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Constant Voltage Output in Two-Chamber Microbial Fuel Cell Under Fuzzy PID Control

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Microbial fuel cells (MFCs) have been receiving more and more attention in simultaneous treatment of wastewater and energy recovery. Past research has been mainly in experiments. Modelling and controlling are new subjects emerging recently. A novel dynamic model of MFC based on biochemical reactions, Butler–Volmer expressions and mass/charge balances is proposed with Matlab/Simulink, and then the fuzzy PID controller is designed for the microbial fuel cell to realize constant voltage output. Simulation results show that the proposed controller can give better control effects compared to PID controller.

Keywords: MFC; constant voltage output; fuzzy PID control; PID control

1. INTRODUCTION

Due to the environmental problems and energy crisis, research on microbial fuel cell (MFC) has been receiving a striking increase in interest in the recent years [1]. The MFC as one of pollution-free energy can directly transform a wide range of organic and inorganic compounds into electricity via electrochemical reactions [2]. Comparison with the conventional fuel cells, MFC shows charming attraction with its advantages such as the abundant fuel resource, mild reaction condition and high efficiency [3]. However, because the MFC is quite complex and is affected by many factors, the MFC technology is still at the initial stage of research, many aspects of the research still need in-depth exploration. Over the past few decades, a major scientific effort in MFC research has been made to study the biological and electrochemical phenomena that drive the oxidation of the fuel in the anode [4].

Although modelling and simulation are widely used methods for analysis of various chemical fuel cells, few MFC models have been reported in the literature. Many of limitations have impeded the modelling in MFC development [5]. In particular, construction and analysis of MFCs demand interdisciplinary concepts and techniques from microbiology, environmental biotechnology, electrochemistry, electrical engineering, and material science. Systematic understanding of the biological and electrochemical factors is not very easy. The development of a model requires identifying each parameter, key components and processes [6]. One of the first MFC models was proposed to simulate a suspended cell with an external mediator in 1995 [7]. In the next few years, almost no progress has been made. Until 2007 one dimensional computational model for biofilm-based microbial fuel cell was developed by Marcus et al [8]. No modelling had been conducted on MFC until the last two years. For analyzing biofilm formation and species distribution within the biofilm 3-dimensional model of anodic compartment biofilm with a detailed description was reported in [9]. These models may not be widely used in the MFC community due to their complexity. So a relatively simple and easy model of MFC can be useful to its practical use in the design and control of MFC. In [5], a simpler model of MFC that consists of differential equations was presented while being suitable for process optimization and control. Based on the modelling study, a suitable controller can be designed to maintain MFC in desired output according to different load requirement.

PID as one of widely used control approaches has many advantages such as simple control structure, easy design and inexpensive cost etc. The PID controller has been used in different controlled plant. However it cannot get a good control effect when controlled system is nonlinear and high order [10].

Fuzzy logic can express the amount of ambiguity in human thinking and possess several advantages such as robustness, model-free, universal approximation theorem. In the past several decades, fuzzy control has been used in many applications [11]. However, the huge amounts of fuzzy rules for a high-order system make the analysis complex. At the same time, the fuzzy controller parameters must go through repeated attempts to determine and be the lack of the stability analysis [12].

To solve these problems fuzzy PID that combines fuzzy control and PID control is studied. The method not only has the advantages of great precision of PID control, but also has the strong points of agility and adaptive of fuzzy control. The fuzzy PID control can get the good control effect which the traditional control can't achieve.

The main body of this paper is organized as follows. The mathematical model for two-chamber microbial fuel cell is described in Section 2. Section 3 discusses a brief description of designing fuzzy PID controllers for MFC. Simulation results are presented in section 4 to confirm the effectiveness and the applicability of the proposed method. Finally, the conclusion is stated in section 5.

2. MATHEMATICAL MODEL OF MFC

Like other fuel cells, MFC consists of an anode, a cathode, a proton exchange membrane and an electrical circuit [13]. In the anode chamber, bacteria growing in the absence of oxygen degrade organic matter (the fuel) and transfer the electrons to the anode. Then these electrons pass through an external current and reach the cathode chamber. Fig.1 shows the basic structure of a class two-chamber MFC.

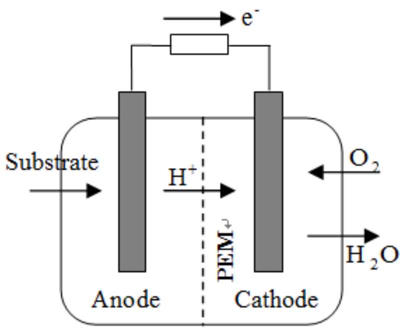

Figure 1. Basic structure of a class two-chamber MFC

For the sake of simplicity, a simple substrate is considered in evaluating all the reactions that take place in the anode. Thus acetate is oxidized at the anode according to the Eq.1 [14].

$$(CH_2O)_2 + 2H_2O \rightarrow 2CO_2 + 8H^+ + 8e^- \quad (1)$$

According to the literature [5], the reaction rate in the anode can be expressed as the following

$$r_1 = k_1^0 \exp(\frac{\alpha F}{RT}\eta_a)\frac{C_{AC}}{K_{AC}+C_{AC}}X \quad (2)$$

where C_{AC} and X are the concentrations of acetate and biomass at the anode surface, respectively; η_a is the anodic overpotential; K_{AC} is the half velocity rate constant for acetate; k_1^0 is the rate constant of the anode reaction at standard conditions; α is the charge transfer coefficient of the anodic reaction; F is the Faraday constant; R is the gas constant; and T is the cell operating temperature.

The reduction of dissolved oxygen in the cathode can be generally written as [15]

$$O_2 + 4e^- + 2H_2O \rightarrow 4OH^- \quad (3)$$

At the cathode it is found that the dissolved oxygen acts as the oxidant for the reduction reaction occurring at the cathode surface [16]. To quantify the rate of reaction in the cathodic chamber at the cathode, the Bulter-Volmer expression is employed

$$r_2 = -k_2^0 \frac{C_{O_2}}{K_{O_2}+C_{O_2}} \exp[(\beta-1)\frac{F}{RT}\eta_c] \quad (4)$$

where C_{O_2} is the concentration of the dissolved oxygen at the cathode surface; K_{O_2} stands for the halfvelocity rate constant for dissolved oxygen; η_c is the overpotential at the cathode; k_2^0 is the rate constant of the cathode reaction at standard conditions and β is the constant related to exchange current density.

According to [17], the mass balances of the four components (namely acetate, dissolved C_{O_2}, hydrogen ion and Biomass respectively) can be written as following

$$V_a \frac{dC_{AC}}{\mathrm{d}t} = Q_a(C_{AC}^{\mathrm{in}} - C_{AC}) - A_m r_1 \quad (5)$$

$$V_a \frac{\mathrm{d}C_{CO_2}}{\mathrm{d}t} = Q_a(C_{CO_2}^{in} - C_{CO_2}) + 2A_m r_1 \quad (6)$$

$$V_a \frac{dC_H}{dt} = Q_a(C_H^{in} - C_H) + 8A_m r_1 \quad (7)$$

$$V_a \frac{\mathrm{d}X}{\mathrm{d}t} = Q_a \frac{X^{\mathrm{in}} - X}{f_x} + A_m Y_{ac} r_1 - V_a K_{dec} X \quad (8)$$

In the above equations, the subscripts 'a' and 'in' stand for the anode and the feed flow, respectively. V, Q and A_m denote the volume of the compartment, the feed flow rate, and the cross-section area of membrane, respectively. f_x given by Eq. (8) represents the reciprocal of the wash-out fraction, Y_{ac} and K_{dec} are the bacterial yield and the decay constant for acetate utilisers, respectively.

In the cathode chamber, the mass balances of dissolved O_2, hydroxyl, and cation M^+ can be expressed respectively as following:

$$V_C \frac{dC_{O_2}}{dt} = Q_C(C_{O_2}^{in} - C_{O_2}) + r_2 A_m \quad (9)$$

$$V_c \frac{dC_{OH}}{dt} = Q_c(C_{OH}^{in} - C_{OH}) - 4r_2 A_m \quad (10)$$

$$V_C \frac{dC_M}{dt} = Q_C(C_M^{in} - C_M) + N_M A_m \quad (11)$$

The subscript 'c' stands for the cathode. N_M given by Eq.(12) represents the flux of M^+ ions transported from the anode to cathode compartment via the membrane. The flux of M^+ ions can be calculated as follows

$$N_M = \frac{3600 i_{cell}}{F} \quad (12)$$

where the coefficient 3600 is the factor of unit conversion.

The charge balance at the anode is given by

$$C_a \frac{d\eta_a}{dt} = 3600 i_{cell} - 8Fr_1 \qquad (13)$$

where C_a is the capacitances of the anode; i_{cell} is the load circuit. The coefficient 3600 and 8 are determined by the unit conversion in specific bio-electrochemical reactions.

Similarly, the charge balance at the cathode is given by

$$C_c \frac{d\eta_c}{dt} = -3600 i_{cell} - 4Fr_2 \qquad (14)$$

where C_c is the capacitances of the cathode.

When the ohmic drops in the current-collectors and electric connections are assumed to be negligible, the relationship between the output voltage U_{cell} and the cell current density i_{cell} of the MFC can be written

$$U_{cell} = U_{open} - \eta_a + \eta_c - \left(\frac{d^m}{k^m} + \frac{d_{cell}}{k^{aq}}\right) i_{cell} \qquad (15)$$

where U_{open} is the open-circuit voltage; d^m is the thickness of the membrane; d_{cell} is the distance of the electrodes; k^m and k^{aq} are the conductivities of the membrane and the solution, respectively.

Table 1. Model parameters of MFC based on modelling results of [5]

Symbol	Description	Value
F	Faraday constant	96485 Asmol^{-1}
R	Gas constant	8.3144 J mol^{-1} K^{-1}
T	Temperature	303K
k^m	Electrical conductivity of membrane	17 Ohm^{-1} m^{-1}
d^m	Thickness of membrane	1.778×10^{-4} m
k^{aq}	Electrical conductivity of the aqueous solution	5 Ohm^{-1} m^{-1}
d^{cell}	Distance between anode and cathode in the cell	2.2×10−2 m
C_a	Capacitance of anode	4×10^2 Fm^{-2}
C_c	Capacitance of cathode	5×10^2 Fm^{-2}
V_a	Volume of anode compartment	5.5×10^{-5} m^3
V_c	Volume of cathode compartment	5.5×10^{-5} m^3
A_m	Area of membrane	5×10^{-4} m^2
Yac	Bacterial yield	0.05 Dimensionless
K_{dec}	Decay constant for acetate utilisers	8.33×10^{-4} h^{-1}
f_x	Reciprocal of wash-out fraction	10 Dimensionless
Q_a	Flow rate of fuel feed to anode	2.25×10−5 m^3 h^{-1}
Q_c	Flow rate feeding to cathode compartment	1.11×10^{-3} m^3 h^{-1}
$C^{in}{}_{ac}$	Concentration of acetate in the influent of anode compartment	1.56 molm^{-3}
$C^{in}{}_{CO2}$	Concentration of CO2 in the influent of anode compartment	0 molm^{-3}
X_{in}	Concentration of bacteria in the influent of anode compartment	0 molm^{-3}
$C^{in}{}_{H}$	Concentration of H+ in the influent of anode compartment	0 molm^{-3}
$C^{in}{}_{O2}$	Concentration of dissolved O2 in the influent of cathode compartment	0.3125 molm^{-3}
$C^{in}{}_{M}$	Concentration of M+ in the influent of cathode compartment	0 molm^{-3}
$C^{in}{}_{OH}$	Concentration of OH− in the influent of cathode compartment	0 molm^{-3}
U^0	Cell open circuit potential	0.77volt

Parameters used in the above equation are listed in Table 1. These parameters are set up according to experiment.

Some parameters listed in table 2 are estimated, but they are not sensitive to simulation results.

Table 2. Estimated parameters of acetate MFC

Symbol	Description	Value
k^0_1	Forward rate constant of anode reaction at standard condition	0.207 $molm^{-2}\ h^{-1}$
k^0_2	Forward rate constant of cathode reaction at standard condition	$3.288\times10^{-5}\ m^{12}\ mol^{-4}\ h^{-1}$
K_{Ac}	Half velocity rate constant for acetate	0.592 $molm^{-3}$
K_{O2}	Half velocity rate constant for dissolved oxygen	0.004 $molm^{-3}$
α	Charge transfer coefficient of anode	0.051 Dimensionless
β	Charge transfer coefficient of cathode	0.663 Dimensionless

3. DESIGN OF FUZZY PID CONTROLLER

Fig.2 shows the closed-loop fuzzy PID controller for MFC. A fuzzy PID control system with dual inputs and three outputs is used to control the output voltage of the fuel cell [18]. The error *e(k)*, the change in error *ec(k)* and the control output *u(k)* of the fuzzy controller are given as follows:

$$e(k) = V_{fc}^* - V_{fc} \quad (16)$$

$$ec(k) = e(k) - e(k-1) \quad (17)$$

$$u(k) = K_P e(k) + K_I \sum_{j=0}^{k} e(j) + K_D ec(k) \quad (18)$$

where V_{fc}^* is the set point of the output voltage, $K_P = K_{P0} + \Delta K_P$, $K_I = K_{I0} + \Delta K_I$, $K_D = K_{D0} + \Delta K_D$.

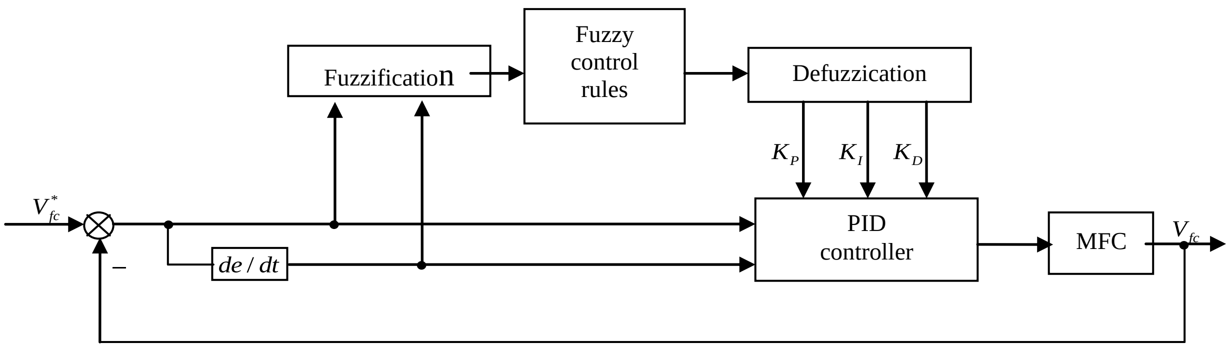

Figure 2. The closed-loop fuzzy PID controller

The triangular type membership function is chosen for error, change of error, and change of control. The fuzzy domain for *e(k), ec(k)* and ΔK_P, ΔK_I, ΔK_D is [-1，1]. The fuzzy sets for *e(k), ec(k)* and Δu are {NB, NM, NS, ZO, PS, PM, PB}. Fuzzy control rule base is shown in Table.3-5.

Table 3. Rule base of ΔK_P for fuzzy control

ΔK_P		*ec(k)*						
		NB	NM	NS	ZO	PS	PM	PB
e(k)	NB	PB	PB	PM	PM	PS	ZO	ZO
	NM	PB	PB	PM	PS	PS	ZO	NS
	NS	PM	PM	PM	PS	ZO	NS	NS
	ZO	PM	PM	PS	ZO	NS	NM	NM
	PS	PS	PS	ZO	NS	NS	NM	NM
	PM	PS	ZO	NS	NM	NM	NM	NB
	PB	ZO	ZO	NM	NM	NM	NB	NB

Table 4. Rule base of ΔK_I for fuzzy control

ΔK_I		*ec(k)*						
		NB	NM	NS	ZO	PS	PM	PB
e(k)	NB	NB	NB	NM	NM	NS	ZO	ZO
	NM	NB	NB	NM	NS	NS	ZO	ZO
	NS	NB	NM	NS	NS	ZO	PS	PS
	ZO	NM	NM	NS	ZO	PS	PM	PM
	PS	NM	NS	ZO	PS	PS	PM	PB
	PM	ZO	ZO	PS	PS	PM	PB	PB
	PB	ZO	ZO	PS	PM	NM	PB	PB

Table 5. Rule base of ΔK_D for fuzzy control

ΔK_D		*ec(k)*						
		NB	NM	NS	ZO	PS	PM	PB
e(k)	NB	PS	NS	NB	NB	NB	NM	PS
	NM	PS	NS	NB	NM	NM	NS	ZO
	NS	ZO	NS	NM	NM	NS	NS	ZO
	ZO	ZO	NS	NS	NS	NS	NS	ZO
	PS	ZO	ZO	ZO	ZO	ZO	ZO	ZO
	PM	PB	PS	PS	PS	PS	PS	PB
	PB	PB	PM	PM	PM	PS	PS	PB

In this paper, the output control u of the fuzzy controller is designed as Q_a. According to fuzzy inference system, output control rules surface of ΔK_P, ΔK_I, ΔK_D for fuzzy variables *e(k)*, *ec(k)* are shown in Fig.3-5.

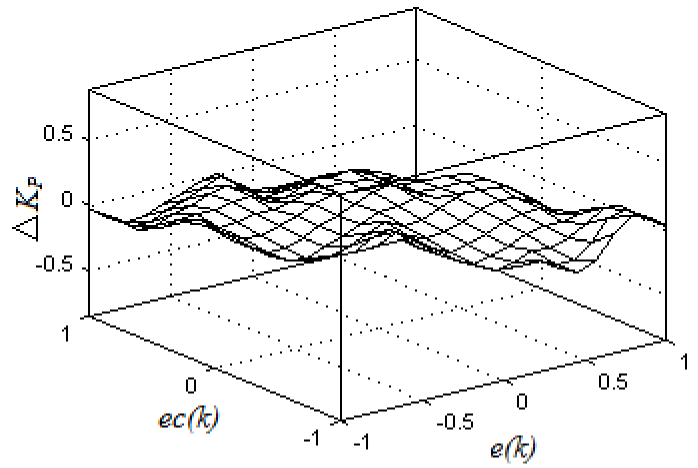

Figure 3. 3-dimensional representation of ΔK_P for fuzzy variation *e(k)*, *ec(k)*

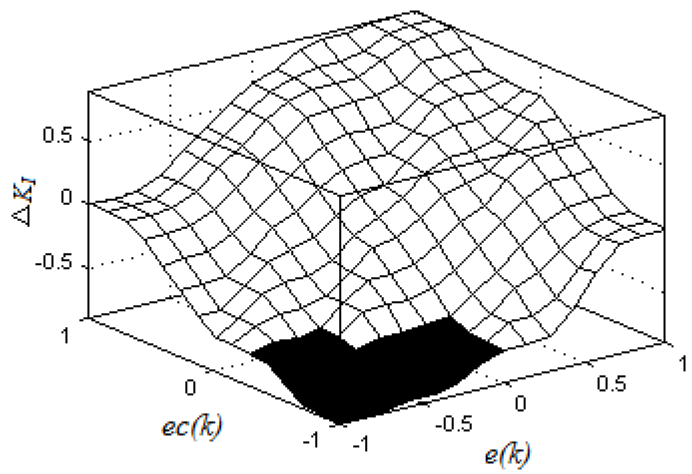

Figure 4. 3-dimensional representation of ΔK_I for fuzzy variation *e(k)*, *ec(k)*

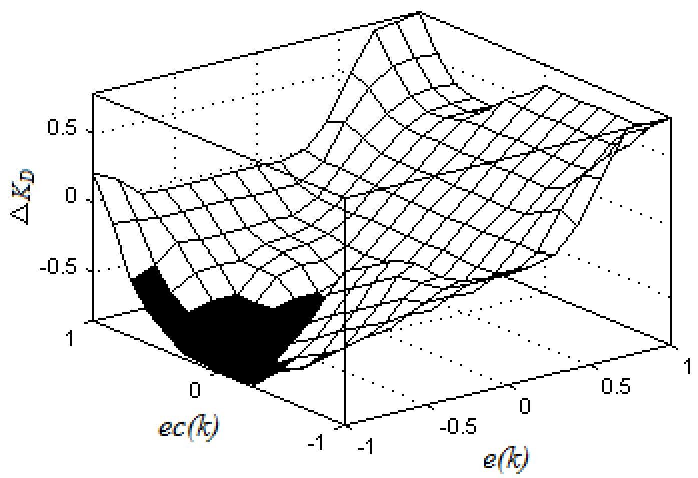

Figure 5. 3-dimensional representation of ΔK_D for fuzzy variation *e(k)*, *ec(k)*

4. SIMULATION RESULTS

In this section, simulation operation is carried out in the MATLAB simulink platform. PID and fuzzy PID are designed to achieving constant voltage output respectively. The parameters in PID are K_P=23.5e-5, K_I=2.2e-5, K_D=2.5e-5, the reference setting output voltage of the microbial fuel cell is 0.44V. The icell changes from 3 Am^{-2} to 6 Am^{-2} at the time of 100h. Simulation results are shown in Fig.6 -10.

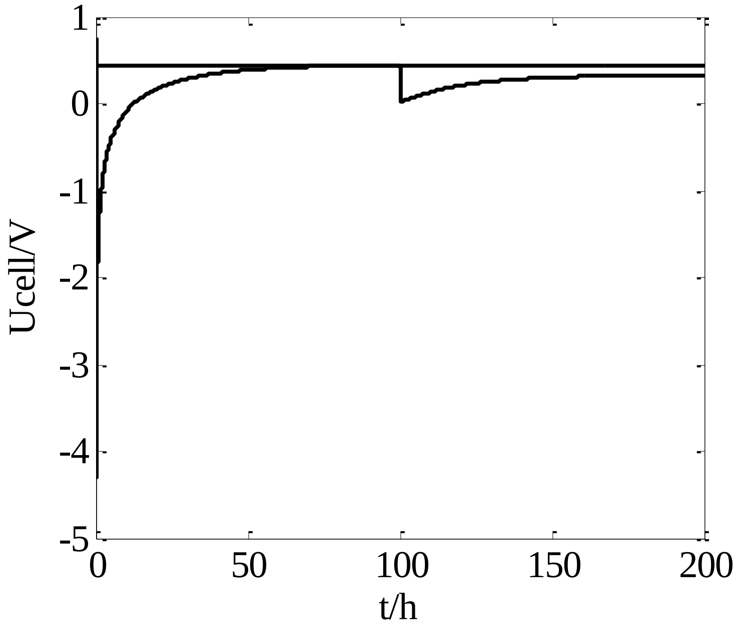

Figure 6. Voltage output of uncontrolled

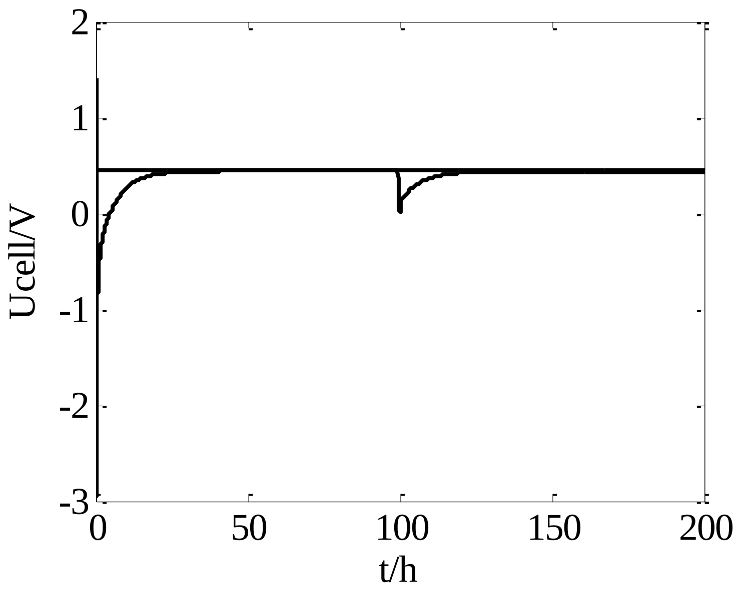

Figure 7. Voltage output of fuzzy PID

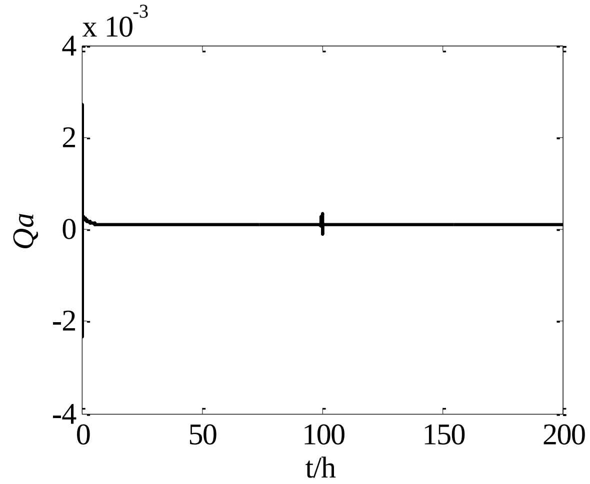

Figure 8. Control input of fuzzy PID

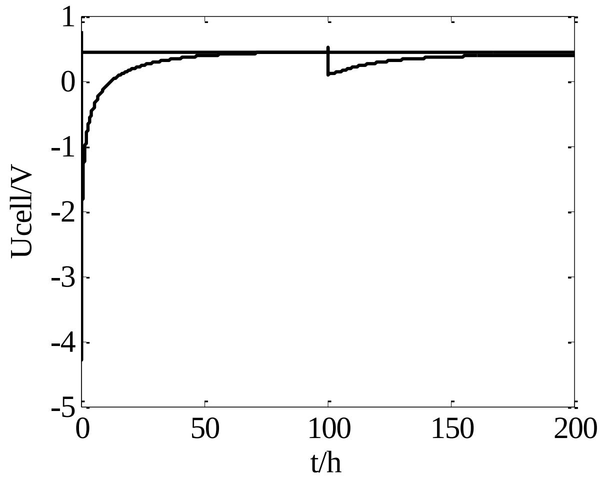

Figure 9. Voltage output of PID

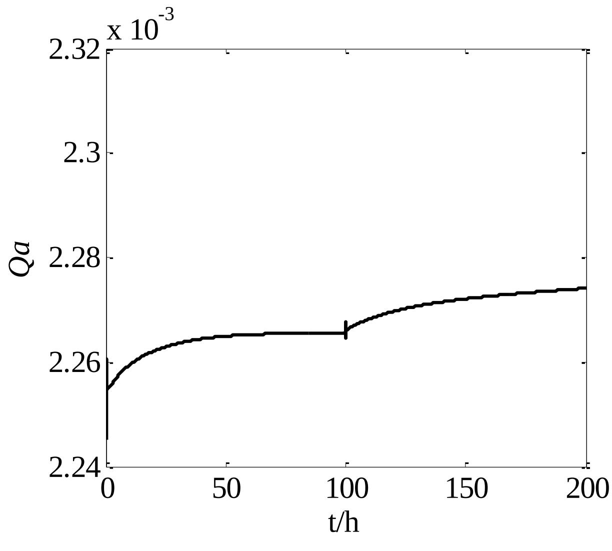

Figure 10. Control input of PID

As can be seen from the figure, in 0-100h, fuzzy PID control can make the MFC track setting voltage quickly and realize constant voltage output. Fuzzy PID control is much faster than conventional PID control, and the former mediation time is almost half of the latter. When the load changes, there exists a large steady-state error in PID control, but Fuzzy PID can overcome the disturbance and reach the desired voltage value quickly. The fuzzy PID controller shows the better control performance than PID controller in terms of settling time, overshot and rise time.

Table 6 shows the performance levels achieved via fuzzy PID and PID controllers.

Table 6. Comparison of fuzzy PID and PID controllers

	i_{cell}=3		i_{cell}=6	
	Rise time(h)	Overshoot(%)	Rise time(h)	Overshoot(%)
fuzzy PID	27.5	0.3	25	2
PID	47.3	0.4	48.7	9.9

By comparing the results with those results by other authors [5, 13, 17], it can be seen that the method proposed in this paper can realize both modelling and controlling while the other references only finished modelling. Further, compared with the former method in the fuel cell [19, 20], a constant output voltage controller was designed for proton exchange membrane fuel cell, but no controller was proposed for microbial fuel cell.

5. CONCLUSION

MFC need constant voltage output when load changes. The fuzzy PID control proposed in this paper can not only have fast response characteristic, but also have good steady-state behavior and strong robustness compared with PID control, Simulation results indicate that the fuzzy PID controller is very effective to realize constant voltage output.

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