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Research article

Improving photovoltaic cell parameter calculations through a puffer fish inspired optimization technique

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ABSTRACT

The precise estimation of solar PV cell parameters has become increasingly important as solar energy deployment expands. Due to the intricate and nonlinear characteristics of solar PV cells, meta-heuristic algorithms show greater promise than traditional ones for parameter estimation. This study utilizes the Puffer Fish (PF) meta-heuristic optimization method, inspired by male puffer fish's circular structures, to estimate parameters of a modified four-diode PV cell. The PF algorithm's performance is assessed against ten benchmark test functions, with results presented as mean and standard deviation for validation. Comparative analysis with Particle Swarm Optimization (PSO), Grey Wolf Optimization (GWO), Rat Search Algorithm (RAT), Heap Based Optimizer (HBO), and Cuckoo Search (CS) algorithms highlights PF's superior performance, achieving optimal solutions with minimal error of 7.8947E-08. Statistical tests, including Friedman Ranking (1st) and Wilcoxon's rank sum (3.8108E-07), confirm PF's superiority. The circular structures of male puffer fish serve as an effective model for optimization algorithms, enhancing parameter estimation. Benchmark tests and statistical analysis consistently underscore PF's superiority over other meta-heuristic algorithms. Future research should explore PF's potential applications in solar energy and beyond.

1. Introduction

In recent years, there has been a significant increase in the energy demand, with a continued upward trajectory. However, the depletion of non-renewable energy sources, such as fossil fuels, is a major concern due to its harmful effects, including global warming,

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Table 1
Optimization method for three and four PV diode model.

Author	Technique/Algorithm	Solar Diode PV Model				Year
		Single	Double	Three	Four	
M. Abd Elaziz et al. [25]	Improved opposition-based whale optimization algorithm	✔	✔	✔	–	2018
M. Abdel-Basset et al. [26]	Improved equilibrium optimizer	✔	✔	✔	–	2020
A. A. Z. Diab et al. [27]	Coyote optimization algorithm	✔	✔	✔	–	2020
M. Naeijian et al. [28]	Whippy Harris Hawks Optimization Algorithm	✔	✔	✔	–	2021
R. Y. Abdelghany et al. [29]	Improved bonobo optimizer	✔	✔	✔	–	2021
W. Zhou et al. [30]	Metaphor-free dynamic spherical evolution	✔	✔	✔	–	2021
G. Xiong et al. [31]	Gaining–sharing knowledge based algorithm	✔	✔	✔	–	2021
A. Singh et al. [32]	Tuna Swarm Optimizer with Newton-Raphson method	–	–	✔	–	2022
C. Kumar et al. [33]	Hybrid particle swarm optimization algorithms	✔	✔	✔	–	2022
J. Gupta et al. [34]	Hybrid Particle Swarm Optimization and Gravitational Search Algorithm	✔	✔	✔	–	2022
M. Premkumar et al. [35]	An enhanced Gradient-based Optimizer	✔	✔	✔	–	2022
M. K. Singla et al. [36]	Hybrid algorithm	–	–	✔	–	2021
A.-E. Ramadan et al. [37]	Improved grey wolf optimizer	–	–	✔	–	2021
P. He et al. [38]	Radial Basis Function Based Meta-Heuristic Algorithms	✔	✔	✔	–	2023
B. Singh et al. [39]	Hybrid algorithm	✔	✔	✔	✔	2022

ozone depletion, and air pollution [1], adversely affecting human health. To combat this issue, renewable energy sources have become one of the most promising alternatives to non-renewable energy sources, as they are inexhaustible, environmentally friendly, and clean. Solar energy, one of the most readily available renewable energy sources, has seen a significant increase in utilization in recent years. Other renewable energy sources include wind energy, gravitational energy, geothermal energy, hydropower, and biomass energy are utilized [2,3]. Solar energy is considered a viable and practical form of renewable energy due to its notable efficiency, low maintenance expenses, and widespread accessibility [4]. A solar power plant comprises a photovoltaic (PV) module comprising a series of photocells, and electric current is produced by PV generators based on silicon semiconductors. The increasing use of renewable energy sources, especially solar energy, can help combat the depletion of non-renewable energy sources and their harmful effects on the environment and human health. Effectively incorporating PV systems into the electrical grid requires the implementation of appropriate and carefully designed control mechanisms. The complexity of this issue is heightened due to the non-linear characteristics (I–V and P–V) of PV systems and their reliance on fluctuating environmental circumstances. Effectively incorporating PV systems into the electrical grid requires the implementation of appropriate and carefully designed control mechanisms [5–7]. The control mechanism primarily relies on evaluating the parameters of PV cells, which become more intricate due to the non-linear characteristics of PV systems and their dependence on fluctuating environmental variables. This is crucial for ensuring the long-term reliability and efficiency of solar PV systems [8–10]. Various researchers have explored numerous strategies to enhance the overall efficiency of PV systems. These techniques include several areas, such as PV design [11–18], material studies [19–21], transportation [22], etc.

Recently, there have been several meta-heuristic algorithms that have been developed, such as the Genetic Algorithm (GA) [11], Improved Hybrid Algorithm Based on Biogeography (IHABB) [6], Particle Swarm Optimization (PSO) [12], Grey Wolf Optimization (GWO) [13], Differential Evolution (DE) [14], and Rat Swarm Algorithm (RSA) [15], among others. One such algorithm, the Moth-Flame optimization algorithm [16], is used to estimate the parameters of three diode models for multi-crystalline solar PV cells. Additionally, two other meta-heuristic algorithms, Elephant Herd Optimization (EHO) and Closed Loop Particle Swarm Optimization (CLPSO) [17], have been developed to estimate the parameters of modified three-diode models of solar PV cells, both of which have shown better convergence rates under different operating conditions.

Furthermore, based on the organizational behaviour of horses, a new algorithm called the Wild Horse Optimizer (WHO) [18] has been created to estimate the parameters of the Double Diode Model (DDM), Modified Double Diode Model (MDDM), Triple Diode Model (TDM), and Modified Triple Diode Model (MTDM) for solar PV cells, with the accuracy evaluated using the Root Mean Square Error (RMSE). Previous studies have indicated that adding a series resistance to a single-diode configuration can enhance the efficiency of PV cells [23,24]. Table 1 shows the optimization techniques used by various researchers to estimate the unknown parameters of solar PV diode model.

This paper aims to introduce a new parameter estimation algorithm for modified four-diode models of solar PV cells. The puffer fish algorithm is a recently created method that addresses the limitations of swarm-based algorithms, particularly the issue of being trapped in local minima. The major contributions of this algorithm are as follows: Firstly, a new four-diode model is presented, which includes a series resistance. Secondly, the algorithm is used to estimate the parameters of the four-diode model. Thirdly, the performance of the algorithm is evaluated by comparing it with other existing algorithms. Finally, the accuracy of the algorithm is tested by using the Root Mean Square Error (RMSE) and compared with other algorithms. In conclusion, the proposed algorithm is expected to provide better results for estimating parameters of modified four-diode models of solar PV cells, thus providing better efficiency and output. The following are some highlights points of the manuscript.

- In this study, the estimation of parameters for solar photovoltaic (PV) cells that contain modified four-diode models is carried out through the application of a met-heuristic optimization algorithm based on the unique circular structures built by puffer fish for the better efficiency.

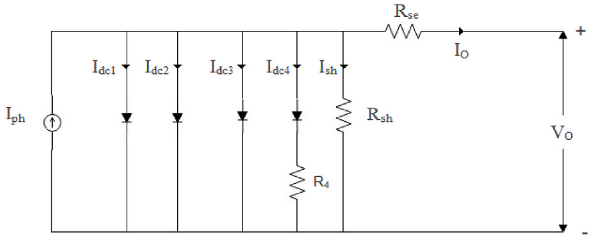

Fig. 1. Equivalent circuit model of solar PV cell.

Begin

The objective function f(X), $x = (x_1, x_2, \ldots\ldots, x_d)^T$

Define Initial Parameters (r_{out}, r_{cen}, n_{peak}, d_{red})

Initialize location vector (x_i, y_i)

Maximum number of circular structures (S_{max})

Error criteria (ε)

While ($c < c_{max}$) or satisfied error criteria

Evaluate its quality/fitness

Update radius according to Equation 4.

If ($r_s < r_{cen}$)

Increase the solution resolution (step size) and create random pattern in center zone

End

Create patterns oriented to the center of the circular structure via sand peaks

Use Optimal Locations for new initial locations

$c = c+1$

End While

Fig. 2. PF algorithm pseudo code.

- A new modified four-diode model is presented, which justifies all the prevailing during operating conditions like grain boundary, internal diode resistance, etc.
- The effectiveness of the Puffer Fish algorithm is justified by using ten benchmark test functions, and the mean and Standard Deviation (SD) are calculated for each.
- The estimation of solar PV cell parameters is performed at 33 °C, and the Root Mean Square Error (RMSE) is then compared with that of other algorithms such as RAT, HBO, PSO, GWO, and CS.
- The I–V and P–V characteristic curves at a temperature of 33 °C are obtained, and the results of the Friedman ranking test and Wilcoxon's rank sum test are presented in addition to the estimated parameters. The findings of this study offer significant insights into applying the PF algorithm for estimating the parameters of PV cells and its potential for future utilization in the field. For evaluation of the performance and efficiency of the Puffer Fish algorithm, a convergence curve is obtained, and its comparison is done with other algorithms which depict a higher pace.

Further next section discuss modelling of modified four diode model in detail. After that the optimization process along with the proposed algorithm (puffer fish) is discussed in the next section. Then in the fourth section the detail discussion is provided for results obtain. The fifth section concludes the overall observation and provide the future path.

2. Modelling of modified four-diode model

There exist four distinct categories of diode-based PV models: the Single Diode Model, Double Diode Model, Triple Diode Model, and Four-diode Model. Each of these models possesses its own set of benefits and detriments, such as precision and intricacy. They are employed for the purpose of examining and emulating the performance of PV systems, as well as for the optimization of PV system designs. PV cells with four-diodes are linked with two different resistances, one in series and the other in parallel, forming twelve parameters. The four diode model consider to incorporate more environmental losses and better study of radioactive and non-radioactive recombination losses. In order to model the losses in the quasi-neutral region, a series resistance (R_4) with a single diode can be incorporated into the four-diode model type, as depicted in Fig. 1. These models play a critical role in the domain of PVs,

Table 2
Algorithm parameters.

Algorithm	Parameters	Values
PSO	Search agents	50
	Maximum iteration	1000
	Cognitive factor C_1	1.5
	Social factor C_2	1.5
	Min inertia weight W_{min}	0.4
	Max inertia weight W_{max}	0.9
	Random variable r1,r2	Rand [0,1]
GWO	Search agents	50
	Maximum iteration	1000
	Random Vector r1, r2	0,1
	Coefficient Vector v	0 to 2
CS	Search agents	50
	Maximum iteration	1000
	Discovery rate	0.24
	cluster	2
HBO	Search agents	50
	Maximum iteration	1000
	Designed vector C	1
	Parameter $\vec{\lambda}$	2r-1, where r is randon variable [0,1]
RAT	Search agents	50
	Maximum iteration	1000
	Variable R	[1,5]
	Variable C	[0, 2]
PF	Search agents	50
	Maximum iteration	1000
	N_{peak}	24
	C_{max}	50
	$Rout/Rcentre$	1.5
	S_{large}/S_{small}	5
	d_{red}	0.7

Table 3
Benchmark test functions.

Function	Dim	Range
$F_1(k) = \sum_{j=1}^{m} k_j^2$	60	[-100, 100]
$F_2(k) = \sum_{j=1}^{m} \lvert k\rvert + \prod_{j=1}^{m} \lvert x\rvert$	60	[-10, 10]
$F_3(k) = \sum_{j=1}^{m} \left(\sum_{j=1}^{m} k_j^2\right)^2$	60	[-100, 100]
$F_4(k) = max_j \lvert k_j\rvert, 1 \le j \le m$	60	[-100, 100]
$F_5(k) = \sum_{j=1}^{m-1} \left[100\left(k_{j+1} - k_j^2\right)^2 + (k_j - 1)^2\right]$	60	[-30, 30]
$F_6(k) = \sum_{j=1}^{m} (\lvert k_j + 0.5\rvert)^2$	60	[-100, 100]
$F_7(k) = \sum_{j=1}^{m} ik_j^4 + random[0,1]$	60	[-1.28, 1.28]
$F_8(k) = \sum_{j=1}^{m} - k_j \sin\left(\sqrt{\lvert k_j\rvert}\right)$	60	[-500, 500]
$F_9(k) = \sum_{j=1}^{m} \left[k_j^2 - 10\cos(2\pi k_j) + 10\right]$	60	[-5.12, 5.12]
$F_{10}(k) = -20\exp\left(-0.2\sqrt{(1/m)\sum_{j=1}^{m} k_j}\right) - \exp\left((1/m)\sum_{j=1}^{m} \cos(2\pi k_j) + 20 + e\right)$	60	[-32, 32]

as they enable PV systems to be analyzed and optimized with greater accuracy and precision. Moreover, implementing these models allows for identifying and mitigating potential losses in PV systems, which is integral to their overall performance. The complexity of each model type depends on the number of diodes included, with the Single Diode Model being the simplest and the Four-diode Model being the most complex. Despite the complexity of the models, they are essential for the optimal design and operation of PV systems, as they allow for a greater understanding of the characteristics and behaviour of PV cells. As such, the use of these models is becoming increasingly common in the contemporary world as the demand for sustainable energy solutions continues to grow [23,24].

The following equation represents the modelling of a modified four-diode model of a solar PV cell.

$$I_O = I_{ph} - I_{rsd1}\left[exp\left(\frac{q(V_O + I_O R_{se})}{n_1 KT}\right) - 1\right] - I_{rsd2}\left[exp\left(\frac{q(V_O + I_O R_{se})}{n_2 KT}\right) - 1\right] - I_{rsd3}\left[exp\left(\frac{q(V_O + I_O R_{se})}{n_3 KT}\right) - 1\right] - I_{rsd4}\left[exp\left(\frac{q(V_O + I_O R_{se} - I_{rsd4} R_4)}{n_4 KT}\right) - 1\right] - \frac{V_O + I_O R_{se}}{R_{sh}} \quad (1)$$

Table 4
Statistical results.

Algorithms		F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
PSO	mean	1.75E+03	1.26E+01	3.98E+04	7.24E+01	8.42E+06	3.28E+03	2.38	−1.43E+03	2.63E+02	1.40E+01
	SD	1.70E+03	2.31E+01	5.45E+03	1.47E+01	2.22E+07	8.69E+03	8.20	1.55E+02	2.06E+01	5.63
GWO	mean	3.26E+01	5.01	1.10E+04	1.08E+01	3.62E+06	1.98E+03	1.66	−3.86E+03	7.96E+01	4.51
	SD	1.26E+02	2.81	1.78E+04	2.33E+01	3.58E+06	1.61E+03	1.04	2.61E+02	8.52E+01	6.69
CS	mean	6.19E-15	4.31E-10	5.86E+01	1.03E-03	2.68E+01	1.79	3.18E-03	−4.38E+03	1.46	9.14E-09
	SD	1.01E-14	4.63E-10	9.54E+01	1.10E-03	9.02E-01	2.35E-01	2.78E-03	2.37E+02	3.30	1.15E-08
HBO	Mean	4.07E-25	1.03E-05	3.40E-16	14.27	477.59	3.33E-01	1.38E-02	−7498.08	46.96	9.44E-01
	SD	2.95E-25	1.32E-05	1.31E-15	4.52	727.79	2.92E-01	4.56E-03	595.43	18.08	6.50E-01
RAT	Mean	5.96E-66	1.03E-30	6.16E-158	1.86E-16	2.75	1.06E-03	6.67E-04	−2562.69	4.77	7.96E-13
	SD	9.52E-66	4.23E-30	0.00E+00	1.49E-16	2.13E-01	4.99E-04	4.30E-04	212.89	1.56	3.48E-13
PF	mean	2.90E-15	4.47E-20	3.01E-09	1.32E-08	2.67E+01	1.31	1.26E-03	−6.72E+03	9.52E-01	3.29E-14
	SD	1.12E-14	4.63E-20	5.25E-09	1.78E-08	3.84E-01	3.25E-01	6.83E-04	6.38E+02	3.69	1.48E-14

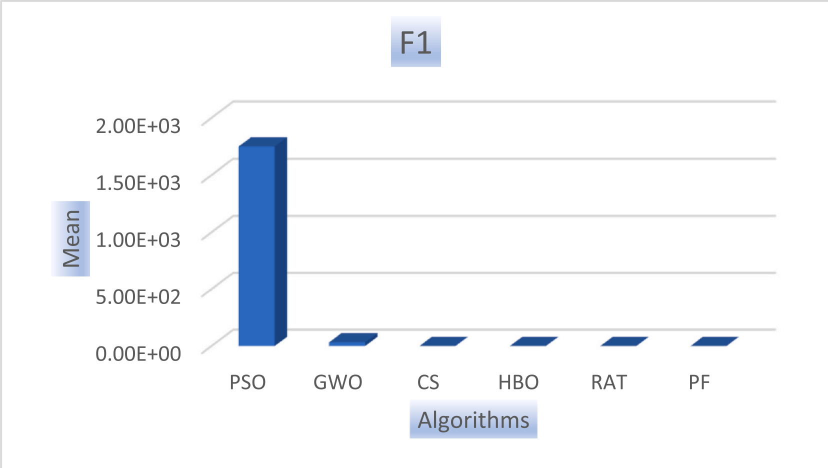

Fig. 3. F1 benchmark test function Bar Graph.

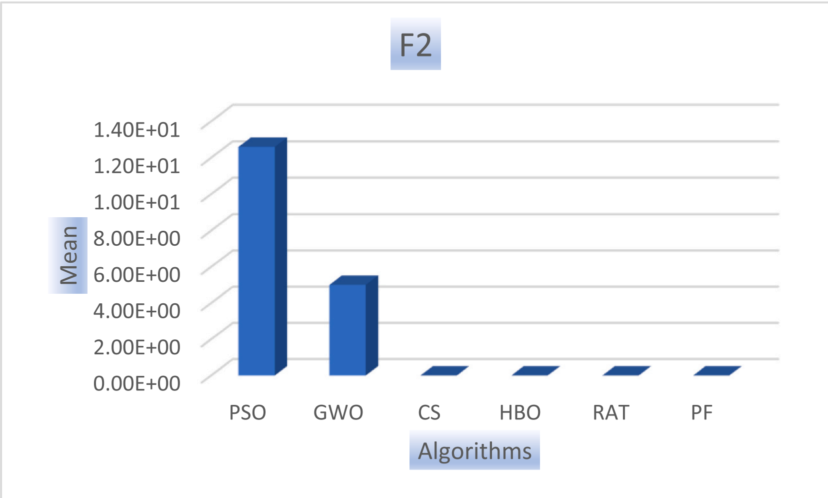

Fig. 4. F2 benchmark test function Bar Graph.

In the context of a P–N junction, where I_{ph} represents photocurrent and I_{dc1}, I_{dc2}, I_{dc3}, and I_{dc4} denote the diode currents, I_o and V_o signify the output current and output voltage, respectively. In addition, I_{rsd1}, I_{rsd2}, I_{rsd3}, and I_{rsd4} are the Reverse saturation currents of the four-diode, while R_4 is an added resistance incorporated in the fourth diode. The value of q represents the absolute value of the current, while n_1, n_2, n_3, and n_4 are the ideal factors. To perform the necessary calculations, one must consider Boltzmann's constant, K, and the absolute temperature (in kelvin) of the P–N junction, denoted by T.

3. Optimization process

In the modified -four-diode model of solar PV cell, collection of experimental I–V data gathered from the real system and an optimization technique may be used to identify the unknown parameters. Vector x, where $x = [R_{se}R_{sh}R_4I_{ph}I_{rsd1}I_{rsd2}I_{rsd3}I_{rsd4}n_1n_2n_3n_4]$ defines each solution in the optimization algorithm for the modified four-diode model of solar PV cell. Equation (1) is written in its homogenous form to define the objective functions, which is presented in Equation (2) [40].

$$f(V_O, I_O, x) = I_O - I_{ph} + I_{rsd1}\left[exp\left(\frac{q(V_O + I_OR_{se})}{n_1KT}\right) - 1\right] + I_{rsd2}\left[exp\left(\frac{q(V_O + I_OR_{se})}{n_2KT}\right) - 1\right] + I_{rsd3}\left[exp\left(\frac{q(V_O + I_OR_{se})}{n_3KT}\right) - 1\right] + I_{rsd4}\left[exp\left(\frac{q(V_O + I_OR_{se} - I_{rsd4}R_4)}{n_4KT}\right) - 1\right] + \frac{V_O + I_OR_{se}}{R_{sh}} \tag{2}$$

For every set of experimental data obtained, the value of f is calculated. This written work assesses the distinction between

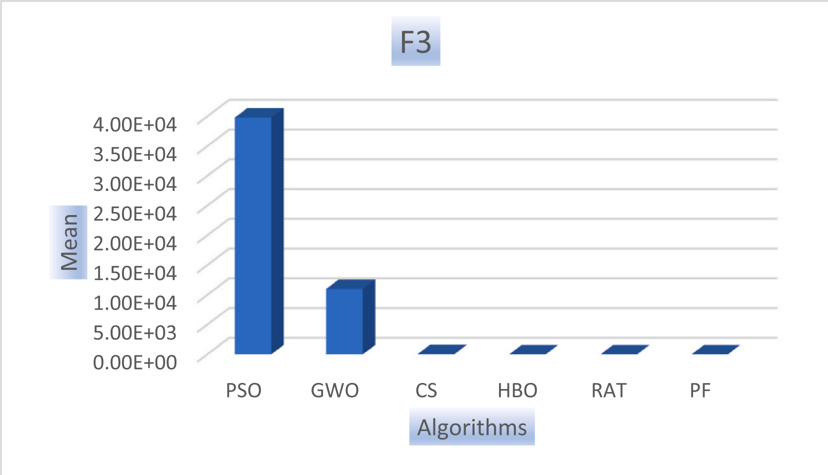

Fig. 5. F3 benchmark test function Bar Graph.

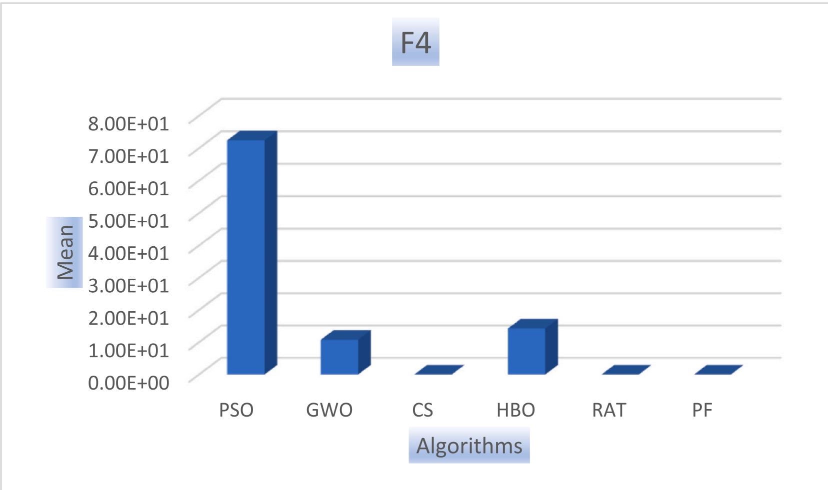

Fig. 6. F4 benchmark test function Bar Graph.

empirical information and model outcomes by utilizing the Root Mean Square Error (RMSE). The main purpose of a solar PV cell's parameter estimation is to reduce the deviation between empirical data and model outcomes. The utilization of RMSE as a metric for identifying the difference between empirical data and model outcomes is crucial in improving the accuracy of solar PV cell systems. The value of RMSE is defined in equation (3).

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(f_i(V_O, I_O, x))} \tag{3}$$

Where x the solution vector and N is the number of model results. The main objective is to minimize the value of RMSE.

Puffer Fish Algorithm.

The PF method, named after its scientific designation Torquigener albomaculosus, is a meta-heuristic computational technique that draws inspiration from the distinctive circular formations structure created by male PF. These structures, with a diameter of approximately 2 m, are skillfully designed to entice female PF [41]. Interestingly, male PF are the only ones that have the ability to construct these impressive structures. The maximum length of PF is 12 cm and 9.1 cm for males and females, respectively. PF offers a fascinating insight into the natural world and could potentially be applied to problem-solving in various fields. Therefore, this algorithm may be an excellent starting point for researchers exploring innovative problem-solving techniques. The circular structures are built according to a precise set of regulations and exhibit a distinctive pattern at their core [42]. This behaviour of circular structures might be used for solving a minimization problem in the form of meta-heuristic optimization algorithm.

The circular structures constructed by PF are defined by several parameters, including the inner and outer zone radii, the initial point, the peak number, the number of iterations, and the radius reduction ratio. In order to obtain the global minimum point of

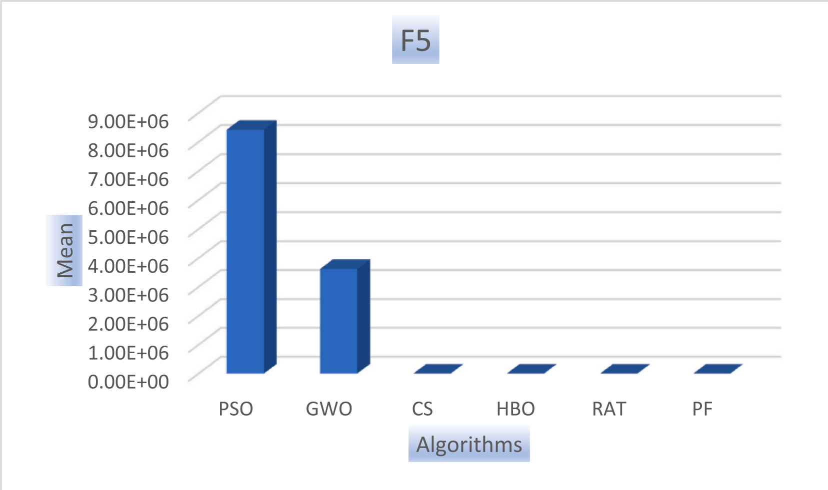

Fig. 7. F5 benchmark test function Bar Graph.

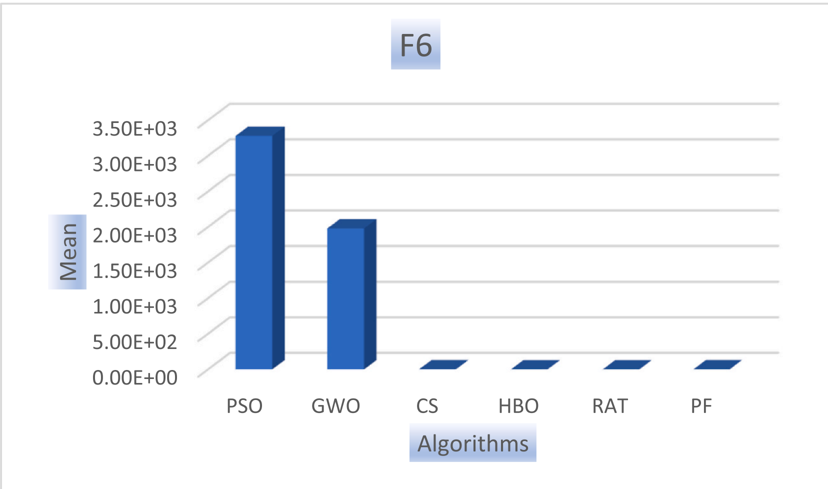

Fig. 8. F6 benchmark test function Bar Graph.

function, a convergence method can be employed that determines new starting points by calculating the lowest points at each iteration. This method ensures the convergence of the global minimum point, facilitating a more accurate and efficient analysis of the circular structures built by PF. The definition of various parameters is as: r_{out} (outer zone radius), n_{peak} (peak number), r_{cen} (center zone), d_{red} (radius reduction ratio), s_{small} (small sand pieces), s_{large} (large sands) and $c_{\max}$ (maximum number of circular structures). Equation (4) updates the r_c parameter defined as a specific radius value per circular structure number [43].

$$r_{c+1} = d_{red} * r_c \tag{4}$$

The representation of Fig. 2 displays the PF algorithm's pseudo code.

4. Results and discussion

4.1. benchmark test functions

This segment presents an evaluation of the efficiency of the PF algorithm by utilizing ten benchmark test functions. The functions used for this study include unimodal functions F_1 (k) to F_7 (k) as well as multimodal functions F_8 (k) to F_{10} (k), all of which have a dimension of 6 all with a dimensionality of 60. To assess the performance of the PF algorithm, we compared it against five other meta-heuristic algorithms, namely PSO, RAT, HBO, GWO, and CS. Table 2 shows the parameters of all parameters. Each algorithm was independently run 20 times using MATLAB 2020a, an Intel CPU 2.50 GHz processor, and 8 GB of RAM. To ensure a fair assessment of

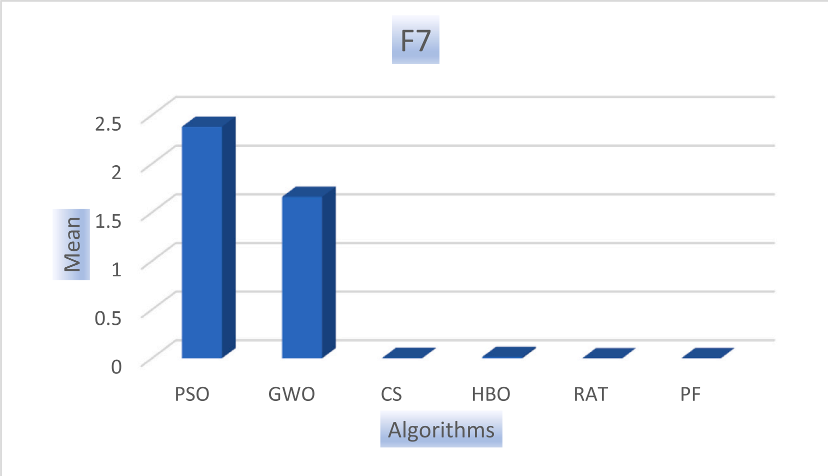

Fig. 9. F7 benchmark test function Bar Graph.

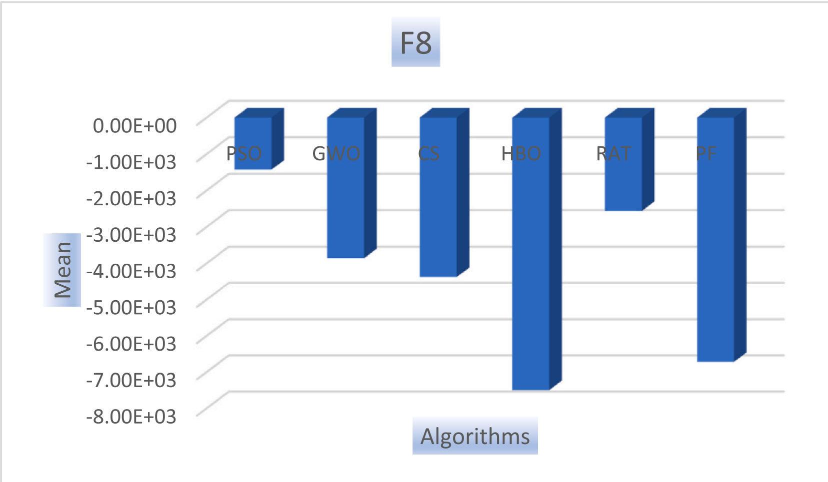

Fig. 10. F8 benchmark test function Bar Graph.

the ten benchmark functions and their comparison with other meta-heuristic algorithms, a limit of 1000 feature evaluations was set, which is shown in Tables 3 and 4.

Upon comparison of the mean and Standard Deviation (SD) values of the benchmark test functions obtained using the various algorithms, it is evident that the PF algorithm provides better values than the other algorithms. The results of this study are displayed in a bar graph, which shows the mean value of the ten benchmark test functions using the PF algorithm as well as a comparison with Rat, HBO, PSO, GWO and CS, as depicted in Figs. 3–12. These results indicate that the PF algorithm is the most efficient of the five algorithms studied, providing better values for the benchmark test functions.

In conclusion, the results of this study highlight the efficiency of the PF algorithm compared to other meta-heuristic algorithms. The use of a fair assessment approach in evaluating the ten benchmark test functions, coupled with multiple independent runs of each algorithm, provides reliable and credible results. The findings of this study hold the potential to provide substantial advantages to scholars and professionals engaged in the domain of optimization, specifically those with a focus on meta-heuristic algorithms. Further studies could explore the application of the PF algorithm in solving other optimization problems, as well as the optimization of its parameters to improve its efficiency and performance. The benchmark test functions used in this study could also be expanded to include more complex functions, thereby providing a more comprehensive evaluation of the algorithm's performance.

4.2. Estimation of solar PV cell parameters using a modified four-diode model

Table 5 displays the parameters of the modified four-diode PV cell, while Table 6 showcases RTC France's data sheet. An evaluation of the PF algorithm's performance is compared to other algorithms such as PSO, RAT, HBO, GWO, and CS. The approach utilized

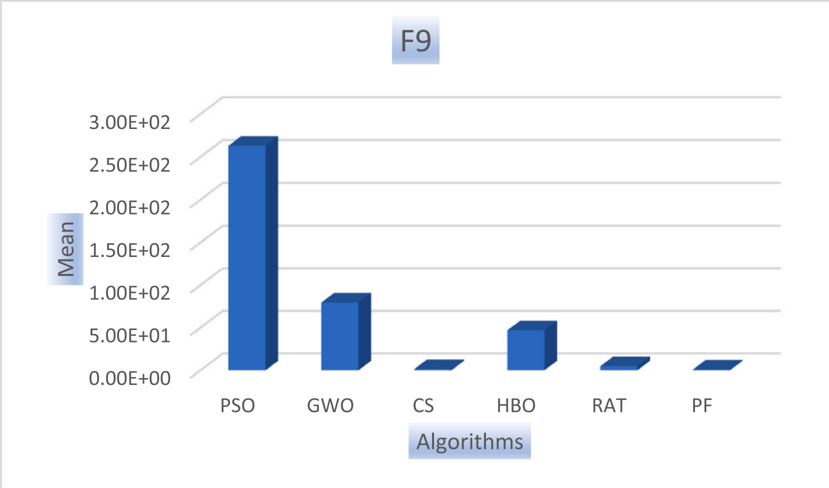

Fig. 11. F9 benchmark test function Bar Graph.

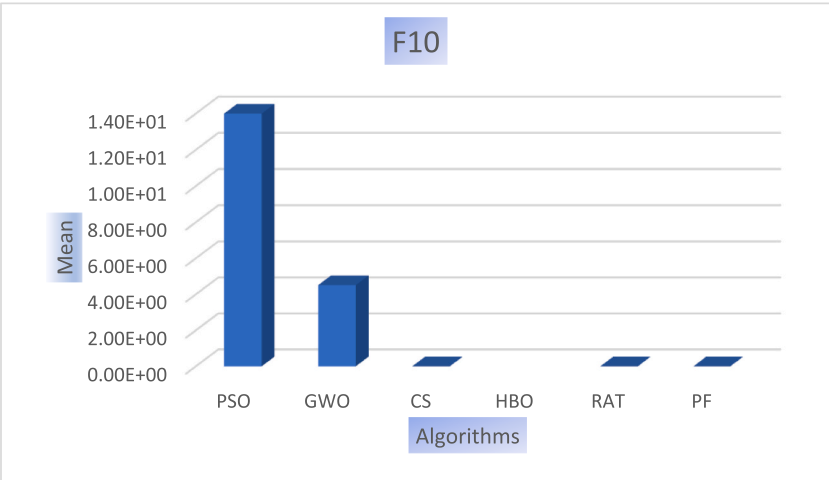

Fig. 12. F10 benchmark test function Bar Graph.

Table 5
Parameter Search Range for Modified Four-diode model of solar PV cell.

Parameters	Lower bound	Upper bound
I_{pv} (A)	0	1
I_{rsd1}, I_{rsd2}, I_{rsd3}, I_{rsd4} (μA)	0	1
R_{se} (Ω)	0	0.5
R_{sh} (Ω)	0	100
R_4(Ω)	0	2
n_1, n_2, n_3, n_4	1	2

involves coding all the programs in MATLAB 2020a and independently running each algorithm 20 times. To ensure a fair assessment of the parameter estimation by the PF algorithm and its comparison with other meta-heuristic algorithms, the same limit number of feature evaluations, i.e., 1000, is set, while the population size is maintained at 50, at 33 °C, Table 7 illustrates the parameter estimation of a modified four-diode PV cell model.

4.3. Solution accuracy analysis

The computation of the Root Mean Square Error (RMSE) for solar PV cell parameters using the modified four-diode model at a

Table 6
Data sheet for estimation of solar PV cell parameters.

Characteristic Data	R.T.C France
I_{sc} (A)	0.7603
V_{oc} (V)	0.5728
V_{mp} (V)	0.4507
I_{mp} (A)	0.6894
R_{sh0} (Ω)	246.80
R_{s0}(Ω)	0.0907
T (K)	306.15
N	1

temperature of 33 °C is presented in Table 8. In Fig. 13, the RMSE value for all algorithms is depicted by a bar graph, indicating that the PF algorithm has the lowest RMSE value compared to other meta-heuristic algorithms. Thus, it is considered the optimal and most efficient method for estimating the parameters of solar PV cells using the modified four-diode model. The computational time for all algorithms is illustrated in Fig. 14, which shows that the PF algorithm has the least computational time.

4.3.1. Convergence analysis

As illustrated in Fig. 15, the PF algorithm demonstrates a convergence curve in contrast to RAT, HBO, PSO, GWO, and CS algorithms. The PF algorithm displays a higher convergence rate than other algorithms. In Fig. 16, Fig. 17, and Table 9, the I–V and P–V curves for the solar PV cell are obtained, respectively. The results clearly reveal that the PF algorithm performs better and more accurately than the others. Therefore, it can be concluded that the PF algorithm is more effective and efficient in solving complex optimization problems. Furthermore, this algorithm has promising potential for application in various fields, including renewable energy systems, manufacturing, and logistics.

4.4. Statistical analysis

The test outcomes for Friedman's ranking are laid out in Table 10. The purpose of the Friedman test is to assess whether there are significant differences in the dependent variable among different levels of a categorical independent variable. Friedman: First, rank each participant's data independently for every condition. Next, determine the mean ranking for every circumstance. Finally, use the chi-square distribution to get the Friedman statistic. Based on the Friedman ranking test PF secured the topmost rank, followed by HBO, RAT, CS, GWO, and PSO. The PF algorithm performs superior to other meta-heuristic algorithms in parameter estimation for modified four-diode solar PV cells, as evidenced by the results obtained from both experimental tests [44–47]. The algorithm is more accurate, efficient, and performs better. Furthermore, additional Friedman ranking test results in comparison of each algorithm are presented in Fig. 18. In conclusion, the data suggests that the PF algorithm is a promising approach for parameter estimation of modified four-diode solar PV cells.

Additionally, the samples are subjected to the Wilcoxon rank sum test, a safe and trustworthy non-parametric technique for integrated statistical analysis in situations where dynamic programming is prevalent and samples are independent. For combined statistical analysis where samples are independent, it appears to be a simple, safe, and trustworthy procedure. Table 11 provides a summary of the computed p-values and demonstrates that the PF performances are significant at the 95 % significance level.

5. Conclusions and future directions

5.1. Conclusion

The main aim of this study is to determine the parameters of a modified four-diode model for PV cells using the data sheet provided by R.T.C France. This will enhance the estimation of parameters for solar PV cells in the solar energy industry, leading to improved efficiency, reliability, financial viability, and environmental sustainability, ultimately promoting the widespread adoption of solar power as a clean and renewable energy source. The current investigation utilizes the PF meta-heuristic optimization method to assess the parameters of a modified four-diode solar PV cell model built by a male PF employing a circular design. The estimated parameters in the study are 12, including incorporating additional series and parallel resistances that enhance the estimation process. The findings of this study have the potential to improve solar photovoltaic (PV) cell performance. The findings based on the results obtained so far are listed below.

- The PF algorithm is an effective method for accurately estimating parameters in a modified four-diode PV cell model. The algorithm is based on minimizing the error between predicted and measured values of the PV cell, making it fast and accurate. In fact, this algorithm can be used in a wide range of conditions with excellent results.
- To demonstrate the effectiveness of the PF algorithm, ten benchmark test functions were performed, and mean and Standard Deviation (SD) values were calculated. The results showed that the PF algorithm performs significantly better than others, indicating that it is an effective tool for solving optimization problems. Furthermore, these results suggest that this algorithm can be used in various applications with excellent outcomes.

Table 7
Parameter estimation of solar PV cell.

Parameters/Algorithm	Ipv	n1	n2	n3	n4	Rse	Rsh	Irsd1	Irsd2	Irsd3	Irsd4	R4
PSO	0.7486	1.0200	1.0932	1.0386	1.0529	2.6581E-03	17.6214	5.0355E-05	6.2215E-05	4.4104E-05	4.7910E-05	1.5236
GWO	0.7903	1.4235	1.5662	1.5345	1.4837	2.5687E-03	52.2348	2.4163E-06	8.2864E-06	2.8972E-07	7.9746E-07	1.3487
CS	0.7553	1.3625	1.5364	1.5580	1.5530	5.3254E-04	34.7921	6.3219E-06	2.6549E-06	7.5896E-07	1.8846E-06	0.2014
HBO	0.7702	1.4031	1.5957	1.5580	1.5203	2.3591E-04	48.6842	5.6512E-06	6.5237E-06	5.9657E-07	2.7988E-06	0.5326
RAT	0.7815	1.3293	1.5465	1.5580	1.4799	2.5804E-04	58.0354	6.7561E-06	4.6259E-06	5.6547E-07	1.9576E-06	0.4984
PF	0.8955	1.8842	1.7852	1.8679	1.8446	2.0246E-02	32.9430	1.4893E-06	7.2215E-07	7.0366E-07	1.8542E-06	0.6602

Table 8
RMSE and Computational Time (sec) of solar PV cell.

Algorithm	RMSE	Computational Time (in sec)
PSO	2.8486E-04	4.8548
GWO	2.5257E-05	4.7964
CS	1.4558E-05	2.9025
HBO	1.0086E-06	2.7614
RAT	2.3714E-06	3.0158
PF	7.8947E-08	2.4587

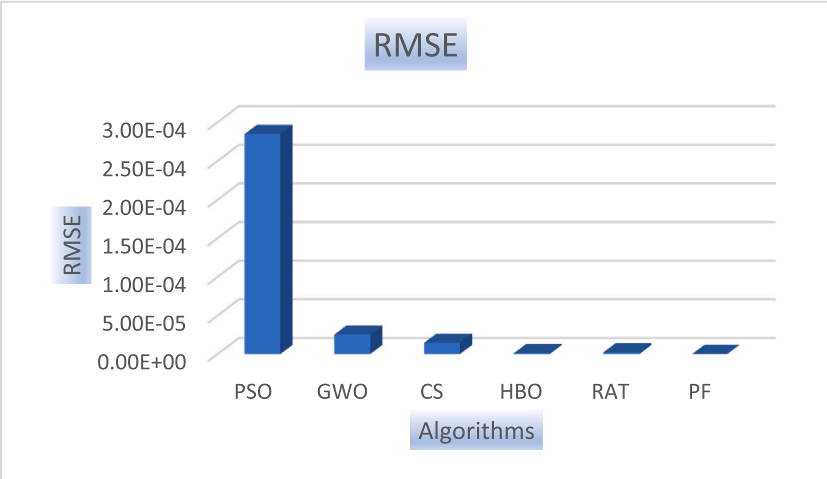

Fig. 13. Bar graph of RMSE of solar PV cell.

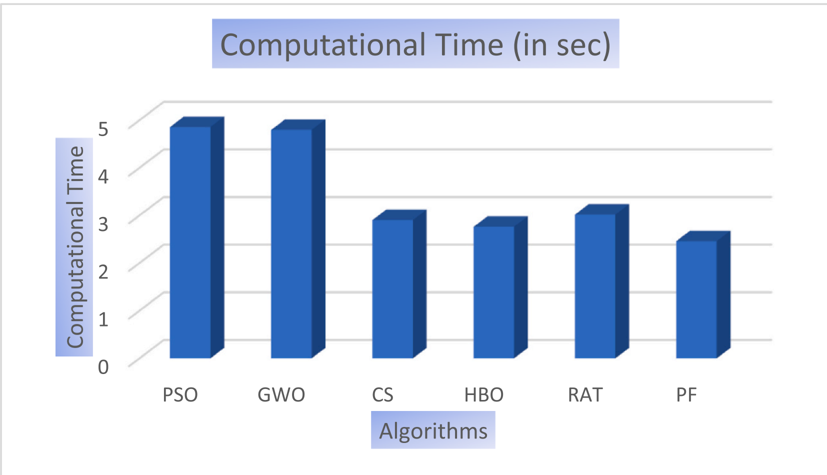

Fig. 14. Bar Graph of Computational Time (sec) of solar PV cell.

- The PF algorithm was also used for parameter estimation of a modified four-diode PV cell model at 33 °C, and RMSE was compared with other meta-heuristic algorithms such as RAT, HBO, PSO, GWO, and CS. Results showed that the PF algorithm had the lowest value of RMSE. Additionally, Friedman Ranking Test and Wilcoxon's rank sum test were conducted, where PF secured the first rank in Friedman Ranking Test, proving its superiority over other algorithms. Based on the convergence curves of all the algorithms, it is evident that the PF algorithm has a higher convergence rate.

In conclusion, the PF algorithm demonstrates efficacy and efficiency in parameter estimation of a modified four-diode PV cell model. The algorithm's excellent performance in terms of error minimization and rapid convergence sets it apart from other meta-heuristic algorithms. The results of benchmark test functions and comparisons with other algorithms indicate that PF is an effective

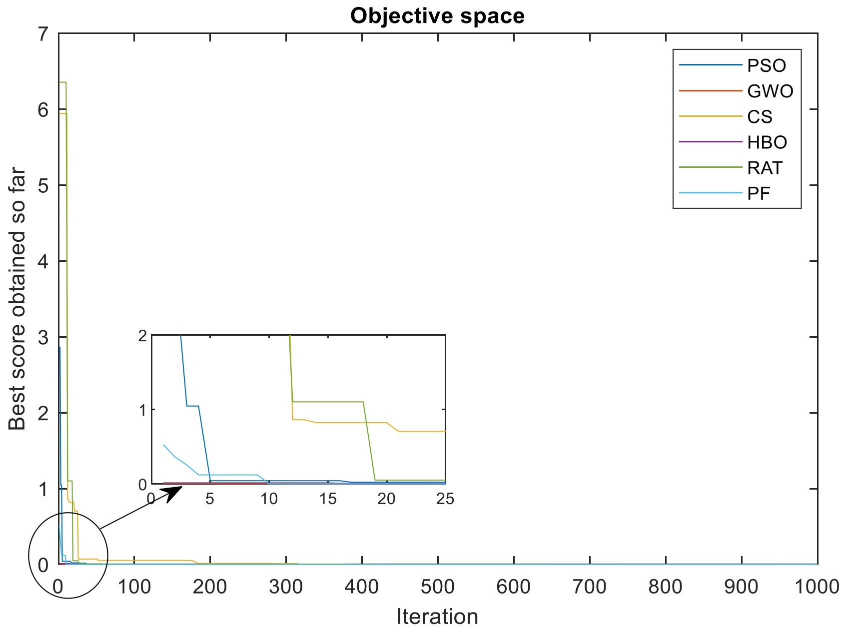

Fig. 15. Convergence graph.

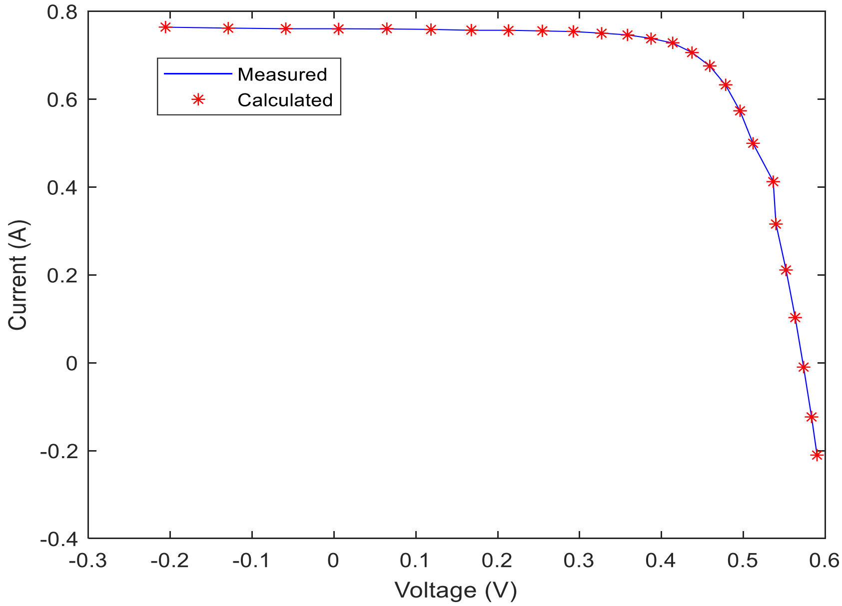

Fig. 16. I–V curve for solar PV model.

algorithm for solving optimization problems and can be used for various applications with excellent outcomes.

The limitations of the PF algorithm exhibit notable similarities to those of the swarm-based methods. The algorithm's developer has successfully addressed the convergence issue to local minima. However, it lacks support for good memory, a significant drawback.

5.2. Future directions

According to the research, PF offers an effective and efficient technique for parameter estimation of modified four-diode model of solar photovoltaic (PV) cells. Not only can this method improve the accuracy of the model, but it can also reduce the time required for parameter estimation. One of the authors' future goals is to hybridize the PF method with a genetic algorithm to improve upon its limitations. Furthermore, it is possible to explore its usage in other domains such as machine learning and control systems. Another

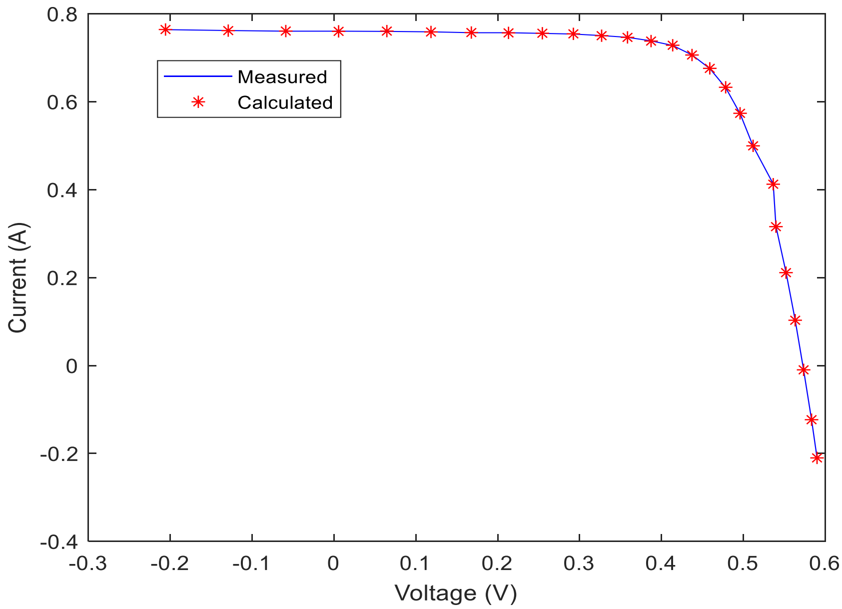

Fig. 17. P–V curve for solar PV model.

Table 9
I–V, P–V and IAE of solar PV cell.

V_L (Measured) (V)	I_L (Measured) (A)	P_L (Measured) (W)	Modified Four Diode		Modified Four Diode	
			I_L (Calculated) (A)	IAE	P_L (Calculated) (W)	IAE
−0.2057	**0.7640**	**−0.1571**	0.7647	0.0007	−0.1572	0.00014
−0.1291	**0.7620**	**−0.0983**	0.7626	0.0006	−0.0984	0.00008
−0.0588	**0.7605**	**−0.0447**	0.7600	0.0005	−0.0446	0.00003
0.0057	**0.7605**	**0.0043**	0.7605	0	0.0043	0
0.0646	**0.7600**	**0.0490**	0.7595	0.0005	0.0490	0.00003
0.1185	**0.7590**	**0.0899**	0.7597	0.0007	0.0900	0.00008
0.1678	**0.7570**	**0.1270**	0.7572	0.0002	0.1270	0.00003
0.2132	**0.7570**	**0.1613**	0.7566	0.0004	0.1613	0.00009
0.2545	**0.7555**	**0.1922**	0.7554	0.0001	0.1922	0.00003
0.2924	**0.7540**	**0.2204**	0.7538	0.0002	0.2204	0.00006
0.3269	**0.7505**	**0.2453**	0.7515	0.0010	0.2456	0.00033
0.3585	**0.7465**	**0.2676**	0.7475	0.0010	0.2679	0.00036
0.3873	**0.7385**	**0.2860**	0.7392	0.0007	0.2862	0.00027
0.4137	**0.7280**	**0.3011**	0.7275	0.0005	0.3009	0.00021
0.4373	**0.7065**	**0.3089**	0.7071	0.0006	0.3092	0.00026
0.4590	**0.6755**	**0.3100**	0.6751	0.0004	0.3098	0.00018
0.4784	**0.6320**	**0.3023**	0.6314	0.0006	0.3020	0.00029
0.4960	**0.5730**	**0.2842**	0.5730	0	0.2842	0
0.5119	**0.4990**	**0.2554**	0.5013	0.0023	0.2566	0.00118
0.5365	**0.4130**	**0.2215**	0.4150	0.0020	0.2226	0.00107
0.5398	**0.3165**	**0.1708**	0.3170	0.0005	0.1711	0.00027
0.5521	**0.2120**	**0.1170**	0.2139	0.0019	0.1180	0.00105
0.5633	**0.1035**	**0.0583**	0.1036	0.0001	0.0583	0.00006
0.5736	**−0.0100**	**−0.0057**	−0.0097	0.0003	−0.0055	0.00017
0.5833	**−0.1230**	**−0.0717**	−0.1231	0.0001	−0.0718	0.00006
0.5900	**−0.2100**	**−0.1239**	−0.2114	0.0014	−0.1247	0.00083
SUM				**0.0173**		**0.00715**

advantage of this method is that it can be utilized to develop more efficient solar cell models. As a result, the PF method has a promising future in renewable energy issues. It is recommended that further research be conducted to determine the full potential and efficacy of this technique in various applications. As well as the manufacture can use this algorithm to save their time and improve efficiency.

Table 10
Friedman ranking test of solar PV cell.

Algorithms	Friedman ranking
PSO	5
GWO	4
CS	3
HBO	2
RAT	3
PF	1

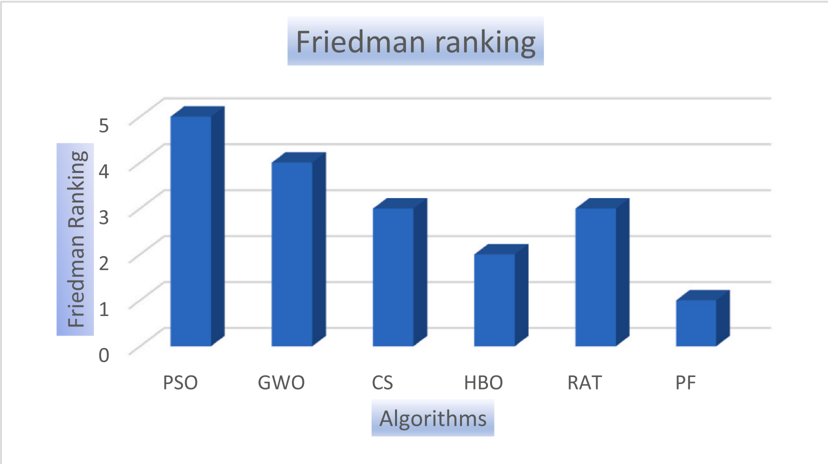

Fig. 18. Bar graph of showing Friedman Ranking Test of solar PV cell.

Table 11
The p Values for Wilcoxon's rank sum test is shown.

Algorithms	PSO	GWO	CS	HBO	RAT	PF
PF vs.,	3.8562e-7	3.8357e-7	3.8305e-7	3.8167e-7	3.8289e-7	3.8108e-7

Data availability

Data included in article/supp. material/referenced in article.

CRediT authorship contribution statement

Manish Kumar Singla: Formal analysis, Data curation. **Jyoti Gupta:** Resources, Investigation, Formal analysis, Conceptualization. **Nijhawan Parag:** Validation, Supervision, Software, Resources. **Thakur Ekta:** Writing – review & editing, Visualization, Validation, Formal analysis, Conceptualization. **Teshome Goa Tella:** Validation, Supervision, Methodology, Conceptualization. **Mohamed I. Mosaad:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Safaraliev Murodbek:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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