

Research on MPPT control strategy for photovoltaic power generation based on improved incremental conductance method

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Abstract

INTRODUCTION: Maximum power point tracking (MPPT) is an important strategy for optimizing the power output of photovoltaic arrays.

OBJECTIVES: The primary objective of this study is to develop an enhanced MPPT control method to address the inherent limitations of long tracking time and low tracking accuracy in the traditional conductance incremental method for MPPT.

METHODS: An improved incremental conductance method is proposed, which introduces the fuzzy control algorithm to the incremental conductance method to dynamically adjust the perturbation step size.

RESULTS: The simulation results show that the improved method proposed shortens the MPPT time and improves the MPPT accuracy under start-up and sudden change operating condition comparing with other incremental conductance method.

CONCLUSION: This study provides an effective and reference-worthy control method for further improving the efficiency of photovoltaic power generation.

Keywords: photovoltaic power generation, MPPT, fuzzy control, incremental conductance method, variable step size

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1. Introduction

In recent years, the excessive development of primary energy has led to increasingly serious problems of energy depletion and environmental pollution. Therefore, countries around the world have invested in the development of new energy such as solar energy, wind energy, geothermal energy, and nuclear energy, aiming to fully utilize their advantages of low pollution, renewability, and abundant reserves to solve energy shortages and environmental pollution problems. In response, China has proposed a "dual carbon" strategic goal, aiming to achieve a non fossil energy consumption proportion of over 80% by 2060 [1,2].

Solar energy has become a research hotspot in the energy field due to its low development cost, flexible application scenarios, and clean and low-carbon characteristics. Among them, photovoltaic power generation technology is becoming increasingly mature and has been promoted and applied to countries around the world. The installed capacity of photovoltaic power generation in China has been continuously expanding over recent years, exceeding 200GW [3,4]. However, photovoltaic power generation also has problems such as large infrastructure investment and long economic return cycles. In addition, the output of photovoltaic arrays as the important facility for photovoltaic power generation has non phenomenal characteristics and varies with the

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temperature and light intensity of the operating environment [5]. In order to improve the operational efficiency and economic benefits, it is necessary to maintain the photovoltaic output at the maximum power point under real-time conditions as much as possible, in order to maximize its equipment utilization. Therefore, maximum power point tracking (MPPT) has become a necessary control strategy in photovoltaic power generation [6].

The common MPPT methods include constant voltage method, perturbation observation method, and incremental conductance method, among which incremental conductance method is widely used due to its high accuracy [7,8,9]. However, the traditional incremental conductance method has disadvantages such as long tracking time and low tracking accuracy, which seriously affect the efficiency of photovoltaic power generation [10,11]. Based on this, the study analyzes the output characteristics of photovoltaic modules according to their mathematical models firstly, and then introduces fuzzy control algorithm into the incremental conductance method to improve the MPPT method, among which, the fixed-step size incremental conductance method or the variable-step size incremental conductance method based on fuzzy control is adopted according to the slope between the photovoltaic output power and the output voltage to adjust step size adaptively. Finally, the relevant models are built in MATLAB/SIMULINK and the simulation tests were conducted for the start-up and sudden changes in operating conditions of photovoltaic array to verify the practicality and superiority of the improved MPPT method.

The remaining sections are organized as follows: the output characteristics of photovoltaic arrays are analyzed in Section 2, and the principle of improved MPPT method are explained in sections 3, system modeling and simulation result analysis are detailed in Section 4, and the conclusions from this study are summarized in Section 5.

2. Characteristics of photovoltaic output

As the main photovoltaic power generation facility, photovoltaic arrays are composed of photovoltaic modules connected in series and parallel. Among them, photovoltaic modules are the smallest power generation units, which convert solar energy into direct current electricity [12,13]. The mathematical model of photovoltaic modules under reference temperature and reference light intensity is as follows [14,15].

$$I = I_s \left[1 - A \left(\exp\left(\frac{U}{BU_{oc}}\right) - 1 \right) \right] \quad (1)$$

$$A = \left(1 - \frac{I_m}{I_s} \right) \exp\left(-\frac{U_m}{BU_{oc}}\right) \quad (2)$$

$$B = \left(\frac{U_m}{U_{oc}} - 1 \right) \left[\ln\left(1 - \frac{I_m}{I_s} \right) \right]^{-1} \quad (3)$$

In Eqs. (1) to (3), A , B are the intermediate variables, I

and U refer to the output current and output voltage of the photovoltaic module, I_s and U_{oc} refer to the short-circuit current and open circuit voltage of the photovoltaic module, I_m and U_m refer to the output current and output voltage at the maximum power point of the photovoltaic module, respectively.

When the operating conditions of photovoltaic modules deviate from the reference temperature and reference light intensity, it is necessary to correct the relevant parameters such as I_s , U_{oc} , I_m , U_m , as shown in Eqs. (4) to (5).

$$\begin{cases} I'_s = I_s (1 + a \Delta T) * \frac{S}{S_{ref}} \\ I'_m = I_m (1 + a \Delta T) * \frac{S}{S_{ref}} \\ U'_{oc} = U_{oc} \ln(e + b \Delta S) * (1 - c \Delta T) \\ U'_m = U_m \ln(e + b \Delta S) * (1 - c \Delta T) \\ \Delta T = T - T_{ref} \\ \Delta S = S - S_{ref} \end{cases} \quad (4)$$

$$\begin{cases} \Delta T = T - T_{ref} \\ \Delta S = S - S_{ref} \end{cases} \quad (5)$$

In Eqs. (4) and (5), T and T_{ref} refer to the actual temperature and reference temperature, S and S_{ref} refer to the actual light intensity and reference light intensity, respectively, while a , b and c are the correction factors. In addition, the output power is calculated as follows:

$$P = UI \quad (6)$$

According to Eqs. (1) to (6), the output of photovoltaic modules is related to the characteristic parameters determined by the model and the environmental conditions such as temperature and light intensity. The characteristic parameters of photovoltaic modules selected in this study are shown in Table 1. Then, the output characteristics of photovoltaic modules at different lighting under reference temperature are shown in Figure 1, and the output characteristics of photovoltaic modules at different temperatures under reference lighting are shown in Figure 2.

Table 1. Parameters of Photovoltaic Modules

Parameter	Parameter values
T_{ref}	25 °C
S_{ref}	1000 W/m ²
I_s	5.3 A
I_m	4.8 A
U_{oc}	44.8 V
U_m	37 V
a	0.0025 /°C
b	0.0005 / (W/m ²)
c	0.00288 /°C

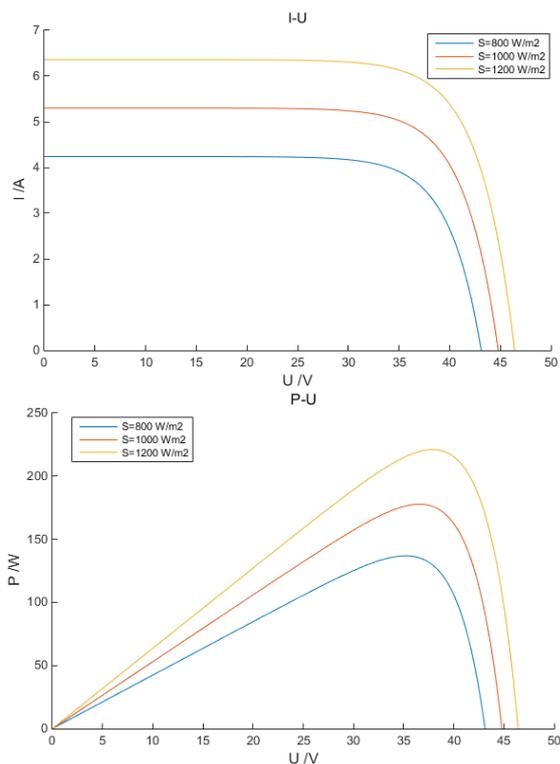


Figure 1. Output characteristics of different light intensities at reference temperature

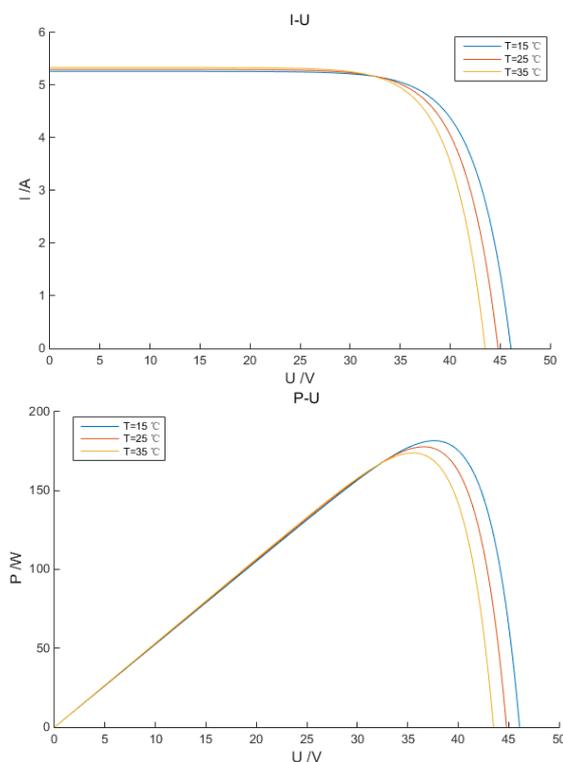


Figure 2. Output characteristics of different temperature at reference light intensities

From Fig. 1 and Fig. 2, it can be seen that the electrical output of photovoltaic modules has nonlinear characteristics, and under any fixed operating condition, it has a unique maximum power point that varies with the operating conditions.

Due to the fact that photovoltaic arrays are composed of photovoltaic modules, the output characteristics of photovoltaic arrays are determined by the photovoltaic modules. This study focuses on the photovoltaic array composed of individual photovoltaic modules, therefore, the photovoltaic arrays and photovoltaic modules have the same output characteristics.

3. Design of MPPT method

3.1. Principle of incremental conductance method

Compared with the constant voltage method [16,17] and the disturbance observation method [18,19] of photovoltaic MPPT, the conductance increment method can adapt quickly to changes in operating conditions [20,21], mainly based on the P-U curve characteristics of the photovoltaic array for MPPT.

According to Fig. 1 and Fig. 2, it can be seen that the P-U output characteristics curve of photovoltaic array is a downward opening parabola, and when the slope of the curve is 0, photovoltaic array operates at the maximum power point exactly; When the slope of the curve is greater than 0, photovoltaic array operates on the left side of the maximum power point; When the slope of the curve is less than 0, photovoltaic array operates on the right side of the maximum power point

While, from Eq. (6), it can be concluded that:

$$\frac{dP}{dU} = I + U \frac{dI}{dU} \quad (7)$$

Therefore, photovoltaic MPPT can be divided into the following three situations:

(1) When $dP/dU=0$, then $-I/U=dI/dU$. The operating voltage U of photovoltaic array should be remained unchanged.

(2) When $dU=0$ and $dI=0$, the operating voltage U remains unchanged; When $dU=0$ and $dI>0$, U should be increased to move the current operating point to the right; When $dU=0$ and $dI<0$, U should be reduced to move the current operating point to the left.

(3) When $dP/dU < 0$, then $dI/dU < -I/U$, U should be reduced to move the current operating point to the left; When $dI/dU > -I/U$, U should be increased to move the current operating point to the right.

In the above process, the adjustment step size of U will directly affect the MPPT performance. when the step size is large, although the speed of MPPT tracking is fast, it can easily cause photovoltaic output oscillation, resulting in lower MPPT accuracy; On the contrary; Conversely, it can

improve the accuracy of MPPT, but the tracking process is slower, which affects the speed of MPPT [22,23].

According to whether the voltage adjustment step size changes, the conductance increment method can be divided into two types: fixed-step size and variable-step size. While, the incremental conductance method of fixed-step size cannot balance the speed and accuracy of MPPT due to the constant voltage adjustment step size, resulting in poor overall performance of MPPT [24,25]. So, this study adopts the variable-step size incremental conductance method.

3.2. Design of variable-step size incremental conductance method

As show the P-U characteristic curves in Fig. 1 and Fig. 2, it can be seen that when the current operating point of the photovoltaic array is far from the maximum power point, the absolute value of the slope of the curve is large; On the contrary, the absolute value of the slope of the curve is small. Therefore, the position of the current operating point of photovoltaic array can be determined by the slope of the P-U curve, and the step size can be adjusted to balance the speed and accuracy of MPPT. That is, when the absolute value of dP/dU is large, a larger step size should be used; On the contrary, it is advisable to adopt a smaller step size.

To In addition, when the current operating point is too far from the maximum power point, in order to enhance the control effect, it is advisable to use a larger fixed-step size to move towards the maximum power point as soon as possible, thereby further improving the MPPT effect. So, a threshold is set for the absolute value of dP/dU denoted as m in this study. When the absolute value of dP/dU is greater than m , the fixed-step size incremental conductance method is adopted, and the step size is set to a larger value; On the contrary, the adaptive-step size conductance increment method is used for fine adjustment, among which, the step size operator is designed as follows.

$$step = N * \left| \frac{dP}{dU} \right| \tag{8}$$

In Eq. (8), $step$ refer to the step size, N refer to the ratio factor, which decides the accuracy and speed of MPPT during the variable step size adjustment process. To further improve MPPT performance, the fuzzy control algorithm is used to adjust the value of N in this study.

3.3. Design of incremental conductance method based on fuzzy control

Fuzzy control is a control method based on fuzzy theory, which maps the input and output signals in the control system to corresponding fuzzy sets through membership functions, and determines the control quantity through fuzzy inference and defuzzification operations [26,27]. So, it has good robustness and adaptability [28,29].

This study takes $|dP/dU|$ and N in Eq. (8) as the input and output variables of fuzzy control, set their domains to $[0,2]$ and $[0,0.005]$, respectively, and set the fuzzy sets to $[SS, MS, S, M, B, MB, BB]$. The membership function curves of the two variables are shown in Figure 3 respectively.

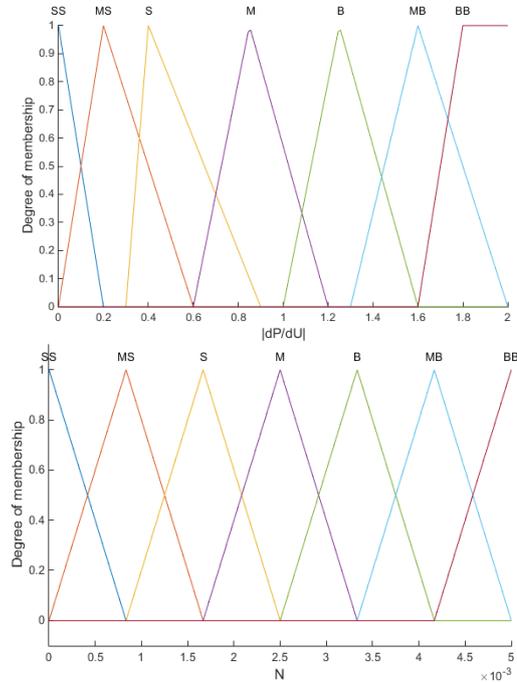


Figure 3. Membership function curve of input and output quantity of fuzzy control

In addition, the fuzzy control rules are designed as shown in Table 2 based on the logical relationship between input and output quantities, and the Mamdani method is used for fuzzy inference.

Table 2. Fuzzy control rules

$ dP/dU $	N
SS	SS
MS	MS
S	S
M	M
B	B
MB	MB
BB	BB

By introducing fuzzy control into the incremental conductance method, the step size can be more accurately adjusted according to the current output state of the photovoltaic array, thereby making MPPT faster and more accurate.

4. Modeling and Simulation

To achieve photovoltaic MPPT, Boost converter is usually used to adjust its output voltage [30,31]. Build the simulation model of main circuit in MATLAB as shown in Figure 4.

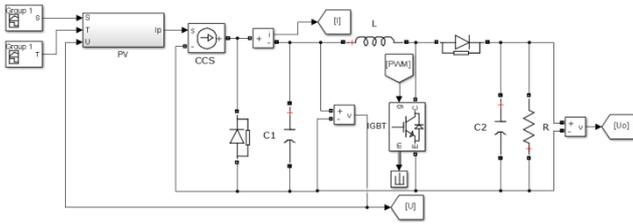


Figure 4. Main circuit model of photovoltaic MPPT

In Figure 4, PV is the photovoltaic model developed based on Eqs. (1) to (5), the electrical parameters of related components are shown in Table 3.

Table 3. Electrical parameters of circuit components

Circuit Components	Electrical Parameter Values
C ₁	10 uF
L	10 mH
C ₂	300 uF
R	100 Ω

According to the analysis of the circuit, it can be concluded that:

$$U = U_o * (1 - D) \tag{9}$$

In Eq. (9), U_o and D refer to the output voltage and the duty cycle of the electronic switch of the BOOST converter, respectively. It is known that D is negatively correlated with U, and the duty cycle of the electronic switch in the boost converter can be adjusted to regulate the photovoltaic output voltage. So build the simulation model of the control loop as shown in Figure 5, and set the sampling period to 8ms.

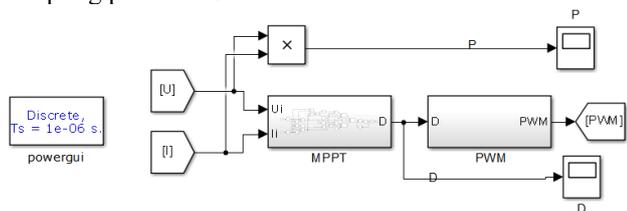


Figure 5. Model of control loop

In Figure 5, the MPPT module is the model of MPPT algorithm, build the simulation model based on the principle of incremental conductance method, as shown in Figure 6, among which, step refer to the step size. The PWM module is the model for generating driving signals for electronic switches, as shown in Figure 7, among which, set the carrier frequency to 20kHz.

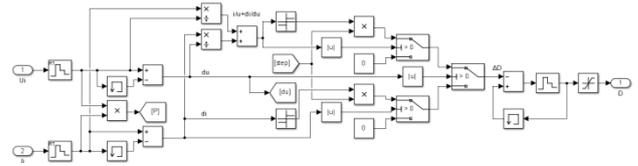


Figure 6. Model of MPPT module

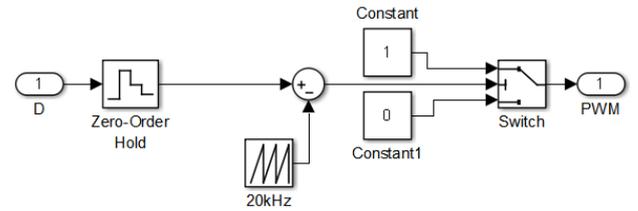


Figure 7. Model of PWM module

To verify the superiority of the improved incremental conductance method proposed in this study, it was compared with the fixed-step size incremental conductance method and the variable-step size incremental conductance method with fixed ratio factor *N*. To ensure the fairness of each method, set the maximum step size to 0.01, and starts to change from 1.0 uniformly. Build the simulation models for adjusting step size of each method as follows:

(1) Fixed-step incremental conductance method

Set the step size to be fixed at 0.01, and be marked as Method 1. The simulation model is shown in Figure 8.



Figure 8. Model of fixed step incremental conductance method

(2) Variable-step size incremental conductance method with fixed ratio factor

Set the ratio factor to be fixed at 0.005, and be marked as Method 2. the simulation model is shown in Figure 9

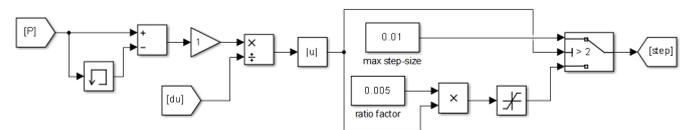


Figure 9. Model of variable step size incremental conductance method with fixed ratio factor

(3) Improved incremental conductance method

Adjusting the ratio factor through fuzzy control, and be marked as Method 3. the simulation model is shown in Figure 10.

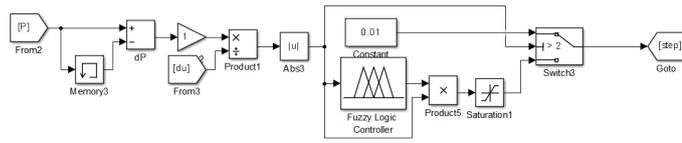


Figure 10. Model of improved incremental conductance method

To analyze the performance of the various MPPT method comprehensively, adjust the light intensity and temperature in Figure 4 according to the parameters shown in Table 4 to simulate three typical operating conditions of photovoltaic operation, among which, 1 # corresponds to the start-up testing condition, and 2 # and 3 # correspond to the dynamic testing condition. The theoretical maximum power marked as P_M under corresponding operating conditions can be obtained by analyzing the photovoltaic output characteristics.

Table 4. Parameters of photovoltaic operating condition

Operating conditions	1#	2#	3#
Time (s)	0~0.5	0.5~1.0	1.0~1.5
S (W/m ²)	800	1200	1000
T (°C)	15	25	25
P_M (W)	137.31	221.03	177.77

After simulation, The duty cycle, photovoltaic output voltage and output power are shown in Figure 11, Figure 12, and Figure 13, respectively.

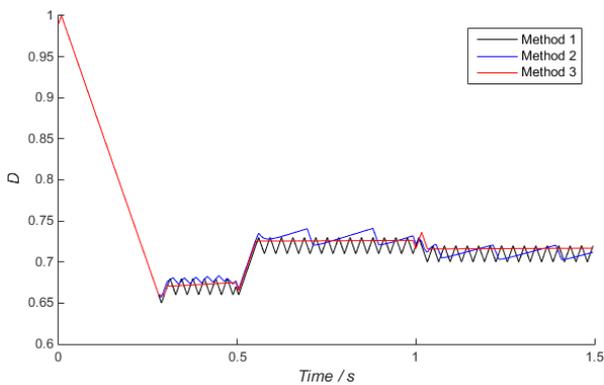


Figure 11. Curve of the duty cycle

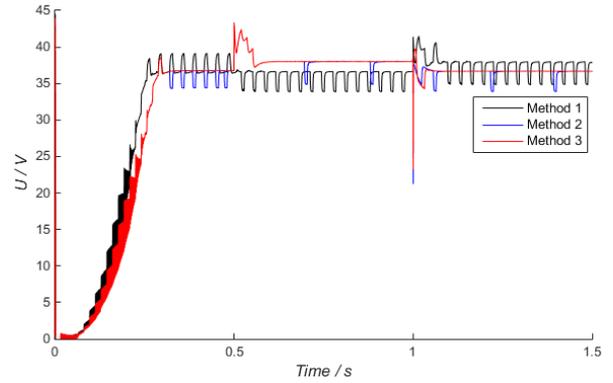


Figure 12. Curve of photovoltaic output voltage

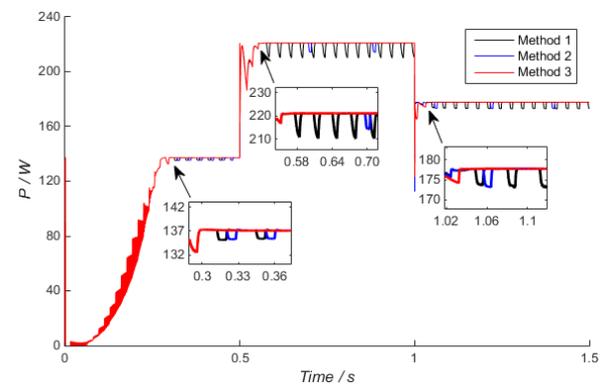


Figure 13. Curve of photovoltaic output power

To evaluate the performance of MPPT method quantitatively, the moment when the duty cycle begins to periodically change or when the amplitude of the duty cycle change between adjacent sampling periods no longer exceeds 0.001 is considered as the end of the photovoltaic MPPT, which is marked as t_1 . Then, the time from the change of photovoltaic operating conditions to t_1 is defined as the MPPT time, which is marked as t_t , and the MPPT accuracy is defined as follows.

$$\gamma = \frac{P_t}{P_M} * 100\% \tag{10}$$

In Eq. (10), P_t refer to the average output power after MPPT, which is defined as follows.

$$P_t = \frac{\int_{t_1}^{t_2} P dt}{t_2 - t_1} \tag{11}$$

In Eq. (11), t_2 refer to the moment when the current operating condition terminates.

Table 5 shows the analysis results of the simulation data in Fig. 11, Fig. 12, and Fig. 13. It can be seen that the above three incremental conductance methods can basically complete photovoltaic MPPT within a certain period of time, among which the MPPT tracking time is longer under the start-up testing condition then the dynamic testing condition. In addition, the improved conductance increment method proposed in this study can achieve the shortest tracking time and highest tracking accuracy under

all operating conditions when comparing with other photovoltaic MPPT methods, which indicates the MPPT method proposed has the highest photovoltaic power generation efficiency.

Table 5. Results of simulation

MPPT Method	Criteria	Operating conditions		
		1#	2#	3#
Method 1	t_t (s)	0.312	0.060	0.048
	P_t (W)	136.74	218.92	176.72
	γ (%)	99.585	99.045	99.409
Method 2	t_t	0.320	0.188	0.056
	P_t	136.73	220.71	177.54
	γ	99.578	99.855	99.871
Method 3	t_t	0.304	0.052	0.032
	P_t	137.09	221.00	177.75
	γ	99.840	99.986	99.989

5. Conclusions

Based on the analysis of the output characteristics of photovoltaic arrays, the improved increment method was proposed in this study to meet the requirements of efficient MPPT for photovoltaic arrays. The MPPT method proposed introduces the fuzzy control into the incremental conductance method, and adjusts the step-size adaptively by the fixed-step conductance increment method or variable-step conductance increment method based on fuzzy control according to the slope between the output power and output voltage of the photovoltaic array to balance MPPT speed and accuracy, and improve MPPT performance ultimately.

The performance of MPPT method was validated through simulation and comparison. The results indicated that the improved increment method of MPPT proposed in this study achieves efficient MPPT effects under the start-up and sudden changes in operating conditions of photovoltaic array. Based on the results of this study, the following conclusions can be reached:

- (1) The method proposed in this study can achieve MPPT under various operating conditions of photovoltaic arrays efficiently.
- (2) The MPPT method proposed in this study has shorter MPPT time and higher MPPT accuracy compared to the fixed-step incremental conductance method and the variable-step size incremental conductance method with fixed ratio factor under various operating conditions of photovoltaic arrays.
- (3) The MPPT method proposed in this study has a tracking time of 0.304s and a tracking accuracy of 99.840% for photovoltaic array MPPT under start-up testing condition.
- (4) The MPPT method proposed in this study has a tracking time of less than 0.06s and a tracking accuracy of 99.98% for photovoltaic array MPPT under dynamic testing conditions.

For the future studies, the photovoltaic MPPT experimental system will be built to implement physical testing of the proposed MPPT method to verify its applicability. Moreover, improve the fuzzy control algorithm in the MPPT method in the future. For instance, optimizing the membership function or fuzzy rules to further enhance the MPPT performance.

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