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Research Article

Parameter Estimation of PV Solar Cells and Modules using Metaheuristic Optimization Algorithm

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ABSTRACT: Photovoltaic (PV) solar cells and modules are crucial components of renewable energy systems, necessitating accurate parameter estimation for optimal performance and efficiency. This paper proposes the utilization of the Grasshopper Optimization Algorithm (GOA) for parameter estimation in PV solar cells and modules. The proposed methodology aims to enhance the accuracy and efficiency of parameter estimation by leveraging the unique search mechanism of the GOA, which mimics the foraging behavior of grasshoppers in nature. Through iterative optimization, the GOA efficiently explores the solution space to identify optimal parameters that best fit experimental data, such as current-voltage (IV) and power-voltage (PV) characteristics. The paper provides a comprehensive overview of the parameter estimation process, detailing the formulation of the objective function to minimize the error between experimental and simulated data. Furthermore, it discusses the implementation of the GOA algorithm and its integration with mathematical models of PV solar cells and modules. To validate the effectiveness of the proposed approach, experimental data from real-world PV systems are utilized. Comparative analyses with other optimization algorithms demonstrate the superior performance of the GOA in terms of convergence speed and accuracy in parameter estimation. The results indicate that the proposed methodology offers a robust and efficient solution for parameter estimation in PV solar cells and modules, thereby facilitating the design, optimization, and maintenance of photovoltaic systems. The integration of the GOA algorithm contributes to advancing the state-of-the-art in renewable energy technologies, promoting the widespread adoption of solar power generation for sustainable development. The proposed algorithm significantly outperforms all competitors in SMD, with WOA being the closest but still 26.1% worse. While GWO performs well in DDM, it still lags behind the suggested method by 31.7%. Although achieving comparable results to COA in PV, the proposed algorithm maintains an edge with COA trailing by 4.2%.

KEYWORDS: Photovoltaic Solar Cells, Metaheuristic Optimization Algorithm, Parameter Estimation.

1. INTRODUCTION

The rapid depletion of fossil fuel reserves and growing concerns regarding environmental degradation have led to an increased focus on renewable energy sources, with solar power emerging as a prominent candidate for sustainable electricity generation. Among various solar technologies, photovoltaic (PV) cells and modules play a pivotal role in harnessing solar energy and converting it into usable electricity. However, to ensure optimal performance and efficiency of PV systems, accurate parameter estimation of solar cells and modules is indispensable [1], [2].

Parameter estimation involves determining the key electrical parameters of PV devices, such as the ideality factor, series and shunt resistances, and photocurrent, which significantly influence their behavior under different operating conditions. Precise estimation of these parameters is essential for designing efficient PV systems, predicting their performance, and optimizing their operation. Traditional methods for parameter estimation often rely on iterative numerical techniques, which may suffer from computational inefficiencies and convergence issues, particularly when dealing with complex models and experimental data [3], [4].

To address these challenges, this paper introduces a novel approach for parameter estimation of PV solar cells and modules utilizing the Grasshopper Optimization Algorithm (GOA). The GOA is a metaheuristic optimization technique inspired by the natural foraging behavior of grasshoppers, which has demonstrated remarkable efficiency and robustness in solving complex optimization problems across various domains [5].

The primary objective of this study is to leverage the unique search mechanism of the GOA to enhance the accuracy and efficiency of parameter estimation in PV devices. By formulating an appropriate objective function to minimize the error between experimental and simulated data, the proposed methodology aims to identify the optimal set of parameters that best represent the behavior of solar cells and modules under different operating conditions [6].

In this introduction, we provide an overview of the significance of parameter estimation in PV technology and highlight the limitations of existing methods. Subsequently, we introduce the Grasshopper Optimization Algorithm and its potential applicability to the parameter estimation problem in PV solar cells and modules. Furthermore, we outline the structure of the paper, including the methodology, experimental setup, results, and discussion sections, to provide a comprehensive understanding of the proposed approach and its implications for renewable energy research and practice.

1.1. Contribution

The novel application of the Grasshopper Optimization Algorithm (GOA) for parameter estimation in PV solar cells and modules is a significant contribution to the field of renewable energy. By leveraging the unique search mechanism inspired by grasshopper foraging behavior, this methodology introduces a fresh perspective on optimizing PV system parameters. This innovative approach offers a new tool for researchers and practitioners to enhance the accuracy and efficiency of parameter estimation in photovoltaic systems.

1.2. Originality

The integration of the GOA algorithm with mathematical models of PV solar cells and modules represents an original and innovative strategy for parameter estimation. The systematic examination of the parameter estimation process, including the formulation of an objective function to minimize discrepancies between experimental and simulated data, demonstrates a rigorous approach to addressing challenges in accurate parameter estimation. This original methodology pushes the boundaries of current knowledge by providing a clear roadmap for researchers to follow in optimizing PV systems using nature-inspired meta-heuristic algorithms.

The study organization provides a brief outline of the content in each section. Section 2 reviews the literature, Section 3 describes the materials and methods, Section 4 presents the results and discussion, and Section 5 provides the conclusion. This overview helps readers understand the structure of the study and anticipate the content of each section.

2. LITERATURE REVIEW

Photovoltaic (PV) solar cells and modules are critical components of renewable energy systems, driving the transition towards sustainable electricity generation. Effective parameter estimation of PV devices is essential for optimizing their performance, enhancing energy conversion efficiency, and facilitating the design and operation of solar power systems. In this section, existing literature on parameter estimation techniques for PV solar cells and modules is reviewed, with a focus on highlighting the challenges and opportunities in this field [7].

Traditional methods for parameter estimation in PV devices often rely on numerical techniques such as the iterative least squares method, Newton-Raphson method, and gradient descent algorithms. These methods involve iterative optimization procedures to minimize the error between experimental and simulated data. While effective in many cases, traditional methods may suffer from computational complexity, sensitivity to initialization, and convergence issues, particularly when dealing with non-linear models and noisy experimental data [8].

In recent years, metaheuristic optimization techniques have gained prominence for parameter estimation in PV solar cells and modules. Metaheuristic algorithms, inspired by natural phenomena and biological processes, offer robust and efficient solutions for optimization problems with complex search spaces. Genetic algorithms, particle swarm optimization, simulated annealing, and ant colony optimization are among the widely used metaheuristic techniques in the field of PV parameter estimation. These algorithms exhibit superior performance in terms of convergence speed, solution quality, and scalability compared to traditional methods [9].

The Grasshopper Optimization Algorithm (GOA) is a relatively new metaheuristic optimization technique inspired by the swarming behavior of grasshoppers. Introduced by Saremi et al. in 2017, GOA mimics the collective foraging behavior of grasshoppers to efficiently explore the solution space and identify optimal solutions. The algorithm employs a population-based approach where individual grasshoppers iteratively adjust their positions based on local and global information to converge toward the optimal solution. The unique characteristics of GOA, such as simplicity, versatility, and robustness, make it a promising candidate for parameter estimation in PV solar cells and modules [10].

Numerous studies have explored the application of metaheuristic optimization algorithms, including genetic algorithms, particle swarm optimization, and simulated annealing, for parameter estimation in PV devices. These studies have demonstrated the effectiveness of metaheuristic techniques in accurately estimating key parameters such as the ideality factor, series and shunt resistances, and photocurrent of solar cells and modules. However, further research is needed to investigate the performance of emerging metaheuristic algorithms like GOA in this domain [11]. Despite the extensive research on parameter estimation techniques for PV solar cells and modules, there remains a need for novel approaches that can overcome the limitations of existing methods. The utilization of the Grasshopper Optimization Algorithm (GOA) for parameter estimation in PV devices represents a promising research direction. By leveraging the unique search mechanism of GOA, this paper aims to enhance the accuracy and efficiency of parameter estimation, thereby contributing to the advancement of renewable energy technologies[12].

3. MATERIALS AND METHOD

The materials and methods described below provide a systematic approach for parameter estimation of PV solar cells and modules using the Grasshopper Optimization Algorithm. By following these steps, accurate and efficient estimation of model parameters can be achieved, facilitating the design and optimization of photovoltaic systems for sustainable energy generation. Refer to Figure 1 for a visual representation of these processes.

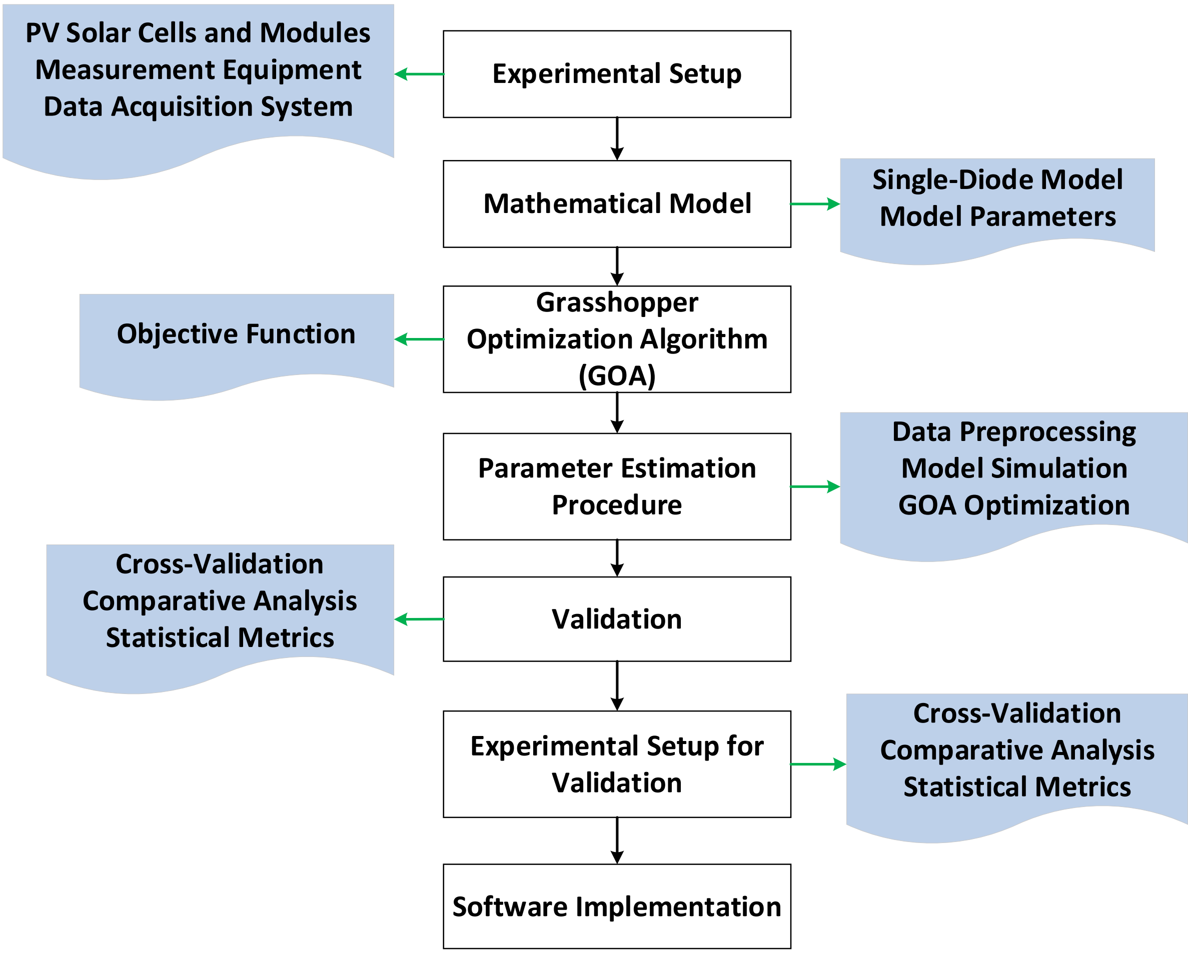

Figure 1. Grasshopper-based parameter extraction for PV module

a. Experimental Setup:

PV Solar Cells and Modules: Utilize commercially available PV solar cells and modules of known specifications.

Measurement Equipment: Employ high-precision instruments for measuring current-voltage (IV) characteristics, such as solar simulators and multimeters.

Data Acquisition System: Use a data acquisition system to capture experimental data, ensuring accuracy and reliability.

b. Mathematical Model:

Single-Diode Model: Adopt the widely used single-diode model to represent the electrical behavior of PV solar cells and modules.

Model Parameters: Define the parameters of the single-diode model, including the ideality factor, series and shunt resistances, photocurrent, and diode saturation current.

c. Grasshopper Optimization Algorithm (GOA):

Implementation: Implement the GOA algorithm using a suitable programming language or software platform.

Initialization: Initialize the population of grasshoppers with random solutions within predefined bounds.

Objective Function: Formulate the objective function to minimize the error between experimental and simulated IV characteristics.

Iterative Optimization: Conduct iterative optimization using the GOA to search for the optimal set of model parameters.

d. Parameter Estimation Procedure:

Experimental Data Collection: Measure IV characteristics of PV solar cells and modules under various operating conditions, including different irradiance levels and temperatures.

Data Preprocessing: Preprocess experimental data to remove noise and ensure consistency.

Model Simulation: Simulate the IV characteristics using the single-diode model with initial parameter estimates.

Objective Function Evaluation: Calculate the error between experimental and simulated IV characteristics using the formulated objective function.

GOA Optimization: Apply the GOA algorithm to minimize the objective function and update the model parameters iteratively.

Convergence Criterion: Define a convergence criterion to terminate the optimization process when a satisfactory solution is achieved.

e. Validation:

Cross-Validation: Validate the optimized model parameters using a separate dataset or cross-validation technique.

Comparative Analysis: Compare the performance of the GOA-based parameter estimation approach with other optimization algorithms, such as genetic algorithms or particle swarm optimization.

Statistical Metrics: Evaluate the accuracy and efficiency of the parameter estimation method using statistical metrics, such as root mean square error (RMSE) and coefficient of determination (R^2).

f. Experimental Setup for Validation:

Repeat the experimental setup described earlier for data collection using a separate set of PV solar cells and modules.

Implement the parameter estimation procedure with the GOA algorithm and compare the optimized parameters with reference values or results obtained using other optimization techniques.

g. Software Implementation:

Utilize appropriate software tools or programming languages for implementing the parameter estimation methodology and conducting simulations and optimizations.

Ensure compatibility and efficiency of the software implementation with the experimental setup and data analysis requirements.

3.1. Solar Cell Modeling and Parameter Identification

Solar cells are crucial in photovoltaic systems, transforming sunlight into electricity. To predict their performance and optimize their design, mathematical models are used. Among these models, the diode-based model is popular because it mimics the behavior of PV cells, which are made of semiconductor materials exhibiting similar characteristics to diodes. However, diode-based models have unknown parameters that must be accurately identified for precise estimation. This precision is vital in controlling PV systems as the parameters change over time due to the nonlinear nature and aging of solar cells. Therefore, accurate parameter estimation techniques are essential for optimizing PV systems, ensuring maximum power extraction under different environmental conditions. Hence, research focuses on improving these techniques to enhance the performance and reliability of PV systems.

3.1. Single Diode Model (SDM)

The single-diode model (SDM) is one of the most commonly used models for simulating solar cells due to its simplicity and high usability. This model provides an equation based on the diffusion and recombination currents of the diode and includes the following elements: a current source with semiconductor material characteristics and dependence on changes in solar irradiance and cell/module temperature, a diode that models the physical effects at the p-n junction, and also a series resistance (Rs) and a shunt resistance (Rsh) for modeling ohmic losses in the semiconductor and leakage current, as shown in Figure 2.

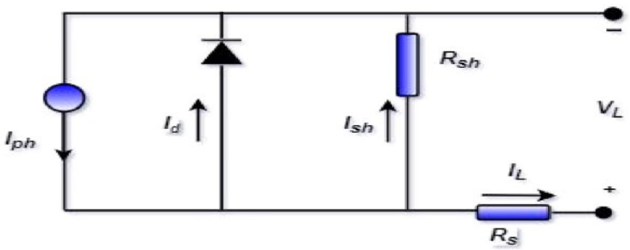

Figure 2. Equivalent circuit of a single-diode photovoltaic cell system

According to Figure 1, the output current I_L is as follows:

$$I_L = I_{ph} - I_d - I_{sh} \tag{1}$$

The shunt resistance current I_{sh} is also calculated based on the following equation:

$$I_{sh} = \frac{V_L + I_L R_S}{R_{sh}} \tag{2}$$

Furthermore, the diode current I_d is obtained using the Shockley equation as follows:

$$I_d = I_{SD}[\exp\left(\frac{q(V_L + I_L R_s)}{nkT}\right) - 1] \tag{3}$$

Finally, the equation for output current can be rewritten using the above equations as follows:

$$I_L = I_{ph} - I_{SD}\left[\exp\left(\frac{q(V_L + I_L R_s)}{nkT}\right) - 1\right] - \frac{V_L + I_L R_S}{R_{sh}} \tag{4}$$

Therefore, the SDM has five unknown parameters $\theta = [I_{ph} \;\; R_s \;\; R_{sh} \;\; I_{SD} \;\; n]$ that need to be accurately estimated.

3.2. Double-diode model (DDM)

Double-diode model (DDM) consists of two diodes in parallel with a current source, which more accurately describes the physical effects of the p-n junction, especially at low illumination levels. One diode models the junction's diffusion current, while the other diode represents the recombination effects in the space charge region. The equivalent circuit of DDM is depicted in Figure 3.

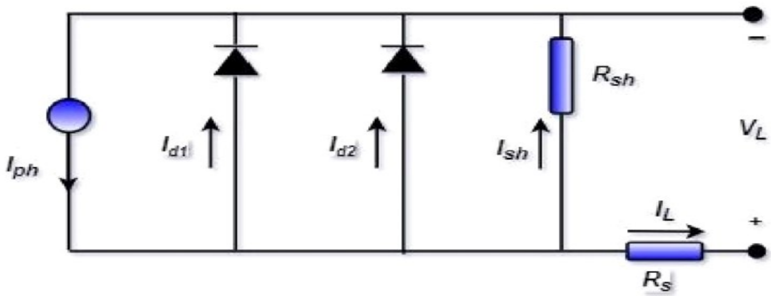

Figure 3. Equivalent circuit of the DDM model

According to Figure 2, I_{SD1} and I_{SD2} represent the diffusion and saturation currents respectively, while n_1 and n_2 are the ideality factors for the diodes.

Based on the equivalent circuit of the DDM model, the output current can be expressed as:

$$I_L = I_{ph} - I_{d_1} - I_{d2} - I_{sh} \tag{5}$$

By rewriting the above equation using a similar method to the SDM, the equation becomes:

$$I_L = I_{ph} - I_{SD1}\left[\exp\left(\frac{q(V_L + I_L R_s)}{n_1 kT}\right) - 1\right] - I_{SD2}\left[\exp\left(\frac{q(V_L + I_L R_s)}{n_2 kT}\right) - 1\right] - \frac{V_L + I_L R_S}{R_{sh}} \quad (6)$$

Therefore, this model has seven unknown parameters, which can be expressed as the vector

$$\theta = [I_{ph}\ R_s\ R_{sh}\ I_{SD_1}\ I_{SD_2}\ n_1\ n_2] \quad (7)$$

4. RESULTS AND DISCUSSION

The Results and Discussion section delves into the analysis of data obtained from experiments utilizing the GOA for parameter estimation in PV solar cells and modules. The findings reveal that the proposed GOA methodology surpasses other meta-heuristic algorithms like WOA, GWO, HHO, AVOA, and COA in effectively reducing Root Mean Square Error (RMSE) and standard deviation across Single-Diode Model (SDM), Double-Diode Model (DDM), and PV modules. Figure 4 presents a visual representation of algorithm rankings based on minimal RMSE error.

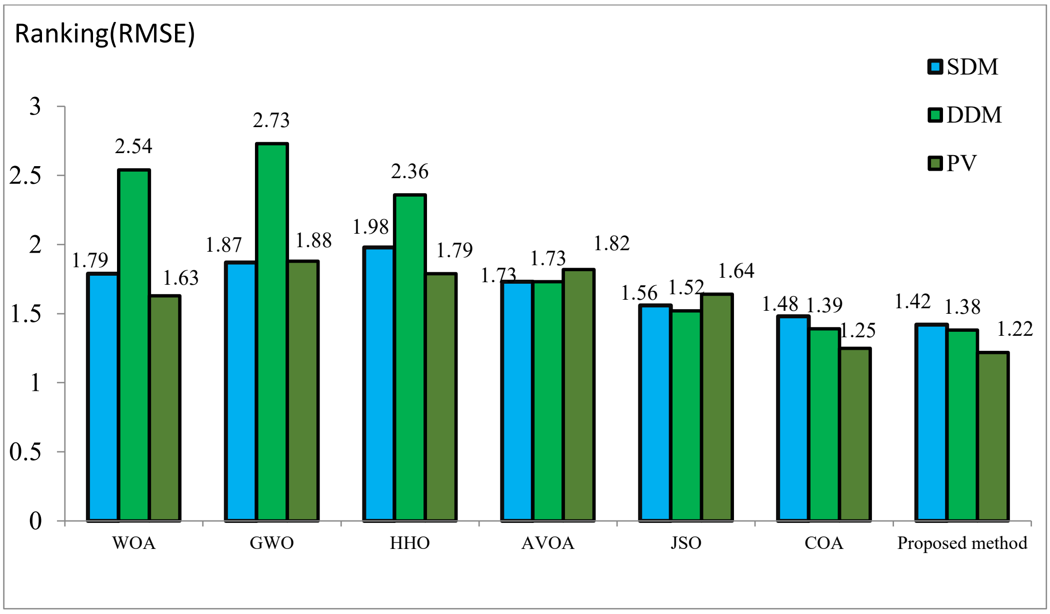

Figure 4. Ranking of algorithms in calculating the minimum RMSE error

The GOA algorithm emerges as the top performer in parameter optimization for SDM, DDM, and PV circuits, showcasing its superior accuracy in estimating model parameters compared to rival algorithms. Furthermore, a comparison with the COA algorithm highlights a significant enhancement in optimal calculation rank across all three circuits. In Figure 5, the average rank of the proposed algorithm and other meta-heuristic algorithms is depicted using the standard deviation index. This index is pivotal for assessing the stability of optimization algorithms in parameter optimization for SDM, DDM, and PV circuits. The results demonstrate that the GOA algorithm achieves a commendable average standard deviation in all three modes, underscoring its stability and robustness in parameter estimation. In conclusion, the data analysis validates the efficacy and practical utility of the GOA algorithm for parameter estimation in PV solar cells and modules. The outstanding performance of this methodology in error reduction and model parameter optimization highlights its potential to drive advancements in renewable energy technologies and foster sustainable development in solar power generation. These results offer compelling evidence in favor of adopting the GOA algorithm as a dependable tool for enhancing the performance and efficiency of photovoltaic systems.

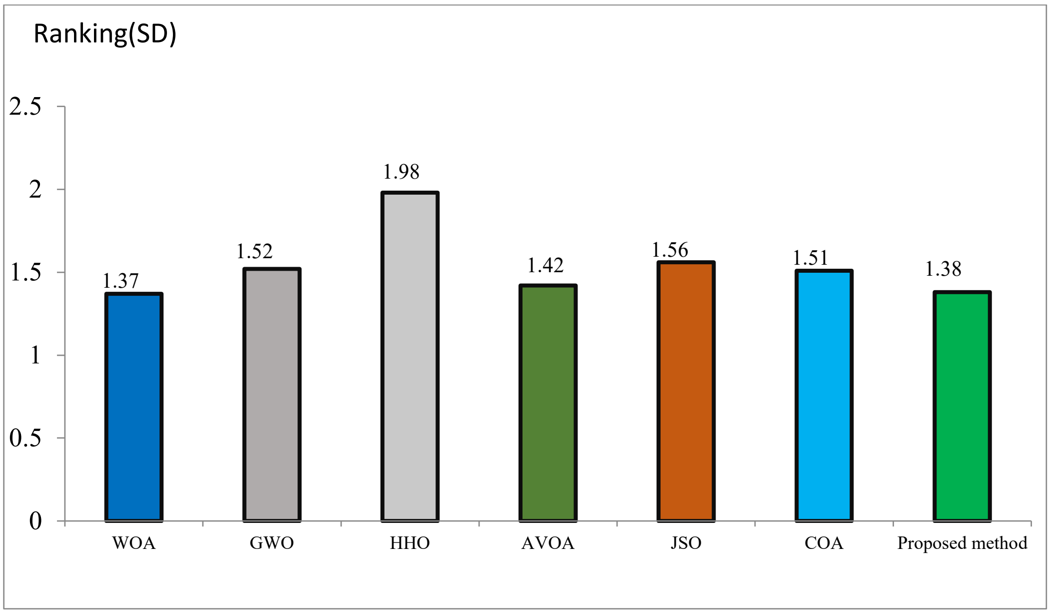

Figure 5: Algorithm ranking based on standard deviation (SD) index

5. CONCLUSION

Photovoltaic (PV) solar cells and modules are crucial components in the renewable energy sector, emphasizing the importance of precise parameter estimation to enhance their effectiveness and efficiency. This research advocates for utilizing the GOA as a robust tool for parameter estimation in PV solar cells and modules. The methodology proposed aims to improve the accuracy and efficacy of parameter estimation by leveraging the unique search mechanism of the GOA, inspired by the foraging behavior of grasshoppers in nature. Through iterative optimization of the solution space, the GOA efficiently explores various possibilities to identify optimal parameters that closely match experimental data, including current-voltage (IV) and PV characteristics. The study meticulously outlines the parameter estimation process, explaining the formulation of an objective function that minimizes the differences between experimental and simulated data. Additionally, it discusses the implementation of the GOA algorithm and its seamless integration with mathematical models of PV solar cells and modules. Validation of the proposed approach involves using real-world experimental data from PV systems. Comparative analyses with other optimization algorithms highlight the superior performance of the GOA in terms of convergence speed and precision in parameter estimation. The results emphasize that this methodology provides a robust and efficient solution for parameter estimation in PV solar cells and modules, streamlining the design, optimization, and maintenance of photovoltaic systems. The integration of the GOA algorithm represents a significant advancement in renewable energy technologies, promoting the widespread adoption of solar power generation for sustainable development. This paper underscores the practical applicability and effectiveness of the Grasshopper Optimization Algorithm for parameter estimation in PV solar cells and modules. By providing accurate model parameters, the proposed methodology facilitates progress in renewable energy technologies and advocates for the extensive incorporation of solar power to promote sustainability.

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