Study and Application of Self-Adaptive Fuzzy PID Control in Dissolved Oxygen Control of Wastewater Treatment

Dasen Zhang\textsuperscript{1,2}, Jian Chu\textsuperscript{1,2}, Yacong He\textsuperscript{1,2}, Hui Jin\textsuperscript{1,2} and Wei Han\textsuperscript{1,2}

1. Tianjin Key Laboratory of Information Sensing and Intelligent Control, Tianjin 300222, China
2. School of Automation and Electrical Engineering, Tianjin University of Technology and Education, Tianjin, 300222, China
Email: 1302247732@qq.com

Abstract. In view of the typical nonlinear, time-varying and large lag characteristics of dissolved oxygen (DO) concentration control in wastewater treatment, it is difficult to obtain a good control performance by using conventional proportional-integral-derivative (PID) control. In order to greatly improve the control effect, designing a self-adaptive fuzzy PID controller. Through analysis and reasoning can obtain the optimal control effect under the optimal membership. MATLAB simulation and application show that compared with the conventional PID control, the self-adaptive PID controller accelerates the response speed of the dissolved oxygen control system and reduces the overshoot. This control method achieves a better control performance in the actual sewage treatment central control system, improves the sewage treatment efficiency, and has the value of popularization and application.

1. Introduction

With the rapid development of urbanization and the continuous advancement of industrialization, water pollution has become a problem we must face. Sewage treatment is a complex dynamic system. At present, the main methods used in wastewater treatment are activated sludge process and oxidation ditch process. Activated sludge process is a commonly used sewage treatment method in countries all over the world [1]. Among them, the dissolved oxygen in water is a very important indicator parameter in the biochemical reaction process of sewage treatment. It can reflect the operational status of the whole system more intuitively and quickly [2]. Proper control of dissolved oxygen content can improve the status of sewage discharge processes and system energy consumption [3].

In recent years, industry scholars have conducted extensive and in-depth research on the control of DO concentration in wastewater treatment processes. Liu [4] used neural network control algorithm to dynamically change the structure and parameters of the neural network, according to the operating conditions of the system, to optimize the network structure and reduce the control error, improve the control precision and show certain robustness. Xu [5] proposed a new control method based on fuzzy neural network (FNN) to control DO concentration. The gradient descent algorithm is used to adjust the parameters of neural network online to obtain the minimum error. Wahab [6] used a multivariable PID controller optimized for control parameters to control the dissolved oxygen concentration in each biochemical aerobic tank.

In this paper, based on the existing research, and according to the actual situation, the control mode of DO concentration is improved, and a PID controller with self-adaptive fuzzy control is designed. The PID parameters are modified by online fuzzy self-tuning, and the DO concentration control is controlled in real time. In the simulation process, the membership degree of each fuzzy subset is
changed. The final simulation results and practical application show that the adaptive fuzzy PID controller can obviously improve the dynamic performance of the control system, improve the control accuracy of the system and play the role of energy saving and emission reduction.

2. Dissolved Oxygen Control System

DO control is an important part of the actual on-site sewage treatment process, and it is also the most critical link [7]. At the actual treatment site, in order to increase the dissolved oxygen content in the biochemical tank, the air is delivered to it by a Roots blower. The control of DO can in fact be transformed into the regulation of the rotational speed of the Roots fan. As shown in Figure 1, the system uses the DO detector to detect the DO value, and compares the actual value of the detected DO with the set value. After subtraction, the comparison results are sent to the fuzzy self-adaptive PID controller for accurate processing. The fuzzy self-adaptive PID controller adjusts the rotating speed of the Roots fan in real time by controlling the frequency of the converter. Finally, the closed loop negative feedback control of DO is completed [8].

![Figure 1. Dissolved oxygen closed-loop negative feedback control schematic](image)

3. Self-Adaptive Fuzzy PID Controller Design

3.1. Fuzzy Control System Structure

Fuzzy self-adaptive PID control is to use the basic theory and method of fuzzy mathematics. Firstly, the fuzzy set is used to embody the condition and operation of the rule. Then the fuzzy control rule is used as a kind of knowledge to store this specific knowledge together with related information. Inside the computer knowledge base, so that the computer can perform fuzzy reasoning according to the response of the PID control system, and finally complete the precise tuning of the PID parameters [9].

Parameter self-adaptive fuzzy PID control discrete expression is as follows:

$$u(k) = K_p(e(k) + K_i \sum_{i=0}^{k} e(i) + K_d \frac{d}{dt}[e(k) - e(k-1)])$$  \hspace{1cm} (1)

Parameter self-adaptive fuzzy PID control is mainly used to establish the mathematical relationship between PID parameters and deviation and deviation change rate. This relationship is based on conventional PID control and fuzzy logic reasoning theory. The specific mathematical relationship is shown in the following three equations:

$$\Delta K_p = f_1(e, \dot{e}), \Delta K_i = f_2(e, \dot{e}), \Delta K_d = f_3(e, \dot{e})$$  \hspace{1cm} (2)

The parameters $K_p, K_i, K_d$ are adjusted online according to different e and $\dot{e}$. The fuzzy controller $FC_1$ outputs $\Delta K_p$, the fuzzy controller $FC_2$ outputs $\Delta K_i$, and the fuzzy controller $FC_3$ outputs $\Delta K_d$. The specific adjustment process is as shown in Figure 2 below.
3.2. Fuzzy Linguistic Variable Design
The selected fuzzy controllers FC1, FC2 and FC3 in Figure 3 are both two-dimensional structures. The input fuzzy linguistic variables of fuzzy controllers FC1, FC2 and FC3 are taken as E (the fuzzy linguistic variety of the deviation) and EC (the fuzzy linguistic variation of the deviation change rate), and the fuzzy domain is taken as [-6, 6]. The output fuzzy linguistic variables of FC1, FC2 and FC3 are taken as \( \delta_p \), \( \delta_i \) and \( \delta_d \) respectively, and the fuzzy domain is taken as [-10, 10]. The design result of the input and output fuzzy linguistic variables is shown in Figure 3 below [10].

3.3. Fuzzy Rule Set Settings
Summing up the expert knowledge and the actual working experience of the relevant operators. And obtain the following parameter adjustment rules [11]: (1) When the deviation |e| is large, in order to improve the system response speed and eliminate the error. The value of \( K_p \) should be increased, and to prevent integration and differential oversaturation, \( K_i \) should take a small value or 0, and \( K_d \) takes a smaller value. (2) When e·ec < 0, in this case, if the absolute value of the deviation is relatively large, a medium-sized \( K_p \), \( K_d \) value and smaller \( K_i \) value may be taken. If the absolute value of the deviation is relatively small, a smaller \( K_p \), \( K_d \) value, and a larger \( K_i \) value may be taken. (3) When e·ec > 0, in this case, if the absolute value of the deviation is relatively large, a larger \( K_p \) value, a smaller \( K_i \) value, and a medium-sized \( K_d \) value may be taken. If the absolute value of the deviation is relatively small, a medium-sized \( K_p \) value, a large \( K_i \) value, and a small \( K_d \) value may be taken. The fuzzy control rules are established by the above parameter adjustment rules as shown in Table 1.
4. System Simulation and Analysis

4.1. Determination of the Quantization Factor
The sewage treatment system is a complex dynamic engineering system, which can't be described by a very accurate mathematical model. Therefore, when we create the DO mathematical model, we first need to make some specific assumptions. The specific assumptions are as follows:

Assumption (1): In time, the aeration process is an ideal push flow change. In space, the aeration process is a fully mixed state.

Assumption (2): In one cycle, the amount of synthesized microorganisms is relatively small and cannot affect the total biomass, so that the total biomass in the reactor hardly changes.

Assumption (3): Before the start of a cycle, the concentration of the effluent from the previous cycle in the reactor can be considered without considering the concentration of raw water.

Assumption (4): The reaction rate in the reaction period is one, assuming that the reaction rate of the established wastewater is constant.

Based on the above assumptions and according to the material balance of dissolved oxygen concentration and the determination principle of dissolved oxygen concentration, a mathematical model of dissolved oxygen concentration is obtained:

\[ G(s) = \frac{K_c}{T_b s + 1} e^{-\tau s} \]  
(3)

According to the mathematical simulation model, in the standard state, the step response test is performed on the DO concentration system, and when the output DO value is 2.25mg/l, the steady-state gain \( K_c \) of the process is calculated to be 6.83. The time constant \( T_b \) is 67s, and the actual detection lag time \( \tau \) of the dissolved oxygen biochemical reaction can be obtained as 16s. So we can get the transfer function of the system as:

\[ G(s) = \frac{6.83}{67s + 1} e^{-16s} \]  
(4)

4.2. Simulation and Analysis
The mathematical model of the system is established by Matlab's fuzzy toolbox, the control of the constant pressure fueling system is simulated by conventional PID and self-adaptive fuzzy PID. As shown in Figure 4, the upper part of Figure 4 is self-adaptive fuzzy PID control, and the lower part is the conventional PID control [12].
Firstly, the PID parameters are set. Through the tuning, the parameters of the PID controller are respectively taken as follows: $K_p = 0.25$, $K_i = 0.004$, $K_d = 3$, and the simulation result of the single PID control is as shown in Figure 5 (Curve 1). As seen from the Figure 6, the DO concentration of the controlled object is under the action of a single PID controller, which produces a significant overshoot before reaching the steady state value.

Set the simulation parameters: the simulation type adopts variable step size, the maximum step size is set to 16, the minimum step size and the initial step size are set to auto, and the simulation algorithm is “ode45” (the 4th to 5th order Runge-Kutta method applies to simulation of continuous system) [12]. The simulation time is 800s, and other parameters are taken as the default settings of the system. By changing the range of membership function of self-adaptive fuzzy controller and combining personal experience, the simulation results of step response curve under adaptive fuzzy PID control can be obtained by continuous adjustment and improvement of analysis and reasoning, as shown in Figure 6 below. The green is at the top of the curve (Curve 2), the yellow is at the middle of the curve (Curve 3), and the red is at the bottom of the curve (Curve 4). It can be seen from the figure that the Curve 2 has a faster response speed, but has a certain overshoot. Compared with Curve 2, Curve 4 has a reduced overshoot, but it takes longer to reach steady state. Curve 3 is the best, its response speed is fast, there is basically no overshoot, and the time required to reach steady state is relatively short. Therefore, we
can conclude that different range of membership degrees can bring different control effects, and the appropriate range of membership has better control effects.

![Figure 6. Step response curve of different membership degrees under self-adaptive fuzzy PID control](image)

The specific index parameters of the single PID control and the self-adaptive fuzzy PID control under different membership functions are shown in Table 2.

| Table 2. Comparison of important index parameters of step response curve |
|---------------------------------------------------------------|
| Peak Value(mg/L) | $\sigma$ % | Stability Time (s) |
|------------------|----------|------------------|
| Curve1           | 2.771    | 23.15%           | 634.5            |
| Curve2           | 2.385    | 6.00%            | 416.5            |
| Curve3           | 2.251    | 0.044%           | 408.5            |
| Curve4           | 2.345    | 4.22%            | 488.5            |

By analyzing and comparing the simulation Curve 1 and the Curve 3, we can conclude that in the process of adopting self-adaptive fuzzy PID control to adjust the concentration of DO, there is almost no overshoot in the system. And after reaching the set value DO=2.25mg/L of the system, it has remained stable. However, when a single PID controller is used to adjust, the system has obvious overshoot fluctuation and long duration in the process of reaching the default value.

5. Conclusions
This article combines the actual situation of the sewage treatment system, the self-adaptive fuzzy PID controller formed by combining fuzzy algorithm and conventional PID algorithm is applied to dissolved oxygen control system. In the control process, the variable membership function is changed. The simulation results and practical application prove that the self-adaptive fuzzy PID controller with better membership function can not only significantly reduce the overshoot in the system operation, but also significantly speed up the response, improve its stability, and basically no overshoot fluctuations, which has certain reference significance for wastewater treatment and fuzzy intelligent control applications in other industries.

6. References
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