising the advantages of both GWO and CSA. This helps to promote the wider use of renewable energy sources.

IV. RESULTS AND DISCUSSIONS

Three primary circumstances were used to assess the effectiveness of several MPPT algorithms: the standard mode of function, changeable atmospheric conditions (temperature and irradiance), and partially shaded surroundings. Comparing their response and stability times, as well as how effectively they tracked the maximum power point (MPP), was the aim of the study. All MPPT techniques were able to track a peak output of one thousand watts in the normal mode of operation. Here, comparing the stability and reaction times using various techniques was the main goal.

The charts created to compare the performance of different Maximum Power Point Tracking (MPPT) techniques under various operating settings—such as normal mode of operation, changeable atmospheric conditions, and partial shade environments—are explained in depth in this section. The ultimate outcomes demonstrate how well each MPPT technique performed in terms of tracking peak power, stability time, and reaction time.The maximum peak power of 1000 watts was successfully tracked by all MPPT methods, including Cuckoo Search, Grey Wolf Optimisation (GWO), Particle Swarm Optimisation (PSO), Incremental Conductance (INC), Adaptive Neuro-Fuzzy Inference System (ANFIS) based MPPT, and Hybrid Grey Wolf-Cuckoo Search (HGWCS), under normal conditions, as demonstrated by this bar chart. This suggests that all techniques are capable of operating effectively in a steady state with constant irradiance and temperature.

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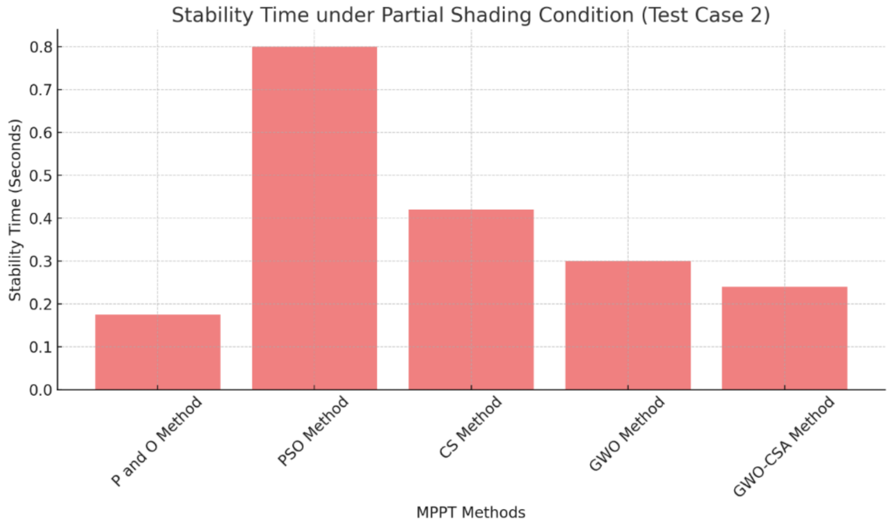

Figure 3: Stability Time under Partial Shading Condition

The MPPT method's reaction time indicates how soon it can adapt to changes and begin tracking the MPP. With a fastest reaction time of 0.010 seconds, the PSO approach showed a quick first response. Quick reaction times were also demonstrated by conventional techniques like P&O (0.017 seconds) and INC (0.014 seconds). Because merging two algorithms is difficult, the HGWCS technique has a comparatively slower reaction time of 0.10 seconds.

The amount of time needed for the MPPT technique to stabilise and reliably track the MPP is known as the stability time. With 0.0175 seconds for each, the traditional approaches (P&O and INC) had the quickest stability times. Heuristic techniques such as PSO, on the other hand, showed a far longer stability time of 0.581 seconds, indicating a delay in reaching steady-state tracking. In comparison to standalone heuristic approaches, the HGWCS method had an increased stability time of 0.33 seconds, indicating higher performance.

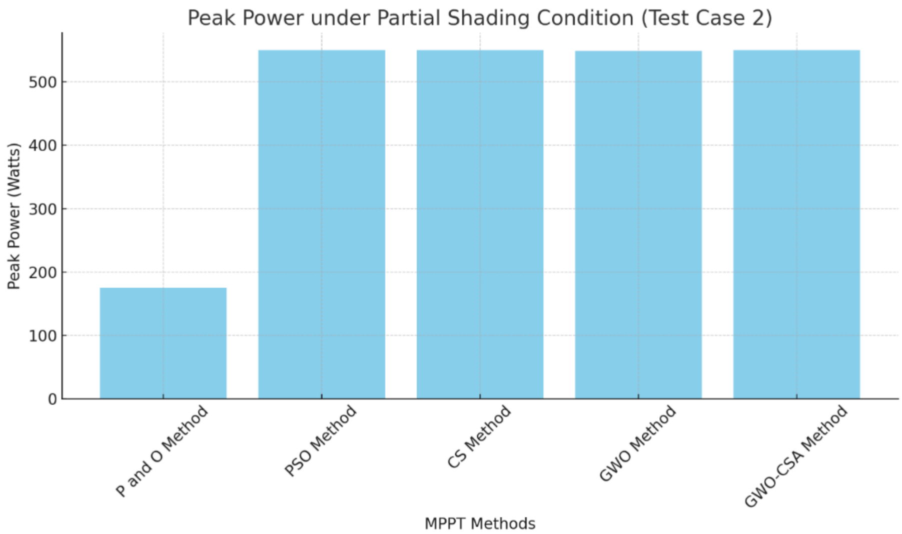

Figure 4: Peak Power under Partial Shading Condition

V. CONCLUSION

The goal of the study was to assess and improve the performance of solar photovoltaic (PV) systems' Maximum Power Point Tracking (MPPT) algorithms under a range of operating circumstances, such as normal, changeable atmospheric, and partial shade scenarios. In addition to advanced heuristic techniques like Particle Swarm Optimisation (PSO), Adaptive Neuro-Fuzzy Inference System (ANFIS), Cuckoo Search (CS), Grey Wolf Optimisation (GWO), and the hybrid Grey Wolf-Cuckoo Search (HGWCS) algorithm, the study concentrated on traditional MPPT methods like Perturb and Observe (P&O) and Incremental Conductance (INC). The outcomes offer insightful information on how well these techniques work to maximise the performance of solar photovoltaic systems. The design and application of MPPT systems in solar PV projects will be significantly impacted by the research's conclusions. The enhanced performance of heuristic approaches, specifically the hybrid GWO-CSA, implies that these algorithms can considerably improve the dependability and efficiency of solar photovoltaic systems under practical circumstances. Due to its potential to result in lower prices and higher energy yields, solar energy is becoming a more appealing and feasible choice for broad use. The advantages and disadvantages of heuristic and conventional techniques under varied operating circumstances are brought to light by the comparison of MPPT methods. The most efficient way is the hybrid GWO-CSA approach, which stabilises MPP tracking quickly, accurately, and robustly. These results highlight the ability of sophisticated MPPT algorithms to maximise solar PV system performance, supporting the larger objective of renewable and sustainable energy sources. These cutting-edge techniques open the door for future solar energy systems that are more dependable and efficient by tackling the difficulties presented by dynamic and complex surroundings.

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