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An Fuzzy improved perturb and observe (P&O) maximum power point tracking (MPPT) algorithm for Microbial Fuel Cells

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Microbial fuel cells (MFCs) are getting more and more attention due to their unique wastewater treatment and synchronous power generation capabilities. In order to improve their power generation efficiency, maximum power point tracking (MPPT) control becomes necessary. Aiming at the problems of slow tracking speed and serious steady-state oscillation in the traditional perturb & observe algorithm (P&O), an improved P&O method based on fuzzy control is proposed, a fuzzy logic controller is designed to adjust the disturbance step in real time to quickly find the maximum power point and make the MFC run stably at the maximum power point. Simulation results show that the proposed fuzzy improved P&O method can greatly improve the response speed, reduce the steady-state oscillation, and effectively resist the influence of various disturbances.

Keywords: fuel cells, maximum power point trackers, perturbation methods, fuzzy control, energy efficiency

1. INTRODUCTION

The global energy crisis caused by the depletion of fossil fuels is escalating, which makes the development of renewable clean energy become a focus of worldwide attention [1-3]. Microbial fuel cell (MFC) is a potential renewable energy option, which can not only be used for wastewater treatment, but also can be used to produce bioenergy [4], so it has received extensive attention in both the environment and energy fields. The application of MFCs will play an important role in solving the problems of energy crisis and environmental pollution [5]. However, MFC is a complex biochemical reaction system, and its operation performance is easily affected by many internal and external factors such as ambient temperature, feed flow, pH value, electrode material, load disturbance and so on [6-8]. Due to the problems of low power generation efficiency, high operation cost and unstable power supply, the application of MFC is still limited. Recently, several methods have been proposed to improve MFC performance, including the development of high-performance electrodes and membranes [9, 10], the modification of conventional membranes and electrodes [11, 12], the preparation of more appropriate catholyte [13], and the cultivation of more active exoelectrogens [14]. However, MFC has not yet been used as a stand-alone external device [15]. The cost and energy efficiency of MFC must reach a satisfactory level before it can be popularized in the actual process [16]. However, the nonlinear and hysteresis characteristics caused by a large number of bioelectrochemical coupling reactions make it difficult for MFC to control and optimize power generation by direct experimental means [17].

In order to improve the power generation efficiency and output stability of MFC, advanced control technology is an alternative solution. In particular, the maximum power point tracking (MPPT) algorithm has been widely used in photovoltaic power generation [18], wind power generation [19], wind-solar hybrid power generation [20] and some other power systems to improve power generation efficiency. In recent years, MPPT technology has gradually appeared in MFC system [21].

At present, the frequently-used MPPT methods mainly include constant voltage (CVT), perturb & observe algorithm (P&O), conductance increment (INC), hill climbing (HC), etc. P&O algorithm is the most widely used method due to its advantages of simple control algorithm and easy operation. However, the traditional P&O algorithm cannot ensure the response speed and stability of the system due to the fixed step length, which leads to continuous oscillation near the maximum power point when the system approaches its steady state [22, 23].

Fuzzy logic control using linguistic information has the advantages of robustness, model free, universal approximation theorem and rule-based algorithm. It is considered as a useful tool to solve the control problems of complex nonlinear systems. In order to solve the problem of accuracy and speed of MPPT control in MFC system, an improved P&O algorithm based on fuzzy control is proposed in this paper, and a hybrid circuit combined with MFC and boost convertor has been designed to realize the MPPT control scheme. By adjusting the duty cycle of the boost converter in real time, the equivalent load resistance of the MFC can match its internal resistance which changes with the reaction conditions in real time, so that the MFC can quickly track and stabilize at its maximum power point, and then achieve the control purpose of maintaining the maximum power output of the MFC.

2. MODEL OF MFC

The popular and basic design of MFC is dual chambered reactor. A dual-chamber MFC system, as shown in Fig. 1, which consists of anode chamber, cathode chamber, proton exchange membrane, cathode and anode. The anode chamber and cathode chamber are separated by the proton exchange membrane. In the anode chamber with anaerobic environment, the substrate is degraded by exoelectrogens, producing protons and electrons; the electrons are transferred to the cathode through an external circuit to produce electric energy, the protons are transferred to the cathode through the membrane. Electrons and protons reaching the cathode produce water by reducing oxygen.

Mathematical model is considered as a fast and effective approach to deeply understand the operation process and verify the effectiveness of the optimized control scheme. In recent years, many researches focus on the fields related to MFCs modeling. Generally, MFC models mainly describe the biochemical reaction process, mass transfer process and power generation process of the system. For a lab scale MFC system shown in Fig. 1, a model that can comprehensively describe the dual chamber microbial fuel cell is needed.

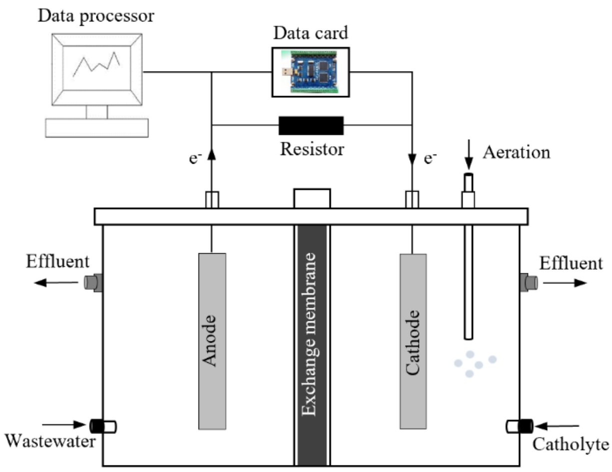


Figure 1. A practical MFC experimental system

For a double-chamber MFC using acetate as fuel, the mass balance equations in the anode can be described as:

$$V_{\mathrm{a}}\frac{\mathrm{d}C_{\mathrm{AC}}}{\mathrm{d}t}=Q_a\left(C_{\mathrm{AC}}^{\mathrm{in}}-C_{\mathrm{AC}}\right)-A_{\mathrm{m}}r_1 \tag{1}$$

$$V_{\mathrm{a}}\frac{\mathrm{d}C_{\mathrm{CO_2}}}{\mathrm{d}t}=Q_a\left(C_{\mathrm{CO_2}}^{\mathrm{in}}-C_{\mathrm{CO_2}}\right)+2A_{\mathrm{m}}r_1 \tag{2}$$

$$V_{\mathrm{a}}\frac{\mathrm{d}C_{\mathrm{H}}}{\mathrm{d}t}=Q_{\mathrm{a}}\left(C_{\mathrm{H}}^{\mathrm{in}}-C_{\mathrm{H}}\right)+8A_{\mathrm{m}}r_1 \tag{3}$$

$$V_{\mathrm{a}}\frac{\mathrm{d}X}{\mathrm{d}t}=Q_{\mathrm{a}}\frac{\left(X^{\mathrm{in}}-X\right)}{f_{\mathrm{x}}}+A_{\mathrm{m}}Y_{\mathrm{ac}}r_1-V_{\mathrm{a}}K_{\mathrm{dec}}X \tag{4}$$

The mass balance equations in the cathode can be described as:

$$V_{\mathrm{c}}\frac{\mathrm{d}C_{\mathrm{O_2}}}{\mathrm{d}t}=Q_{\mathrm{c}}\left(C_{\mathrm{O_2}}^{\mathrm{in}}-C_{\mathrm{O_2}}\right)+r_2A_{\mathrm{m}} \tag{5}$$

$$V_{\mathrm{c}}\frac{\mathrm{d}C_{\mathrm{OH}}}{\mathrm{d}t}=Q_c\left(C_{\mathrm{OH}}^{\mathrm{in}}-C_{\mathrm{OH}}\right)-4r_2A_{\mathrm{m}} \tag{6}$$

$$V_{\mathrm{c}}\frac{\mathrm{d}C_{\mathrm{M}}}{\mathrm{d}t}=Q_{\mathrm{c}}\left(C_{\mathrm{M}}^{\mathrm{in}}-C_{\mathrm{M}}\right)+N_{\mathrm{M}}A_{\mathrm{m}} \tag{7}$$

In Equ. (1) to Equ. (7), the subscripts ‘a’ and ‘c’ stand for the anode and the cathode respectively, and the superscript ‘in’ denotes feed flow; C_{AC}, C_{H}, C_{OH}, C_{O2}, C_{CO2} and X are the concentrations of acetate, hydrogen ions, hydroxyl ions, oxygen, carbon dioxide and biomass, respectively; and C_{M} is the concentration of M^+ ions, N_{M} is the flux of M^+ ions transferred from the anode chamber to cathode chamber through the proton exchange membrane, which can be derived by:

$$N_{\mathrm{M}} = \frac{3600I}{F} \tag{8}$$

where F is the Faraday's constant, I is the output current of MFC.

The reaction rates of the anode and cathode chamber can be described as:

$$r_1 = k_1^0 \exp\left(\frac{\alpha F}{RT}\eta_a\right)\frac{C_{\mathrm{AC}}}{K_{\mathrm{AC}} + C_{\mathrm{AC}}} X \tag{9}$$

$$r_2 = -k_2^0 \frac{C_{\mathrm{O_2}}}{K_{\mathrm{O_2}} + C_{\mathrm{O_2}}} \exp\left[(\beta - 1)\frac{F}{RT}\eta_c\right] \tag{10}$$

where r_1 and r_2 denote the reaction rates of the anode and cathode chamber, respectively; η_{a} and η_{c} are the over potential of at the anode and the cathode, respectively.

The charge balance equations at the anode and cathode can be described as:

$$C_{\mathrm{a}} \frac{\mathrm{d}\eta_{\mathrm{a}}}{\mathrm{d}t} = 3600I - 8Fr_1 \tag{11}$$

$$C_{\mathrm{c}} \frac{\mathrm{d}\eta_{\mathrm{c}}}{\mathrm{d}t} = -3600I - 4Fr_2 \tag{12}$$

The output voltage U of the MFC is calculated as follows:

$$U = U^0 - \eta_{\mathrm{a}} + \eta_{\mathrm{c}} - \left(\frac{d^{\mathrm{m}}}{k^{\mathrm{m}}} + \frac{d_{\mathrm{cell}}}{k^{\mathrm{aq}}}\right) I \tag{13}$$

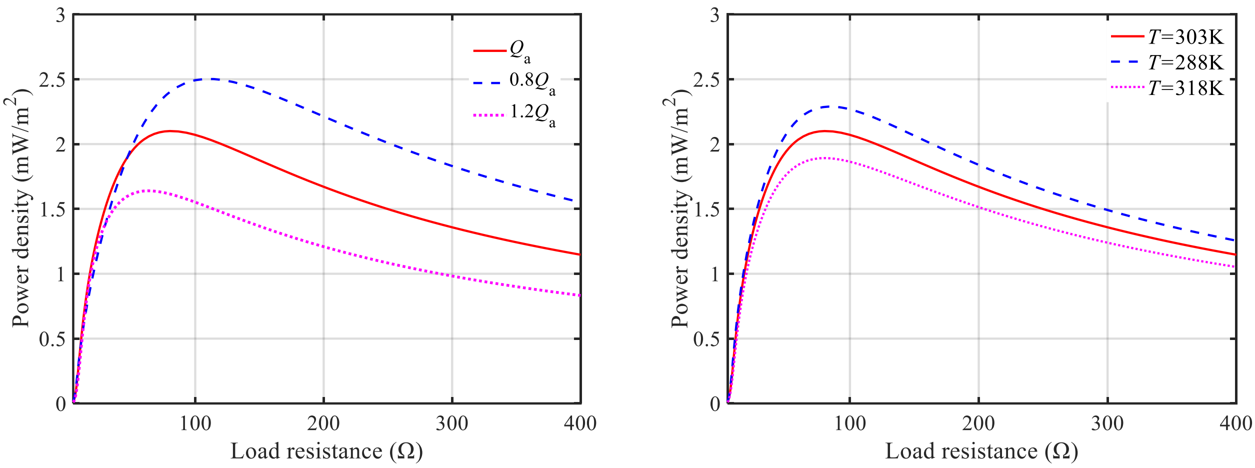
The physical meanings and their corresponding initial values of all the variables and parameters in the above equations are mainly derived from references [24].

Based on the dual-chamber MFC model described above, am integrated simulation platform of MFC has been established with MATLAB/Simulink in our preliminary work, which can effectively test the real-time operation status of MFC under different conditions [25].

3. MPPT ALGORITHM

3.1 Basic control ideas

The output power of MFC varies with the reaction conditions. But many studies have found that no matter how the reaction conditions change, there is always a peak point on the power curve, and the peak point is the maximum power point. The power density characteristic curves of the MFC system under different feed flow and different temperatures are shown in Fig. 2. It can be seen from these curves that there is an obvious peak value on each power curve, which indicates that the maximum power point is inevitable, which proves that the maximum power point really exists. According to the relevant circuit knowledge, when the external resistance is equal to the internal resistance of a power supply, the output power of the electric source can reach the maximum power point; when the internal resistance and the external resistance are not equal, about 50% of the power produced by the fuel cell may be lost [26]. Therefore, MPPT control is one of the necessary technologies to dynamically extract the maximum possible power from MFC and thus reduce energy loss.



(a) different feed flow (b) different temperatures

Figure 2. Power density curve of an MFC under different feed flow

The MFC power generation system including MPPT controller is shown in Fig. 3. The boost converter is used as a regulator to implement the MPPT control scheme due to its simple structure, ease control and voltage amplification. On the other hand, the inductance at the input port of the boost convertor can also effectively ensure the continuity and stability of the output current of the whole MFC system, so as to ensure the safe and stable operation of the load and greatly reduce the power loss.

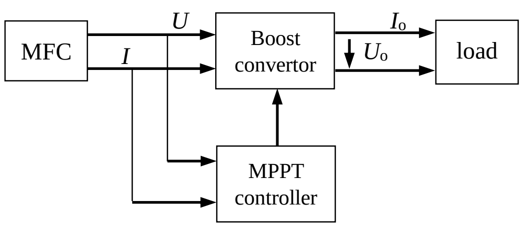


Figure 3. Diagram of control system of MFC

Assuming that the Boost convertor is an ideal circuit; U and I are the input voltage and current of the boost convertor, respectively (in other words, the output voltage and current of the MFC, respectively); U_o and I_o are the output voltage and current of the boost convertor, respectively. According to the relevant theories of circuit and power electronics technology, some variables used to analyze system performance in this study can be expressed as:

$$U_O = \frac{1}{1-D}U \tag{14}$$

$$I_O = (1-D)I \tag{15}$$

$$R_L = \frac{U_O}{I_O} \tag{16}$$

$$R_{eq} = \frac{U}{I} = (1-D)^2 R_L \tag{17}$$

$$P_A = \frac{UI}{A} \qquad (18)$$

in which, D is the duty ratio of the boost converter; R_L is the external load resistance; R_{eq} is the equivalent load resistance of MFC; P_A denotes the output power density of MFC; and A denotes the area of membrane.

It can be seen from Equ. (17) that adjusting the duty ratio of the boost convertor is equivalent to adjusting the equivalent load resistance of MFC. Thus, when the internal resistance of MFC changes with the change of some reaction conditions, by adjusting the duty ratio of the boost converter, the external load resistance can be controlled to a value equal to the internal resistance of MFC, so as to control and maintain the output power at the maximum power point.

3.2 Traditional P&O algorithm

P&O is an MPPT algorithm based on iterative algorithms. Its basic idea is to continuously impose disturbance on the output voltage, so that the output power is constantly approaching the maximum power point. The specific process is shown in Fig. 4. Assuming that the initial system is working at point A and its corresponding output power is P_A; then a positive perturbing voltage is exerted on the system and the output power changes to P_B, and then judge the change of power and determine the disturbance direction in the next step. If $P_B > P_A$, then continue to carry out forward disturbance; otherwise, reverse disturbance is imposed.

The focus of the P&O algorithm is to determine the direction of the applied disturbance. For MFCs, it is difficult to directly control its output voltage, so the duty cycle of boost convertor is selected as the manipulated variable to indirectly control the output voltage. According to Equ. (19), the direction of duty cycle disturbance is completely opposite to the direction of voltage disturbance, and the search direction of the maximum power point tracked by P&O algorithm is adjusted accordingly.

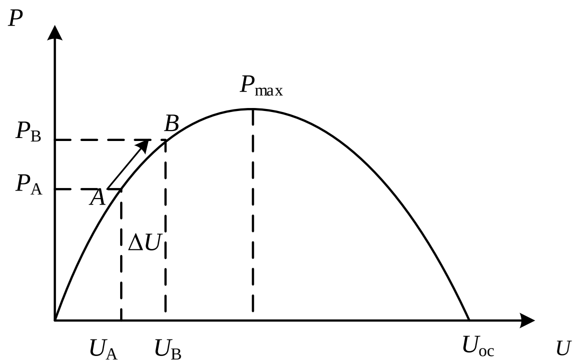


Figure 4. Schematic diagram of P&O algorithm

Compared with photovoltaic system and wind generation system, MFC system is much more complex, and its problems of multivariable, nonlinear, strong coupling, time-delay are very serious. Due to the change of microbial activity or environmental conditions, the output power of MFC fluctuates continuously, so it is difficult to maintain under its maximum power point. There is a big gap in tracking accuracy and tracking speed of MFC controlled by traditional P&O algorithm [27]. In the previous research, our research group compared the application effects of conventional P&O algorithm and variable-step P&O algorithm in MFC, and the research results show that the conventional P&O algorithm can only make the output of MFC close to its maximum power point, but can not make it stable at the maximum power point, and there is a large oscillation in the output power; especially when the load changes, the conventional P&O algorithm often loses the tracking ability, resulting in the output power far deviates from its maximum power point. A logarithmic function was introduced to the improved P&O algorithm to adjust the search step [28], which can greatly improve the accuracy and stability of tracking power; however, when the load changed, the variable step P&O algorithm made the MFC stable at another power point rather than its actual maximum power point, which means that the variable step P&O algorithm failed to track the actual maximum power point when the load changed. Therefore, we try to further improve the P&O algorithm based on the fuzzy theory to achieve more effective MPPT control of MFC.

3.3 Fuzzy-improved P&O algorithm

Conventional P&O algorithm has become the most widely used method because of its simple and easy implementation. However, it can only make the system close to but not stabilize at the maximum power point, and the steady state fluctuation is relatively serious, thus the tracking speed and accuracy cannot be guaranteed.

MPPT based on fuzzy logic can track the global maximum power point through soft computing. But in practice, designing fuzzy rules can be considered as design complexities, and the accuracy of simple fuzzy control is highly dependent on expert experience. Compared with fuzzy MPPT method, P&O algorithm can be classified as methods that are not very complex to design and implement.

Considering the advantages and disadvantages of conventional P&O algorithm and fuzzy logic control, a fuzzy-improved P&O algorithm is proposed for maximum power tracking control of MFC. According to the output characteristics of the MFC, the fuzzy control system uses reasonable fuzzy logic rules to correct the magnitude and direction of the disturbance in real time, then make the MFC reach the vicinity of the maximum power point quickly and accurately, and thus the problem of tracking speed and accuracy of traditional P&O algorithm is solved.

Fig. 5 shows the flow chart of the proposed fuzzy P&O algorithm. In the process of using fuzzy improved P&O algorithm to track the maximum power point, the main reasoning process of fuzzy controller is as follows: First the output voltage $U(k)$ and current $I(k)$ of the MFC are first collected to calculate the output power $P(k)$, then the voltage variation ΔU and power variation ΔP are obtained by comparing with the values $U(k\text{-}1)$ and $P(k\text{-}1)$ at the previous sampling time to used as the inputs of the fuzzy controller. If $\Delta P > 0$ and $\Delta U > 0$, the working point is on the left side of the MPP, and $\Delta d > 0$ is obtained, thus the duty cycle need to be reduced; If $\Delta P > 0$ and $\Delta U < 0$, the working point is on the right side of the MPP, and Δd <0 is obtained to increase the duty cycle; If $\Delta P < 0$ and $\Delta U < 0$, the working point is on the left side of the MPP, and Δd >0 is obtained to reduce the duty cycle; If $\Delta P < 0$ and $\Delta U > 0$, the working point should be on the right side of the MPP, and Δd <0 is obtained to increase the duty cycle. Because the fuzzy controller constantly adjusts the disturbance direction and size according to the changes of voltage and power, the search speed and accuracy of MPP can be guaranteed.

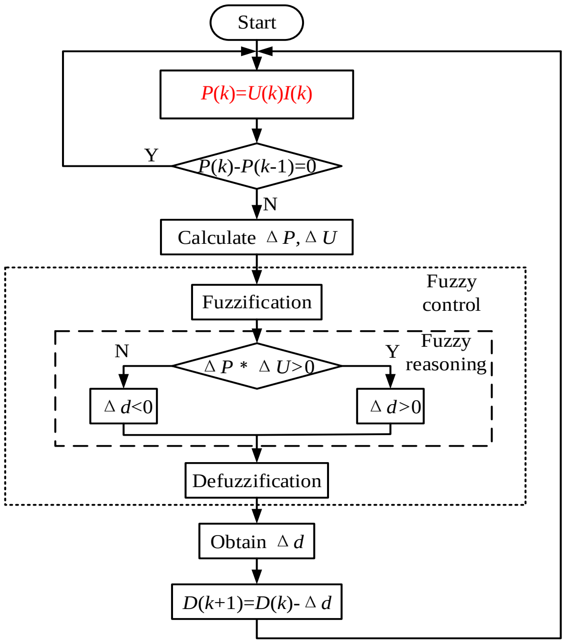


Figure 5. Flow chart of fuzzy improved P&O algorithm

3.4 Design of Fuzzy Controller

Fuzzy controller is the core part of the fuzzy P&O system. The main design steps of the fuzzy controller mainly include:

(1) Confirmation of fuzzy input and output

The changes of power and voltage of MFC, namely ΔP, ΔU, are used as the inputs of the fuzzy controller, and their fuzzy set is {NB, NS, ZE, PS, PB}, and NB denotes negative big, NS denotes negative small, ZE represents zero, PS represents positive small, and PB represents positive big; the output of the fuzzy controller is actually used as the adjustment of the duty cycle, that is, Δd, and its fuzzy set is designed as {NB, NM, NS, ZE, PS, PM, PB}, and here NM indicates negative middle, PM indicates positive middle. The basic domain of input and output is defined as [-1, 1].

(2) Determination of membership function

Since the output characteristics of MFC near the maximum power point are approximately symmetrical, triangular functions with symmetrical structure is used as the input and output membership function, which is shown in Fig. 6.

(3) Determination of fuzzy rules

The Mamdani fuzzy inference algorithm is used in designing the fuzzy controller. In order to achieve the purpose of MPPT control, by following the principle that the closer to the maximum power point, the smaller the disturbance step, the fuzzy control rules have been designed as shown in Table 1.

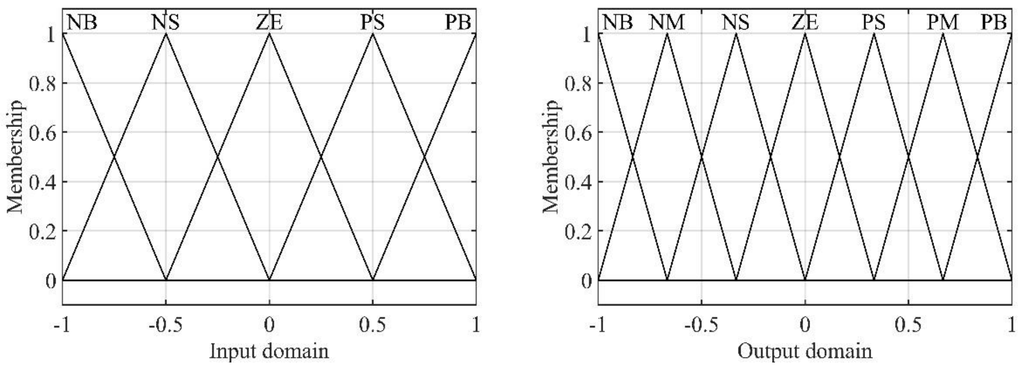


Figure 6. Membership function of input and output

Table 1. Fuzzy control rules

Δd	ΔU					
		NB	NS	ZE	PS	PB
ΔP	NB	PB	PB	ZE	NB	NB
	NS	PM	PS	ZE	NS	NM
	ZE	NS	ZE	ZE	ZE	PS
	PS	NM	NS	ZE	PS	PM
	PB	NB	NB	ZE	PB	PB

4. SIMULATION AND ANALYSIS

4.1 Basic operating conditions

Both the conventional P&O and the fuzzy improved P&O control schemes are simulated in Matlab/Simulink, and the results are compared and analyzed. A fixed step of 0.05 is used in P&O algorithm. The total simulation time is set to 1500 h.

The selection of sampling period has an important influence on the accuracy of sampling data and the performance of MPPT algorithm. If the sampling period is too large, the MPPT algorithm continues to misjudge, and the system cannot converge to the maximum power point. If the sampling period is too small, the sampled data is transient, which leads to severe system oscillation and serious power loss. After many simulations of MFC, it is found that the time from start to steady state of MFC studied in this paper is about 15 h. In order to ensure the relative stability of the sampling values, the sampling time of current and voltage are set to 15 h.

4.2 Operation with varying feed flow

Fig. 7 shows the output power density curves of MFCs under different feed flow and the corresponding duty cycle curves of the boost convertor. In Fig. 8, the ambient temperature is kept at 303 K, and the load resistance is fixed at 500 Ω. In the initial stage, the anode feed flow rate is Q_a (=2.25×10^{-5} m^3/h). When the running time reaches 500 h, the anode feed flow changes from Q_a to $0.8Q_a$, and after 1000 h of operation, the anode feed flow changes from $0.8Q_a$ to $1.2Q_a$.

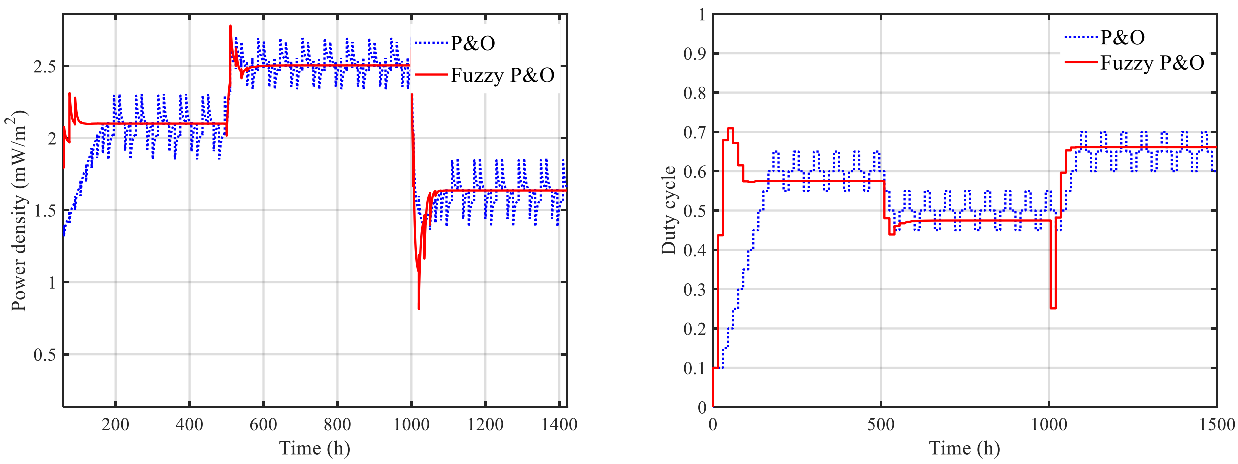


Figure 7. The power density of MFC and the duty cycle of boost convertor under different feed flow

It can be seen from the operation results that the conventional P&O algorithm has a certain tracking ability for the maximum power point of MFC, but the tracking speed is slow and the tracking accuracy is low. In the initial stage, it takes about 180 h to approach the maximum power point (2.1 mW/m^2), and it can not make the MFC stabilize but make it fluctuate up and down centered on the maximum power point, with a fluctuation range of about 10%. However, when the fuzzy improved P&O algorithm is adopted, MFC can quickly approach the maximum power point, and in the initial stage, it takes about 100 h to reach the maximum power point and stabilize at it; even better, the steady-state error in this case is close to 0.

Further analysis shows that both the P&O algorithm and the improved P&O algorithm can re-track the new maximum power point again when encountering feed flow fluctuation. However, the control effects of the two methods are significantly different. P&O algorithm can not make the MFC completely stable at the maximum power point, but can only make it oscillate near the new maximum power point; while the fuzzy improved P&O algorithm can make the MFC quickly track the new maximum power point, that is, 2.5 mW/m^2 at $0.8Q_a$ and 1.65 mW/m^2 at $1.2Q_a$, and stabilize it with an error close to zero. The maximum power values tracked by the fuzzy improved P&O algorithm under the three feed flows are completely consistent with the actual maximum power points of MFC under these three corresponding conditions as shown in Fig. 2. This means that the improvement of P&O algorithm by fuzzy logic is much effective, which not only significantly improves the tracking speed and tracking accuracy, but also improves the steady-state performance index.

4.3 Operation with varying temperature

Fig. 8 shows the output power density curves of MFC under different ambient temperature and the corresponding duty cycle curves of the boost convertor. Here the feed flow of anode chamber is Q_a (=2.25×10^{-5} m^3/h), and the load resistance remains at 500 Ω. The ambient temperature T is started at 303 K. At the time of 500 h, the ambient temperature changes from 303 K to 288 K; and changes from 288 K to 318 K at the time of 1000 h.

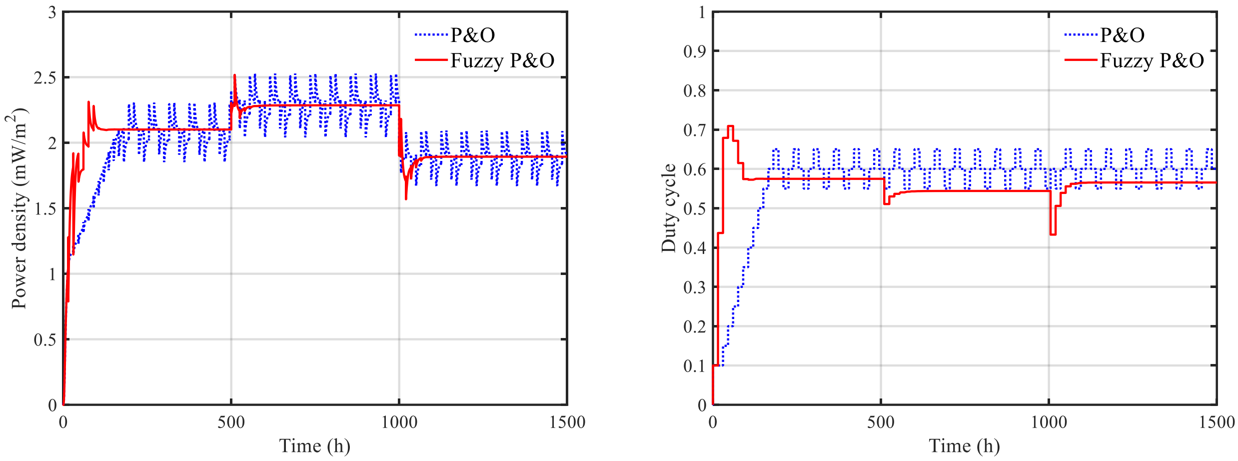


Figure 8. The power density of MFC and the duty cycle of boost convertor under different temperature

As can be seen from Fig. 8, when the ambient temperature changes, both the general P&O tracking algorithm and the fuzzy improved P&O algorithm can basically track the maximum power point according to the changing working conditions. However, by comparing the results, it can be found that there are some significant differences in the control effect between the the general P&O algorithm and the fuzzy improved P&O algorithm. On the one hand, the maximum power point tracking based on P&O algorithm still cannot solve the problems of slow tracking speed and steady-state oscillation, while the tracking speed and steady-state performance of fuzzy P&O method have been significantly improved. The fuzzy P&O algorithm can make the MFC track and stabilize at the respective maximum power values under the three different temperature conditions, that is, 2.1 mW/m^2 at 303 K, 2.3 mW/m^2 at 288 K and 1.9 mW/m^2 at 318 K, which is completely consistent with the maximum power values at the three conditions shown in Fig. 2(b). On the other hand, when the general P&O method is adopted, the duty cycle fluctuates violently and frequently, which virtually increases the difficulty of realizing the controller; but when the fuzzy improved P&O method is adopted, the corresponding duty cycle remains constant for most of the time except for a short adjustment time at the beginning of temperature change, which means that it is very advantageous for the implementation of the controller. Therefore, the fuzzy improved P&O method can make MFC realize the maximum power point tracking output accurately and quickly, and can also effectively resist the influence of temperature change.

4.4 Operation under different load

In order to test the anti-interference ability of the proposed improved method to load disturbance, variable load simulation experiments were carried out. Here the anode feed flow rate was 2.25×10^{-5} m^3/h, the ambient temperature was 303 K, and the load resistance changed from 500 Ω to 1000 Ω at 800 h. The simulation results are shown in Fig. 9.

It can be seen from the operation results that the fuzzy improved P&O method can quickly track the maximum power point of MFC and keep stable run at its global maximum power point approximately without error, even if it encounters the change of load. No matter whether the load resistance is 500 Ω or 1000 Ω, the maximum power point tracked and stabilized by the fuzzy improved P&O algorithm is 2.1 mW/m^2, which is completely consistent with the actual maximum power value under the same temperature and feed flow shown in Fig. 2. The tracking speed of the conventional P&O algorithm is obviously slower than that of the fuzzy improved P&O method. More obviously, after encountering the load disturbance, although the conventional P&O algorithm can make the system return to the vicinity of the maximum power point after a period of adjustment, the oscillation of the system output near the maximum power point is more serious than that before the disturbance occurs. These comparisons clearly show that the conventional P&O algorithm is not well adapted to the influence of load disturbance, while the fuzzy improved P&O algorithm not only completely overcomes the defects of slow tracking speed and large steady-state fluctuation of the conventional P&O algorithm, but also improves the adaptive ability to resist load disturbance.

In addition, compared with the variable step P&O algorithm mentioned in Section 3, the fuzzy improved P&O algorithm can still accurately track the actual maximum power point without causing misjudgment even after the load disturbance occurs in the system, rather than deviate from the actual maximum power point.

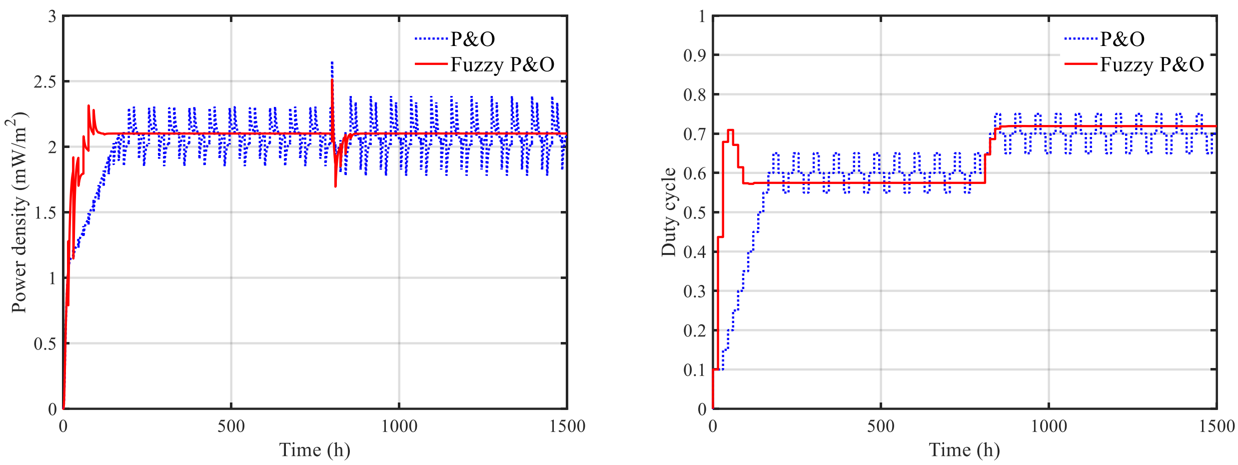


Figure 9. Power density and duty cycle under different load

It can also be found through comparative analysis of Fig. 7 to Fig. 9 that the change of temperature and feed flow rate causes change of the maximum power point of MFC, while the change of load has no effect on that. This means that the temperature and the feed flow rate are the "internal factors" that affect the power generation capacity of a MFC, while the load, as the external factor, has no impact on the power generation capacity of MFC. Therefore, when designing the control system to improve the power generation capacity of MFC, the influencing factors such as temperature or feed flow can be selected as manipulated variables.

Energy is also an important indicator to reflect the capacity of power generation device. In order to further compare the power generation capacity of MFC under different operating conditions, the power generation energy values of MFCs with P&O algorithm and fuzzy improved P&O algorithm is calculated and compared. Considering the time-varying power generation of MFC, the power generation energy W in a certain operation period T_C can be calculated according to the following formula:

$$W=\int_0^{T_C} P\mathrm{d}t=\int_0^{T_C} P_A A\mathrm{d}t \tag{19}$$

Here, the electric energy values generated by the MFCs running for 500 hours with P&O algorithm and fuzzy improved P&O algorithm are calculated, that is, T_C is set 500 h. The power generation energy of MFC under the action of P&O algorithm is 21.4 J, while the power generation energy of MFC under the control of fuzzy improved P&O algorithm is 22.5 J, which shows that the fuzzy improved P&O algorithm also improves the power generation capacity of MFC to a certain extent.

In the current literature, there are relatively few studies on MPPT control of MFC. The comparison between the proposed MPPT scheme for MFCs and some MPPT schemes based on similar MFC models mentioned in the literature is shown in Table 2, where η is the MPPT tracking efficiency that can be obtained by the following formula:

$$\eta=\frac{P_{ms}}{P_{max}}\times 100\% \tag{20}$$

In the above formula, P_{ms} represents the steady-state output average power tracked by MPPT algorithm; P_{max} represents the actual maximum power of PEMFC.

Table 2. Performance comparison of several different schemes

algorithm	Tracking speed (h)	Stable fluctuation (%)	η (%)	references
P&O	180	10	98.6	This work
Fuzzy-P&O	100	0	99.9	This work
Q-learning	350	0	100	[28]
Q Learning with greedy policy	200	0	100	[28]
Improved P&O	330	0	98.7	[29]
Improved P&O	unknown	10.4	66.7	[30]
Improved P&O	24	5.1	98.5	[31]

It can be seen from the data in the table that MPPT control scheme based on the Fuzzy-P&O algorithm proposed in this paper has certain advantages in tracking speed and tracking accuracy.

5. CONCLUSIONS

The problems of slow tracking speed and large tracking error in conventional maximum power point tracking method can be solved by introducing advanced control method. The "human like" logical thinking ability and reasoning ability of fuzzy logic control has great advantages for solving control problems of nonlinear systems. The fuzzy improved P&O algorithm proposed in this paper can realize the maximum power tracking control of MFC. Results show that the fuzzy improved P&O algorithm can significantly accelerate the maximum power tracking response, reduce the steady-state oscillation and make the steady-state tracking error close to 0, which effectively overcome the shortcomings of the traditional P&O method in MPPT, make the MFC achieve the maximum power output, improve anti-interference ability and reduce the power loss. Using fuzzy logic to optimize the traditional P&O algorithm is a very effective and feasible method for MFC system to achieve maximum power point tracking control, which provides an alternative way to improve the overall performance of MFC.

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