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Maximum Power Tracking System for Photovoltaic Power Generation in Local Shadow Environment Based on Ant Colony Optimization Fuzzy Algorithm

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Abstract

INTRODUCTION: Photovoltaic power generation, as a rapidly developing new energy technology, is increasingly receiving attention from countries around the world. However, the efficiency of photovoltaic power generation systems is influenced by various factors. Local shadows have become one of the bottlenecks restricting the development of photovoltaic systems.
OBJECTIVES: The research aims to improve the maximum power tracking performance of photovoltaic systems under local shadow conditions.
METHODS: A maximum power tracking system based on ant colony optimization fuzzy algorithm is proposed. Research can effectively solve local optimal problems caused by local shadows through ant colony algorithm. Combining fuzzy algorithms can not only improve the tracking accuracy of the maximum power tracking system, but also enhance the adaptability to complex environments.
RESULTS: In the simulation experiment results, the error between the ant colony optimization fuzzy algorithm and the actual maximum power in four local shadow environments was 0.21W, 0.55W, 0.27W, and 0.98W, respectively. Both stability and accuracy were superior to ant colony algorithm, fuzzy algorithm, and perturbation observation method.
CONCLUSION: Research has confirmed the potential value of ant colony optimization fuzzy algorithm in maximum power tracking of photovoltaic power generation, providing a new solution for the operation and management of photovoltaic power plants.

Keywords: Photovoltaic power generation, Local shadows, Maximum power tracking system, Ant colony fuzzy algorithm

Received on 23 November 2023, accepted on 22 July 2024, published on 12 September 2024

doi: 10.4108/ew.4487

1. Introduction

With the increase in global energy demand and the advancement of renewable energy technologies, photovoltaic power generation has become one of the most promising clean energy sources for development [1]. In photovoltaic power generation systems, Maximum Power Point Tracking (MPPT) is a core technology. It can ensure that the photovoltaic system operates at the maximum power point under different environmental conditions to optimize electrical energy output [2]. However, due to the local shadows, traditional MPPT technology faces reduced efficiency and insufficient tracking accuracy. This not only reduces the efficiency of photovoltaic systems, but may also cause significant energy waste [3]. Therefore, how to improve MPPT technology to adapt to local shadow conditions and improve the overall efficiency and stability of the system has become an important research topic in the photovoltaic power generation [4]. The fuzzy algorithm is a kind of control strategy based on fuzzy logic principle, which deals with uncertainty and lack of precision by imitating human decision-making process. In photovoltaic power generation systems, environmental conditions, such as temperature, light intensity and shadows, are dynamic and uncertain. By defining a set of fuzzy rules and membership functions, fuzzy algorithms can make continuous and adaptive control

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decisions based on these fuzzy and imprecise inputs. A MPPT system based on ant colony optimization fuzzy algorithm (ACOFA) is proposed to solve the photovoltaic power generation problem in local shadow environments. Ant colony algorithm, with the global search ability and good parallelism, can effectively overcome the local optimization problem caused by local shadows [5]. When combined with fuzzy logic, this algorithm can improve tracking accuracy and enhance the system's adaptability to complex environments. The main contributions of the research include three aspects. Firstly, a new MPPT system is proposed, which combines the global search ability of ant colony algorithm and the strong adaptability of fuzzy control to provide a new strategy for overcoming the local shadow problem. Secondly, a mathematical model is established to accurately describe the behavior of photovoltaic power generation system under local shadow conditions, and an algorithm is designed based on this model. Finally, simulation experiments verify the effectiveness of ant colony optimization fuzzy algorithm in improving the maximum power tracking performance of photovoltaic power generation system under local shadow conditions, and the experimental results show that the proposed method significantly improves the tracking efficiency and stability compared with the traditional method. This study is mainly divided into six parts. The first part is introduction. The second part is a summary of relevant work at home and abroad. The third part is divided into two sections. The first section constructs a mathematical model for photovoltaic power generation systems. In the second section, a photovoltaic power generation MPPT system based on ACOFA is studied. The fourth part is the experimental analysis for the proposed method. The fifth part is the discussion of the research results. The sixth part is a summary of this study and prospects for future work. The research aims to demonstrate the advantages of ant colony optimization fuzzy algorithm in improving the performance of photovoltaic power generation systems, providing new solutions for achieving efficient and stable photovoltaic power generation.

2. Related work

With the continuous progress of artificial intelligence algorithms, many experts have combined a series of algorithms to optimize and control photovoltaic MPPT systems. Chiu C S et al. tracked the maximum power point by simulating track and field sprint races. The direct current-direct current boost converter was used to transmit the energy of the photovoltaic panel to the load. The maximum power point was always tracked to prevent it from being affected by environmental temperature and solar radiation. The research results indicated that the proposed method had excellent maximum power tracking ability, as well as high convergence speed and oscillation free characteristics. It could overcome local traps and achieve global power point tracking [6]. Tafti et al. proposed a new global flexible power point tracking algorithm for the operational characteristics of photovoltaic systems in partial shadow conditions. This algorithm could maintain constant power control and adjust the output power of the photovoltaic system to a preset reference value. It could also achieve power reserve control. A constant power reserve for the photovoltaic system was maintained under steady-state conditions to support the power grid under transient conditions. The experimental results showed that the proposed algorithm could effectively provide constant power control and power reserve control under dynamically changing partial shadow conditions [7]. There were problems with power oscillation, unstable fluctuations, and slow tracking speed in photovoltaic systems. Therefore, Manna S et al. proposed a novel model reference adaptive control method. This method was used in the maximum power point tracking controller in rapidly changing environment and parameter conditions. The research results indicated that the proposed method effectively improved tracking efficiency and reduced steady-state oscillations. The proposed model reference adaptive control method could demonstrate a tracking efficiency of up to 99.96%. The time to reach the maximum power point was only 3.7 milliseconds [8]. Chauhan U et al. designed an efficient MPPT controller for photovoltaic systems by using expert fuzzy systems and traditional incremental conductance algorithms. This controller is adaptive and retains the simplicity of traditional MPPT controllers. In order to improve the tracking accuracy, the mixed gray Wolf Cuckoo search optimization method is used to optimize the member functions in the controller. Experimental results prove the effectiveness of the proposed technology in terms of power tracking accuracy and average efficiency [9].

Ant colony algorithm and clustering algorithm are inspired by behavior in nature. Many experts have conducted a series of studies on the performance of the two algorithms in various fields. Nagendranth et al. proposed a new improved ant colony optimization algorithm routing protocol based on type 2 fuzzy logic to achieve secure data transmission in mobile ad hoc networks. Firstly, a cluster was constructed using Type 2 fuzzy logic. Then an ant colony optimization algorithm with tumbling technology was used to solve the routing problem, achieving cross cluster routing from cluster head to base station. The research results indicated that the model outperformed the comparison method in clustering overhead, cluster head, and cluster member change rate, demonstrating good performance [10]. To analyze the yield of different crops in different seasons, Ezhilarasi T P et al. used fuzzy ant colony clustering algorithm to detect overlapping nodes, thereby reducing redundancy and improving clustering quality. Compared to crop recommendation systems using ant colony clustering and association rule mining, the fuzzy ant colony algorithm using overlapping cluster detection could control the yield prediction error rate to 8%. The accuracy rate was improved to 91.9%, showing good recommendation effect [11]. Chauhan U et al. designed an efficient maximum power point tracking controller that combined expert fuzzy systems and incremental conductivity algorithms. This controller was used in solar photovoltaic systems. The proposed controller had adaptive ability by integrating optimized fuzzy logic knowledge, while maintaining the simplicity of traditional maximum power point tracking control systems. The research results indicated that the proposed hybrid incremental conductivity algorithm performed well with the maximum power point tracking controller. Its power tracking accuracy and average efficiency were improved [12]. He W et al. proposed an improved ant colony algorithm to solve problems such as manual scheduling difficulties in weaving production. The optimized algorithm uses an iterative threshold to form the initial path pheromone distribution according to the urgency of the optimization order to ensure the balance between each target. By comparing the performance of this algorithm with other algorithms, it is proved that this algorithm model can better balance the problem of manual scheduling in the weaving industry [13].

In summary, although existing research has made significant progress in the photovoltaic power generation MPPT systems, there are still some shortcomings. The method proposed by Chiu CS et al. can effectively track the maximum power point and exhibit high convergence speed. However, the adaptability in changing environments and the ability to handle complex local shadows still need to be verified. Tafti et al.'s study performs well under dynamically changing partial shadow conditions. However, in practical applications, there may still be power loss and slow response speed. Even the most advanced existing algorithms, such as the MPPT controller with mixed gray Wolf cuckoo search optimization adopted by scholars such as Chauhan U, provide power tracking accuracy and average efficiency, but still cannot solve the problem of slow response speed. The optimization of ant colony algorithm by HeW et al. proved the advantage of ant colony algorithm in solving response speed. It can be seen that ant colony algorithm has the potential to find the global optimal solution, and fuzzy logic can deal with uncertainty and fuzziness. The combination of the two may help solve the limitations of the existing photovoltaic MPPT technology in the local shadow environment. Therefore, the ant colony optimization fuzzy algorithm is applied to construct a photovoltaic power generation MPPT system to solve the high-power loss, slow response speed, and low tracking accuracy of photovoltaic systems in local shadow environments. It is expected that this algorithm can not only optimize power output, but also improve the stability and adaptability of the system under complex environmental changes, ultimately achieving efficient and reliable photovoltaic power generation.

3. Construction of maximum power tracking system for photovoltaic power generation in local shadow environment

Firstly, a mathematical model of photovoltaic power generation system is constructed based on the composition. On this basis, the working principles of ant colony algorithm and fuzzy algorithm are analyzed to address the local shadow problem that occurs on photovoltaic arrays. A photovoltaic power generation MPPT system based on ACOFA is designed using the global optimization ability of ant colony algorithm and the system stability of fuzzy control.

3.1 Establishment of mathematical model for photovoltaic power generation system

Clean energy has gradually become a key industry direction for countries and even the world. Photovoltaic power generation has received unprecedented widespread attention. The biggest feature of photovoltaic power generation systems is to directly transmit solar energy into the power grid. It has advantages such as energy conservation, environmental protection, and flexible layout [14]. Photovoltaic power generation systems generally consist of individual photovoltaic cells, photovoltaic modules, photovoltaic arrays, controllers, inverters, batteries, etc. Among them, the most important among them are power generation equipment, photovoltaic cell units, photovoltaic modules, and photovoltaic arrays. The relationship between the three is shown in Figure 1.

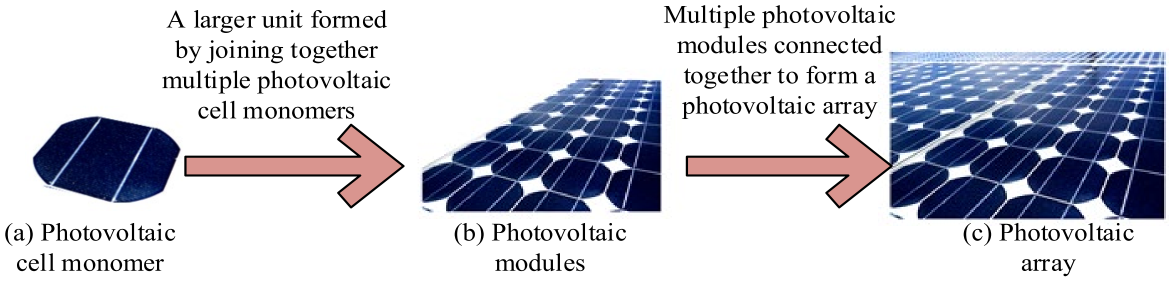


Figure 1. Relationship diagram of photovoltaic cells, photovoltaic modules, and photovoltaic arrays

In photovoltaic power generation systems, the generated electricity is stored through batteries. When the output power is below the power consumed by the load, the battery can still supply power to the load. The inverter can convert direct current into alternating current. The controller ensures the normal operation of photovoltaic equipment and increases the usage time of the battery by controlling the application. The working principle of a photovoltaic power generation system is the photovoltaic effect, which refers to the conversion of solar energy into electrical energy, as shown in Figure 2.

In Figure 2, I_{ph} refers to the current produced by sunlight. I_d refers to the dark current flowing through the diode. U_d represents the voltage of the diode. R_{sh} represents the equivalent bypass resistance. I_{sh} represents the current flowing through the equivalent bypass. R_s represents the equivalent internal resistance. I represents the current output from the photovoltaic cell to the load. In photovoltaic power generation systems, the actual output voltage U_l is shown in equation (1).

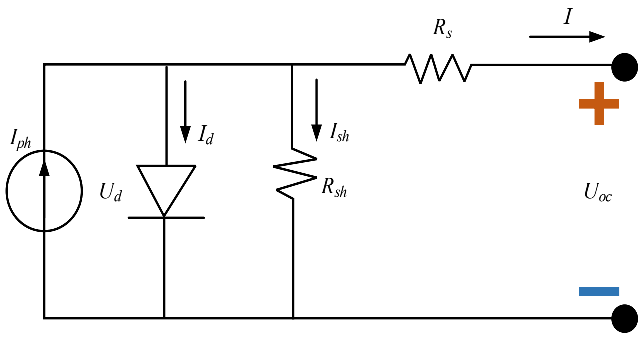


Figure 2. Working principle of photovoltaic power generation system

$$U = U_d - (I_{ph} - I_d - I_{sh})R_s \quad (1)$$

The I_d is displayed in equation (2).

$$I_d = I_0[exp(\frac{qU_d}{AKT}) - 1] \quad (2)$$

In equation (2), I_0 represents the reverse saturation current of the PN junction. q represents electronic charge. A represents the curve constant of the PN junction. K refers to the Boltzmann constant. T refers to absolute temperature. At this point, the internal short-circuit current I_{sc} of the photovoltaic cell is shown in equation (3).

$$I_{sc} = I_0[exp(\frac{qU_{oc}}{AKT}) - 1] \quad (3)$$

If it is a load short circuit, the dark current flowing through the diode is ignored. At this time, I_{sc} is equal to I_{ph}. Most photovoltaic cells are actually made of silicon wafers. R_{sh} is approximately 200 to 300Ω/cm2. R_{sh} is approximately 7.7 to 13.5mΩ/cm2. When calculating the output current, the current I_{sh} on R_{sh} is ignored, as shown in equation (4).

$$I = I_{sc} - I_0[exp(\frac{qU_d}{AKT}) - 1] \quad (4)$$

Therefore, the output power P can be obtained, as shown in equation (5).

$$P = UI = UI_{ph} - UI_0[exp(\frac{qU_l}{AKT}) - 1] \quad (5)$$

When the photovoltaic cell is in the maximum power state, $I = I_m$, $U = I_m$, the output current is shown in equation (6).

$$I_m = I_{sc} - I_0[exp(\frac{q(U + IR_s)}{AKT}) - 1] \quad (6)$$

When the photovoltaic cell is in an open circuit state, $I = 0$, and $U = U_{oc}$, the output current is shown in equation (7).

$$0 = I_{sc} - I_0[exp(\frac{q(U + IR_s)}{AKT}) - 1] \quad (7)$$

Based on equations (6) and (7), the output current of the solar cell is displayed in equation (8).

$$I = I_{sc}\{1 - C_1[exp(\frac{U}{C_2 U_{oc}}) - 1]\} \quad (8)$$

In equation (8), C_1 and C_2 respectively represent two different coefficients, as shown in equation (9).

$$\begin{cases} C_1 = (1 - \frac{I_m}{I_{sc}})exp(\frac{-U_m}{C_2 U_{oc}}) \\ C_2 = (\frac{U_m}{U_{oc}} - 1) / [ln(1 - \frac{l_m}{l_{sc}})] \end{cases} \quad (9)$$

According to equations (8) and (9), the main factors that have the greatest impact on the output of photovoltaic cells are open circuit voltage U_{oc}, short circuit current I_{sc}, maximum output power P_m, maximum output voltage U_m, and maximum output current I_m. After obtaining the photovoltaic cell model, a photovoltaic power generation system model is built using Simulink simulation software to simulate the operating output characteristics under different environmental temperatures and lighting effects. In the simulation model, the battery parameter is U_{oc} =21.6V, I_{sc} =8.32A, U_m =16.6V, and I_m =7.5A. A photovoltaic array model for 5*3 is build. From the principles of photovoltaic power generation systems, when the ambient light changes, the photovoltaic cell temperature also changes. As a result, the lighting and temperature parameters cannot reflect the actual output amount. Therefore, a local shadow environment photovoltaic power generation MPPT system is constructed.

3.2 Maximum power tracking system constructed by ant colony optimization fuzzy algorithm

In the practical work of photovoltaic power generation systems, a completely unobstructed and fully covered photovoltaic array has only one peak output power. However, in cases of partial occlusion or uneven lighting, multiple peaks may appear in the output. At this point, traditional power tracking methods may fail. The result may fall into a non optimal state, thereby reducing efficiency [15]. For this reason, fuzzy algorithm is gradually being used in MPPT. The control system structure based on fuzzy algorithms includes different functional modules, as shown in Figure 3.

In Figure 3, the fuzzification interface module is used to process the input quantity to clarify the fuzzy value. The knowledge base module stores all the rules and membership functions of the fuzzy control system, including the core knowledge of fuzzy control strategies and fuzzy logic [16]. The fuzzy inference module infers or calculates the fuzzy input based on the fuzzy rules in the knowledge base, and obtains the fuzzy output. The clarity interface module is used to convert fuzzy output into precise output, thereby guiding the control object to complete control tasks [17]. In the MPPT system, the fuzzy algorithm takes the rate and direction of power change as input to the controller. The ratio and change rate of the power and voltage difference sampled by the photovoltaic system at t and $(t-1)$ are used as two inputs to the fuzzy algorithm. The duty cycle at time t serves as the output of the controller. The application of fuzzy algorithm in MPPT system is shown in Figure 4.

When examining the MPPT efficiency of photovoltaic power generation systems under local shadow conditions, two key factors determine the quality of MPPT control, namely global optimization and system stability [18]. Although fuzzy algorithm can ensure stable output of the system, the performance on MPPT is slightly insufficient. Previous studies have shown that ant colony algorithms have excellent global optimization capabilities. Considering the advantages of these two methods, an MPPT system that combines global optimization with stable output is designed. Ant colony algorithm is essentially a heuristic global optimization algorithm [19]. A positive feedback mechanism is adopted to continuously converge the search process. Heuristic search avoids falling into local optima. Distributed computing in search is a parallel computing technology that can effectively improve computing power and operational efficiency [20]. The basic ant colony algorithm evolved from the foraging process of ants. The foraging process is shown in Figure 5.

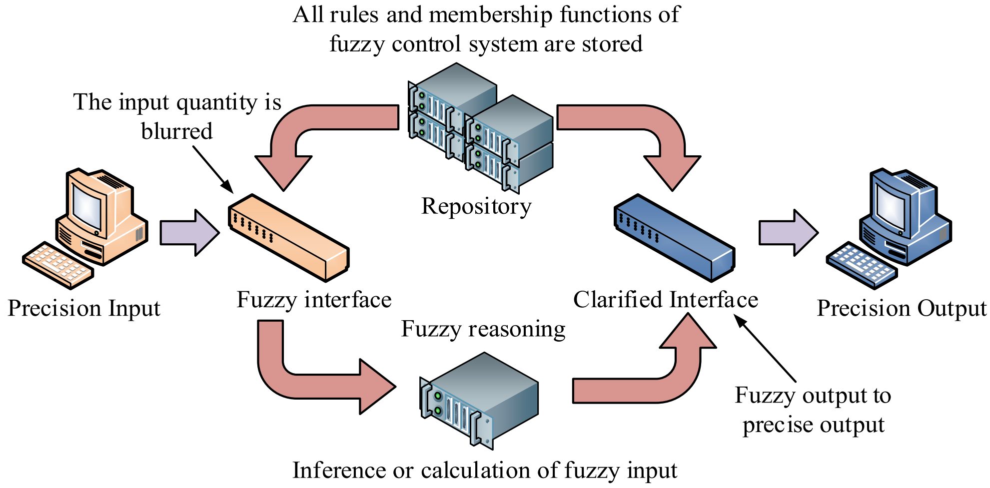


Figure 3. Functional structure of fuzzy control system

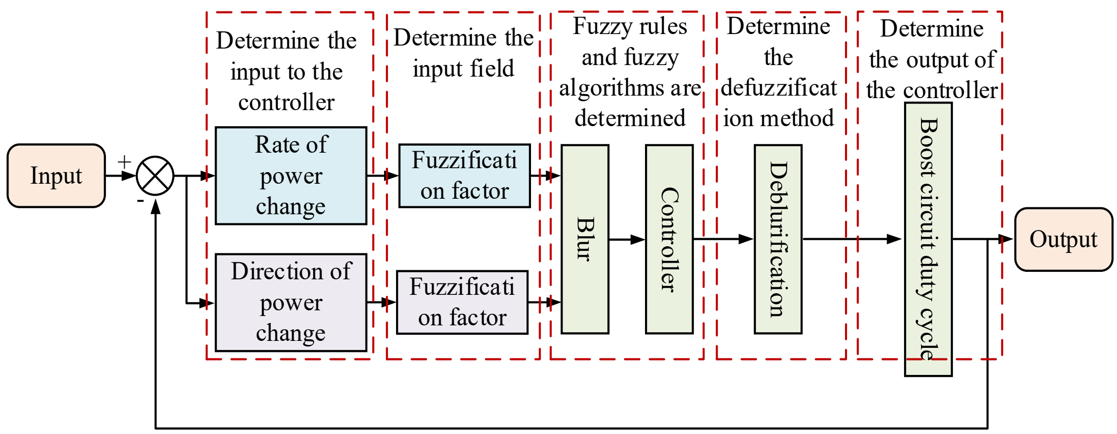


Figure 4. Maximum power tracking of photovoltaic power generation based on fuzzy control

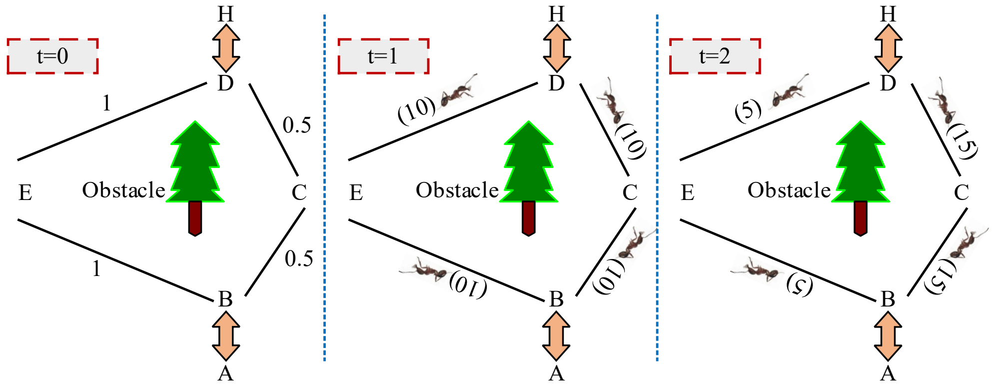


Figure 5. Ant foraging process in ant colony algorithm

Figure 5 shows the foraging process of ants. Point A in the figure represents the nest. The H-point represents the food source. Due to obstacles, ants have two foraging routes, ABCDH and ABEDH, with path lengths BE=ED=1 and BC=CD=0.5. When t=1, the ants on both routes are the same. When t=2, the ants on BCD are significantly higher than that on BED. The ability of ants to search for the best path based on environmental changes during foraging mainly relies on secretion pheromones [21]. When applying the ant colony algorithm to the photovoltaic power generation system MPPT, the objective function needs to be set to maximize the output power. The ant position is the duty cycle of the DC/DC converter. When the duty cycle changes, the output power also changes accordingly [22]. To directly represent the optimization effect of ant colony optimization, the position of the k-th ant is the working voltage x_k of the photovoltaic array. In the photovoltaic array model built in this study, if the open circuit voltage U_{oc} is 120V, then the value boundary of x_k is [0, 120]. Within this boundary range, k positions are randomly generated to form the initial population. The population M is 30. The initial pheromone concentration τ_t corresponding to the location of each ant is 0. The working voltage corresponding to the position of each ant is the exact value. The judgment is based on whether τ_t is equal to the output power. The default direction for each ant colony movement is the optimal working voltage direction [23]. The movement step size is randomized, as shown in equation (10).

$$x_k(t) = x_k(t-1) + \alpha\left[ub(t-1) - x_k(t-1)\right] \quad (10)$$

In equation (10), $x_k(t)$ refers to the position of the k-th ant at t, which is the voltage value. $x_k(t-1)$ represents the position of the k-th ant at $t-1$. $ub(t-1)$ represents the optimal voltage value at $t-1$. α represents a random number. When the k-th ant moves from position u_i to u_j, the increase in pheromone concentration is shown in equation (11).

$$\Delta\tau_k(t) = C_3[p_{pv}(u_i) - p_{pv}(u_j)] \quad (11)$$

In equation (11), C_3 is a positive number. $p_{pv}(u_i)$ refers to the power level corresponding to the ant at position u_i. $p_{pv}(u_j)$ refers to the power level corresponding to the ant at position u_j. The higher the value of $p_{pv}(u_i) - p_{pv}(u_j)$, the higher the information concentration. More ants are moving towards u_j. Therefore, for each iteration completed, the pheromone concentration at u_j is shown in equation (12).

$$\Delta\tau_k(t+1) = (1-\rho)\tau_j(t) + \Delta\tau_j(t) \quad (12)$$

Both ant colony algorithm and fuzzy algorithm perform real-time sampling and calculation of the voltage and current of the photovoltaic array, outputting changes in the duty cycle. The characteristic of photovoltaic power generation system MPPT is to directly control the Boost circuit system after tracking, thereby affecting the output power of the photovoltaic array. Therefore, based on the characteristics of real-time sampling data, the decision criterion is whether to complete the global maximum power. On the 5*3 photovoltaic array model built in the study, ant colony algorithm samples real-time data. The maximum power value is traced at 0.004s. Based on experimental experience, the running time is limited to 0.004s. After 0.004s, it is converted into a fuzzy algorithm for real-time data collection to ensure the stability of the output. Therefore, in a local shadow environment, the operation process of ant colony optimization fuzzy algorithm in photovoltaic power generation MPPT is shown in Figure 6.

As shown in Figure 6, when the algorithm starts running, the initialization of the fuzzy controller and ant colony algorithm is started in parallel. Subsequently, the system samples the data of the photovoltaic power generation system to obtain the current operating data. After sampling, ant colony algorithm performs global optimization to find the optimal solution to improve the power output of the photovoltaic system. During the optimization process, the system constantly checks whether the scheduled run time has been reached. If not, the system will continue the global optimization process; If it has been reached, proceed to the next step. Finally, the fuzzy controller is used to ensure the stability of the system, thus completing a power tracking cycle and finally ending the process.

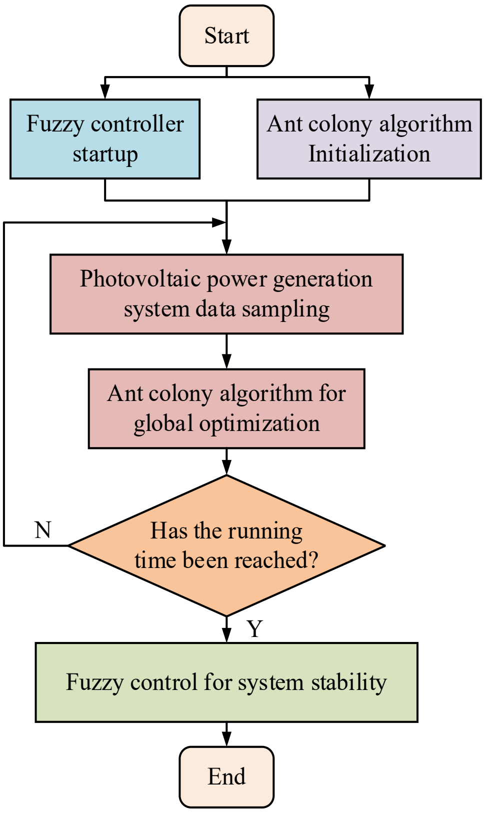


Figure 6. Flow Chart of particle swarm optimization fuzzy control algorithm operation

4. Experimental results

To improve the efficiency of photovoltaic arrays in local shadow environments, an MPPT system based on ACOFA was designed in this study. Firstly, a mathematical model of photovoltaic power generation system was established to provide a basis for analyzing the photovoltaic power generation systems in local shadow environments. Then, the performance of fuzzy algorithm and ant colony algorithm was analyzed. Their advantages were combined to construct an MPPT system. To verify the effectiveness of the proposed method, an MPPT system experiment based on ACOFA was designed. The experimental results were analyzed.

4.1 Analysis of simulation experiment results

To reduce the systematic error of the experiment, performance testing of the algorithm model was conducted in the same experimental environment. The graphics card of the computer used is NVIDIA GTX1080Ti. The CPU is I7-8700K. The Gpu-accelerated library is CUDA 10.0. The memory is 16 GB. The operating system is Windows 10. The algorithm framework is Python. The simulation software is Simulink. Simulink can adjust parameters to simulate photovoltaic arrays under different temperatures and lighting conditions. The simulation parameters involved in this experiment are shown in Table 1.

Table 1. Simulation parameter

Simulation parameter	Values
Open-circuit voltage U_{oc}	120V
Value boundary of the operating voltage x_k	[0，120]
Population size M	30
Initial pheromone concentration τ_t	0
Voltage Sampling	Real-time
Current Sampling	Real-time
Duty Cycle Output	Varies based on algorithm output
Tracking Time for Ant Colony Algorithm	0.004s
Transition to Fuzzy Algorithm	After 0.004s

In the simulation experiment, the output characteristic curves in four local shadow environments were designed, as shown in Figure 7.

In Figure 7, the output characteristic curves of the photovoltaic array under different local shadow environments were obtained using the constructed model. The actual maximum power of the photovoltaic array in four different environments was 1363.71W, 1024.49W, 898.81W, and 695.63W, respectively. On this basis, the MPPT effects of ant colony optimization fuzzy algorithm, disturbance observation method, ant colony algorithm, and fuzzy algorithm were compared, as shown in Figure 8.

Figure 8 (a) shows the MPPT of ant colony optimization fuzzy algorithm. The error between the actual maximum power and the four environments was 0.21W, 0.55W, 0.27W, and 0.98W, respectively. Figure 8 (b) shows the MPPT situation of the ant colony algorithm. The error between the four environments and the actual maximum power was 1.19W, 2.03W, 3.11W, and 2.76W, respectively. Figure 8 (c) shows the MPPT of the fuzzy algorithm. The error between the actual maximum power and the four environments is 163.86W, 83.21W, 166.07W, and 106.26W, respectively. Figure 8 (d) shows the MPPT of the perturbation observation method. The error between the four environments and the actual maximum power was 323.67W, 292.17W, 374.83W, and 308.25W, respectively. Overall, the output power of ant colony optimization fuzzy algorithm and fuzzy algorithm was more stable, but the accuracy of fuzzy algorithm was insufficient. On the other hand, ant colony optimization fuzzy algorithm and ant colony algorithm had higher output accuracy. However, the stability of ant colony algorithm was significantly lower than that of ant colony optimization fuzzy algorithm. The experimental results verified that the ant colony optimization fuzzy algorithm had excellent stability and accuracy. To further validate the advantages and disadvantages of the four algorithms, local shadow environments with actual maximum power of 1024.49W and 695.63W were selected to compare the global performance, as shown in Figure 9.

Figure 9 (a) showed the global performance comparison of the algorithm in a local shadow environment with a maximum power of 1024.49W. Figure 9 (b) showed the global performance comparison of the algorithm in a local shadow environment with a maximum power of 695.6W. From the global performance of the four algorithms, the stability of average tracking varied from high to low, including ant colony optimization fuzzy algorithm, fuzzy algorithm, ant colony algorithm, and disturbance observation method. The accuracy of average tracking varied from high to low, including ant colony optimization fuzzy algorithm, ant colony algorithm, fuzzy algorithm, and disturbance observation method. The global comparison results further validated the effectiveness of this study.

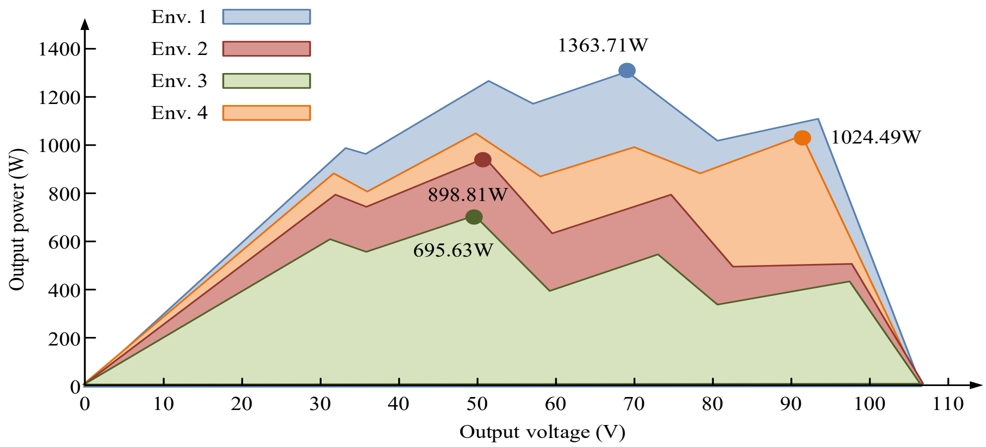


Figure 7. Output characteristic curves of PV arrays with different localized shading environments

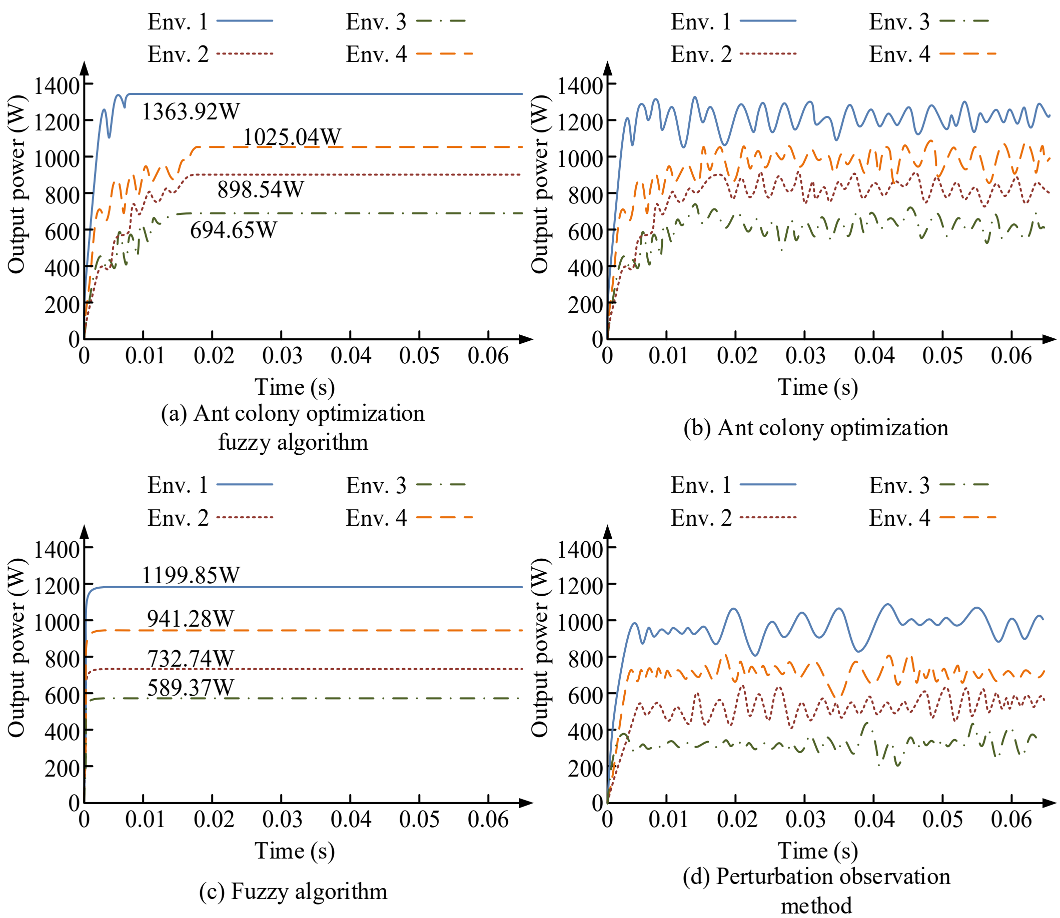


Figure 8. Maximum power tracking output of different algorithms in different localized shadow environments

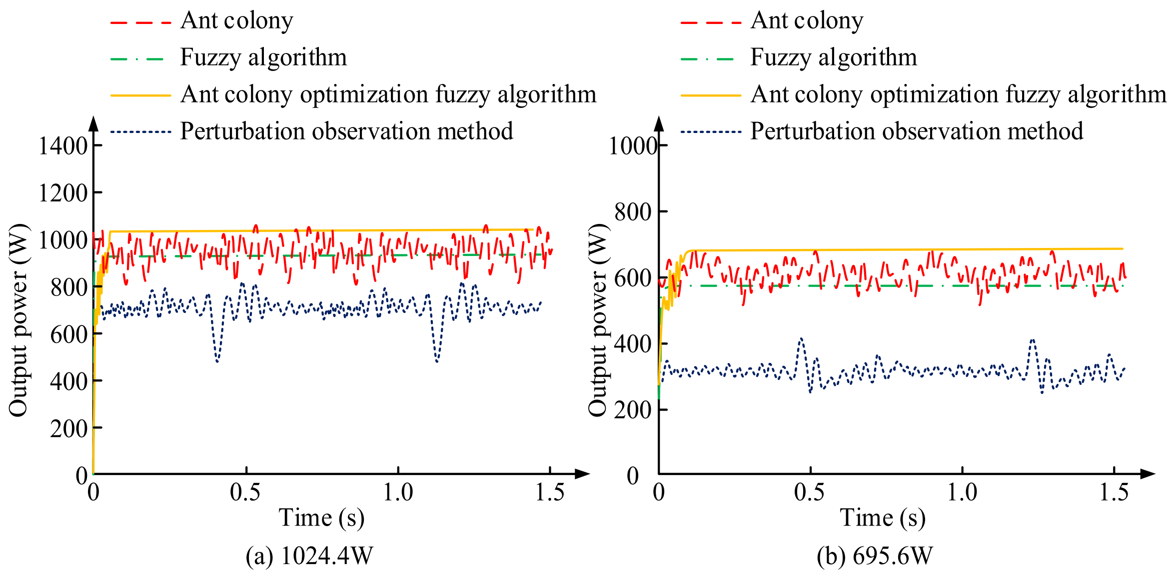


Figure 9. Global comparison plot of maximum power tracking output of different algorithms

4.2 Analysis of practical application results

To verify the effectiveness in practical applications, the performance of MPPT systems based on different algorithms was tested in real photovoltaic arrays. The comparison algorithms include the Ant colony optimization fuzzy optimization MPPT algorithm (ACOF-MPPT) and the existing advanced methods, including the improved particle swarm optimization MPPT algorithm (IPSO-MPPT); Improved genetic optimization MPPT algorithm (IGA-MPPT); MPPT algorithm for multiverse optimization (MVO-MPPT). Three indicators, namely tracking efficiency, system response time, and expert scoring, were used to evaluate different algorithms. The MPPT efficiency among different algorithms was shown in Figure 10.

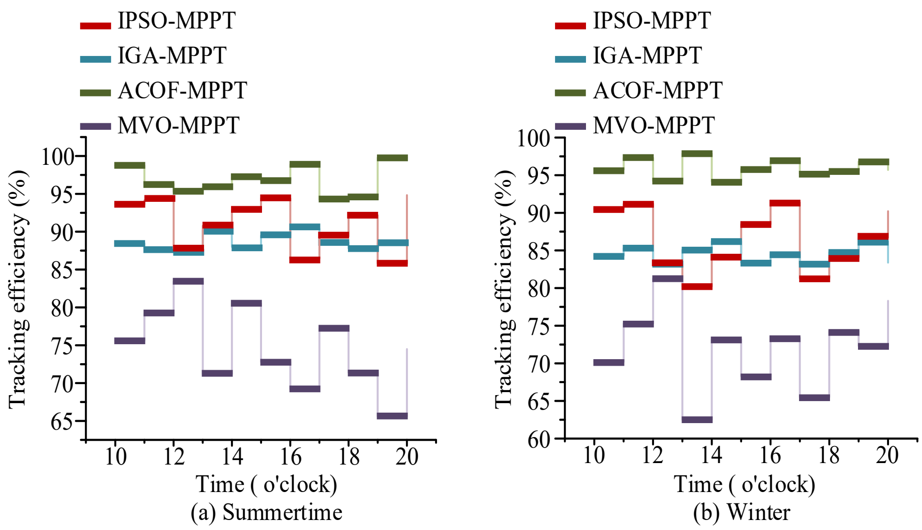


Figure 10. Comparison of tracking efficiency of different algorithms

Tracking efficiency was an important indicator for measuring the performance of MPPT systems, which referred to the ratio of the actual output power to the theoretical maximum possible output power under changing environmental conditions. Figure 10 (a) showed the average results in summer, which is from June to August. Figure 10 (b) showed the average results in winter, which was from December to March. The testing time was from 10:00 to 20:00 every day. The testing was conducted every hour. As can be seen from Figure 10, in practical applications, the proposed ACOF-MPPT algorithm has significantly better performance, followed by IPSO-MPPT and IGA-MPPT, while MVO-MPPT algorithm has poor performance. The average tracking efficiency of ACOF-MPPT algorithm reaches 97.23% in summer and 98.11% in winter, which verifies the validity of the study. The system response time of different algorithms was shown in Figure 11.

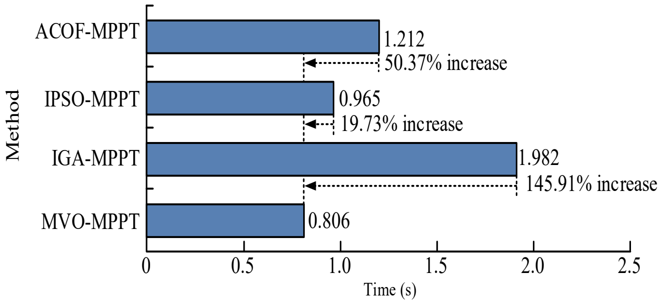
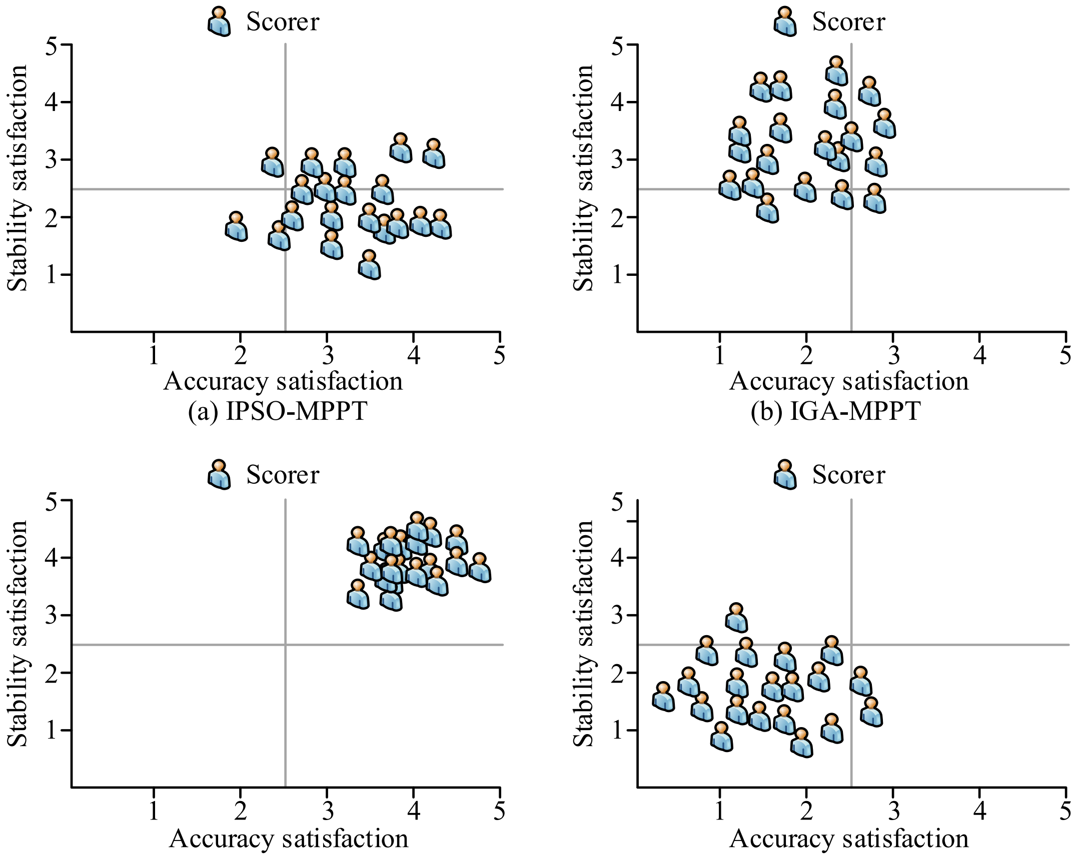


Figure 11. Comparison of response time of different algorithmic systems

As shown in Figure 11, MVO-MPPT system has the shortest response time (0.806s), followed by IPSO-MPPT, ACOF-MPPT and IGA-MPPT. Compared with MVO-MPPT, the system response time of IPSO-MPPT, ACOF-MPPT and IGA-MPPT was increased by 19.73%, 50.37% and 145.91%, respectively. The results of research methods in system response time testing were not optimal. However, considering that the research method greatly improved the stability and accuracy of the MPPT system, a slight increase in system response time was acceptable. Finally, 30 experts in the field of photovoltaic power generation were invited to rate the MPPT systems participating in the comparison from accuracy satisfaction and stability satisfaction. The total score for each dimension was 5 points. A high score indicated high satisfaction. The results were shown in Figure 12.



(a) IPSO-MPPT

(b) IGA-MPPT

(c) ACOF-MPPT

(d) MVO-MPPT

Figure 12. Comparison of expert scores for different algorithms applied in practice

Figure 12 (a) shows the score results of IPSO-MPPT, most of which are distributed in the lower right area, indicating that the raters are more satisfied with the accuracy and less satisfied with the stability. Figure 12 (b) shows the score results of IGA-MPPT, most of which are distributed in the upper left area, indicating that raters are more satisfied with stability and less satisfied with accuracy. Figure 12 (c) shows the score results of ACOF-MPPT, most of which are distributed in the upper right area, indicating that raters are satisfied with both accuracy and stability. Figure 12 (d) shows the score results of MVO-MPPT, most of which are distributed in the lower left area, indicating that raters are not satisfied with the accuracy and stability. The expert scoring results were consistent with the research experimental results, further confirming the value of this study.

5. Discussion

It is found that the ant colony optimization fuzzy algorithm can significantly improve the performance of MPPT system in local shadow environment. The realization of this achievement is mainly due to the global search advantage of ant colony algorithm and the decision logic optimization of fuzzy algorithm. The ant colony algorithm can effectively identify the global maximum power point under partial shadow condition by simulating the behavior of ants seeking food path in nature. On this basis, the fuzzy control logic enhances the adaptability and response ability of the algorithm to real-time environment variables, and improves the response speed and accuracy of the system to complex illumination changes. Compared with the MPPT technology proposed by Hai T et al., ACOF-MPPT proposed in the research shows significant performance advantages, especially in the case that local shadows have a significant impact on photovoltaic arrays, the proposed method can effectively avoid the problem of local optimization and show more accurate power tracking [24]. Moreover, compared with the optimization method proposed by Kandemir E et al., ACOF-MPPT's performance in adapting to rapidly changing environmental conditions also avoids the limitations of the algorithm when applied alone [25]. In addition, the research results are not only limited to the theoretical and experimental levels, but also have broad prospects in potential application fields. In urban and industrial environments, where buildings and other obstacles often create irregular shadows that affect the performance of photovoltaic panels, the solutions presented in this study can improve the energy output and stability of photovoltaic systems in these complex environments. Future applications can also be extended to mobile platforms, such as photovoltaic powered vehicles and drones, to maintain optimal energy harvesting efficiency in dynamically changing light conditions. Considering the growing global demand for renewable energy, the results of this study provide innovative solutions in the field of sustainable energy technologies, especially in the development of intelligent energy management systems.

6. Conclusion

Photovoltaic power generation systems often encounter unstable power output and reduced efficiency when facing local shadow problems. This is mainly due to the uneven distribution of light caused by buildings, trees, and other obstructions. For this purpose, a MPPT system based on ACOFA is proposed. This system integrates the efficiency of ant colony algorithm in finding the global optimal solution and the powerful ability of fuzzy logic in dealing with uncertainty and fuzziness. The performance of the system is evaluated through simulation and actual photovoltaic array testing. In practical application testing, the MPPT system based on ant colony optimization fuzzy algorithm achieved an average tracking efficiency of 97.23% in summer. The average tracking efficiency in winter reached 98.11%. The performance was significantly better than the other three comparison methods. The experimental results verify that the research method can effectively improve the performance of photovoltaic power generation systems under local shadow conditions. Future research will focus on further optimizing algorithms to enhance robustness in more extreme and dynamically changing shadow conditions. Meanwhile, the research will extend to large-scale distributed photovoltaic systems to explore the universality and scalability of this algorithm in various photovoltaic application environments. In addition, considering the application of IoT technology in energy monitoring and management, future systems will combine IoT technology to achieve more intelligent and automated energy management.

Appendix

Summary of variable symbols and their interpretations

Variable symbol	Explanation	Variable symbol	Explanation
I_{ph}	The electricity generated by sunlight	I_{sc}	Short-circuit current
I_d	Dark current flowing through the diode	P_m	Maximum output power
U_d	Diode voltage	U_m	Maximum output voltage
R_{sh}	Equivalent bypass resistance of photovoltaic cells	I_m	Maximum output current
I_{sh}	Current flowing through the equivalent bypass of a photovoltaic cell	t	Time
R_s	Equivalent internal resistance of photovoltaic cells	k	Position
I	The current output of the photovoltaic cell to the load	x_k	The position of the k ant, that is, the working voltage of the photovoltaic array
U_l	The actual output voltage of photovoltaic power generation system	M	Population size
I_0	Reverse saturation current of PN junction in photovoltaic cell	τ_t	Initial pheromone concentration
q	Electron charge	$x_k(t)$	The position of the k ant at time t, that is, the voltage value

A	Curve constant of PN junction	$ub(t-1)$	The optimal voltage value at time $t-1$
K	Boltzmann constant	α	Random number
T	Absolute temperature	C_3	Positive number
I_{sc}	Internal short circuit current of photovoltaic cell	$p_{pv}(u_i)$	The power corresponding to the ant in position u_i
P	Output power	$p_{pv}(u_j)$	The power corresponding to the ant in position u_j
C_1, C_2	They represent two different coefficients	u_i, u_j	The ant moves in two places
U_{oc}	Open-circuit voltage	\	\

References

[1] Nadeem A, Hussain A. A comprehensive review of global maximum power point tracking algorithms for photovoltaic systems. Energy Systems, 2023, 14(2): 293-334.

[2] Chang J, Niu F, Chen T. An Overall Improved Ant Colony Optimization algorithm trained BPNN for PV MPPT. Journal of Electrical Engineering and Automation, 2022, 3(4): 322-339.

[3] Awan MMA. A technical review of MPPT algorithms for solar photovoltaic system: SWOT Analysis of MPPT Algorithms. Sir Syed University Research Journal of Engineering & Technology, 2022, 12(1): 98-106.

[4] Sarvi M, Azadian A. A comprehensive review and classified comparison of MPPT algorithms in PV systems. Energy Systems, 2022, 13(2): 281-320.

[5] Prathaban AV, Karthikeyan D. Grey wolf optimization-recurrent neural network based maximum power point tracking for photovoltaic application. Indonesian Journal of Electrical Engineering and Computer Science, 2022, 26(2): 629-638.

[6] Chiu CS, Ngo S. A Novel Algorithm-based MPPT Strategy for PV power systems under partial shading conditions. Elektronika ir Electrotechnical, 2022, 28(1): 42-51.

[7] Tafti HD, Wang Q, Townsend CD, Pou J, Konstantinou G. Global flexible power point tracking in photovoltaic systems under partial shading conditions. IEEE Transactions on Power Electronics, 2022, 37(9): 11332-11341.

[8] Manna S, Akella AK, Singh DK. A novel MRAC-MPPT scheme to enhance speed and accuracy in PV systems. Iranian Journal of Science and Technology, Transactions of Electrical Engineering, 2023, 47(1): 233-254.

[9] Chauhan U, Chhabra H, Rani A, Kumar B, Singh V. Efficient MPPT Controller for Solar PV System Using GWO-CS Optimized Fuzzy Logic Control and Conventional Incremental Conductance Technique. Iranian Journal of Science and Technology, Transactions of Electrical Engineering, 2023, 47(2): 463-472.

[10] Dagal I, Akın B, Akboy E. Improved salp swarm algorithm based on particle swarm optimization for maximum power point tracking of optimal photovoltaic systems. International Journal of Energy Research, 2022, 46(7): 8742-8759.

[11] Nagendranth M, Khanna MR, Krishnaraj N, Mohamed YS, Mohamed AA, Surendran R. Type II fuzzy-based clustering with improved ant colony optimization-based routing (t2fcatr) protocol for secured data transmission in manet. The Journal of Supercomputing, 2022, 78(7): 9102-9120.

[12] Ezhilarasi TP, Rekha KS. Improved fuzzy ant colony optimization to recommend cultivation in Tamil Nadu, India. Acta Geophysica, 2022, 70(6): 2873-2887.

[13] Motameni H, Kalantary KR, Ebrahimnejad A. An efficient improved ant colony optimization algorithm for dynamic software rejuvenation in web services. IET Software, 2020, 14(4):369-376.

[14] Mansour RF. Artificial intelligence based optimization with deep learning model for blockchain enabled intrusion detection in CPS environment. Scientific Reports, 2022, 12(1): 12937.

[15] PK VK, Jijesh JJ. Comparative Analysis of Bio-Inspired Maximum Power Point Tracking Algorithms for Solar Photovoltaic Applications. International Journal of Intelligent Systems and Applications in Engineering, 2023, 11(1): 100-110.

[16] Mansour RF. Understanding how big data leads to social networking vulnerability. Computers in Human Behavior, 2016, 57: 348-351.

[17] Yu S, Heidari AA, He C, Cai Z, Althoabaiti MM, Mansour RF. Parameter estimation of static solar photovoltaic models using Laplacian Nelder-Mead hunger games search. Solar Energy, 2022, 242: 79-104.

[18] Omar FA, Pamuk N, Kulaksiz AA. A critical evaluation of maximum power point tracking techniques for PV systems working under partial shading conditions. Turkish Journal of Engineering, 2023, 7(1): 73-81.

[19] Mahesh PV, Meyyappan S, Alla R. Maximum power point tracking with regression machine learning algorithms for solar PV systems. International Journal of Renewable Energy Research, 2022, 12(3): 1327-1338.

[20] Mansour RF. Blockchain assisted clustering with intrusion detection system for industrial internet of things environment. Expert Systems with Applications, 2022, 207: 117995.

[21] Mehdi G, Hooman H, Liu Y, Peyman S, Arif R. Data Mining Techniques for Web Mining: A Survey. Artificial Intelligence and Application, 2022, 1(1): 3-10.

[22] Alotaibi MF, Omri M, Abdel-Khalek S, Khalil E, Mansour R F. Computational intelligence-based harmony search algorithm for real-time object detection and tracking in video surveillance systems. Mathematics, 2022, 10(5): 733.

[23] Mahesh PV, Meyyappan S, Alla RKR. A new multivariate linear regression MPPT algorithm for solar PV system with boost converter. ECTI Transactions on Electrical Engineering, Electronics, and Communications, 2022, 20(2): 269-281.

[24] Hai T, Zain JM, Nakamura H. Maximum power point tracking technique based on variable step size with sliding mode controller in photovoltaic system. Soft Computing, 2023, 27(7): 3829-3845.

[25] Kandemir E, Cetin NS, Borekci S. Single-stage photovoltaic system design based on energy recovery and fuzzy logic control for partial shading condition. International Journal of Circuit Theory and Applications, 2022, 50(5): 1770-1792.