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Comparative study of nature-inspired maximum power point tracking algorithms for partially shaded photovoltaic systems

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ABSTRACT

Photovoltaic (PV) systems are widely used for converting solar energy into electrical energy. However, PV systems are susceptible to partial shading, leading to fluctuations in temperature and irradiation that degrade the system's performance. To overcome this challenge, maximum power point tracking (MPPT) algorithms are implemented in PV systems. This research paper provides a comprehensive comparative analysis of three nature-inspired MPPT algorithms, namely cuckoo search, grey wolf and fish swarm optimization, to improve the performance of PV systems under partially shaded conditions. The study evaluates the speed, complexity, compatibility, and stability of each algorithm, and concludes that the fish swarm optimization algorithm is the most effective among the three. The novelty of this research lies in the in-depth comparison of nature-inspired MPPT algorithms (specifically fish swarm optimization) for partially shaded PV systems, offering valuable insights for researchers to improve the performance of PV systems.

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1. INTRODUCTION

The world is facing the daunting challenge of meeting increasing energy demands while traditional fossil fuels are depleting [1]. The recent conflict between Russia and Ukraine has further aggravated the situation. Furthermore, conventional energy sources such as coal and oil are causing environmental damage, resulting in global warming [2]. In light of these concerns, renewable energy has gained significant attention. Among various renewable energy sources, solar energy has been widely embraced due to the abundant sunlight available on earth.

While photovoltaic (PV) cells are used to convert sunlight into electricity [3], their effectiveness can be hampered by changes in solar irradiance and temperature, intermittency, low efficiency, lower rating, high cost, and maintenance difficulties. Partial shading of the PV panels by clouds, trees, or other objects causes these variations in solar irradiance and temperature fluctuations. To mitigate these issues, a DC-DC converter with a maximum power point tracking (MPPT) technique is necessary to extract the maximum power output from the PV panel under all conditions. The MPPT control algorithm [4] adjusts the duty cycle of the DC-DC converter according to changes in solar irradiation and temperature, improving the lower voltage output of the PV system.

PV cells are low-power rating devices and are connected in series or parallel to achieve the required current and voltage rating, forming a PV module that is combined with other modules to form a PV array [5], [6]. PV panels can be installed on rooftops and function in standalone or grid-connected mode. The temperature of the panel and the current irradiance level are critical factors that influence the output voltage of a PV system [7], [8]. The MPPT trackers [9] use a control algorithm and converter to track the maximum power point (MPP) to achieve the most power from PV panels. However, this tracking scheme may be ineffective if the PV panels are partially shaded. Therefore, researchers are exploring efficient and reliable MPPT algorithms, and there has been a shift toward nature-inspired search algorithms [10] in recent years. In this context, the novelty of this study lies in presenting a comparative analysis of different nature-inspired MPPT algorithms for mitigating the challenges faced by PV systems due to fluctuations in temperature and irradiation [11]. This work offers valuable insights into the effectiveness of these algorithms in overcoming partial shading-related issues and improving the performance of PV systems under challenging conditions.

Figure 1 shows schematic diagrams of all three nature-inspired algorithms. Figure 1(a) depicts the cuckoo search algorithm, an optimization technique inspired by the egg-laying behavior of cuckoo birds [12], [13]. The algorithm is used for duty cycle optimization of a boost converter in a partially shaded solar panel system to maximize the panel's output power. It generates a set of potential solutions represented as cuckoo eggs, with each egg corresponding to a duty cycle value for controlling the boost converter.

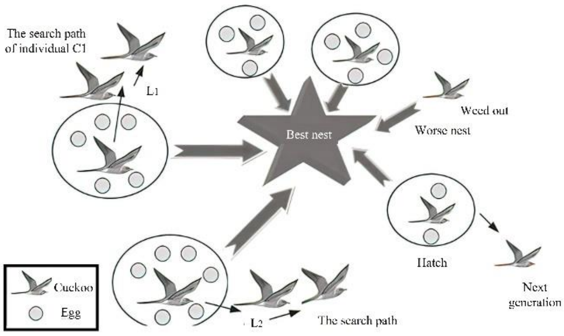
The fitness of each egg is evaluated based on how well the corresponding duty cycle performs in maximizing the panel's output power using the MPPT technique, which adjusts the duty cycle according to changes in solar irradiation and temperature. The algorithm updates the duty cycle values in the population using a combination of random walk and levy flight inspired by cuckoo bird behavior. The random walk helps to explore the solution space, while the levy flight [14], [15] is useful in exploiting the promising solutions. The process continues for a certain number of iterations until a stopping criterion is met, such as reaching a maximum fitness value or a set number of iterations. Figure 2 shows all three algorithms' flowcharts. Figure 2(a) specifically shows the cuckoo search algorithm flow chart.

The grey wolf algorithm is as shown in Figure 1(b) is an optimization technique inspired by how grey wolves hunt [16]. The algorithm works in four phases: i) making a group of grey wolves, ii) picking the strongest grey wolf as the leader, iii) having the other wolves look for prey near the leader, and iv) surrounding the prey to catch it. This algorithm can be used for duty cycle optimization of a boost converter in a partially shaded solar panel system to find the best duty cycle for maximizing the power output of the solar panel. The grey wolves represent different solutions, and the fitness function determines the best solution based on the power output of the solar panel. The grey wolf algorithm, as illustrated in Figure 2(b), can help find the optimal duty cycle that maximizes the power output of the solar panel, leading to more efficient and effective solar panel systems.

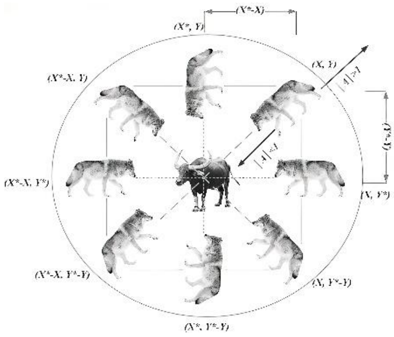
The fish swarm algorithm shown in Figure 1(c) is an optimization technique inspired by the behavior of fish, which swim in groups and communicate with each other to find food and avoid predators [17]–[19]. Each fish represents a potential solution, and they swim in the search space to find the best solution. The position of each fish represents a candidate solution, and the fitness function evaluates the quality of each solution based on the power output of the solar panel. Fish communicate with each other by emitting signals called "bubbles," which contain information about their current position and fitness value. The other fish in the swarm use this information to adjust their own positions and search for better solutions. The fish swarm algorithm shown in Figure 2(c) uses social behavior to improve search efficiency and avoid getting stuck in local optima. This algorithm has been shown to be effective in optimizing the duty cycle of a boost converter in a partially shaded solar panel system.

Figure 1(d) shows the model simulation diagram. The partially shaded solar panel gives input parameters to the three nature-inspired algorithms. The data from each optimization algorithm is stored. This data is used to carry out formal analysis on all three algorithms. The best duty cycle for which maximum power is applied to the DC-DC conversion for current work, the DC shunt motor is considered a load.

Conventional algorithms designed for MPPT perform well in situations where solar conditions are consistent, but they struggle when faced with partial shading or rapidly changing environmental conditions [20]. To address these challenges, researchers have turned to nature-inspired algorithms, such as particle swarm optimization (P&O) [21], [22], ant colony optimization (ACO) [23], artificial bee colony (ABC), whale optimization [24], and differential evolution (DE). These nature-inspired algorithms excel in global search problems and demonstrate effectiveness across diverse environmental conditions. To enhance their performance and reliability, hybridization techniques have been employed. Among the various approaches, the swarm-chasing technique has proven to be particularly advantageous for module-integrated converters, outperforming the traditional P&O method. A comparative study of global peak tracking algorithms is available in a research forum, and some researchers have specifically investigated the sustainability of conventional algorithms in the context of partial shading.



(a)



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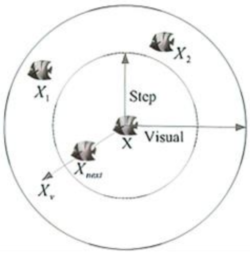

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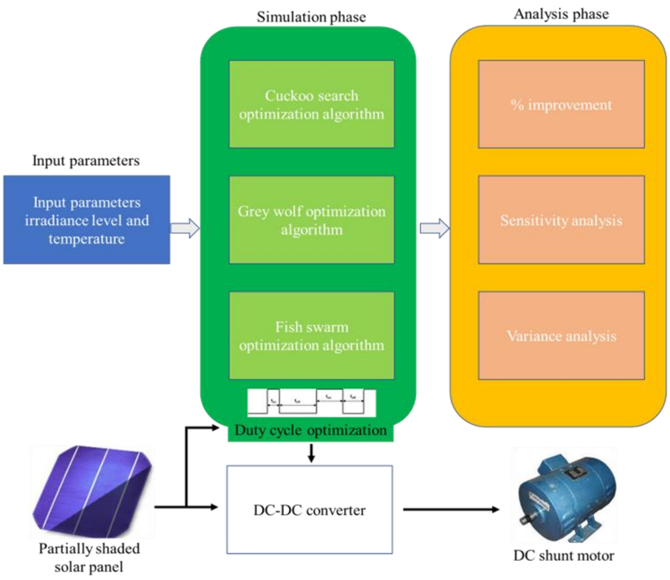

(d)

Figure 1. Concept diagram; (a) the cuckoo search algorithm, (b) the grey wolf algorithm, (c) fish swarm optimization algorithm, and (d) model simulation diagram

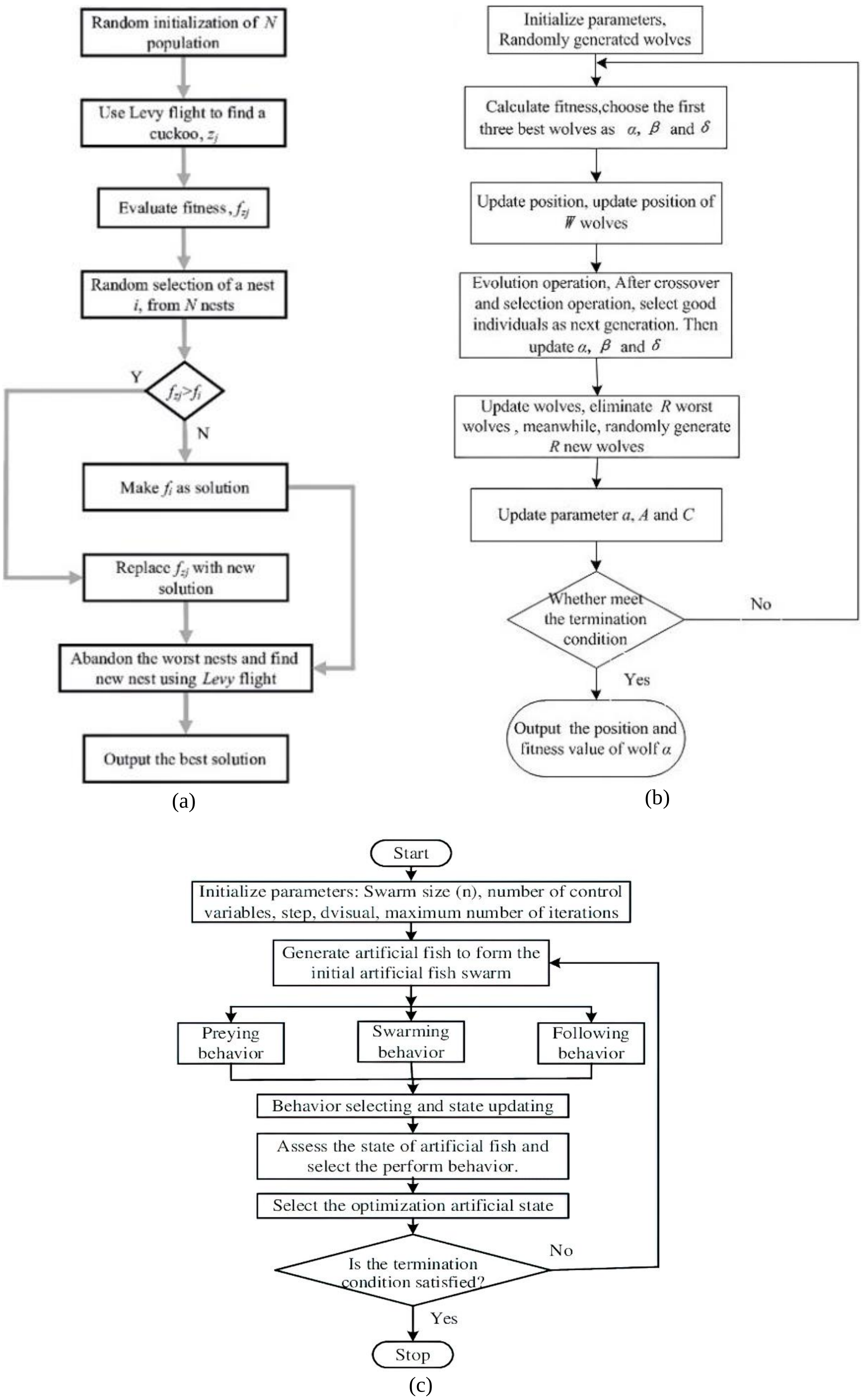

Figure 2. Flow chart of; (a) the cuckoo search algorithm, (b) the grey wolf algorithm, and (c) fish swarm optimization algorithm

To overcome the limitations of conventional methods under varying environmental conditions, soft computing (SC) algorithms have been proposed for MPPT. These SC algorithms include artificial neural network (ANN), fuzzy logic controller (FLC), genetic algorithm (GA), and particle swarm optimization (PSO). However, it is important to note that SC algorithms generally exhibit increased complexity and slower processing speeds. Nevertheless, the cuckoo search (CS) [12], [25] algorithm has garnered attention due to its robustness, superior convergence, higher efficiency, and reduced tuning parameters. Tagayi *et al.* [26] employed a global peak search algorithm inspired by flower pollination to address the optimization of partially shaded solar panels. Ibrahim *et al.* [27] utilized a step size perturb and observe approach, optimized through MPPT, with a specific emphasis on incremental conductance and particle swarm optimization for grid-tied PV systems. Gong *et al.* [28] introduced a two-stage MPPT controller incorporating an enhanced artificial Bee colony and simultaneous heat transfer search algorithm. Rajeshwari and Venkatanarayanan [29] employed honey badger optimization to tackle the challenges posed by partial shading in solar cells. Additionally, Pal and Mukherjee [30] proposed a comparative MPPT method based on metaheuristics for partially shaded panels.

Most of these studies drew inspiration from nature and were primarily focused on addressing the MPPT problem in the context of partially shaded panels. Their objective was to determine the optimal MPPT points. In contrast, our work aimed to identify the optimal duty cycle for the DC-DC converter, which in turn maximizes the power delivered to the load. Rather than solely focusing on MPPT points, our approach takes a broader perspective.

Our study aimed to investigate the effectiveness of three nature-inspired optimization algorithms: the cuckoo search algorithm, the grey wolf algorithm, and the fish swarm optimization. Specifically, we focused on their performance in achieving maximum power output from partially shaded solar panels. To conduct our research, we developed simulation codes for all three algorithms using MATLAB and conducted a thorough evaluation based on criteria such as speed, complexity, compatibility, and stability. The primary objective of our research was to provide a comprehensive comparison among these algorithms regarding their capability to track the MPP for solar panels, commonly known as MPPT. By analyzing the advantages and disadvantages of each algorithm, our study aimed to offer valuable insights into their suitability for different scenarios. Through our research, we aimed to assist in identifying the most appropriate algorithm for specific MPPT requirements.

2. METHOD

To conduct a comparative analysis of all three nature-inspired optimization algorithms for maximizing the power output of partially shaded solar panels through duty cycle optimization, we employed the following methodology. First, we formulated the duty cycle optimization problem for partially shaded solar panels as a constrained optimization problem. The objective was to maximize the power output of the solar panel under varying shading conditions by optimizing the duty cycle of the DC-DC converter.

Next, we implemented three algorithms, namely the cuckoo search algorithm (CSA), grey wolf algorithm (GWA), and fish swarm optimization (FSO), using MATLAB. Each algorithm's simulation code was developed as per the flowcharts given in Figures 2(a)-2(c) respectively to optimize the duty cycle of the DC-DC converter to achieve the maximum power output for partially shaded solar panels. We conducted the simulations for a solar panel with different shading conditions and evaluated their performance.

To evaluate the performance of each algorithm, we utilized the following performance metrics: convergence rate, stability, and efficiency. The convergence rate was assessed by measuring the number of iterations required for the algorithm to converge. Stability was evaluated by measuring the variance in the power output of the solar panel during the simulation. Efficiency was determined by measuring the power loss resulting from the optimization algorithm. Based on these performance metrics, we compared the performance of the CSA, GWA, and FSO algorithms. The results of the analysis were then utilized to identify the most suitable algorithm for duty cycle optimization of partially shaded solar panels.

3. RESULTS AND DISCUSSION

Figure 3 displays a comparative analysis of three nature-inspired algorithms concerning sensitivity, convergence improvement, normalized variance, and computation time. Figure 3(a) showcases a bar chart depicting the sensitivity of the algorithms. Among the three algorithms, CCS exhibits the highest sensitivity, measuring 5.23 Watts per 1 W/m^2 change in irradiance. Conversely, GWO demonstrates the lowest sensitivity at 1.27 Watts per 1 W/m^2, while FSO falls in between with a sensitivity of 3.44 Watts per 1 W/m^2. These results imply that CCS is the most sensitive, whereas GWO is the least responsive to changes in irradiance.

In Figure 3(b), the results indicate that FSO achieves the highest convergence improvement at 35.48%, followed by GWO at 21.47%, and CCS at 18.2%. These findings suggest that FSO may be the most efficient algorithm among the three in terms of achieving convergence. The variance results presented in Figure 3(c) demonstrate that the FSO algorithm exhibits the highest stability with a variance value of 0.02, followed by GWO with 0.06. In contrast, CCS shows the lowest stability with a variance value of 0.051. These findings suggest that the FSO algorithm may offer greater robustness and consistency in performance compared to the other two algorithms.

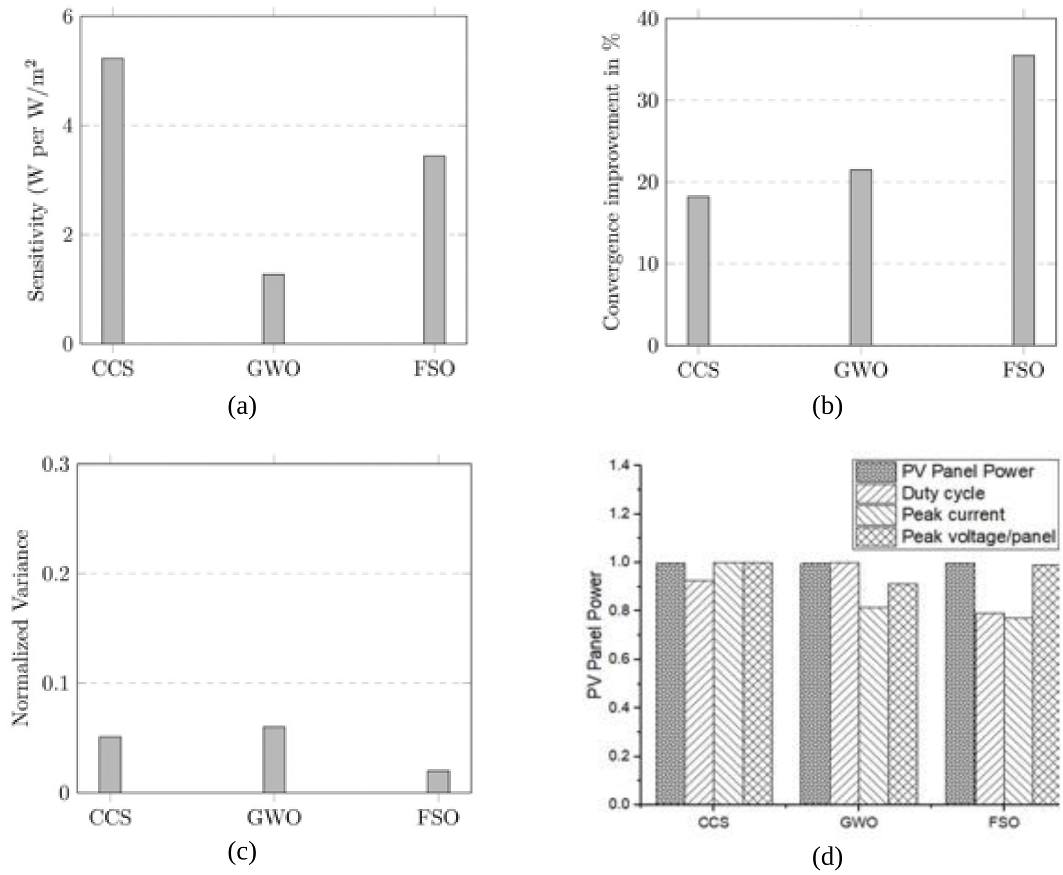

Figure 3. Comparative analysis of three nature-inspired algorithms; (a) sensitivity bar chart for the CCS the GWO and fish swarm optimization algorithm FSO, (b) convergence improvement bar chart for CCS, GWO and FSO, (c) normalized variance for CCS, GWO and FSO, and (d) simulation results obtained with each algorithm

Regarding computation time, CCS has a recorded time of 0.099 seconds, while GWO and FSO took 0.259210976 and 0.192995604 seconds, respectively. These results indicate that CCS is the fastest algorithm among the three, being approximately 2.6 times and 1.9 times faster than GWO and FSO, respectively. However, it is important to note that the computation time can vary depending on the specific hardware and software configurations used in the experiments. The simulation results depicted in Figure 3(d) exhibit the outputs generated by three nature-inspired algorithms when a DC shunt motor is connected to the output. All values are normalized relative to the peak. The maximum power output achieved by the PV panel was 537 watts. The grey wolf algorithm yielded the highest duty cycle, which was 0.67. The peak current reached a maximum of 1.93 Amps, while the peak voltage per panel was 17.8 volts.

4. CONCLUSION

Based on the obtained results, it can be inferred that the FSO algorithm exhibits superior efficiency compared to the CCS and GWO algorithms in terms of convergence, with a remarkable improvement of 35.48%. Moreover, the FSO algorithm demonstrates higher stability, suggesting greater robustness and consistency in its performance when compared to the other two algorithms. Nonetheless, it is important to note that the FSO algorithm requires a computation time of 0.192995604 seconds, which is slower than the CCS algorithm's computation time of 0.099 seconds. Therefore, the selection of the algorithm should consider the specific requirements of the problem at hand, necessitating a trade-off between performance and computation time.

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