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Intelligent Optimization Control Method for Photovoltaic Power Generation Systems Under Shadow Occlusion Conditions

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Abstract. In the process of photovoltaic power generation, maximum power point tracking is an important method to improve the efficiency of photovoltaic power generation. Under the actual local shadow condition, the maximum power point of Photovoltaic system fluctuates. For this reason, this paper establishes the mathematical model and output characteristic equation of photovoltaic cells according to the actual application, and then uses the adaptive inertia weight Particle Swarm Optimization algorithm to solve the problem of slow search speed and low accuracy in the process of maximum power point tracking. After optimization, the method proposed in this paper can significantly improve the tracking effect efficiency, and the optimization results in real operation scenarios can improve the photovoltaic cell power generation efficiency by 21.3%, which proves the effectiveness of the algorithm.

Keywords: photovoltaics, Particle Swarm Optimization, battery characteristics

1 Introduction

Under the trend of global transformation towards clean and low-carbon energy, not only are international countries vigorously developing new energy technologies, but China is also actively developing and continuously increasing investment and research in the field of new energy to achieve the “dual carbon” goal. The characteristics of efficient and flexible photovoltaic power generation and low Cost of electricity by source make photovoltaic power generation occupy an important position in the new energy development strategy. However, in practical applications, the influence of external environment and weather factors will lead to the emergence of local shadows, making the Photovoltaic system multi peak, thus reducing the power generation efficiency of Photovoltaic system. So avoiding getting stuck in local extremum and improving the global maximum power point tracking (MPPT) ability has become a research hotspot.

The targeted work done in this article is as follows:

1) Analyzed the composition and elements of photovoltaic power generation, simplified and modified its basic model, and established a mathematical model for photovoltaic cell engineering.

2) In the process of solving the maximum power point, in order to avoid local optimization and other Confounding, an improved adaptive inertia weight Particle swarm optimization algorithm is proposed.

The composition of this article is as follows: Chapter 2 mainly discusses the relevant research results of relevant scholars, and Chapter 3 mainly establishes a reasonable engineering mathematical model for real photovoltaic power generation scenarios containing influencing factors. In Chapter 4, in order to solve the optimal value of MPPT, the algorithm was improved and optimized. In Chapter 5, the simulation verification process was conducted to prove the feasibility and effectiveness of the algorithm. In Chapter 6, the conclusion section summarized the article and made further research plans.

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2 Related Work

Scholars in China have achieved fruitful research on MPPT. Han Hongyan proposed a Lion Group (LE-LSO) algorithm that introduces the Levy flight mechanism and chaotic optimization strategy, which can significantly improve the search efficiency of the results [1]. Wenquan Shao, for the photovoltaic system with Boost boost circuit, constructed segmented adjustment strategies at different stages of the convergence process. Analysis proved that the designed improved sliding mode control MPPT strategy can further improve the dynamic response speed and anti vibration performance of the photovoltaic system [2]. Bing Zhang, based on the characteristics of solar cells, established a simulation model of solar cells in MATLAB/Simulink, modeled and simulated the output characteristics of solar cells in different environments, and then proposed an adaptive anti-interference strategy to search for MPPT [3]. Renming Wang discussed the influence factors of local shadows and other factors on battery power generation, and adopted a comprehensive strategy based on sliding mode control method to track the maximum power point and boost the DC-DC conversion circuit. The simulation results showed that the improved strategy is based on efficiency [4]. Kai Sun proposed an improved Particle swarm optimization algorithm, taking the maximum power point as the control target, considering the photovoltaic emission law under the condition of local shadow. The simulation experiment proved that the algorithm has the characteristics of Rate of convergence, high accuracy and small search oscillation in the control process [5].

3 Establishment of Engineering Mathematical Models

3.1 Establishment of Mathematical Models

The main components of the equivalent circuit of photovoltaic cells include a current source and a forward bias diode. The equivalent circuit model of a single photovoltaic cell is shown in Fig. 1.

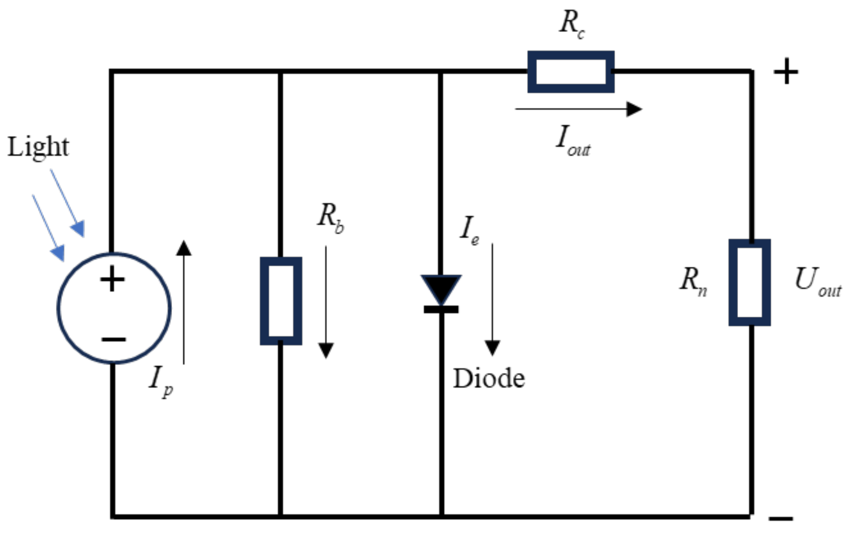


Fig. 1. Equivalent circuit

In the figure, U_{out} represents the output voltage of the photovoltaic cell, I_{out} represents the output current of the photovoltaic cell, R_c represents the Equivalent series resistance, I_b represents the current flowing through the equivalent parallel resistance R_b , I_e represents the current flowing through the diode D, Light represents the photoelectric conversion module in the photovoltaic circuit, I_p represents the current generated therein, and R_n represents the internal resistance of the power supply. The output current I_{out} of the photovoltaic cell port is expressed as [6]:

$$I_{out} = I_p - I_e - I_b. \quad \textbf{(1)}$$

The photogenerated current I_p is represented by the following formula:

$$I_p = \frac{s_a}{s_n} \times \left[I_{scr} - K_i \times (T_a - T_r) \right]. \quad \textbf{(2)}$$

Where, s_n is the light intensity under standard environment (S = 1000$W/\ m^2$), I_{scr} is the short-circuit current of the photovoltaic cell S_n represents the light intensity under the current environment, K_i represents the environmental coefficient, T_r represents the standard temperature, the expression is applicable to the photovoltaic system under Standard temperature and pressure, and I_p is a constant when the environment does not change. The dark current I_e flowing through the forward biased diode is expressed as:

$$I_d = I_0 \times \left\{ \exp\left[\frac{q(U_d)}{nkT_a} \right] - 1 \right\}. \quad \textbf{(3)}$$

Where, I_0 is the equivalent diode reverse Saturation current, U_{out} is the output voltage of the photovoltaic cell port, q is the charge contained in a single electron, and the value is 1.6 × $10^{-9}C$, n is the ideal factor of the cell, and the value is generally taken as 1.3, K is the Boltzmann constant, and the value is 1.38 × $10^{-23}J/\ K$, T_a is the ambient temperature of the photovoltaic cell, T_r is the standard ambient test temperature, and n is the ideal factor of the photovoltaic cell, and the value is generally taken as 1.3. Where, I_0 is the reverse Saturation current of equivalent diode, which is expressed as follows:

$$I_0 = I_{dr} \times \left(\frac{T_a}{T_r} \right)^3 \times \exp\left[\frac{qE_{go}}{NK} \times \left(\frac{1}{T_r} - \frac{1}{T_a} \right) \right]. \quad \textbf{(4)}$$

I_b is the leakage current of the photovoltaic cell flowing through the equivalent parallel resistance R_b. Analyzing its circuit relationship can obtain the following formula:

$$I_b = \frac{U_{out} + I_{out} R_c}{R_b}. \quad \textbf{(5)}$$

In summary, the output expression of the photovoltaic cell port is obtained:

$$I_{out} = I_p - I_o \left\{ \left[\exp\frac{(U_{out} + I_{out} R_c) q}{nKT_a} \right] - 1 \right\} - \frac{U_{out} + I_{out} R_c}{R_b}. \quad \textbf{(6)}$$

When the difference between R_b and R_c is significant, $\frac{U_{out} + I_{out} R_c}{R_b}$ in the above formula can be ignored. When the forward conduction resistance of the diode is greater than R_s , it can be considered as $I_p = I_{sc}$. Therefore, the expression for the output current of the photovoltaic cell port is further simplified as follows:

$$I_{out} = I_{sc} \left\{ 1 - M \left[\exp\left(\frac{U_{out}}{NU_{oc}} \right) - 1 \right] \right\}. \quad \textbf{(7)}$$

Substituting the data parameters I_m and U_m corresponding to the photovoltaic cell into the above formula, as the influence of 1 can be ignored under standard testing conditions, the following improved formula can be obtained.

$$I_m = I_{sc}\left\{1 - M\left[\exp\left(\frac{U_m}{NU_{oc}}\right)\right]\right\}. \tag{8}$$

After sorting, the engineering mathematical expression for the output characteristics of photovoltaic cells under standard test conditions is expressed as:

$$I = I_{sc}\left\{1-(1-\frac{I_m}{I_{sc}})\exp\left[\frac{-U_m \ln(1-\frac{I_m}{I_{sc}})}{U_m - U_{oc}}\right]\left[\exp\left(\frac{U\ln\left(1-\frac{I_m}{I_{sc}}\right)}{U_m - U_{oc}}\right)-1\right]\right\}. \tag{9}$$

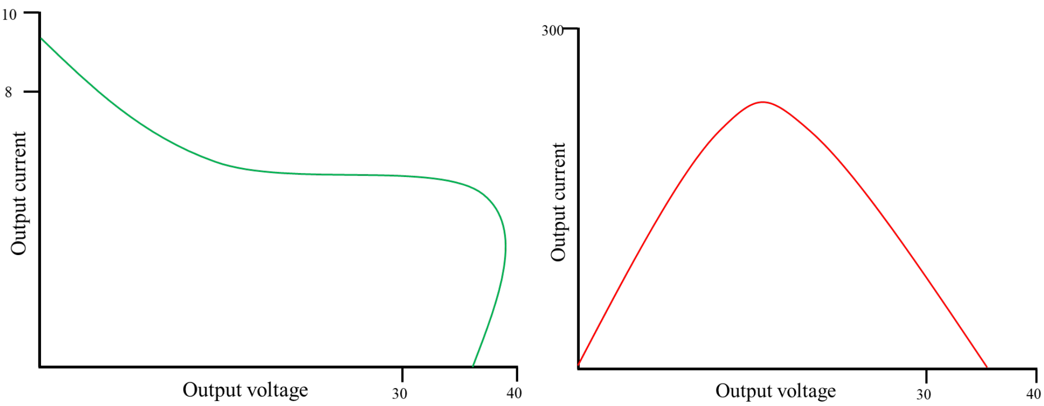
In fact, the simplified expression for photovoltaic cells usually needs to be corrected according to different usage environments before being applied in engineering. The engineering mathematical expression for the output characteristics of photovoltaic cells after correction is as follows:

$$I = I_{sc}\left\{1 - M\left[\exp\left(\frac{U+\Delta U}{B_2 U_{oc}}\right)-1\right]\right\} + \Delta I. \tag{10}$$

By using the mathematical expressions obtained above and based on the basic parameters U_{oc}, I_{sc}, U_m, and I_m provided by the manufacturer, the unknown number values in the formula can be calculated. The above is the mathematical model of photovoltaic cell engineering.

3.2 Analysis of Output Characteristics of Photovoltaic Cells

Photovoltaic cells form a photovoltaic matrix through a series parallel structure to obtain the actual required voltage requirements. Therefore, the output of Photovoltaic system depends on the output of each photovoltaic cell and the series parallel structure between photovoltaic cells. During actual use, due to factors such as weather changes and the distribution of surrounding obstructions, the photovoltaic cells experience local shading. The parameters of the tested cells are shown in Table 1. Using Matlab software for simulation modeling, in order to facilitate research, the photovoltaic cell model is packaged into modules. The input terminals of the packaged modules are illumination S and temperature T, and the output is voltage and current [7]. The simulation output $P-U$ and $I-U$ characteristic curves of the photovoltaic cell model under standard test conditions are shown in Fig. 2.



(a) $I-U$ curve (b) $P-U$ curve

Fig. 2. Output characteristics

When the photovoltaic cells in the Photovoltaic system are shaded, the difference in the local Irradiance of each photovoltaic cell causes the output characteristics of each photovoltaic cell to be inconsistent, so the output power of the Photovoltaic system will be less than the sum of the output power of all photovoltaic cells, and then the Photovoltaic system will have a "mismatch" phenomenon. If a shaded photovoltaic cell consumes power for a long time, it will cause local overheating within the cell, leading to the "hot spot effect". Moreover, the long-term occurrence of the "hot spot effect" will cause irreversible damage to the photovoltaic cell. Therefore, if the "hot spot effect" is not dealt with in a timely manner, the photovoltaic cell will be severely damaged.

In the case of partial shading, the shaded module outputs a small current, and the output power is also greatly reduced, so there are multiple inflection points in the $I-U$ characteristic of the Photovoltaic system and multiple extreme points in the $P-U$ characteristic. The multi peak situation caused by the $P-U$ characteristic brings certain difficulties to MPPT control, which greatly reduces the tracking effect. The output characteristic diagram of Photovoltaic system after occlusion is shown in Fig. 3.

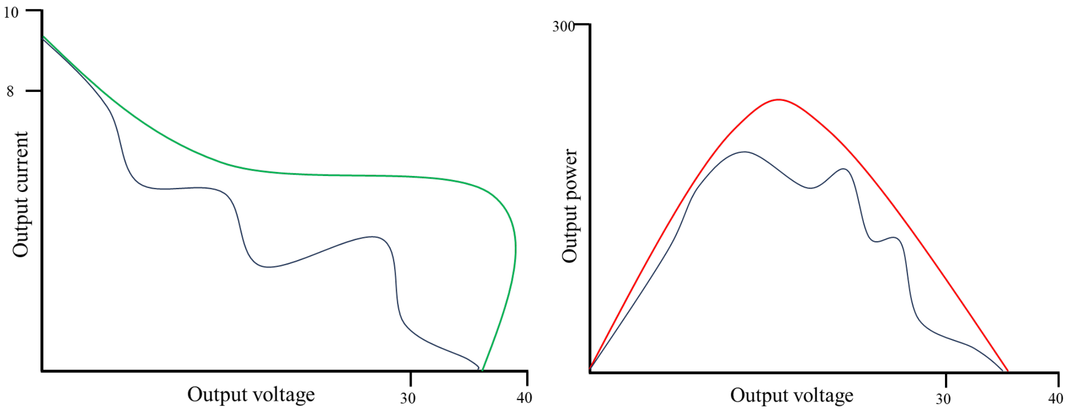


Fig. 3. $I-U$ and $P-U$ curves with shading

From the above curve, it can be seen that the output characteristics of photovoltaic modules are highly nonlinear. Under any working condition, there always exists a maximum power point in the power output characteristic curve, and the position of the maximum power point will change with changes in external environmental factors such as light intensity and temperature.

4 Adaptive Particle Swarm Optimization Algorithm

Use an improved particle swarm optimization algorithm to search for the optimal solution of the photovoltaic cell model, add weights to the adaptive algorithm, and update adaptively.

4.1 Adaptive Optimization Algorithm Process

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Assuming a group of N particles flying at a certain speed in the K -latitude search space, the state attributes of particle j are set as follows at time t:

1) Location: $x_l = \left(x_{l1}^l, x_{l2}^l, \cdots, x_{lm}^l\right)^T$, $x_{ij}^i \in \left[L_d, U_d\right]$, L_l and U_l are the upper and lower limits of the search space,

respectively.

2) Speed: $v_j = \left(v_{j1}, v_{j2}, \cdots, v_{jl}\right)^T$, $v_{jd}^t \in \left[v_{\min}, d, v_{\max,} d\right]$, $v_{\min}$, $v_{\max}$ are minimum and maximum speeds.

The evolution process of particle swarm is as follows:

$$v_{jl}^{d+1} = \rho \cdot v_{jl}(d) + \rho D_1 r_1(d)\left[p_{jl}(d) - x_{jl}(d)\right] + D_2 r_2(d)\left[p_{gj}(d) - x_{jl}(d)\right]. \quad \textbf{(11)}$$

$$x_{ij}(d+1) = x_{ij}(d) + v_{ij}(d+1). \quad \textbf{(12)}$$

In the formula, ρ is the inertia weight, and the size of ρ has a significant impact on local and global search capabilities. Controlling the value of ρ is the key to achieving optimization. The learning factors D_1 and D_2 are a set of random non negative constant learning factors, D_1 represents the acceleration weight of particles flying to their best position, D_2 represents the acceleration weight of particles flying to the global best position, and selecting an appropriate learning factor can accelerate convergence. d represents the current number of iterations, and the two constants between r_1 and $r_2 \in [0, 1]$ are independent of each other. Where $x(i)$ represents the position of the i -th particle, and the flight position and velocity of the particle vary according to the following formula:

$$f = I(P_{prog}(I_1, S_1, T_1)) + P_{prog}(I_2, S_2, T_2) + P_{prog}(I_3, S_3, T_3). \quad \textbf{(13)}$$

4.2 Optimization of Particle Swarm Optimization

In order to improve the speed and robustness of the algorithm, the weight value $\rho \in (0, 1]$ is set, and ρ is linearly reduced to a minimum during the iteration process to enhance the tracking ability. At the beginning of the iteration, $D_1 = 4$ and $D_2 = 0.3$ are set to avoid falling into local optima. As the particles continue to update, D_1 gradually decreases and D_2 continuously increases. The expressions for each parameter are as follows:

$$\rho(d) = \rho_{start} - (\rho_{start} - \rho_{end})\left(\frac{d}{T_{\max}}\right)^2. \quad \textbf{(14)}$$

$$D_1 = \left(D_{1start} - D_{1end}\right)\left(\frac{d}{d_{\max}}\right)^2 + \left(D_{1end} - D_{1start}\right)\frac{2d}{d_{\max}} + D_{1start}. \quad \textbf{(15)}$$

$$D_2 = \left(D_{2start} - D_{2end}\right)\left(\frac{d}{d_{\max}}\right)^2 + \left(D_{2end} - D_{2start}\right)\frac{2d}{d_{\max}} + D_{2start}. \quad \textbf{(16)}$$

In the formula, ρ_{start} is the initial inertia weight, ρ_{end} is the inertia weight at the maximum number of iterations, d is the current number of iterations, and $T_{\max}$ is the maximum number of iterations. Based on the algorithm flowchart in Fig. 1, the process of the algorithm is as follows:

1) Initialize the initial positions of all particles

2) Determine the Irradiance, temperature parameters, target location, and calculate the total output power of the photovoltaic module.

3) Calculate the fitness values of all particles, search for the optimal value, and update the speed and position of particles using formulas 1 and 2

4) Calculate the output power of the photovoltaic module again, use formula 3 to update the optimal value of a single particle and the global optimal value, and adaptively adjust the weight ρ and learning factors D_1 and D_2 .

5) The termination condition for adaptive iteration is $\frac{\left|P_{test} - P_m\right|}{P_m} \le 0.5$, otherwise the iteration continues until the condition is met.

5 Simulation Experiment Analysis

The parameters of a certain model of photovoltaic cell are shown in Table 1.

Table 1. Parameters of photovoltaic cells

Parameter	Value
open circuit voltage	36.2V
short-circuit current	11A
Maximum power point voltage	23.2V
Maximum power point current	8.27A

Considering the actual situation, shadows are dynamic shadows, that is, the area and position of the shadows are constantly changing. Simulation testing is conducted under operating conditions, and the number of iterations is set to 80. Firstly, the advantages and disadvantages of the improved adaptive particle algorithm are verified. The comparison with the Whale algorithm, Particle Swarm algorithm, and Lion Swarm algorithm is used to illustrate this, as shown in Fig. 4.

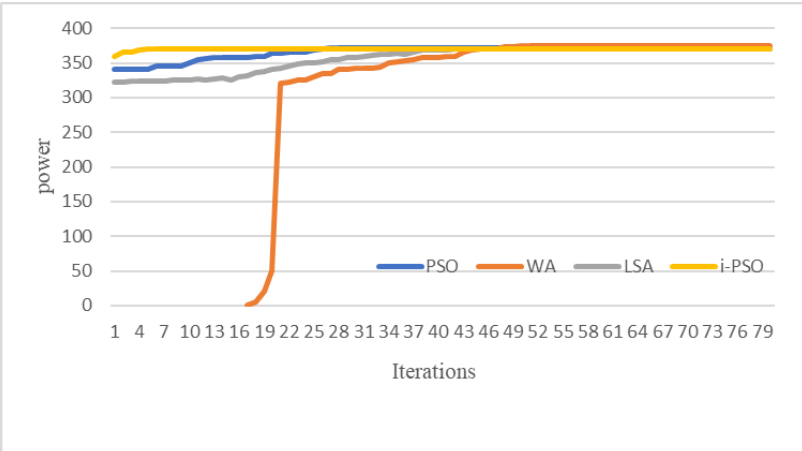

Fig. 4. Comparison of algorithm iteration results

From the above figure, it can be seen that the algorithm only tracks the maximum power point after about 36 iterations, resulting in slow and unstable iteration speed. The algorithm has been iterated about 30 times to track the maximum power value, but it is easy to fall into local optima. The algorithm has been iterated 14 times to reach the power value, and it is also easy to fall into local optima. The improved algorithm in this article can search for the maximum power after 5 iterations. The maximum power values found by the four algorithms are close. In summary, the improved algorithm proposed in this article has faster iteration speed, stronger ability to jump out of local optima, stronger global optimization ability, and can more accurately search for the maximum power point.

Validate the effectiveness of the method proposed in this paper under dynamic shadow conditions. The operating conditions are set as the starting condition, where the illumination intensity of Block 1:3 photovoltaic module is $S_1 = 1000W/m^2$, $S_2 = 800W/m^2$, and $S_3 = 1000W/m^2$. At 0.1 seconds, the illumination intensity suddenly changes step by step as scenario 2:3 photovoltaic module's illumination intensity is $S_1 = 1000W/m^2$, $S_2 = 800W/m^2$, and $S_3 = 600W/m^2$. At 0.5 seconds, the illumination intensity suddenly changes step by step as scenario 3:3 photovoltaic module's illumination intensity is $900W/m^2$, $700W/m^2$, and $500W/m^2$, The maximum power values of photovoltaic system output under the three scenarios are shown in Fig. 5.

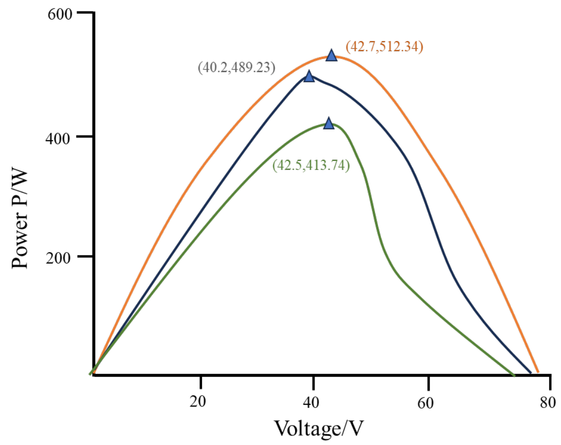

Fig. 5. Power characteristic curve

In scenario 1, the theoretical maximum output power of the photovoltaic power generation system for the photovoltaic module is 512.34W; At 0.1 s, a sudden step change in light intensity occurs for scenario 2, and the theoretical maximum output power of the photovoltaic power generation system is 489.23 W; At 0.5 seconds, a sudden step change in light intensity occurs for scenario 3, and the theoretical maximum output power of the photovoltaic power generation system is 413.74 W.

Fig. 6 shows the schematic diagram of the algorithm's tracking results for the highest power point. In scenario 1, after 0.031 seconds of illumination intensity, the maximum output power of the photovoltaic power generation system stabilizes at around 512.34 W, and the tracking accuracy of the algorithm is about 99.6%; When the lighting intensity suddenly changes to scenario 2, the algorithm searches for the maximum power point after about 0.036 seconds, and the maximum output power is 489.23W. The tracking accuracy of the algorithm is about 99.5%; At 0.5 seconds, the illumination intensity suddenly changed to scenario 3. The algorithm took approximately 0.029 seconds to search for the maximum power point, and the maximum output power was 413.74W. The tracking accuracy of the algorithm was approximately 99.3%. After the above analysis, it can be seen that when the light intensity suddenly changes in steps, the algorithm has fast response speed, short transient process, and can efficiently track to the maximum power point.

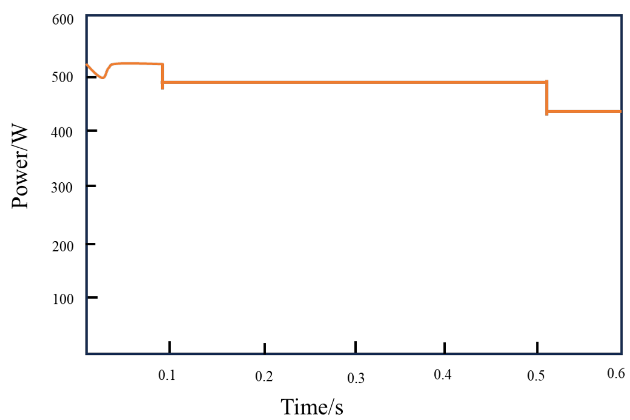

Fig. 6. Power tracking results

6 Conclusion

This article studies the method of tracking the maximum power point of photovoltaic cell power generation using an improved particle swarm optimization algorithm under normal and shaded conditions. The experiment proves that the proposed method is scientifically effective and can track the optimal result at the fastest speed.

As research deepens, this article will continue to make the setting of shading conditions more complex and detailed, enabling simulation of various shading conditions to a greater extent.

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