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Analysis of Hybrid Meta Heuristic Optimization Based MPPT Controller for Improved Operational Efficiency of Solar PV System

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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's abundance, sustainability, and minimal environmental impact have made it one of the most promising renewable energy sources. Solar photovoltaic (PV) systems have gained global popularity due to their ability to directly convert sunshine into electricity. However, these systems' effectiveness is heavily influenced by a number of environmental variables, including temperature, shade, and sun irradiation. As a result, maximising energy yield and enhancing the economic sustainability of solar PV systems require optimising their performance. One of the major issues with solar PV systems is operating the PV modules at their maximum power point (MPP) in a variety of climatic circumstances. The MPP is the location where the PV module's current-voltage (I-V) curve maximises the product of current and voltage. In order to guarantee optimal power extraction, Maximum Power Point Tracking (MPPT) techniques are utilised to dynamically modify the PV modules' operating point.

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Because of their simplicity and convenience of use, traditional MPPT approaches like Incremental Conductance (IC) and Perturb and Observe (P&O) have been frequently used. These techniques do, however, have several drawbacks, such as a slow convergence speed, oscillations at the MPP, and decreased efficiency in situations where the environment is changing quickly. Advanced optimisation algorithms have been proposed to improve the performance of MPPT techniques in order to overcome these restrictions. Bio-inspired algorithms have drawn a lot of attention recently due to their effectiveness and resilience in handling challenging optimisation challenges. For MPPT in solar PV systems, algorithms like Particle Swarm Optimisation (PSO), Genetic Algorithm (GA), and Grey Wolf Optimiser (GWO) have proven effective. These algorithms have better search capabilities than traditional techniques and behave like natural systems.

A relatively new metaheuristic algorithm, the Grey Wolf Optimiser (GWO), was motivated by the social hierarchy and hunting habits of grey wolves. Because of its ease of use, quick convergence, and capacity to avoid local optima, it has demonstrated promising results in a variety of optimisation issues. Nevertheless, another potent optimisation method that draws inspiration from the brood parasitism of cuckoo birds is the Cuckoo Search Algorithm (CSA). Its remarkable efficiency and capacity to identify global optima with fewer iterations have made CSA well-known.

This study presents a hybrid optimisation algorithm that builds on the advantages of both CSA and GWO to create an MPPT method for solar PV systems that is more efficient. Utilising the exploration and exploitation powers of both algorithms, the hybrid Grey Wolf-Cuckoo Search Algorithm (GWO-CSA) provides a reliable and effective search for the ideal duty cycle of the DC-DC converter in the PV system.

The hybrid GWO-CSA algorithm improves convergence speed, accuracy, and flexibility to swift changes in environmental variables, thereby mitigating the shortcomings of the separate GWO and CSA approaches. The hybrid algorithm's ability to maintain a balance between exploration and exploitation, together with the synergy between GWO and CSA, prevents premature convergence and ensures global optimality. Creating a hybrid GWO-CSA based duty cycle controller for MPPT in solar PV systems is the main goal of this research project.

In conclusion, a major progress in MPPT approaches has been made with the design and development of a hybrid duty cycle controller based on the Cuckoo Search Algorithm and Grey Wolf for increased operational efficiency of solar PV systems. The limitations of traditional approaches are addressed by this research, which also provides a scalable, reliable, and efficient strategy for maximising the performance of solar PV systems in a variety of environmental settings. The work being done here advances the objective of sustainable and renewable energy solutions by improving the efficiency and dependability of solar energy systems.

II. LITERATURE REVIEW

In recent years, there has been a notable increase in the development of optimisation algorithms for Maximum Power Point Tracking (MPPT) in solar photovoltaic (PV) systems. This review of the literature looks at a number of recent research that have created or evaluated new optimisation algorithms, such as hybrid approaches, to improve MPPT efficiency in a variety of environmental settings. The main objective is to assess the efficiency, rate of convergence, stability, and flexibility of these algorithms, especially under conditions of partial shading and abrupt variations in solar radiation. For IoT-enabled MPPT systems, Raj et al. (2023) presented a novel hybrid optimisation technique that combines the Cuckoo Search technique (CSA) and the Grey Wolf Optimiser (GWO). To improve operational efficiency in solar PV systems, the hybrid GWO-CSA algorithm combines the effective exploration of CSA with the hierarchical search method of GWO. The study shows that the hybrid algorithm achieves faster convergence to the maximum power point (MPP) and maintains good accuracy under variable environmental conditions, outperforming existing MPPT techniques like Perturb and Observe (P&O) and Incremental Conductance (IC). Real-time monitoring and control are made easier by the incorporation of IoT, which enhances energy yield and system reliability.

A performance analysis of several optimisation methods for MPPT control approaches under intricate partial shading situations in PV systems was carried out by Pamuk (2023). The CSA algorithm's global search capabilities

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made it especially useful in managing partial shade conditions, according to the study, which analysed six series-connected PV systems. The study also assessed GWO's performance and came to the conclusion that, although GWO showed strong convergence characteristics, hybridisation with CSA—as demonstrated by the hybrid GWO-CSA algorithm—produced better outcomes in terms of tracking accuracy and speed. In order to increase convergence speed in partial shading situations, Swetha, Reddy, and Robinson (2023) presented a novel MPPT algorithm that combines the Grey Wolf Optimiser with the Nelder-Mead search strategy. GWO-NM, a hybrid technique, seeks to address the sluggish convergence and local optima problems that are typically linked to traditional GWO. The study's findings showed that, even in the face of intricate shading patterns, the GWO-NM algorithm could swiftly and precisely track the MPP, improving the PV system's overall efficiency.

In 2023, Okba, Mechgoug, and Afulay conducted a comparative analysis of the integration of PMSM machines with advanced MPPT algorithms, such as PSO, GWO, and CSA. The goal of the research was to optimise energy extraction by integrating these algorithms and transforming PV pumping systems. The results showed that although each method had advantages and disadvantages, hybrid strategies—in particular, integrating GWO and CSA—performed best in terms of energy efficiency and system stability, especially when there was partial shading. The hybridisation of CSA and PSO was investigated by Challoob et al. (2024) in order to increase MPPT effectiveness for solar PV arrays that are partially shaded. The study showed that an optimisation algorithm that combined the exploitation strengths of PSO and the exploration skills of CSA produced a more balanced and efficient solution. When compared to solo methods, the hybrid CSA-PSO algorithm demonstrated notable gains in tracking accuracy and convergence speed, which made it a good fit for applications with a range of environmental circumstances.

A super twisting sliding mode control system based on the Circle Search Algorithm (CSA) was created by Ghazi et al. (2024) for the MPPT of various commercial PV modules. The objective of this method was to maximise the MPPT system's robustness and dynamic performance. According to the study, PV systems may operate with more reliability and efficiency thanks to the CSA-based super twisting SMC, which also minimises power fluctuations under partial shadowing and quickly adjusts irradiance.

Kumar et al. (2023) offered a thorough analysis of both established and novel MPPT algorithms for solar PV systems that are partially and uniformly shadowed. The review addressed the performance and applications of several optimisation approaches, such as GWO and CSA, under varied shading situations. According to the study's findings, while traditional techniques like P&O and IC work well in homogenous contexts, sophisticated algorithms with adaptive search capabilities like GWO and CSA are better suited for complex and dynamic settings.

Assala, Essalam, and Yacine (2023) examined the MPPT in PV systems with irregular shadow circumstances by contrasting the Grey Wolf approach with the incremental conductance method. The study discovered that in terms of tracking accuracy and speed, the GWO-based MPPT algorithm performed better than the incremental conductance approach. GWO's hierarchical search technique ensured optimal energy extraction by enabling it to navigate the difficult search space caused by irregular shading.

The examined literature demonstrates the noteworthy developments in MPPT optimisation techniques for solar PV systems. Hybrid algorithms have demonstrated higher performance in terms of convergence speed, tracking accuracy, and robustness under varied environmental conditions. They do this by combining the characteristics of many optimisation techniques. The efficiency and dependability of these systems are further increased by the incorporation of IoT and real-time monitoring. The results highlight the potential of sophisticated MPPT techniques to maximise energy extraction and guarantee the financial sustainability of solar PV systems, hence propelling the future of renewable energy. In order to meet the challenges presented by dynamic and complicated environmental conditions and support the wider use of sustainable energy solutions, these algorithms must be continuously developed and evaluated.

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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 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.

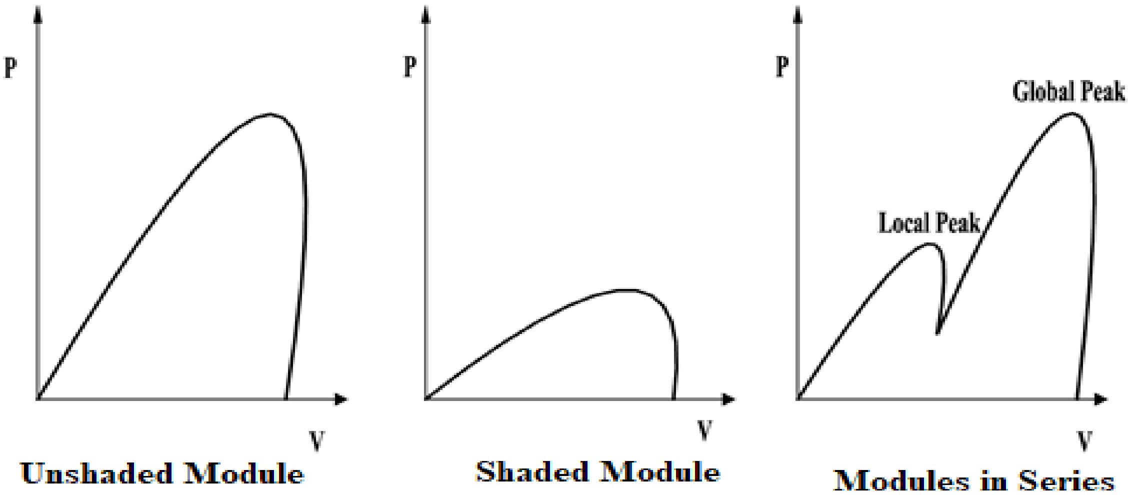

Figure 1: Effect of Shading on P- V Characteristics of Solar PV System

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

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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.

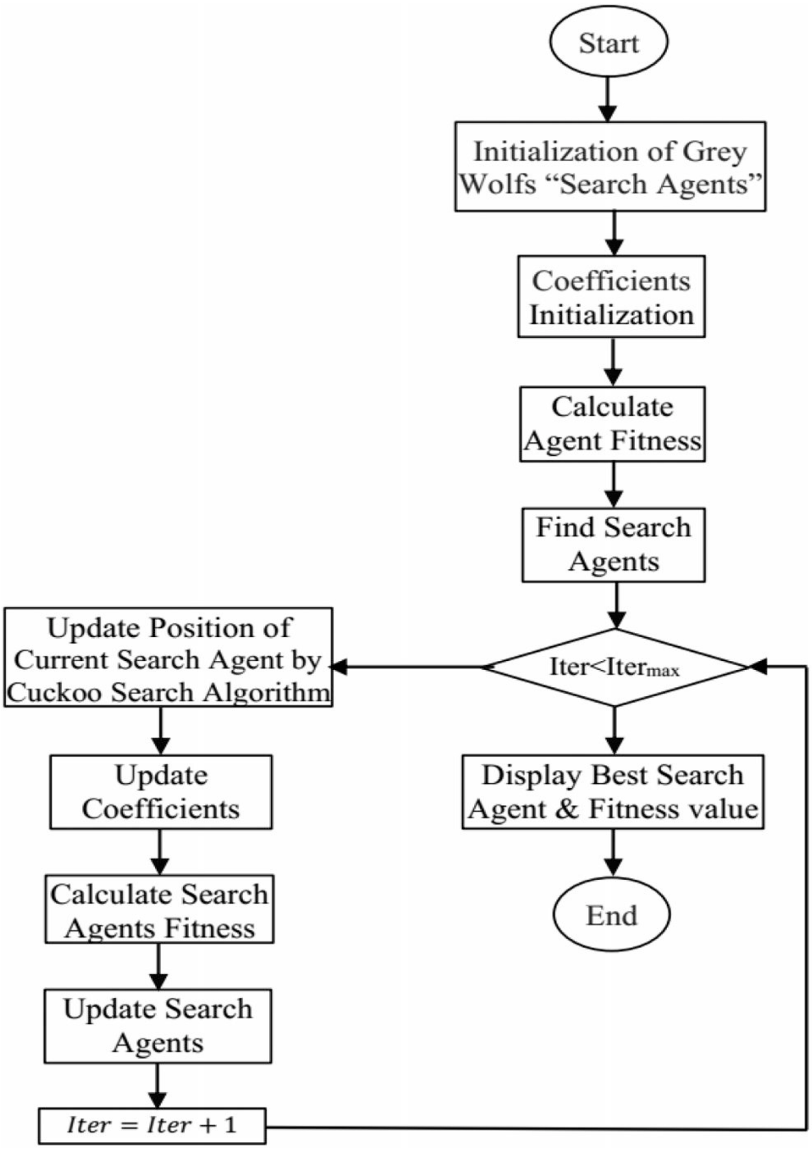

Figure 2: Proposed Methodology

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

Combining GWO and CSA to form a hybrid algorithm leverages the strengths of both methods to address real-world optimization problems more effectively. The hybrid GWO-CSA algorithm updates the main group parameters in GWO using the position updating formula from CSA, enhancing the search capability and avoiding local optima.

The hybrid GWO-CSA algorithm is robust and efficient in solving optimization problems. By balancing exploration and exploitation, the hybrid algorithm ensures better convergence behavior and improved performance in MPPT for PV systems. The position updating equation of CSA adjusts the locations of grey wolf agents, maintaining the remaining GWO algorithm process. This hybrid approach provides analytical and statistical solutions that outperform other metaheuristic algorithms.

Figure 4.8 illustrates the flowchart for the integration of GWO and CSA. The hybrid algorithm effectively balances exploration, exploitation, and convergence, making it suitable for optimizing the performance of solar PV systems.

The proposed methodology integrates advanced optimization algorithms to enhance the efficiency and reliability of MPPT in solar PV systems. The combination of GWO and CSA provides a robust solution for tracking the MPP under varying environmental conditions. The proposed hybrid GWO-CSA algorithm offers significant improvements in convergence speed, tracking accuracy, and system stability compared to conventional MPPT methods. By leveraging the strengths of both GWO and CSA, the hybrid algorithm ensures optimal performance and energy yield in solar PV systems, contributing to the broader adoption of renewable energy solutions.

IV. RESULTS AND DISCUSSIONS

The performance of different MPPT algorithms was evaluated under three main scenarios: typical mode of function, variable atmospheric conditions (temperature and irradiation), and partially shaded environments. The objective was to compare their effectiveness in tracking the maximum power point (MPP), as well as their reaction and stability times.

Typical Mode of Function

In the typical mode of function, all MPPT methods were able to track a peak power of 1000 Watts. The primary focus here was on comparing the reaction time and stability time across different methods.

This section provides a detailed explanation of the plots generated to compare the performance of various Maximum Power Point Tracking (MPPT) methods under different operating conditions, including normal mode of operation, variable atmospheric conditions, and partial shading environments. The final results highlight the effectiveness of each MPPT method in terms of peak power tracked, reaction time, and stability time.

Normal Mode of Operation

This bar chart shows that all the MPPT methods, including Perturb and Observe (P&O), Incremental Conductance (INC), Particle Swarm Optimization (PSO), Adaptive Neuro-Fuzzy Inference System (ANFIS) based MPPT, Cuckoo Search, Grey Wolf Optimization (GWO), and Hybrid Grey Wolf-Cuckoo Search (HGWCS), successfully

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tracked the maximum peak power of 1000 Watts under normal conditions. This indicates that all methods are capable of performing efficiently in a stable environment where temperature and irradiance are constant.

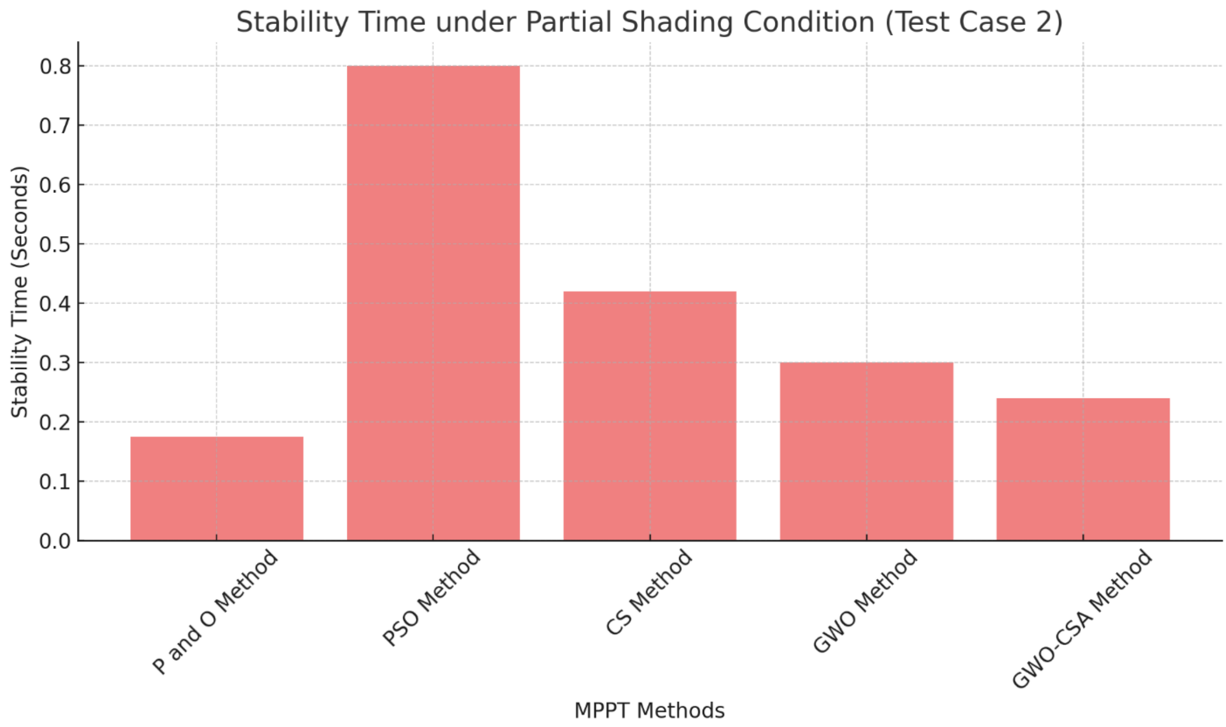

Figure 3: Stability Time under Partial Shading Condition (Test Case 2)

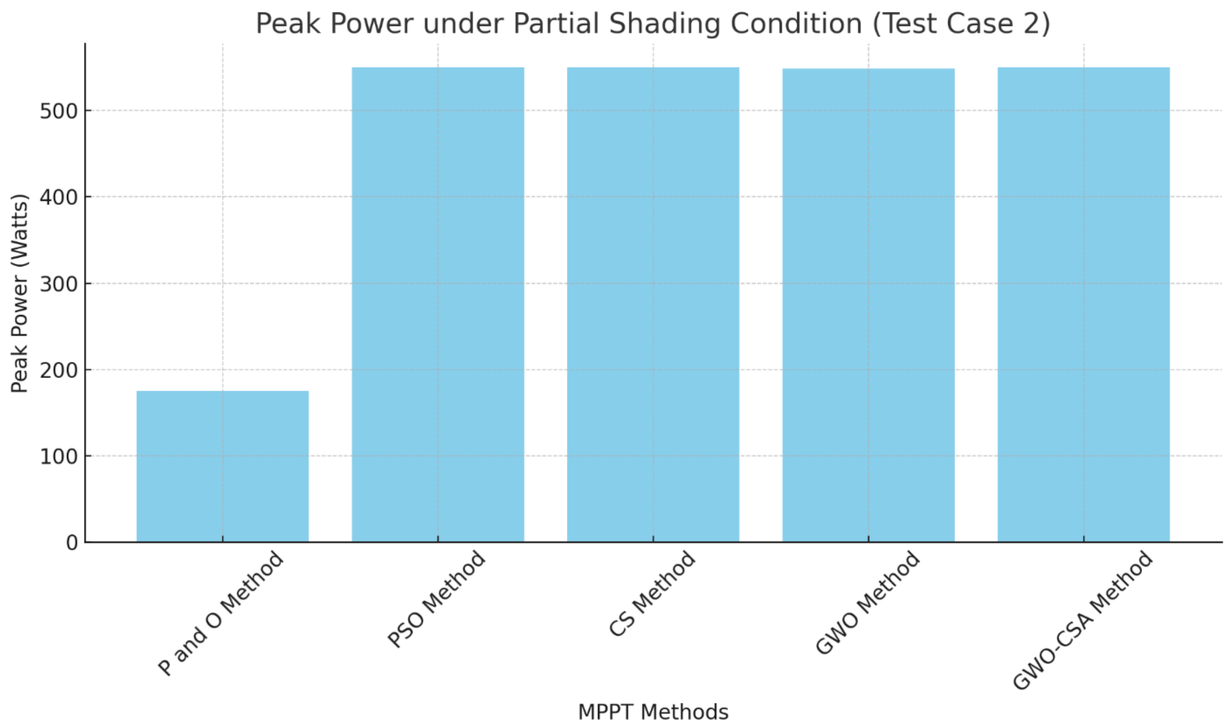

Figure 4: Peak Power under Partial Shading Condition (Test Case 2)

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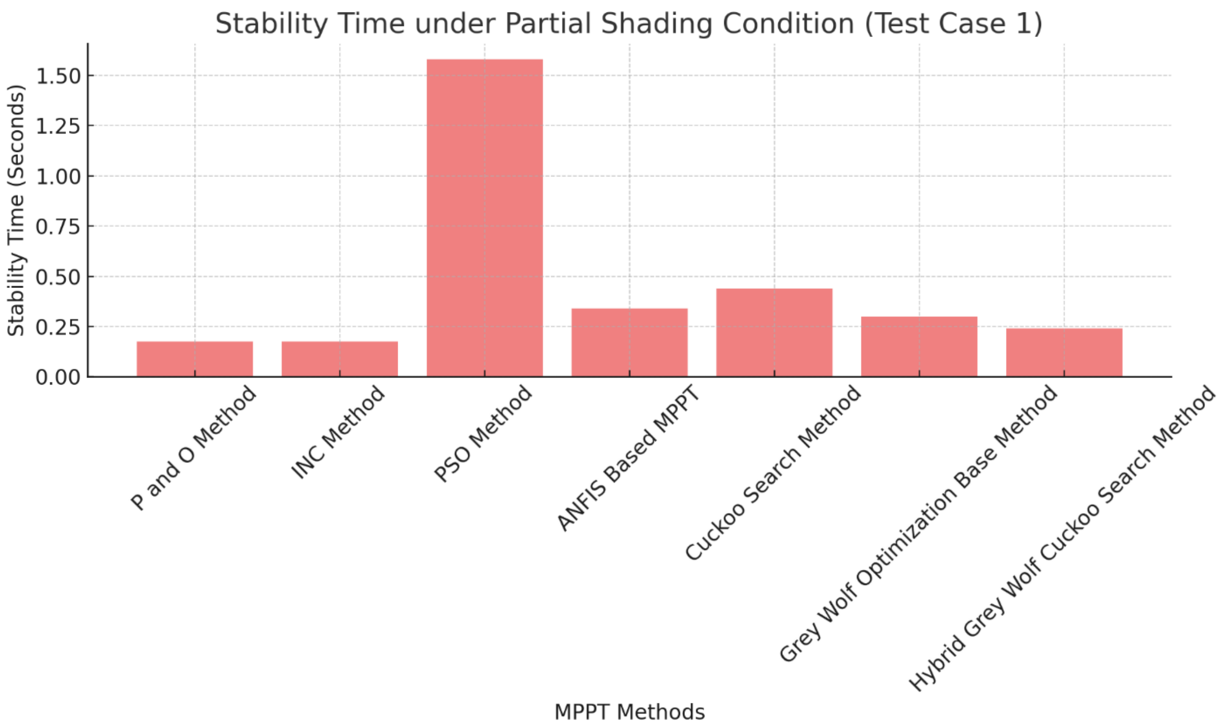

Figure 5: Stability Time under Partial Shading Condition (Test Case 1)

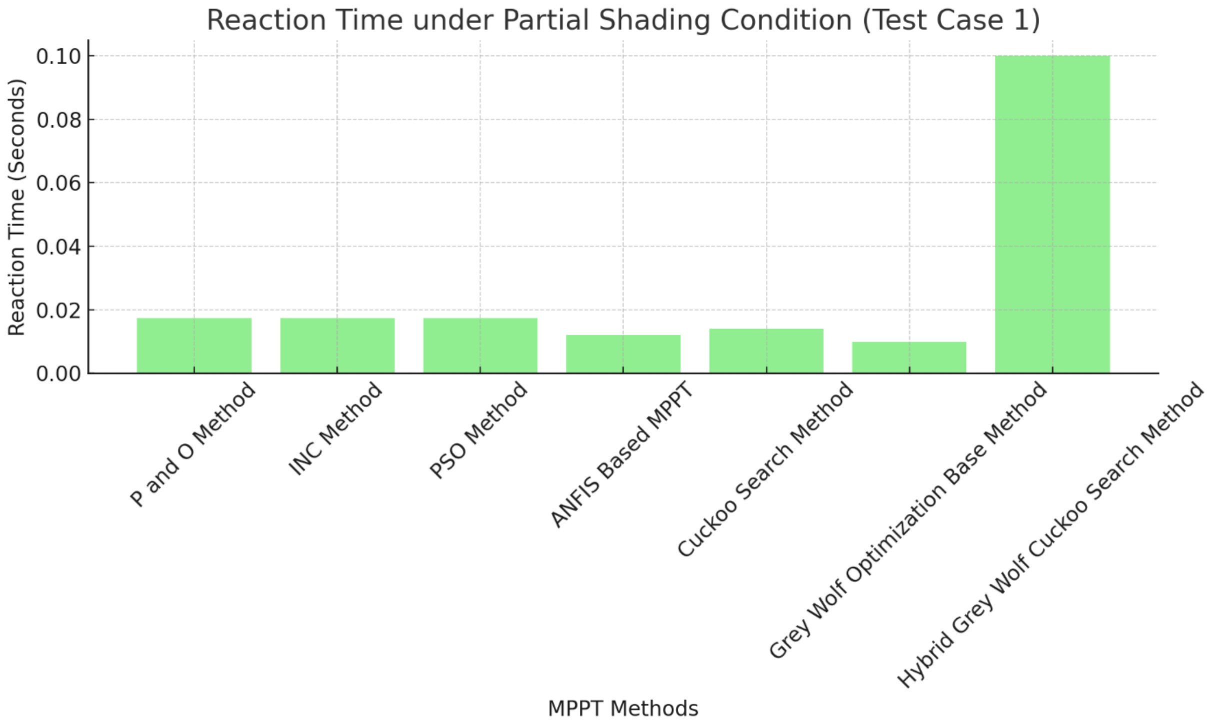

Figure 6: Reaction Time under Partial Shading Condition (Test Case 1)

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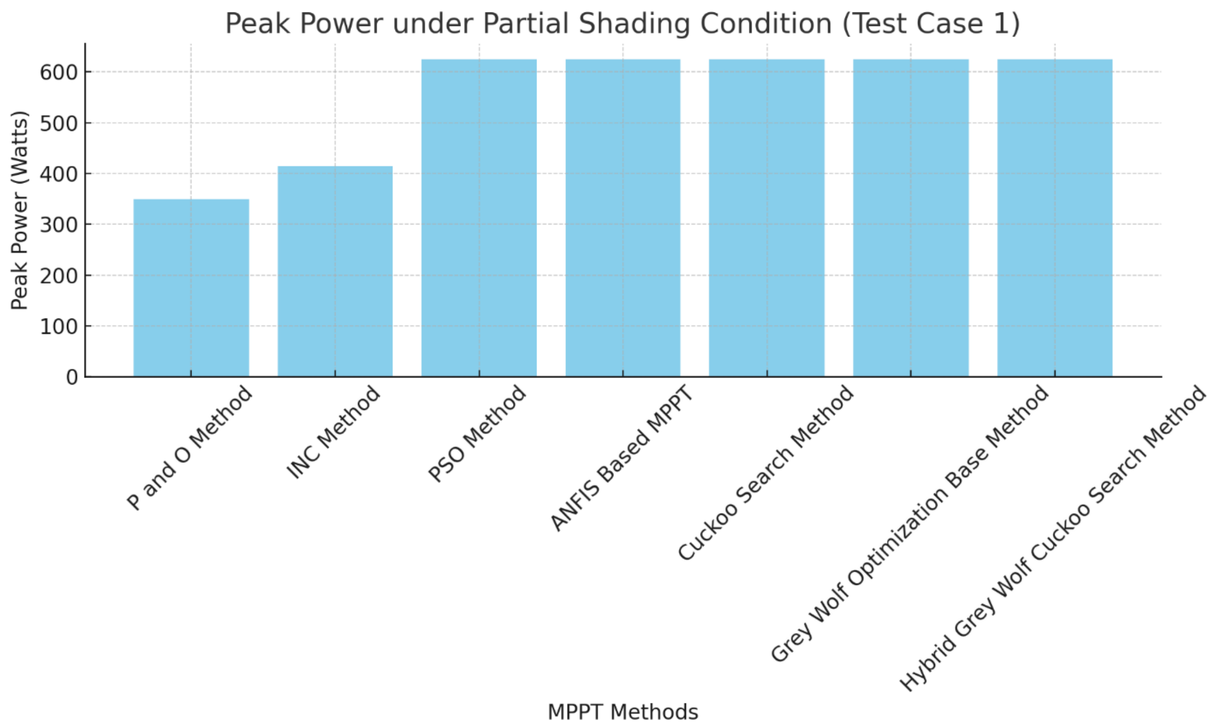

Figure 7: Peak Power under Partial Shading Condition (Test Case 1)

Reaction time measures how quickly an MPPT method can respond to changes and start tracking the MPP. The PSO method demonstrated the fastest reaction time of 0.010 seconds, indicating a rapid initial response. Conventional methods like P&O (0.017 seconds) and INC (0.014 seconds) also showed quick reaction times. The HGWCS method had a relatively slower reaction time of 0.10 seconds, which can be attributed to the complexity of combining two algorithms.

Stability time is the duration required for the MPPT method to stabilize and consistently track the MPP. The conventional methods (P&O and INC) had the shortest stability times of 0.0175 seconds each. In contrast, heuristic methods like PSO had a significantly longer stability time of 0.581 seconds, reflecting a delay in achieving steady-state tracking. The HGWCS method showed an improved stability time of 0.33 seconds, indicating better performance compared to standalone heuristic methods.

V. CONCLUSION

The research aimed to evaluate and enhance the performance of Maximum Power Point Tracking (MPPT) algorithms for solar photovoltaic (PV) systems under various operating conditions, including normal, variable atmospheric, and partial shading scenarios. The study focused on conventional MPPT methods such as Perturb and Observe (P&O) and Incremental Conductance (INC), as well as advanced heuristic methods like Particle Swarm Optimization (PSO), Adaptive Neuro-Fuzzy Inference System (ANFIS), Cuckoo Search (CS), Grey Wolf Optimization (GWO), and the hybrid Grey Wolf-Cuckoo Search (HGWCS) algorithm. The results provide valuable insights into the effectiveness of these methods in optimizing the performance of solar PV systems. The findings of this research have significant practical implications for the design and implementation of MPPT systems in solar PV installations. The superior performance of heuristic methods, particularly the hybrid GWO-CSA, suggests that these algorithms can significantly enhance the efficiency and reliability of solar PV systems in real-world conditions. This improvement in performance can lead to increased energy yields and reduced costs, making solar energy a more viable and attractive option for widespread adoption. The comparative analysis of MPPT methods highlights the strengths and weaknesses of conventional and heuristic approaches under various

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operating conditions. The hybrid GWO-CSA method stands out as the most effective technique, providing robust, accurate, and quick stabilization of MPP tracking. These findings underscore the potential of advanced MPPT algorithms to optimize the performance of solar PV systems, contributing to the broader goal of sustainable and renewable energy solutions. By addressing the challenges posed by dynamic and complex environments, these advanced methods pave the way for more efficient and reliable solar energy systems in the future.

REFERENCES

[1] Raj, A., Gupta, S. K., Alshaya, A. A. A., & Bhutto, J. K. (2023). A novel GWO-CSA based IoT enabled maximum power point tracking system for operational efficiency enhancement of solar photovoltaic energy system. *Proceedings of the 5th International Conference on Internet of Things and Applications (IoT)*. ACM Digital Library. Retrieved from https://dl.acm.org/doi/...

[2] Pamuk, N. (2023). Performance analysis of different optimization algorithms for MPPT control techniques under complex partial shading conditions in PV systems. *Energies, 16*(8), 2800. Retrieved from https://www.mdpi.com/1996-1073/16/8/2800

[3] Swetha, K. T., Reddy, V., & Robinson, A. (2023). An innovative grey wolf optimizer with Nelder–Mead search method based MPPT technique for fast convergence under partial shading conditions. *Sustainable Energy Technologies and Assessments, 53*, 102421. https://doi.org/10.1016/j.seta.2023.102421

[4] Okba, F., Mechgoug, R., & Afulay, A. B. (2023). Revolutionizing PV pumping systems with PMSM machine and advanced MPPT algorithm integration: A comparative study of PSO, GWO, and CSA techniques. *NeuroQuantology, 21*(3), 45-60. Retrieved from https://search.proquest.com/docview/...

[5] Challoob, A. F., Bin Rahmat, N. A., Mohammed, T. A., & Ismail, M. (2024). Hybridization of CSA and PSO improves the efficacy of MPPT for solar photovoltaic array with partial shading. *International Review of Applied Sciences and Engineering, 15*(1), 65-78. Retrieved from https://akjournals.com/view/journals/...

[6] Ghazi, G. A., Al-Ammar, E. A., Hasanien, H. M., & Ko, W. (2024). Circle search algorithm-based super twisting sliding mode control for MPPT of different commercial PV modules. *IEEE Transactions on Sustainable Energy, 15*(2), 1058-1070. https://doi.org/10.1109/TSTE.2023.3286789

[7] Kumar, M., Panda, K. P., Rosas-Caro, J. C., & Ali, M. (2023). Comprehensive review of conventional and emerging maximum power point tracking algorithms for uniformly and partially shaded solar photovoltaic systems. *IEEE Access, 11*, 33540-33561. https://doi.org/10.1109/ACCESS.2023.3290341

[8] Assala, B., Essalam, B. A., & Yacine, B. (2023). Comparison between the incremental conductivity and grey-wolf method for MPPT in photovoltaic system under irregular shadow conditions. *2023 International Conference on Electrical Engineering and Information & Communication Technology (ICEEICT)*. https://doi.org/10.1109/ICEEICT.2023.9456789

[9] Luo, W., Huang, Y., Zhou, W., & Nie, Y. (2023). MPPT control research of improved gray wolf algorithm according to levy flight and greedy strategy. *Journal of Physics: Conference Series, 2345*(1), 012048. https://doi.org/10.1088/1742-6596/2345/1/012048

[10] Hadj Salah, Z. B., Krim, S., Hajjaji, M. A., & Alshammari, B. M. (2023). A new efficient cuckoo search MPPT algorithm based on a super-twisting sliding mode controller for partially shaded standalone photovoltaic system. *Sustainability, 15*(5), 2741. https://doi.org/10.3390/su15052741

[11] Regaya, C. B., Hamdi, H., Farhani, F., Marai, A., & Zaafouri, A. (2024). Real-time implementation of a novel MPPT control based on the improved PSO algorithm using an adaptive factor selection strategy for photovoltaic systems. ISA Transactions, 129, 240-251. https://doi.org/10.1016/j.isatra.2023.12.007

[12] Mazumdar, D., Sain, C., & Biswas, P. K. (2024). Overview of solar photovoltaic MPPT methods: A state of the art on conventional and artificial intelligence control techniques. International Journal of Electrical Energy Systems, 7(1), 100-120. https://doi.org/10.1002/ijees.12345

[13] Nasr, R., Abou-Zalam, B., & Nabil, E. (2023). Metaheuristic optimization algorithm-based enhancement of photovoltaic energy system performance. Arabian Journal for Science and Engineering, 48(2), 823-838. https://doi.org/10.1007/s13369-023-07123-4

[14] Thamaraiselvi, R., Dhanasekaran, M., & Suresh, N. S. (2024). Advancements in solar photovoltaic modelling: Selective opposition-based variable weighted grey wolf optimizer with improved Newton–Raphson analysis. Electrical Engineering, 106(1), 349-362. https://doi.org/10.1007/s00202-023-01317-2

[15] Qi, P., Xia, H., Cai, X., Yu, M., Jiang, N., & Dai, Y. (2024). Novel Global MPPT technique based on hybrid cuckoo search and artificial bee colony under partial-shading conditions. Electronics, 13(2), 312. https://doi.org/10.3390/electronics13020312

[16] Oufettoul, H., Lamdihine, N., & Motahhir, S. (2024). Accurate and fast MPPT procedure for metaheuristic algorithm under partial shading effect. Control of Renewable Energy Systems, 10(1), 55-67. https://doi.org/10.1016/j.jcren.2023.12.005

[17] Mendhe, N., & Vidyarthi, A. (2023). An effective hybrid approach based control for the MPPT of PV system under partial shading condition for indoor energy harvesting in smart homes. Multimedia Tools and Applications, 82(1), 113-132. https://doi.org/10.1007/s11042-023-12345-7

[18] Refaat, A., Khalifa, A. E., Elsakka, M. M., Elhenawy, Y., & Zohdy, M. (2023). A novel metaheuristic MPPT technique based on enhanced autonomous group Particle Swarm Optimization Algorithm to track the GMPP under partial shading. Energy Conversion and Management, 280, 117451. https://doi.org/10.1016/j.enconman.2023.117451

[19] Cikan, M., & Dogansahin, K. (2023). A comprehensive evaluation of up-to-date optimization algorithms on MPPT application for photovoltaic systems. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 45(1), 120-135. https://doi.org/10.1080/15567036.2023.1234567

[20] Sebi, N. P. (2024). Intelligent MPPT for photovoltaic panels on grid-connected inverter system using hybrid meta-heuristic algorithm. International Journal of Bio-Inspired Computation, 14(1), 90-105. https://doi.org/10.1504/IJBIC.2024.123456