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Adaptive PSO MPPT Algorithm for Solar PV System under Partial Conditions

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Abstract: ***The rapid growth of the global population has significantly increased the demand for electricity, prompting extensive research into sustainable and renewable energy sources. Among these, solar photovoltaic (PV) systems have gained considerable attention due to their availability, cleanliness, and scalability. A solar cell exhibits a nonlinear current–voltage (I–V) characteristic with a unique operating point known as the Maximum Power Point (MPP), where the system achieves its highest power output. However, this point continuously shifts due to variations in irradiance, temperature, and inherent cell parameters. To minimize the cost of solar- generated electricity and enhance overall system efficiency, real-time Maximum Power Point Tracking (MPPT) is essential. The performance of GSA is evaluated and compared against another widely adopted evolutionary optimization technique, Particle Swarm Optimization (PSO). The comparative analysis aims to determine the effectiveness, response time, and accuracy of both algorithms in tracking the MPP under dynamic environmental conditions.***
Keywords: Gravitational Search Algorithm (GSA), Particle Swarm Optimization (PSO), Maximum Power Point Tracking (MPPT), Solar Photovoltaics.

I. INTRODUCTION

In recent years, optimization algorithms have experienced rapid development, providing effective solutions for complex engineering and computational problems. Among these techniques, the Gravitational Search Algorithm (GSA) has attracted considerable attention due to its strong optimization capability. GSA is inspired by Newton's laws of gravity and motion, where candidate solutions are treated as objects that interact with each other through gravitational forces. This mechanism enables the algorithm to search for optimal solutions in a multidimensional space efficiently. Several researchers have investigated different variants of the Gravitational Search Algorithm by modifying key parameters such as Kbest, velocity, and position. Adjusting these parameters improves the convergence behavior, exploration ability, and overall adaptability of the algorithm in solving diverse optimization problems. Performance comparisons of these variants are commonly conducted using benchmark test functions, including unimodal and multimodal functions as well as unconstrained optimization problems. To better understand the role of GSA in optimization, it is important to consider related techniques such as Maximum Power Point Tracking (MPPT) and Particle Swarm Optimization (PSO). MPPT is widely used in photovoltaic (PV) systems to continuously track the optimal operating point and maximize the power output of solar panels. Meanwhile, PSO is a population-based optimization algorithm inspired by the collective behavior observed in bird flocking and fish schooling. Through cooperation among particles, PSO efficiently searches for optimal solutions in complex problem spaces. Researchers have evaluated different GSA variants using metrics such as mean fitness value and convergence characteristics, which provide insights into the balance between exploration and exploitation capabilities of the algorithm. Among these variants, the Improved Gravitational Search Algorithm (IGSA) has demonstrated better precision and a more balanced search performance. Some studies have also applied GSA-based techniques to real-world datasets, including medical image analysis tasks such as nuclei segmentation in triple-negative breast cancer datasets. Another significant challenge in photovoltaic systems is the partial shading condition. Shading caused by clouds, buildings, or trees leads to multiple peaks in the power–voltage (P–V) characteristics of a PV array. Under such conditions, conventional MPPT methods like Perturb and Observe (P&O) and Incremental Conductance.

II. METHODS AND MATERIAL

Maximum Power Point Tracking (MPPT) is an essential technique used in photovoltaic (PV) systems to improve the efficiency of solar energy conversion. MPPT acts as an intelligent control mechanism that continuously adjusts the operating conditions of the solar panel to obtain the highest possible power output. By dynamically regulating parameters such as voltage and current, the controller ensures that the PV system operates near its maximum power point.

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In practical PV applications, environmental conditions such as solar irradiance, temperature, and shading can vary frequently. These variations cause changes in the current–voltage (I–V) and power–voltage (P–V) characteristics of the solar panel. The MPPT system continuously monitors these characteristics and identifies the operating point where the generated power is maximized. Through the use of sensors and control algorithms, the MPPT controller modifies the duty cycle of the power converter, enabling the PV system to maintain optimal performance under changing environmental conditions.

Therefore, MPPT technology plays a vital role in improving the overall efficiency and energy yield of solar power systems, making it an important component in modern renewable energy applications.

A. Gravitational Search Algorithm (GSA)

The Gravitational Search Algorithm (GSA) is a metaheuristic optimization technique inspired by Newton's law of gravity and the motion of celestial bodies. This algorithm was introduced by Rashedi, Nezamabadi-Pour, and Saryazdi in 2009. In GSA, candidate solutions are treated as objects with masses that interact with each other through gravitational forces.

The search process is performed by allowing these masses to attract one another, where heavier masses represent better solutions. As the algorithm progresses, the movement of these masses helps guide the search toward the global optimal solution. Due to its ability to balance exploration and exploitation, GSA has been applied to various engineering and optimization problem

B. Particle Swarm Optimization (PSO)

Particle Swarm Optimization (PSO) is a population-based optimization algorithm inspired by the collective behavior of birds flocking or fish schooling. In this method, a group of particles represents potential solutions within a defined search space. Each particle adjusts its position and velocity based on both its own previous experience and the best experience found by the entire swarm. The particles share information with each other during the search process, enabling them to move toward promising regions of the solution space. This cooperative behavior helps the swarm gradually converge to an optimal or near-optimal solution. Due to its simple structure, fast convergence, and ease of implementation, PSO has been widely applied in engineering optimization problems, including maximum power point tracking in photovoltaic systems. MPPT techniques are widely used in photovoltaic systems because the output power of a solar panel depends strongly on environmental conditions such as solar irradiance and temperature. Without MPPT control, the operating point of the PV system may not coincide with the maximum power point, resulting in significant energy loss. Various MPPT methods have been developed, including Perturb and Observe (P&O), Incremental Conductance (INC), Hill Climbing, and intelligent optimization techniques. Conventional methods are simple and easy to implement, but they often suffer from drawbacks such as oscillations around the maximum power point and reduced efficiency during rapidly changing weather conditions. To overcome these limitations, modern MPPT approaches use advanced optimization algorithms and intelligent control strategies. These methods improve tracking accuracy, reduce steady-state oscillations, and provide faster convergence toward the global maximum power point, especially under partial shading conditions.

C. The PV System

The photovoltaic (PV) system is designed to generate electrical power from solar energy while ensuring maximum efficiency through an MPPT control strategy. The implementation of the MPPT system is modeled using the MATLAB Simulink environment, which allows detailed analysis of system architecture and operational behavior.

The Simulink model represents the overall structure of the PV system, including the solar PV array, power electronic converter, MPPT controller, and load. The controller continuously monitors system parameters and adjusts the operating conditions of the PV array to ensure maximum power extraction under varying environmental conditions.

Figure 1 illustrates the block diagram of the PV system, highlighting the main components and their interactions within the MPPT-based solar energy conversion system.

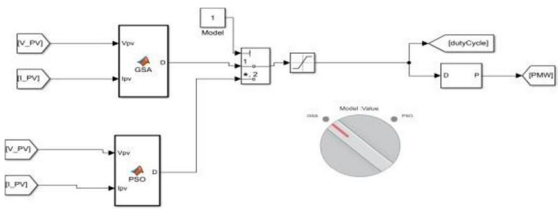


Figure 1: Block diagram of PV system

1) Base PV Model

At the heart of the MPPT system is the Base PV Model, a detailed representation of a solar panel that exhibits electrical characteristics akin to real- world PV cells. This simulation model is particularly sensitive to two key environmental inputs: irradiance and temperature. The Simulink model, as depicted in figure 2, is constructed with a granular level of detail, incorporating the nuanced physical processes of solar energy conversion.

This PV model is an assembly of several sub- components, including a source that simulates solar irradiance, a thermal model to account for temperature variations, and an equivalent circuit comprising diodes, resistors, and capacitors. These components collectively mimic the I-V (current- voltage) characteristics of a solar panel. By altering the irradiance and temperature inputs, one can observe the corresponding changes in the PV cell's output, thus enabling a dynamic analysis of the system's behavior.

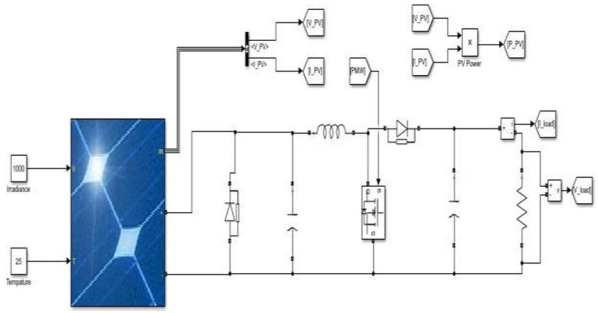


Figure 2: PV system implementation

Within Simulink, the model goes beyond mere simulation of solar cells—it extends to the encapsulation of an entire PV module or array, complete with the interconnection of multiple cells and bypass diodes. The entire setup is designed to emulate the power-generation process as accurately as possible, thereby laying a solid foundation for the implementation of MPPT algorithms.

2) MPPT Algorithms integration

The MPPT algorithms are implemented as distinct functional blocks within the Simulink model, each designed to interface seamlessly with the Base PV Model. The schematics depict the utilization of both the Particle Swarm Optimization (PSO) and Gravitational

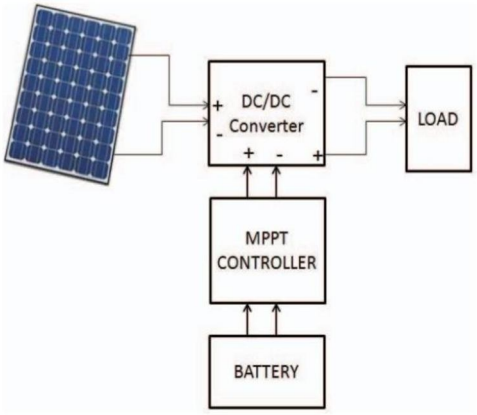


Figure 3: MPPT algorithms integration

These algorithms are represented in a way that abstracts the complex optimization processes into manageable blocks, The algorithms receive inputs directly from the PV model—such as the current and voltage—and apply their respective optimization techniques to iteratively adjust the duty cycle of a DC-DC converter. This process is inherently aimed at finding the optimal operating point that maximizes the power output from the PV module, irrespective of the static nature of the system's environmental inputs. The rotate switch allows to change which algorithms will be implemented inside the system.

3) Visualization

The visualization of simulation outcomes in a Simulink model of an MPPT system is pivotal to understanding the efficiency and effectiveness of the MPPT algorithms being used. The schematics provided suggest a systematic method of collecting and displaying data that highlights the dynamic performance of the system, particularly the power outputs from the PSO and GSA algorithms.

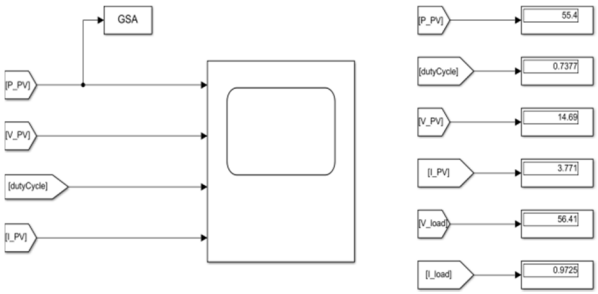


Figure 4: Block design for Visualization

4) PSO implementation

The implementation of the Particle Swarm Optimization (PSO) algorithm follows a well- defined process, as illustrated in the flowchart provided.

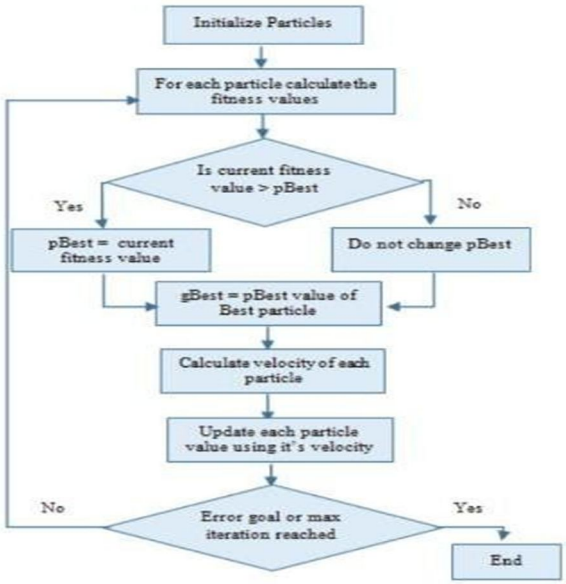


Figure 5: Flow of PSO algorithms

III. HARDWARE KIT

The hardware implementation of the proposed MPPT system consists of several components that work together to extract maximum power from the photovoltaic (PV) system. The hardware kit is designed to measure the output parameters of the PV panel, process them through a controller implementing the optimization algorithm, and regulate the operating point of the PV system through a power electronic converter. The major components of the hardware kit are described below.

1) Solar Photovoltaic (PV) Panel: The solar PV panel is the primary source of energy in the system. It converts solar radiation directly into electrical energy through the photovoltaic effect. The output of the PV panel varies depending on environmental conditions such as solar irradiance, temperature, and shading. Therefore, it is necessary to use an MPPT controller to ensure that the panel operates at its maximum power point.
2) DC–DC Boost Converter: The DC–DC boost converter is used to regulate and increase the voltage obtained from the PV panel. It also helps control the operating point of the PV system by adjusting the duty cycle of the switching device. By controlling the converter, the MPPT algorithm ensures that the PV panel operates at the optimal voltage and current levels for maximum power extraction.

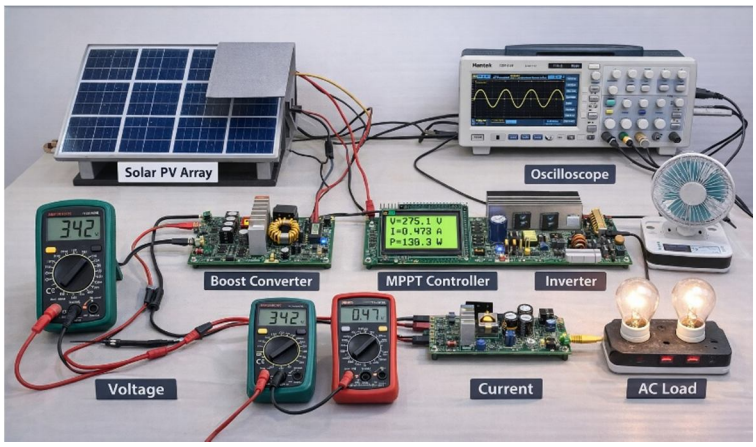
3) Microcontroller / Controller Unit: The controller unit is responsible for implementing the MPPT algorithm and controlling the entire system. A microcontroller processes the input signals obtained from sensors, calculates the power output, and determines the optimal duty cycle for the converter. Based on the optimization algorithm, the controller continuously updates the operating point to achieve maximum power output from the PV panel.

4) Voltage and Current Sensors: Voltage and current sensors are used to measure the electrical parameters of the PV system. These sensors provide real-time feedback to the controller, allowing it to calculate the instantaneous power of the PV panel. Accurate measurement of these parameters is essential for effective MPPT operation.

5) Battery / DC Load: A battery or DC load is connected to the output side of the converter to store or utilize the generated electrical energy. The battery helps maintain power stability and stores excess energy generated by the PV system. Alternatively, a resistive DC load may be used to test and evaluate system performance.

6) Display Unit: A display module is used to show system parameters such as voltage, current, and power output. This allows users to monitor the performance of the PV system and observe how the MPPT controller optimizes power generation under different conditions.

7) Power Supply Unit: The power supply unit provides the required regulated voltage for operating the controller, sensors, and other electronic components used in the hardware kit.



IV. RESULTS AND DISCUSSION

A. *Analysis*

In a comprehensive academic exploration, we delve into the algorithmic efficacy of two predominant strategies in the domain of photovoltaic system optimization: Gravitational Search Algorithm (GSA) and Particle Swarm Optimization (PSO). The investigation employs an experimental setup where both methodologies deploy three agents over a span of 3000 iterations in the span of time of 0.3 seconds.

B. *Finding*

The data are visually represented across several key performance indicators: power, duty cycle, voltage, and current

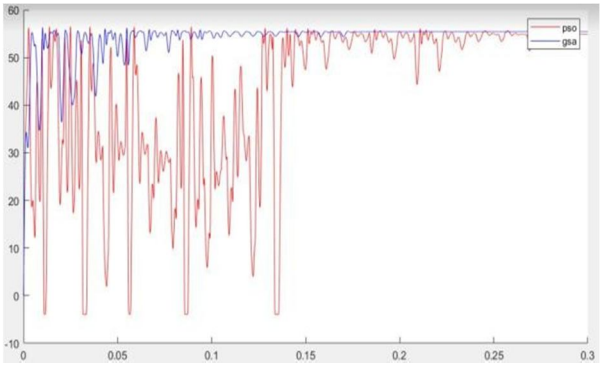


Figure 6: Maximal Power convergent pattern between GSA and PSO

The power graphs indicate that GSA quickly stabilizes to an optimal power level, exhibiting minor fluctuations, suggestive of a robust and effective tracking approach. In contrast, PSO's power graph is marked by a more varied performance, with power levels taking a longer time to stabilize, reflecting its expansive exploration of the search space.

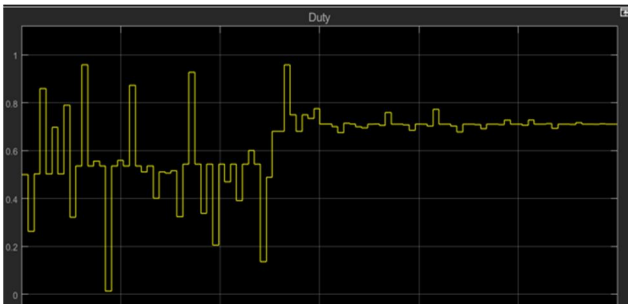


Figure 8: Duty pattern of PSO

Examining the duty cycle adjustments, GSA demonstrates a swift approach to identifying an optimal duty cycle, as evidenced by fewer and smaller adjustments.

The findings of this experimental analysis resonate with the results presented in the paper titled "A GSA Based" Improved MPPT System for PV Generation." This affirms the superior performance of GSA in terms of faster convergence and less oscillatory behavior

Table 1: Performance of GSA and PSO

	GSA	**PSO**
Max Power (Watt)	55.4	54.32
Stabilize Time (Sec)	0.173	0.278
Oscillation	less	more
Convergence	faster	slower

C. Discussion

Optimization (PSO) within the realm of Maximum Power Point Tracking (MPPT) unveils distinct operational profiles for each algorithm.

GSA's proficiency is evident in the data, which highlights its rapid convergence to the maximum power point, suggesting an innate capability to efficiently home in on the optimal solution. The consistent maintenance of a steady state following convergence further exemplifies GSA's stability, marking it as an effective tool for MPPT where rapid and reliable tracking is indispensable. Such performance is advantageous in dynamic environments where swift adaptation to changing solar irradiance and temperature conditions is essential. In contrast, PSO's performance is defined by its exploratory nature. The algorithm's oscillatory convergence pattern, as reflected in the experimental data. On the other hand, PSO is praised for its simplicity and ease of implementation, characterized by fewer parameters that need adjusting. This simplicity makes PSO accessible for a variety of applications, supported by its adaptability todifferent problem domains, including discrete and combinatorial optimization tasks. Nevertheless, PSO faces challenges, such as the risk of getting stuck in local optima in complex landscapes, which necessitates maintaining swarm diversity. The algorithm's performance is also highly sensitive to parameter settings, including inertia weight and acceleration coefficients, which can significantly impact outcomes.

V. FUTURE SCOPE

Although the proposed Adaptive Particle Swarm Optimization (PSO) based Maximum Power Point Tracking (MPPT) method demonstrates improved performance in extracting maximum power from photovoltaic systems under partial shading conditions, several areas remain open for further research and development.

In future work, the proposed algorithm can be implemented in real-time hardware platforms such as microcontrollers, Digital Signal Processors (DSP), or Field Programmable Gate Arrays (FPGA) to validate its practical feasibility and performance in real-world solar energy systems. Hardware implementation would provide better insight into system efficiency, computational requirements, and response time.

Additionally, the proposed MPPT technique can be extended to hybrid renewable energy systems that combine solar photovoltaic systems with other energy sources such as wind turbines, fuel cells, or battery energy storage systems. Such integration would enhance the reliability and stability of renewable power generation.

Another potential direction for future research is the integration of intelligent techniques such as artificial neural networks, fuzzy logic, and machine learning algorithms to further improve the accuracy and convergence speed of the MPPT controller under rapidly changing environmental conditions.

Furthermore, the algorithm can be applied to large-scale grid-connected photovoltaic power plants where efficient power extraction and system stability are critical. Advanced monitoring techniques and Internet of Things (IoT) based systems may also be incorporated to enable remote supervision, fault detection, and performance analysis of PV systems.

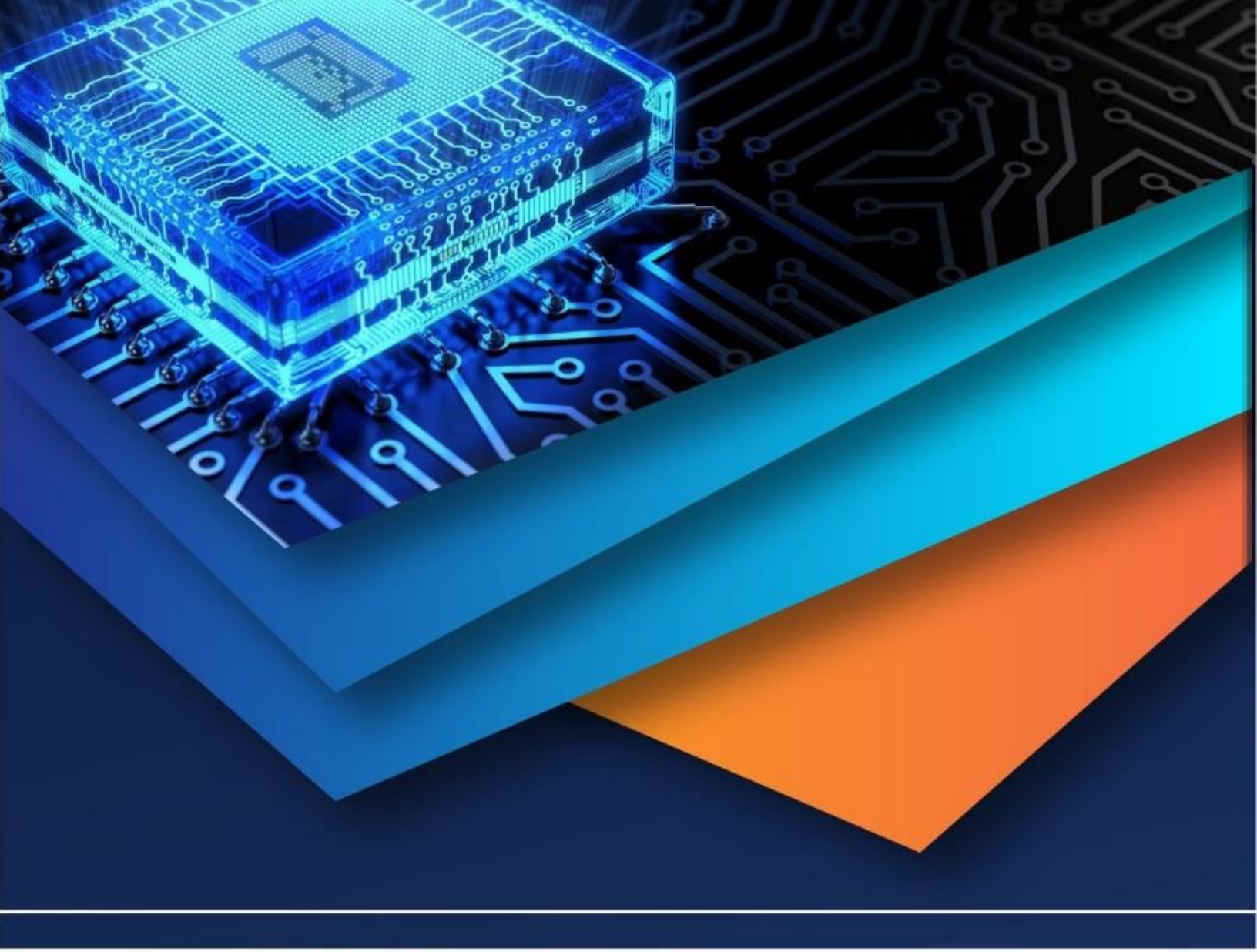
VI. CONCLUSION

In summary, the application of Particle Swarm Optimization (PSO) and the Gravitational Search Algorithm (GSA) in Maximum Power Point Tracking (MPPT) systems provides a meaningful comparison between these two optimization approaches. Both algorithms exhibit distinct advantages and limitations when applied to the task of maximizing power extraction in photovoltaic systems. This comparison emphasizes the importance of selecting an appropriate optimization technique based on the specific design requirements and operating conditions of the MPPT system. Among the studied methods, the implementation of GSA demonstrates promising potential for improving the performance of MPPT control strategies

The outcomes of this study are expected to contribute to further research in the area of MPPT optimization for renewable energy systems. With the increasing demand for efficient solar energy utilization, future investigations may focus on developing hybrid optimization techniques, improving algorithm parameters, and evaluating the scalability and adaptability of these methods for different PV system configurations. Such advancements could significantly enhance the efficiency and reliability of solar energy harvesting technologies.

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