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Fuzzy controller optimized by the grasshopper algorithm to realize maximum power in photovoltaic systems

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Original Research

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Abstract:

In this paper, a fuzzy controller is presented in order to achieve the maximum power in a solar cell. For improvement of the controller performance and achievement of the maximum power, the fuzzy controller variables are improved by the Grasshopper Optimization Algorithm (GOA). This algorithm has flexibility and fast convergence. In this paper, the ISE evaluation index is employed as the cost function of algorithm to verify the obtained results. The results show that under the supposed conditions, the power value of the solar cell utilizing the suggested algorithm has increased compared to other algorithms. In the simulation, the power value using the proposed algorithm is 182.3 watts and the cell efficiency in this case is 99.97%. Therefore, the achieved results show at least 0.03% and 1.2% improvement, respectively in power and efficiency, compared to some examined methods.

Keywords: Fuzzy controller; Grasshopper optimization algorithm; Maximum power point tracking; Coati optimization algorithm

1. Introduction

Today, solar energy as a cheap and clean energy has considerably affected human life [1–3]. However, the conversion efficiency of solar energy into electrical one is challenging in this field. To solve this problem and also reduce the cost of manufacturing solar cells, maximum power point tracking (MPPT) methods are utilized. In this way, according to the current and voltage diagram obtained from a cell at different temperatures and ambient radiation values, the cell working point is determined regarding the maximum power value. The solar cell model is non-linear and has asymmetric slopes on both sides of the maximum power point in the graph of power versus voltage. Accordingly, employing a non-linear control method to reach the maximum power point has been considered by the researchers. Mathematical optimization algorithms are widely suggested by the researchers. However, local optima entrapment is the main imperfection of such algorithms, especially in partial shading conditions. Moreover, highly variables circumstances are a serious challenge for such algorithms in order to follow the best result. Nature-inspired optimization algorithms are extensively replacing mathematical methods to overcome such problems. In [4] authors has suggested a robust PID (RPID) controller which is a combination of a proportional-integral-derivative (PID) controller and a linear quadratic Gaussian (LQG) controller. Furthermore, Improved Lightning Attachment Procedure Optimization (ILAPO) technique is applied for determining the optimal setting of the parameters for the introduced RPID controller. In [5] M. Ebeed et al have proposed optimal integration inverter-based PVs with inherent DSTATCOM functionality for reliability and security improvement at seasonal uncertainty. Considering all the attempts for MPPT improvement, according to the importance of simplicity, accuracy, and speed of approaches, research is still ongoing.

The grasshopper optimization algorithm (GOA) is able to improve the initial random population for a real problem. The target is improved throughout iterations, so the approximation of the global optimum becomes more accurate proportional to the number of iterations [6]. A modified grasshopper optimization algorithm (MGOA) is suggested by Taher et al to solve the optimal power flow (OPF) problem [6]. The offered method is based on the basic model of GOA with modifying the mutation process to avoid trapping into local optima stagnation. Simulation results reveal the superiority of the proposed technique. Therefore, an improved GOA is employed in this paper for MPPT purposes. In the proposed method in this article, first, the power difference at each moment compared to the previous moment is obtained for a common solar cell. Also, the voltage value at each moment is calculated in comparison to the previous moment. Since the ratio of the calculated power difference to the voltage difference is the same as the slope of the power diagram versus voltage, while this slope value is zero at the point where the maximum cell power is obtained, therefore this value is used as an error signal. This error and its derivative are imposed on the fuzzy system inputs. In the next step, fuzzy controller is designed by specifying the input and output membership functions, as well as determining the fuzzy rules. Ultimately, the fuzzy system variables are optimized by the grasshopper optimization algorithm and then the results are evaluated. In summary, in this paper, the fuzzy system is employed as a controller in order to track the maximum power in solar cells. Considering MPPT increases the power and efficiency. In addition, some fuzzy parameters are modified utilizing GOA algorithm.

2. Research background

Saif al-Islam et al. have presented state-of-the-art control methods for photovoltaic simulators utilizing Finite Set Model Predictive Control (FS-MPC). In this research, a predictive PV emulator (PPVE) is introduced and evaluated under severe weather conditions and load changes. The optimal performance of PVE is experimentally verified in compare with PI controller operating under common conditions [7]. One earlier research has been presented by Hosseini et al. who explored fuzzy logic controllers (FLC) for MPPT in photovoltaic systems [8]. This paper employs four different algorithms in order to optimize the fuzzy membership functions (MFs) and deliver suitable duty cycle to the converter. Some optimization algorithms such as learning-based optimization (TLBO) and particle swarm optimization (PSO), are compared with previous references. The results reveal that the perturb and observation (P&O) algorithm deals with considerable fluctuations and energy waste. Moreover, sometimes it is unable to obtain the MPP. Furthermore, the simulation outputs demonstrate that the asymmetric fuzzy MFs based on TLBO increase both the convergence speed of MPPT and tracking accuracy compared to PSO:
Mohapatra and co-workers have proposed an adaptive P&O MPPT that can quickly track the MPP with less steady-state fluctuations in compared with the regular MPPT P&O algorithm [9]. Partial shading is one of the main challenges for PV systems and MPPT. It occurs when several parts of the solar array are exposed to various levels of solar radiation. Subsequently, it results in multi-peak performance in the system's output characteristics. Distributed maximum power point tracking (DMPPT) is a technique that partially can overcome such problem suggested by Femia and et al. for PV arrays [10].
Ali Mahmoud and his colleagues have proposed a new design of a fuzzy logic-based algorithm to change the step size of the incremental conductance (INC) MPPT method for PV [11]. The voltage step size is estimated in accordance with the ascending or descending degree of the power-voltage relationship. The results show improvement of the MPPT efficiency.
Krishnan et al. suggested Ant colony optimization for MPPT in photovoltaic (PV) systems [12]. Using the proposed approach leads to MPPT improvement.
In addition, some other methods are proposed by the researchers in order to enhance the [13–16]. However, due to the importance of achieving maximum power, research on this field continues. In this article, due to the flexibility and fast convergence characteristics of the grasshopper algorithm, the optimization of the fuzzy controller for MPPT is investigated employing this algorithm.

3. Methodology

3.1 Solar cell structure

Fig. 1 shows the schematic of a solar cell with a boost converter and controller [17]. Voltage and current achieved from the PV cell is fed to both the boost converter and the MPPT controller. DC-DC boost converter is to deliver higher output voltage, whereas its duty cycle is controlled by MPPT in order to hand maximum power over the load. The suggested MPPT is based on the fuzzy controller optimized by a GOA algorithm.
The PV module model used in the proposed approach is shown in Fig. 2.
PV cells play a crucial role as the primary components within the framework of a PV module. The energy received from sunlight is transformed into electrical energy within these PV cells. Several researchers have elucidated the nonlinear and exponential relation between the current and voltage of a PV module. The magnitude of the output current is contingent upon factors such as temperature, solar radiation, and load current. Among various models for PV modules, the single diode model, illustrated in figure 1, is most common for its accuracy and simplicity. The equations

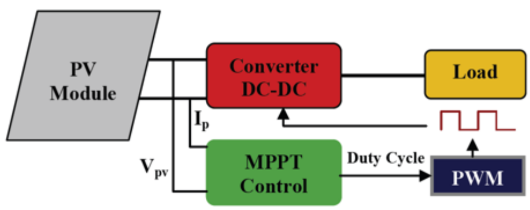

Figure 1. Solar cell diagram with controller and boost converter [17].

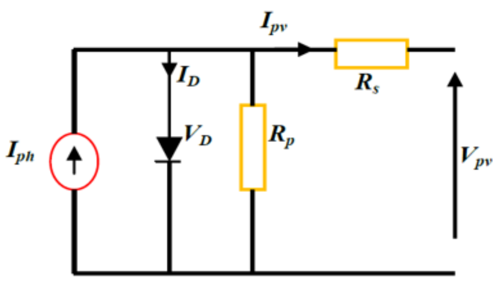

Figure 2. The equivalent circuit of a solar cell [17].

describing the output voltage and current of the PV solar cell model are as follows [17],

$$0 = I_{ph} - I_D - I_{PV} - \frac{V_{PV} + R_S \times I_{PV}}{R_P} \quad (1)$$

$$I_{ph} = I_O(e^{\frac{V_D}{V_T}} - 1) \quad (2)$$

$$V_D = V_{PV} + R_S \times I_{PV} \quad (3)$$

$$V_T = \frac{n \times K \times T}{q} \quad (4)$$

The parameters of the above equations are described in Table 1.
Moreover,

$$I_{pv} = I_{sc}\left\{1 - c_1\left(e^{\frac{V_{pv}-\Delta V}{c_2 \times V_{oc}}} - 1\right)\right\} + \Delta I \quad (5)$$

$$c_1 = I_{sc}(1 - \frac{I_m}{I_{sc}})e^{\frac{-V_m}{c_2 \times V_{oc}}} \quad (6)$$

$$c_2 = (\frac{V_m}{V_{oc}} - 1)/\ln(1 - \frac{I_m}{I_{sc}}) \quad (7)$$

$$\Delta I = I_{ph} - I_{sc} \quad (8)$$

$$I_{ph} = \frac{E}{E_n}\{I_{sc} + K_I \times \Delta T\} \quad (9)$$

$$\Delta V = R_s \times \Delta I - K_v \times \Delta T \quad (10)$$

$$\Delta T = T - T_n \quad (11)$$

The parameters of the model are generally considered as Table 2 [18].

3.2 Fuzzy controller design

Fuzzy rules considered in the design of the fuzzy controller for the suggested system, are as shown in Table 3.
PG, PM, PP, M, GP, GM, GG, and M are the labels for very low, medium-low, low, medium, high, medium high, and very high, respectively.
The initial membership functions are randomly determined by the grasshopper algorithm according to the input or output intervals. Integral Square Error (ISE) is used as the error function to verify the results. The fuzzy variables undergoing the optimization include the parameters of the input/output membership functions and the input/output gains. The output of the fuzzy system is first applied to a pulse generator and then applied to the thyristor located

Table 1. Solar cell equivalent circuit parameters.

Description	Parameter
PV current (A).	I_{PV}
output current (A).	I_{ph}
Shockley diode equation (A).	I_D
diode saturation current (A).	I_O
series resistance (Ohms).	R_S
shunt resistance (Ohms).	R_P
diode voltage (V).	V_D
thermal voltage (V).	V_T
output voltage (V).	V_{PV}
Ideality factor.	n
Boltzmann constant 1.38*10e23 J/K.	K
temperature (Celsius)	T
electron charge 1.602*10e19C.	q

Table 2. Solar cell model parameters.

parameter	abbreviation	value
Current at Maximum Power	I_m	*1.22 A*
Voltage at Maximum Power	V_m	*147.6 V*
Open Circuit Voltage	V_{oc}	*194 V*
Short Circuit Current	I_{sc}	*1.5 A*
Temperature Coefficient of Short Circuit Current	K_1	*0.097*
Temperature Coefficient of Open Circuit Voltage	K_v	*-0.349*
Internal Series Resistance	R_s	*0.348*
Reference Solar Radiation	E_n	*1000*
Reference Temperature	T_n	*25*

Table 3. Fuzzy rules for fuzzy system design.

Change of Error \Error	Very small (vs)	Small (s)	Medium (m)	Large (l)	Very large (vl)
(vs)	PG	PM	PP	GM	PG
(s)	PG	PP	GP	M	PM
(m)	PM	M	GM	GP	PP
(l)	PP	GP	GG	GM	M
(vl)	M	M	GG	GG	GP

in the boost converter. This pulse generator must have a switching frequency. This parameter is also determined by the optimization algorithms. The general diagram of the system, which is performed in the simulation with MATLAB software, is shown in Fig. 3.

3.3 Grasshopper optimization algorithm (GOA)

Grasshoppers (locusts) are recognized as agricultural pests due to their devastating impression on crops. Fig. 4 depicts the life cycle of grasshoppers [19]. The main advantages of the GOA method are as follows:

- Exploitation of the GOA is satisfactory on problems involving unimodal test functions.
- Exploration of the GOA is intrinsically high for multi-modal test functions.
- GOA properly balances exploration and exploitation when solving challenging problems involving composite test functions.
- GOA has the potential to significantly outperform several current algorithms when solving a range of current or new optimization problems.
- GOA can improve the initial random population for a real problem. The target is improved throughout iterations, so the approximation of the global optimum becomes more accurate proportional to the number of iterations.
- GOA is able to solve real problems with unknown search spaces.

Grasshoppers belong to one of the largest groups of creatures. The swarming behavior of these insects can be seen in both nymphs and adults. On their way, they eat almost all plants. They migrate over long distances in huge groups. Searching for a food source is one serious characteristic of grasshopper swarms. Inspired by this behav-

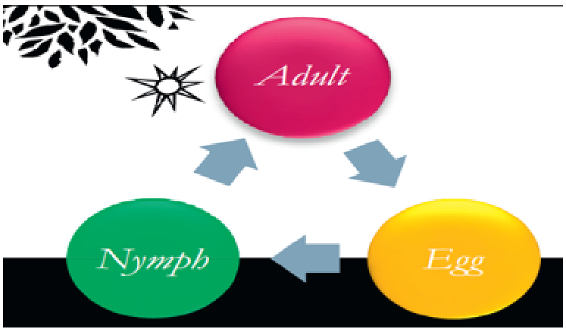

Figure 4. Life cycle of grasshoppers [19].

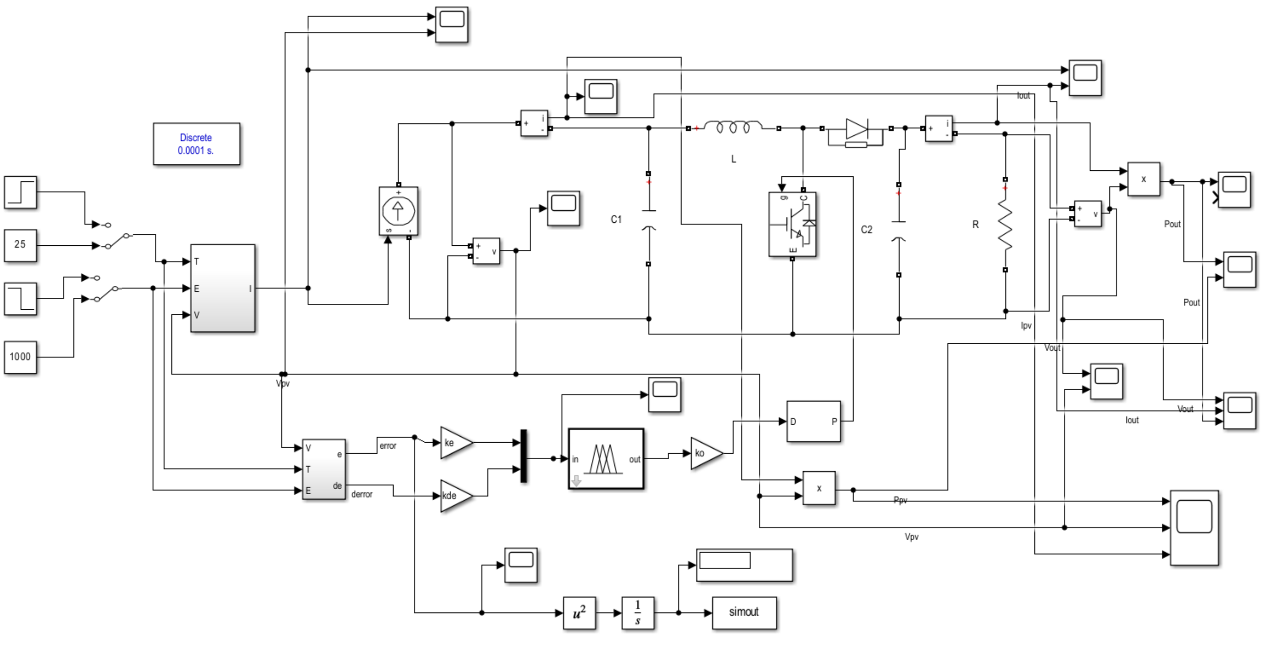

Figure 3. Simulation model of PV system with suggested optimized MPPT.

ior, the grasshopper optimization algorithm is suggested divided into exploration and exploitation sections. Search agents move impulsively in exploration, whereas during exploitation, they preferably search locally. The mathematical model simulating grasshopper swarming is represented as follows [19]:

$$X_i = S_i + G_i + A_i \tag{12}$$

where, X_i, S_i, G_i, and A_i are the position, the social interaction, the gravitational force, and the wind advection on the i-th propeller, respectively. For random purposes, the equation can be written as $X_i = r_1\ S_i + r_2\ G_i + r_3\ A_i$ where r_1, r_2, and r_3 are random numbers in the interval [0,1]

$$S_i = \sum_{j=1, i\neq j}^{N} s(d_{ij})\widehat{d_{ij}} \tag{13}$$

where $d_{ij} = |x_i - x_j|$ that x_i and x_j are the positions of the i-th and j-th grasshopper, respectively. $(\widehat{d_{ij}}) = \frac{x_i - x_j}{d_{ij}}$ is a unit vector from the i to the j-th locus. The function of the social forces is defined as:

$$s(r) = fe^{\frac{-r}{l}} - e^{-r} \tag{14}$$

where f and l represent the attraction intensity and length, respectively.

The function s in Fig. 5 is illustrated for variables l and f equal to 1.5 and 0.5, respectively to determine the way it affects locusts' social interaction in terms of attracting and repelling their kind. Also, in the same figure, the distance changes between 0 and 15 distance units are considered, and the repulsion occurs in the interval [0 2.079]. When the propeller is in the comfort zone, where it is 2.079 units away from the other propeller, there is neither attraction nor repulsion. Fig. 5 also shows that the gravity rises from 2.079 distance units to nearly 4 and then declines gradually. In this research, the values of l = 1.5 and f = 0.5 have been chosen. The G component in equation (12) is defined by considering g as the gravitational constant and $\widehat{e_g}$ as a unit vector towards the center of the earth. Therefore, G is calculated as follows:

$$G_i = -g\widehat{e_g} \tag{15}$$

In addition, A component in equation (12) is defined as bellow:

$$A_i = u\widehat{e_w} \tag{16}$$

where u and $\widehat{e_w}$ are a constant thrust and a unit vector in the wind direction, respectively.

Equation (12) can be expanded by replacing equations (14)-(16) in this equation. Therefore,

$$X_i = \sum_{j=1, i\neq j}^{N} s(|x_j - x_i|)\frac{x_j - x_i}{d_{ij}} - g\widehat{e_g} + u\widehat{e_w} \tag{17}$$

where $s(r) = fe^{\frac{-r}{l}}$-e^{-r} and N is the number of locusts.

4. Results and discussions

4.1 Simulation results

After simulating the optimal fuzzy system utilizing the grasshopper algorithm, the output and input membership functions are obtained as shown in Figs. 6, 7 and 8.

Other parameters determined by the algorithm are the input and output gains of the fuzzy system as well as the switching frequency of the pulse generator including 1.23, 0.22, 1.86, and 303, respectively.

In Fig. 9, the output power calculated by different algorithms reported in [16] is illustrated.

The simulation of the optimized system with the grasshopper algorithm results in output power depicted in Fig. 10. For comparison purpose, a temperature of 25 degrees Celsius and a radiation of 1000 watts per square meter has been considered for simulation as those of in [16]. The results are compared in Table 4: As it is clear from the Table 4, the efficiency and maximum output power based on GOA-FLC algorithm are improved. The only disadvantage of this simulation is the increase in the sitting time. Considering that a solar cell is used throughout the day and night, therefore the settling time of around 1 second can be ignored.

4.2 Discussions

Figs. 9 and 10 show a general comparison of the power output in different methods. Also, this comparison is given in Table 4 between the proposed method and other approaches. The simulation results show the better performance of the

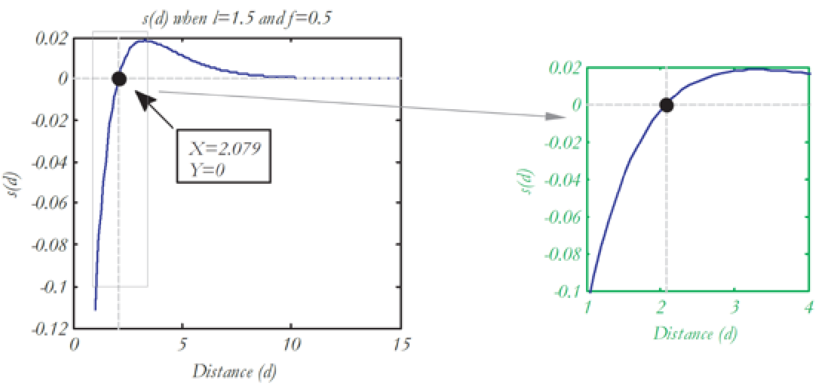

Figure 5. s function for (l,f)=(1.5,0.5), expanded for d in the [1,4] interval [19].

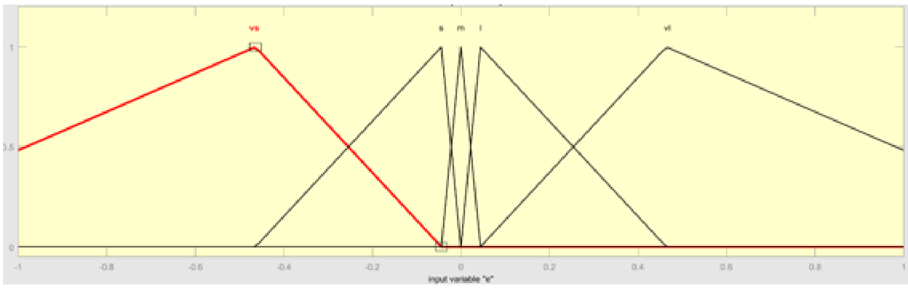

Figure 6. Membership functions of error input.

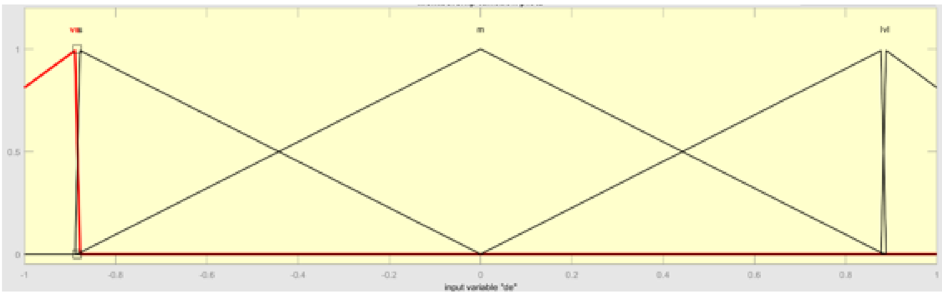

Figure 7. Membership functions of derivative of error input.

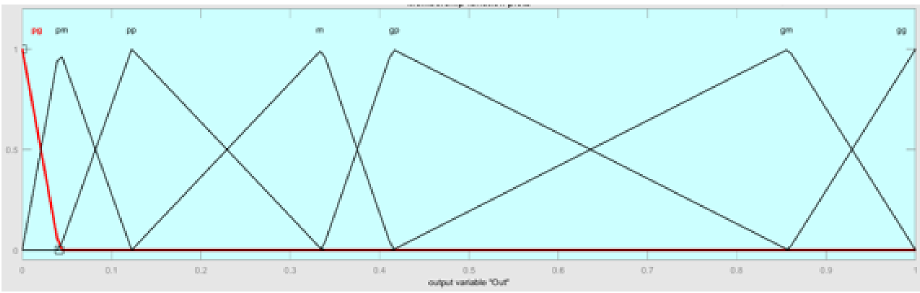

Figure 8. Output membership functions.

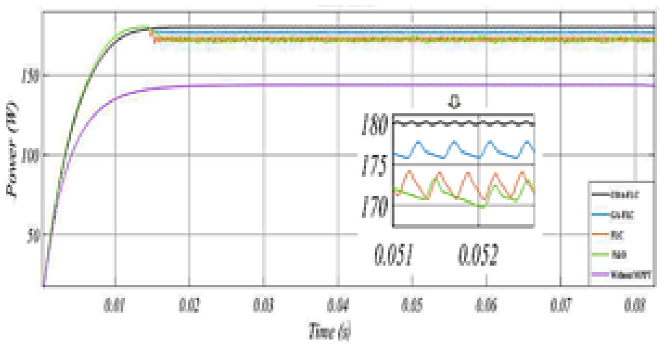

Figure 9. The output power is obtained with different algorithms [16].

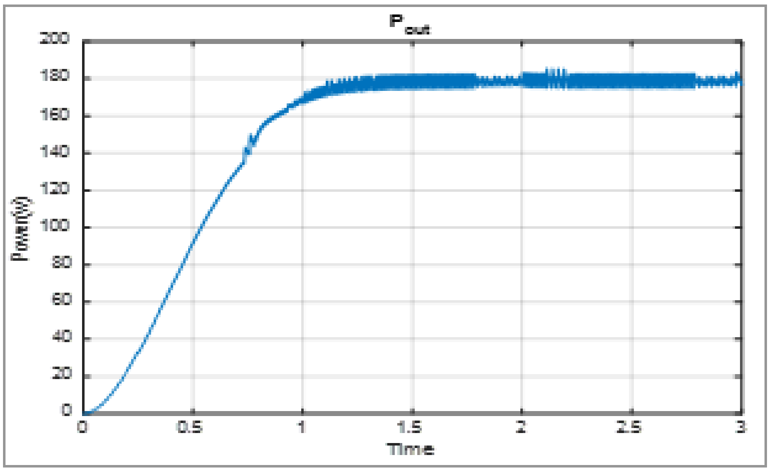

Figure 10. Output power attained by GOA algorithm.

Table 4. Output power and efficiency based on different optimization algorithms in [16] and GOA-FLC algorithm.

Method	Power(W)	Efficiency(%)
Without MPPT	135	75
P&O	171.1	95
FLC	172.9	96
GA-FLC	177	98.2
COA-FLC	180	99.94
GOA-FLC	**182.3**	**99.97**

proposed method (GOA-FLC) compared to other examined methods. Considering the suggested MPPT increases the power and efficiency by around 35% and 25%, respectively, compared to the output results acquired with no employed MPPT method. In addition, the achieved results show at least 0.03% and 1.2% improvement, respectively in power and efficiency, compared to another benchmark method. According to Table 4, for the GOA-FLC method, the power and efficiency are 182.3 W and 99.97% but in other benchmark methods, in the best case (COA-FLC method), the value of power and efficiency are equal to 180 W and 99.94%, respectively. In short, the results show that the proposed method has better performance in output power and efficiency rather than other examined methods.

5. Conclusion

The conversion efficiency of solar energy into electrical one is challenging in this field. To solve this problem and also reduce the cost of manufacturing solar cells, maximum power point tracking (MPPT) methods are utilized. In this way, according to the current and voltage diagram obtained from a cell at different temperatures and ambient radiation values, the cell working point is determined regarding the maximum power value. In this paper, the fuzzy system was employed as a controller to track the maximum power in solar cells. The fuzzy controller variables were improved by the Grasshopper Optimization Algorithm (GOA) which has flexibility and fast convergence. The simulation results show the superior performance of the proposed method. According to Table 4, in GOA-FLC the power and efficiency are 182.3 W and 99.97% but in other benchmark methods, in the best case (COA-FLC method), the value of power and efficiency are equal to 180 W and 99.94%, respectively. Accordingly, at least 0.03% and 1.2% improvement, respectively in power and efficiency is obtained. In short, the results show that the proposed method has better efficiency and output power that can contribute to the better performance of MPPT.

Authors contributions
All authors have contributed equally to prepare the paper.

Availability of data and materials
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of interests
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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