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Research on MPPT control strategy for photovoltaic power generation based on improved perturbation and observation method

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Abstract

INTRODUCTION: The output of photovoltaic (PV) arrays has nonlinear characteristics and is affected byambient conditions, so maximum power point tracking (MPPT) is crucial for efficient photovoltaic power generation.
OBJECTIVES: This study aims to propose an MPPT control strategy based on improved perturbation and observation (P&O) method to overcome the shortcomings of traditional MPPT methods.
METHODS: The method proposed integrates slope control and fuzzy control algorithms for hybrid control to achieve adaptive adjustment of control step size. In addition, the simulation test for start-up and sudden changes in operating conditions of PV were conducted to verify the practicability and progressiveness of the improved method proposed.
RESULTS: The results confirm that the improved method proposed can reduce the output fluctuations of PV array and achieve shorter MPPT time and higher MPPT efficiency.
CONCLUSION: The improved MPPT method has better MPPT performance, which provide effective reference for further improving the efficiency of PV power generation.

Keywords: PV Power Generation, MPPT, P&O Method, fuzzy control, hybrid control, simulation

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1. Introduction

With the development of the global economy and society, the demand of world's energy has surged, and the global energy crisis is becoming increasingly severe [1,2]. How to efficiently develop and utilize renewable energy has become a current research hotspot [3]. PV power generation has become a widely used method of electricity production due to the advantages of cleanliness, environmental protection, abundant resources, and convenient development. However, due to the inherent characteristics of PV arrays, the output has nonlinear features and varies with external environmental factors such as operating temperature and light intensity [4,5], which makes their actual output power easily lower than the theoretical maximum power. Therefore, it is necessary to implement MPPT control for PV array to maximize the power output of the PV generation system [6,7].

Traditional MPPT strategies for PV, such as the constant voltage, incremental conductance and P&O method, have been extensively studied. Among them, the P&O method stands out in practical implementations, having become the dominant approach owing to its simple principle, ease of implementation, and low hardware demands [8,9]. However, the ordinary P&O method cannot adaptively adjust the control step size according to the real time operational status of the PV array, resulting in low MPPT accuracy, long tracking time, and easy oscillation of the PV array output, seriously affecting its MPPT efficiency [10,11].

To remedy the intrinsic deficiencies of the traditional P&O method, the control strategy is improved in this study. Firstly,

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a simulation model of PV was built according to the mathematical model, and the output characteristics were analyzed through the simulation data. Subsequently, the improved P&O method featuring variable-step-size for PV MPPT is developed, which combining slope ratio control with fuzzy control to achieve hybrid control, and adjusting the step size adaptively based on the real-time output of PV arrays. Finally, the PV MPPT system is implemented in simulation and tested under both start-up and abrupt operating condition of PV transitions. Then the progressiveness of the improved method proposed is demonstrated by the comparison and analysis of the simulation results.

The remainder of this paper is structured as follows: Section 2 discusses the nonlinear output characteristics of PV arrays. Section 3 introduces the fundamental MPPT control principle. Based on that, Section 4 proposes the control methods. Section 5 performs system modeling and simulation. Section 6 summarizes the key findings.

2. Output characteristics of PV array

2.1. Mathematical model of PV

As the basic unit that constitutes a PV array, PV modules function as energy-conversion devices that harness sunlight to yield electrical power through the photovoltaic effect, and the correlation between the input, output, and various influencing factors can be expressed as [12]:

$$I = I_{sc}\left\{1\text{-}C_1\left[\exp\left(\frac{U}{C_2 U_{oc}}\right)-1\right]\right\} \tag{1}$$

$$\begin{cases} C_1 = \left(1\text{-}\dfrac{I_{mp}}{I_{sc}}\right)\exp\left(\text{-}\dfrac{U_{mp}}{C_2 U_{oc}}\right) \\ C_2 = \left(\dfrac{U_{mp}}{U_{oc}}\text{-}1\right)\left[\ln\left(1\text{-}\dfrac{I_{mp}}{I_{sc}}\right)\right]^{-1} \end{cases} \tag{2}$$

$$\begin{cases} I_{sc} = I_{sR}\left[1+\mathrm{a}(T-T_R)\right]\dfrac{S}{S_R} \\ U_{oc} = U_{oR}\left[1-\mathrm{b}(T-T_R)\right]\ln\left[\mathrm{e}+\mathrm{c}(S-S_R)\right] \\ I_{mp} = I_{mR}\left[1+\mathrm{a}(T-T_R)\right]\dfrac{S}{S_R} \\ U_{mp} = U_{mR}\left[1-\mathrm{b}(T-T_R)\right]\ln\left[\mathrm{e}+\mathrm{c}(S-S_R)\right] \end{cases} \tag{3}$$

$$P = IU \tag{4}$$

In Eq. (1) to (4), C1 and C2 are intermediate variables, which are determined by other variables; T and S denote the ambient temperature and light intensity of the PV module under the actual operating conditions; I, U, P, Isc, and Uoc, represent the actual current, voltage, power, short-circuit current, and open-circuit voltage, respectively; Imp and Ump refer to the current and voltage corresponding to the maximum power point (MPP); e ≈ 2.71828 is the Euler's number, and other variables are characteristic parameters which are only determined by the particular model of PV module, and remain unchanged. Table 1 lists the key specifications of the PV module type adopted in this study.

Table 1. Characteristic Parameters of PV Module

Parameter	Physical meaning	Parameter values
a	Correction coefficient between current and temperature	0.0025 /℃
b	Correction coefficient between voltage and temperature	0.00288 /℃
c	Correction factor of light intensity	0.0005 /(W·m^{-2})
T_R	Temperature under standard Standard Test Conditions (STC)	25 ℃
S_R	Light intensity under STC	1000 W·m^{-1}
I_{sR}	Isc under STC	5.1 A
U_{oR}	Uoc under STC	45 V
I_{mR}	MPP current under STC	4.5 A
U_{mR}	MPP voltage under STC	35 V

Typically, PV modules are interconnected to form PV array. As a deliberate simplification, this research defines the PV array as consisting of only one PV module. Therefore, the modeling framework for the PV array is derived directly from, and is synonymous with, that of an individual PV module.

To simulate the PV output under various operating conditions, a simulation model was built based on the established mathematical model. The simulation results, which illustrate the key output characteristics, are shown in Figures 1 and 2.

2.2. The output characteristics of PV

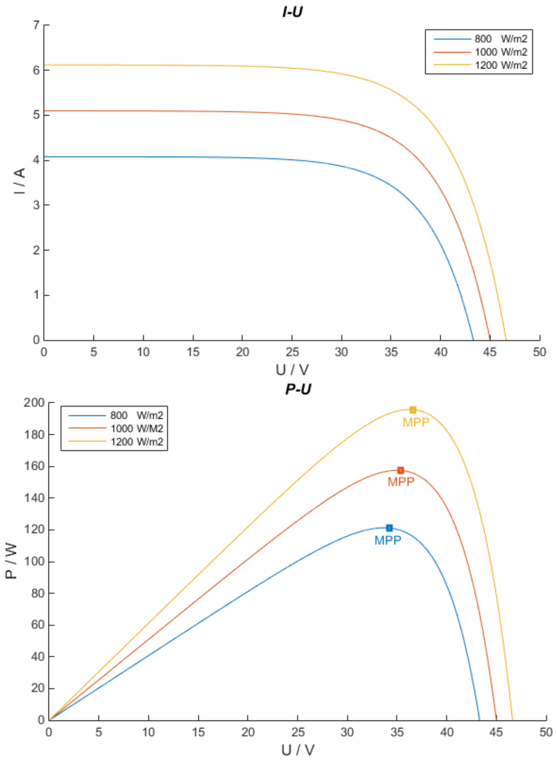

Figure 1. Output characteristics under different light intensities at T=25℃

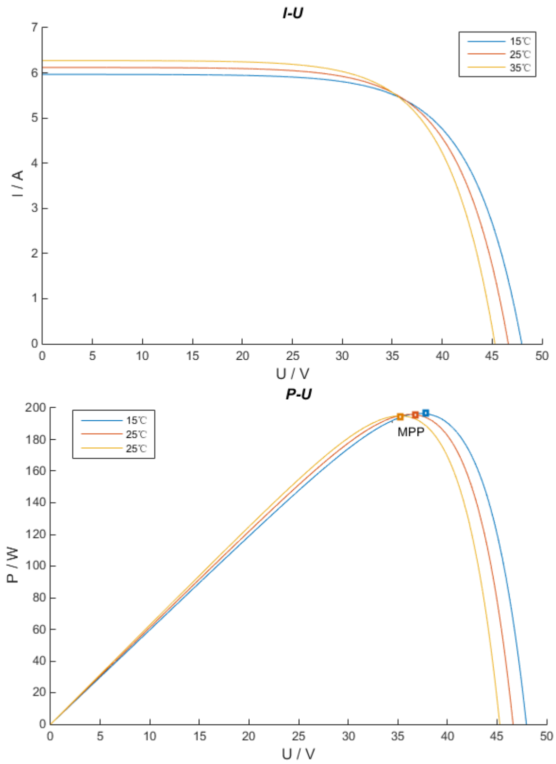

Figure 2. Output characteristics under different temperature at S=1200W/m²

The analysis results of Figures 1 and 2 are as follows:

(1) Operating conditions, mainly ambient temperature and light intensity, strongly affect the PV array output.

(2) Under fixed operating conditions, the output power of the PV array varies with the output voltage and exhibits convex nonlinear characteristics, with a unique MPP.

(3) A change in the operating parameters of PV arrays (e.g., irradiance or temperature) induces a corresponding shift in the position of its Maximum Power Point (MPP).

3. Principle of PV MPPT control

An analysis of PV array output characteristics reveals that the output voltage must be adjusted to match the MPP voltage under current conditions to achieve MPPT. While, the condition for maximizing the output power of a PV array, according to the maximum power transfer principle, is a match between its equivalent internal resistance and the input impedance of its external circuit. Therefore, MPPT of PV array is based on impedance matching and is usually achieved using Boost converter [13], which is shown in Figure 3.

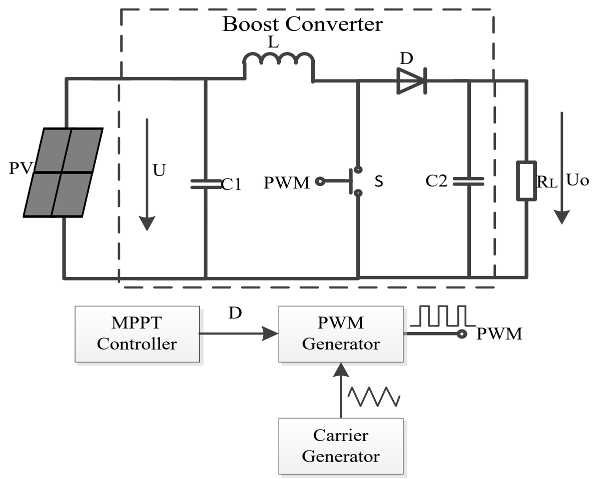

Figure 3. Principle of PV MPPT Control

In Figure 3, if the impedance and efficiency loss of the Boost converter are ignored, it can be seen that:

$$R_{eq} = R_L * (1-D)^2 \qquad (5)$$

In Eq. (5), R_{eq} refer to the equivalent input impedance of the Boost converter, and R_L refer to the load impedance, D refer to the duty cycle of the PWM wave driving the open and turn off of power electronic switches S in the Boost converter in the figure 3.

According to Eq. (5), R_{eq} will be changed when adjusting D. When R_{eq} corresponding to a certain value of D is equal to the equivalent internal resistance corresponding to the MPP of PV array, the output power is maximized, and MPPT is achieved.

Furthermore, according to the analysis of Figure 2, the output voltage of the Boost converter (denoted Uo) is expressed in terms of the input voltage U as:

$$U = (1 - D)U_O \quad (6)$$

As can be seen from equation (6), U will change with the change of D when Uo remains unchanged, and D is inversely correlated with U. Therefore, MPPT of PV array is actually a control process that aims to optimize output power via duty cycle regulation of the electronic switch to search the MPP voltage under the real-time operating conditions.

4. Design of PV MPPT control method

4.1. Principle of P&O method

The PV output curves (Figures 1 and 2) reveal that the slope of the *P-U* characteristic curve (denoted as *dP/dU*) of PV is zero precisely at the MPP. Relative to this point, *dP/dU* changes from positive to negative as the operating voltage crosses the voltage of MPP from below to above. Thus, the instantaneous operating point of the PV array can be located by evaluating *dP/dU*, and then the duty cycle of the switching pulses applied to power electronic switch in the Boost converter's is modulated to track and maintain the MPP. The changes in P and U are denoted as ΔP and ΔU, respectively, then the principle of P&O method is as follows [14]:

(1) if ΔP =0, the actual operating point of PV is located at the MPP, then there is no need to adjust U.

(2) if ΔP and ΔU share the same sign (both positive or both negative) , the operating point lies to the left of the MPP, then a reverse perturbation step size be marked ΔD should be applied to the duty ratio in order to increase U.

(3) if ΔP and ΔU have opposite signs, the operating point lies to the right of the MPP, then a forward perturbation step size be marked ΔD should be applied to the duty ratio in order to decrease U.

The P&O method are primarily classified by whether the perturbation step size (ΔD) is fixed or variable. In the fixed-step approach, ΔD remains constant, which simplifies implementation but compromises performance due to the lack of adaptive adjustment. In contrast, for the P&O method with variable-step size, ΔD adapts in accordance with the PV output conditions, so it is relatively more complex, but can reduce the MPPT convergence time and improve MPPT accuracy, exhibiting superior performance [15].

Beyond locating the operating point relative to the MPP, the magnitude of |*dP/dU*| also functions as a measure of its distance from the optimum. This relationship forms the basis for adaptive step-size adjustment: a larger |*dP/dU*| necessitates a larger ΔD to achieve faster movement toward the MPP, and a smaller |*dP/dU*| necessitates a smaller ΔD to slow down the movement speed toward the MPP. So, ΔD can be dynamically adjusted according to *dP/dU*.

4.2. Design of improved P&O method

4.2.1. Variable-step size P&O method based on fuzzy control

As an intelligent control strategy, fuzzy control employs fuzzy logic to emulate human-like reasoning and decision-making processes, which can handle uncertain input and output quantities, and has good robustness and adaptability, so it is widely used in the field of control [16,17]. The basic principle is to fuzzify the input quantities firstly, and then obtain the corresponding fuzzy output quantities through fuzzy reasoning, and precise values of output quantities are obtained through defuzzification processing at the end. The three main steps of fuzzy control are as follows [18,19]:

(1) Fuzziness: Mapping input and output output quantities onto a fuzzy set, and usually using membership functions to describe their membership in the fuzzy set.

(2) Fuzzy reasoning: associating fuzzy input and output output quantities according to fuzzy control rules.

(3) Defuzzification: Obtain the precise value of the output control quantities based on fuzzy reasoning results.

According to the previous analysis, taking *dP*/*dU* and ΔD as the input sensing quantity and output control quantity of the fuzzy controller respectively in order to automatically modulate the step size of D, and set the fuzzy domains to [-5.1, 5.1] and [-6, 6], respectively, set the corresponding fuzzy sets as [NB, NM, NS, Z, PS, PM, PB]. Figure 4 depicts the designed membership functions, while Table 2 summarizes the fuzzy control rules, which are derived from the logical relationship between the input and output variables.

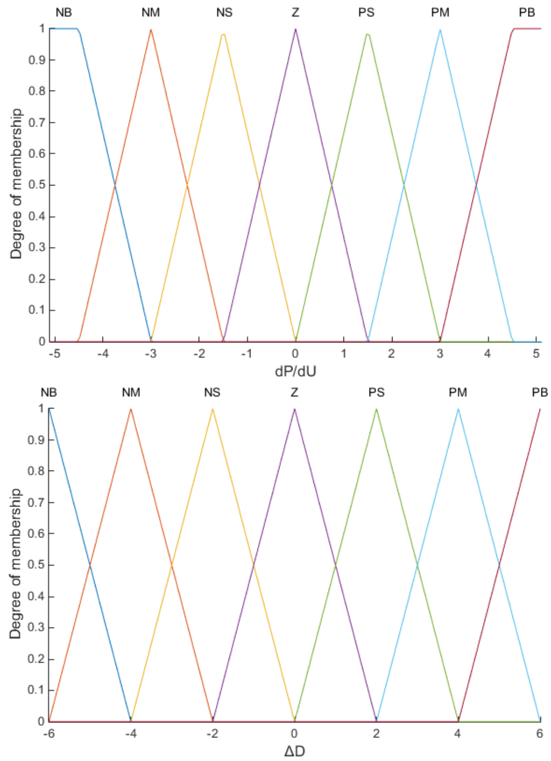

Figure 4. Membership function curve of input and output quantity of fuzzy controller

Table 2. Fuzzy control rules

dP/dU	ΔD
NB	NB
NM	NM
NS	NS
Z	Z
PS	PS
PM	PM
PB	PB

4.2.2 Improved P&O method based on hybrid control

Although the variable-step size P&O method based on fuzzy control offers dynamic step size adjustment according to the output status of the PV array, the effectiveness of the control degrades as the operating point moves away from the MPP, which delays the progress of MPPT.

Based on this, this study combines slope ratio control with fuzzy control to implement hybrid control, that is, setting a threshold be denoted as δ for $|dP/dU|$. When $|dP/dU|<\delta$, the fuzzy control is employed to regulate the step size; conversely, slope ratio control is applied, ΔD is adjusted as follows [20]:

$$\Delta D = \alpha \frac{dP}{dU} \tag{7}$$

In Eq. (7), α refers to the slope ratio coefficient.

5. Modeling and Simulation

A simulation model was developed, as depicted in Figure 5, to evaluate the applicability of the control method for PV MPPT proposed in this study.

Within the simulation architecture, the PV array in the main circuit is implemented as a packaged subsystem model, as detailed in Figure 5, which is built according to Eq. (1) to (3), and the changes in light intensity and temperature of operating conditions are simulated through the step modules. The control part includes two functional blocks: MPPT control module and PWM generator module. In addition, adopt 4ms as the sampling period of simulation system.

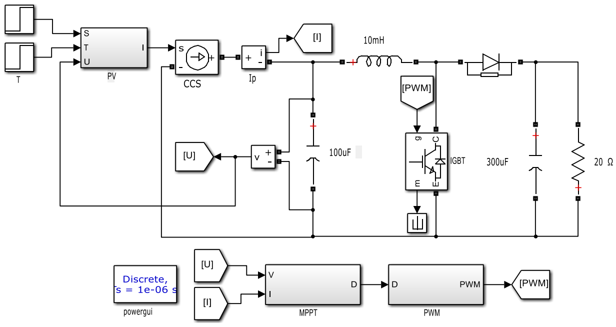

Figure 5. Simulation model of MPPT for PV

Figure 6 illustrates the simulation model of the PWM generator module, in which, set the carrier frequency to 20kHz, and set the variation range to [0,1].

The proposed improved P&O method based on hybrid control for PV MPPT was evaluated against two conventional approaches: the fixed-step size P&O method and the variable-step size P&O method based on fuzzy control. All methods were initialized with the same duty cycle (D=0.5) to guarantee equitable comparison.

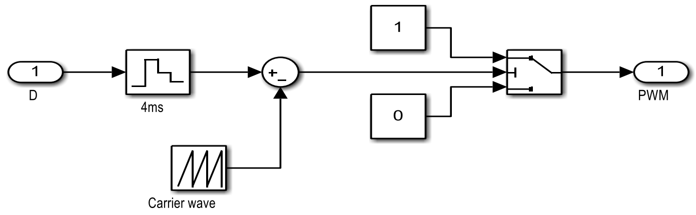

Figure 6. Model of PWM module

The simulation models for each control method are constructed below:

(1)Fixed-step size P&O method (be denoted as Method 1)

The step size is set to be 0.01, and the corresponding simulation model was developed and is depicted in Figure 7.

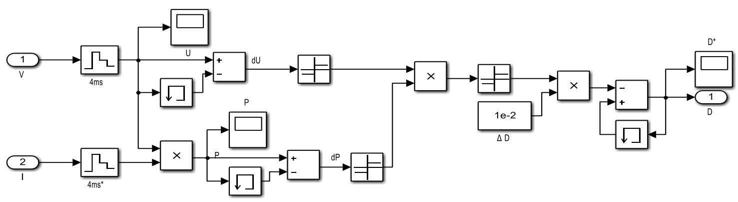

Figure 7. Model of fixed-step size P&O method

(2)Variable-step size P&O method based on fuzzy control (be denoted as Method 2)

Set the output scaling factor of the fuzzy control to be 0.02/6, and the corresponding simulation model was developed and depicted in Figure 8.

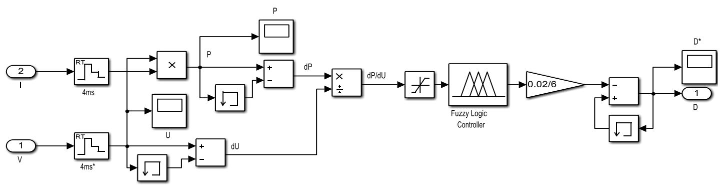

Figure 8. Model of variable-step size P&O method based on fuzzy control

(3)Improved P&O method based on hybrid control (be denoted as Method 3)

Set δ and α to be 3 and 0.01respectively , and the fuzzy controller is configured to be identical to Method 2. The corresponding simulation model was developed and depicted in Figure 9.

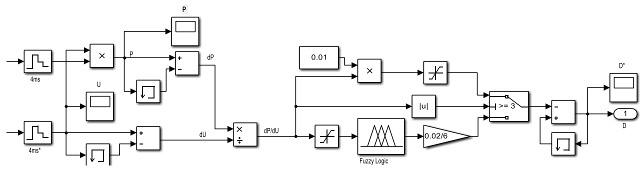

Figure 9. Model of improved P&O method based on hybrid control

To comprehensively and systematically evaluates and compares the performance of different MPPT control method, adjust the PV operating conditions according to the parameters shown in Table 3 to execute simulation tests covering start-up scenarios and sudden changes in operating conditions. In addition, analysis of Figures 1 and 2 yields the maximum power (denoted as P_M) for each operating condition.

Table 3. Parameters of PV operating condition

Test Type	Time (s)	S (W/m^2)	T (°C)	P_M (W)
Test for start-up	0~0.1	800	25	121.2863
Test for sudden changes in operating conditions	0.1~0.2	1200	35	194.9574

Figs. 10, 11 and 12 depict the curve variations of D, U and P of the various method after simulation, respectively.

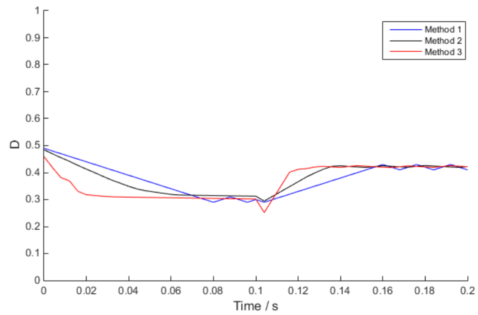

Figure 10. Curve of D

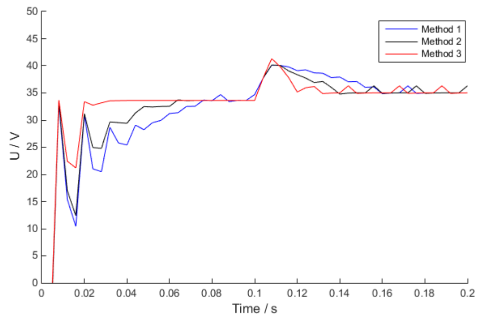

Figure 11. Curve of U

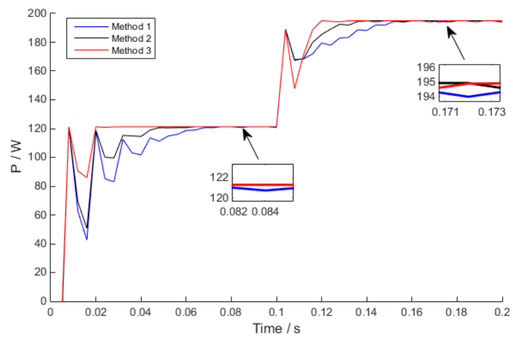

Figure 12. Curve of P

From the simulation curves presented above, the following observations can be made:

(1) In both test scenarios, the improved P&O method proposed completes MPPT more rapidly.

(2) In the start-up test, after completing MPPT, the fixed-step P&O method induces pronounced oscillations in the PV output power, a drawback effectively mitigated by the variable-step, which maintains a stable power output, especially in the improved P&O method based on hybrid control proposed in the study.

(3) During the test for sudden changes in operating conditions, all three methods show some degree of oscillation after completing MPPT, with roughly comparable magnitudes of fluctuation.

(4) Overall, the oscillation of photovoltaic output is minimized when using the improved control method in MPPT process.

To evaluate the performance of various control method of PV MPPT more accurately, the quantitative analysis of MPPT speed and precision is conducted. The instant when the change of D between two adjacent sampling points is less than 0.05% or when the D begins to exhibit periodic variation is considered as the moment when MPPT is completed, which is denoted as t_c. and the time interval from the start of the current operating condition to t_c is taken as the MPPT time (denoted as t_{MPPT}), and the average output power from t_c to the end moment of the current operating condition being denoted as t_e is defined as the MPPT power (denoted as P_{MPPT}), and it is computed as below:

$$P_{\mathrm{MPPT}} = \frac{\int_{t_c}^{t_e} P dt}{t_e - t_c} \tag{8}$$

Then, the MPPT accuracy be denoted as ρ is calculated as follows:

$$\rho = \frac{P_{\mathrm{MPPT}}}{P_{\mathrm{M}}} * 100\% \tag{9}$$

The analysis results derived from the simulation data are presented in Table 4.

Table 4. Results of simulation

MPPT Method	Criteria	Test Type	
		Test for start-up	Test for sudden changes in operating conditions
Method 1	t_{MMPT} (s)	0.072	0.052
	P_{MPPT} (W)	121.0619	194.6840
	ρ	99.8149%	99.8598%
Method 2	t_{MMPT} (s)	0.064	0.036
	P_{MPPT} (W)	121.2832	194.7180
	ρ	99.9974%	99.8772%
Method 3	t_{MMPT} (s)	**0.040**	**0.028**
	P_{MPPT} (W)	**121.2833**	**194.7285**
	ρ	**99.9975%**	**99.8826%**

As shown in Table 4, the three control methods mentioned above can all achieve MPPT within a certain period of time, and the MPPT time in the start-up test is longer than that in the test for sudden changes in operating conditions. In addition, in the two tests, the proposed improved P&O method based on hybrid control yields the shortest MPPT time, the largest output power and the highest MPPT accuracy. Therefore, it has the highest MPPT efficiency relatively, which verifies its progressiveness and applicability.

6. Conclusions

This study proposes an improved P&O method based on hybrid control for PV MPPT after comprehensive analyzing the output characteristics of PV array, which integrates fuzzy control algorithm and slope ratio control algorithm, and adaptively adjusts the step size based on dP/dU to shorten the time and improve the accuracy for PV MPPT.

The proposed method was benchmarked against both fixed-step P&O method and variable-step size P&O method based on fuzzy control by performing simulation tests under start-up and sudden changes in operating conditions of PV to compare their efficiencies. The results indicated that the improved method yielded very promising results and outperformed the other methods. Analysis of the results of this study leads to the following conclusions:

(1) The improved control method proposed in this study can achieve high-precision MPPT in both start-up scenarios and scenario involving a sudden change in operating conditions of PV.

(2) The proposed MPPT method can achieve MPPT quickly in both start-up scenarios and scenario involving a sudden change in operating conditions of PV.

(3) Compared to the other two MPPT methods, the proposed MPPT method can reduce the fluctuations of output power of PV arrays to a certain extent and shorten tracking time and improve tracking accuracy. Therefore, it achieves higher MPPT efficiency.

For the future studies, a physical PV MPPT system can be built to validate the practicality of the improvement MPPT control method through physical testing. Moreover, Some aspects of the proposed MPPT method can be further improved in the future. For instance, introducing emerging intelligent algorithms such as Gradient optimization, Simulated annealing Algorithm, and Grey wolf optimization to adjust the output scaling factor of fuzzy control to enhance the control effect of fuzzy control, which can further enhance the MPPT performance.

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