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Design of fan speed regulation control system based on fuzzy logic algorithm

Lili Wu[1] and Qiming Gao[2,*]
[1] College of Education, Handan University, Handan, Hebei, 056005, China
[2] Handan Key Laboratory, Intelligent Perception and Application, Handan University, Handan, Hebei, 056005, China
Corresponding authors: (e-mail: wgg@hdc.edu.cn).

Abstract Fan speed regulation is crucial to the safe operation of mines, and traditional PID control is less stable under dynamic disturbances. With the development of industrial control technology, fuzzy logic and fractional-order PID are combined to form a new control strategy, which can deal with system nonlinearity and uncertainty. In this study, we first established a mathematical model of fan speed control, analyzed the characteristics of fuzzy set and affiliation function, and designed a fuzzy rule-based fractional-order PID controller to adaptively adjust the control parameters Kp, Ki, Kd, λ and μ. The control system performance was verified by Simulink and Fluent software simulation tests. The results show that compared with the traditional PID controller, the fuzzy fractional-order PID controller reduces the time for the wind turbine speed to reach the steady state by 30s, and the amount of overshooting decreases by about 15%. In the anti-interference performance test, the fuzzy fractional-order PID controller can restore the steady state faster when the system adds a 5% set value interference signal. The system stabilization time is shortened from 37.03s for the conventional PID to 6.97s for the fuzzy fractional-order PID, and the overshoot is only 0.01%. This study proves that the fuzzy fractional-order PID control strategy has good dynamic performance and adaptive ability in fan speed control, which provides a new solution for industrial control system.

Index Terms fuzzy logic, fractional order PID, fan speed regulation, affiliation function, control strategy, anti-interference performance

I. Introduction

Modern industrial production requires efficient and reliable machinery and equipment, and fans, as an important part of them, are extremely important for the efficient operation of their functions for production applications [1], [2]. The operation of the fan is closely related to its rotational speed and air volume output, and if the rotational speed and air volume output of the fan cannot be accurately controlled, it will lead to energy waste, equipment wear and safety accidents and other problems [3]-[5]. The fan speed regulation control system based on fuzzy algorithm is a kind of advanced technology that is widely used in modern industrial production, and through fuzzy logic control, it can control the operation of the fan more accurately and improve the production efficiency and safety [6]-[8].

The fan speed regulation control system based on fuzzy logic algorithm is a control technology based on fuzzy sets, fuzzy rules and fuzzy reasoning [9], [10]. Fuzzy theory is a mathematical descriptive tool that can solve the fuzzy and uncertainty problems that cannot be described by existing mathematics [11]. Fuzzy theory quantifies the fuzzy characteristics of things and transforms them into mathematical operations, which enables fuzzy problems to be accurately described and solved [12], [13]. In the fan speed regulation control system based on fuzzy logic algorithm, some key performance parameters, such as rotational speed, airflow, pressure, etc., need to be determined first [14]-[16]. Then, these parameters are established as fuzzy variables and represented by fuzzy sets. For example, the rotational speed of the fan can be described by three fuzzy sets of low, medium and high speed [17], [18]. Then, for these fuzzy variables, several fuzzy rules are established to describe the relationship between these parameters [19]. Finally, the fuzzy inference method is applied to reason on the basis of the fuzzy rules to derive the parameters such as fan speed and air output that should be achieved in the current state, so as to realize precise control [20]-[22].

In industrial production, the precise control of fan speed has an important impact on system operation efficiency and safety. Especially in the mine ventilation system, the fan speed is directly related to the efficiency of harmful gas emission and the safety of the working environment. Traditional control methods often show large limitations in the face of system nonlinearity, parameter uncertainty and external interference, PID controller is widely used because of its simple structure and wide range of applications, but it is difficult to achieve the desired control effect under complex working conditions. The traditional PID controller with fixed control parameters is difficult to adapt to the dynamic changes in the system, especially when the system is perturbed, its response speed and stability often do not meet the actual demand. In recent years, fuzzy logic control has been widely used in all kinds of control systems because it does not rely on precise mathematical models and can handle nonlinear problems. At the same time, the development of fractional order calculus theory provides new ideas for control system design, and the fractional order PID controller has more degrees of freedom and better robustness than the integer order PID controller. Combining fuzzy logic and fractional-order PID control can give full play to the advantages of the two methods, realize the adaptive adjustment of control parameters, and improve the dynamic performance and anti-interference ability of the system. Currently, for the wind turbine speed control system, how to effectively integrate fuzzy logic and fractional-order PID control technology to construct an efficient and stable control strategy is still a problem that requires in-depth research.

In this study, a design method of fan speed regulation control system based on fuzzy fractional-order PID is proposed. Firstly, a mathematical model of fan speed control is established to analyze the magnetic induction density and torque characteristics of the fan; secondly, the fuzzy control theory is elaborated in detail, including fuzzy set, affiliation function and fuzzy inference mechanism; thirdly, a fuzzy fractional-order PID controller is designed to realize adaptive adjustment of the control parameters by means of the fuzzy rules; lastly, the system is simulated by using the Simulink and Fluent software, and the effects of different order parameters on the system are analyzed. Analyze the effect of different order parameters on the system performance, and compare with traditional PID and other optimization algorithms to verify the effectiveness of the proposed method.

II. Fuzzy fractional-order PID-based fan speed regulation control system

II. A. Structure of wind turbine system and mathematical model of speed control

The fan rotation speed optimization parameters are modeled as: fan rotation electromagnetic coupling pole pair number P, pole arc coefficient β, fan rotor blade coil thickness l_m, rotor/stator yoke thickness l_y, magnetic leakage inductance L, stator/rotor core reluctance l_w, fan air gap length l_g, fan fan rotor radius r_i, fan core permeability J_{cu}, fan coil diameter l. The stator/rotor axial length ratio of the magnetic dipole of the fan is $\lambda = d_b / l_s$, so that $l = l_s, r = r_r + l_g, NI = A_w J_{cu} k_f$, and the fan radial magnetic moment can be expressed as:

$$\dot{E}_\phi = \frac{\omega \dot{M}}{4\pi R^2} \sin\theta (KR - j) e^{-jKR} \tag{1}$$

Construct the optimal control objective function of fan rotor blade speed regulation, divide the fan rotor blade magnetic dipole radiation electromagnetic field into three regions, and get the fan magnetic induction density as:

$$B_g = \frac{F_m}{A_g \Re} \tag{2}$$

The wind turbine rotor blades are acted upon by the wind force by exciting the aerodynamic gates, and the force on the operating conductor of the wind turbine is: $f = Il \times B$ and the magnetic field vector is:

$$\dot{H} = \sqrt{\dot{H}_R^2 + \dot{H}_\theta^2} \tag{3}$$

where R is the frontal winding air gap area of the machine, $\dot{H}_\theta^2$. Is the rotor rotation FM amplitude, ignoring the armature reaction and stator/rotor core magnetoresistance, and considering the coupled leakage coefficient k_i of the fan rotor, the torque of the fan rotation speed control is obtained as:

$$\dot{H}_\theta = \frac{\dot{M}}{4\pi\mu R^3} \sin\theta [1 + \chi + j\chi(1 + 2\chi)] e^{-\chi} \tag{4}$$

$$|H_\theta| = \frac{M}{4\pi\mu R^3} \sin\theta \sqrt{1 + 2\chi + 2\chi^2 + 4\chi^3 + 4\chi^4} e^{-\chi} \tag{5}$$

Calculate the stator d shaft current, a certain initial state of the voltage signal between (0 ~ 4.1V), the fan in the t_0 moment current error is reduced, through the above analysis, the fan rotation speed regulation control parameter model.

II. B.Fuzzy control theory

II. B. 1) Fuzzy sets and affiliation functions

In classical set theory, the domain is usually denoted by U, and let the subset A be contained in the domain U, then the element u, or $u \in A$, or $u \notin A$, is in the domain. The result must be obtained in classical set theory. Suppose the characteristic function μ_A is denoted by $u_A = 1$ if the element $u_A \in A$; If $u_A \notin A$, then it is denoted by $u_A = 0$. Thus the characteristic function of the element u_A with respect to the set A is denoted by:

$$\mu_A(u) = \begin{cases} 1, & u \in A \\ 0, & u \notin A \end{cases} \tag{6}$$

If the value of the characteristic function of a set A is extended from discrete 0 and 1 to a continuous closed interval [0, 1], the meaning of the function $\mu_A(u)$ changes to denote the degree to which the element u belongs to the set A, referred to as the degree of affiliation, and accordingly, the classical set A changes to the fuzzy set A.

The affiliation function [23] has the following four ways to represent a fuzzy set:

(1) Sequential Pair Representation If the domain U of a fuzzy set A is a set of finite elements, the fuzzy set A is denoted as:

$$\begin{aligned} A &= \{(x_i, \mu(x_i)) \mid x_i \in U, i = 1, 2, \cdots, n\} \\ &= \{(x_1, \mu(x_1)), (x_2, \mu(x_2)), \cdots, (x_n, \mu(x_n))\} \end{aligned} \tag{7}$$

(2) Vector Representation If the the thesis domain U of a fuzzy set A is a set of finite elements and the order of the elements is constant, the affiliation degrees can be arranged in the order of the set elements. The method can be expressed as:

$$A = \{\mu(x_1), \mu(x_2), \cdots, \mu(x_n)\} \tag{8}$$

(3) When the argument domain is a countable set, the fuzzy set A is:

$$A = \sum \frac{\mu(x_1)}{x_i} = \frac{\mu(x_1)}{x_1} + \frac{\mu(x_2)}{x_2} + \cdots + \frac{\mu(x_n)}{x_n}, i = 1, 2, \cdots, n \tag{9}$$

denoted when the domain of the argument is an uncountable set:

$$A = \int \frac{\mu(x)}{x} \tag{10}$$

In Zadeh representation, the operation symbols represent some kind of correspondence between the degrees of affiliation.

(4) Functional Representation If the domain of fuzzy set is an uncountable set, it can be expressed by the affiliation function. Let the domain $U = \{0, 1, 2, \cdots, 10\}$, the fuzzy set A is the “integer close to 0”, in the domain U each element of the degree of affiliation of $\mu_F(x_i)$, then the fuzzy set is:

Sequential Pair Method:

$$A = \begin{Bmatrix} (0,1), (1,0.9), (2,0.8), (3,0.7), (4,0.6), \\ (5,0.5), (6,0.4), (7,0.3), (8,0.2), (9,0.1), (10,0) \end{Bmatrix} \tag{11}$$

Vector method:

$$A = \{1.0, 0.9, 0.8, 0.7, 0.6, 0.5, 0.4, 0.3, 0.2, 0.1, 0\} \tag{12}$$

Zadfa:

$$A = \frac{1.0}{0} + \frac{0.9}{1} + \frac{0.8}{2} + \frac{0.7}{3} + \frac{0.6}{4} + \frac{0.5}{5} + \frac{0.4}{6} + \frac{0.3}{7} + \frac{0.2}{8} + \frac{0.1}{9} + \frac{0}{10} \tag{13}$$

The 5 commonly used affiliation functions are as follows.

Triangular affiliation function [24]:

$$f(x,a,b,c)=\begin{cases}0 & x\le a\\ \dfrac{x-a}{b-a} & a\le x\le b\\ \dfrac{c-x}{c-b} & b\le x\le c\\ 0 & x\ge c\end{cases} \tag{14}$$

Bell-type affiliation function:

$$f(x,a,b,c)=\frac{1}{1+|\frac{x-c}{a}|^{2b}} \tag{15}$$

The shape of its affiliation function is determined by the parameters a,b and the center position is determined by c.

Trapezoidal affiliation function:

$$f(x,a,b,c,d)=\begin{cases}0 & x\le a\\ \dfrac{x-a}{b-a} & a\le x\le b\\ 1 & b\le x\le c\\ \dfrac{d-x}{d-c} & c\le x\le d\\ 0 & x\ge d\end{cases} \tag{16}$$

Gaussian type affiliation function:

$$f(x,\sigma,c)=e^{-\frac{(x-c)^2}{2\sigma^2}} \tag{17}$$

The width parameter σ of the curve of this affiliation function is determined and the center position is determined by c.

Sigmoid type affiliation function:

$$f(x,a,b)=\frac{1}{1+e^{-a(x-b)}} \tag{18}$$

The shape of this affiliation function is determined by a,b and the image is centrosymmetric about the point $(a,0.5)$.

II. B. 2) Fuzzy Propositions and Fuzzy Reasoning

Compared to ordinary propositions, fuzzy propositions have a broader meaning, especially in line with the way people think. The general form of a fuzzy proposition is:

$$A: e \quad is \quad F \tag{19}$$

where, A -fuzzy propositions; e -fuzzy variables; F -fuzzy sets corresponding to fuzzy concepts. The fuzzy propositions are represented by the affiliation function, i.e.:

$$A=\mu_F(e) \tag{20}$$

When $\mu_F(e)=1$, A is a true proposition; when $\mu_F(e)=0$, A is a false proposition. Fuzzy logic differs from ordinary logic in that fuzzy logic can take continuous values between the closed intervals [0, 1], which also shows that it is a special kind of logic.

The following definition is made for the operations on fuzzy sets:

Suppose A,B are fuzzy sets with affiliation functions $\mu_A(x),\mu_B(x)$ respectively. Equality of fuzzy sets: if all x affiliation functions in A,B are equal, then A and B are equal. I.e:

$$\mu_A(x)=\mu_B(x)\Leftrightarrow A=B \tag{21}$$

Complementary set operation: B is called the complementary set of A if the affiliation function $\mu_B(x)=1-\mu_A(x)$ of B. Denote it as $\overline{A}=B$.

Containment operation: B is said to be contained in A if $\mu_B(x)\le\mu_A(x)$. Denote as $B\subseteq A$.

Concatenation operation: the concatenation of A and B is a fuzzy set C, denoted as $C=A\cup B$, and expressed in terms of the degree of affiliation as:

$$\mu_C(x)=\max[\mu_A(x),\mu_B(x)] \tag{22}$$

Intersection operation: the intersection of fuzzy sets A and B is the fuzzy set C, denoted as $C=A\cup B$, and expressed in terms of the degree of affiliation as $\mu_C(x)=\min[\mu_A(x),\mu_B(x)]$.

Commonly used defuzzification methods:

Center of gravity method: find the center of gravity of the area enclosed by the curve of the affiliation function and the x-axis, and use its horizontal coordinate as the exact value after the defuzzification calculation. I.e.:

$$x_0=\frac{\int_V x\mu(x)dx}{\int_V \mu(x)dx} \tag{23}$$

If the argument domain U is discrete, then the exact value x_0 after defuzzification can be obtained by the following equation:

$$x_0=\frac{\sum_{i=0}^{n} x_i\mu(x_i)}{\sum_{i=0}^{n}\mu(x_i)} \tag{24}$$

Maximum affiliation method: first find the highest point on the affiliation curve, and project its value x_0 on the x-axis as the exact value after defuzzification.

Area Equalization Method: It is to divide the area equally to solve the problem. First find the area of the graph enclosed by the affiliation image curve and the x-axis, and then find a straight line perpendicular to the x-axis, which is required to divide the area into two equal parts. The horizontal coordinate of this line is the exact value x_0. If the area of the graph enclosed by the curve of the affiliation function and the x-axis is difficult to calculate, then it can be calculated according to the following formula:

$$\int_a^{x_0}\mu(x)dx=\int_{x_0}^{b}\mu(x)dx=\frac{1}{2}\int_a^b\mu(x)dx \tag{25}$$

II. B. 3) Typical fuzzy controllers and how they work

In general, the more inputs and outputs a fuzzy controller has, the better the control performance. The higher the input dimension, the more control bases the fuzzy controller has, the more the fuzzy rules formulated meet the requirements of the application, and the better the control effect is naturally. Fuzzy controllers can be categorized into Mamdani type and T-S type.

(1) The biggest advantage of Mamdani type fuzzy controller is that it does not need an accurate mathematical model. This controller transforms the expert's knowledge of the control model or the control experience of the controlled model into an automatic control strategy through fuzzy reasoning, and its fuzzy control rules are in the form of:

$$\begin{gathered}
R_1\ \text{IF}\ x_1\ \text{is}\ A_1^1\ \text{AND}\ x_2 is A_2^1\ \text{AND}\ \cdots x_m\ \text{is}\ A_m^1,\ \text{then}\ y\ \text{is}\ Y^1\\
R_2\ \text{IF}\ x_1\ \text{is}\ A_1^2\ \text{AND}\ x_2 is A_2^2\ \text{AND}\ \cdots x_m\ \text{is}\ A_m^2,\ \text{then}\ y\ \text{is}\ Y^2\\
\vdots\\
R_n\ \text{IF}\ x_1\ \text{is}\ A_1^n\ \text{AND}\ x_2 is A_2^n\ \text{AND}\ \cdots x_m\ \text{is}\ A_m^n,\ \text{then}\ y\ \text{is}\ Y^n
\end{gathered} \tag{26}$$

where, R_n - the n th fuzzy control rule; x_m - the input variables of the controller; A_m^n - the fuzzy set of input variables; Y^n - the fuzzy set of output variables; y -controller output.

(2) The T-S type fuzzy controller1 does not require a defuzzification process and the outputs can be either functions on the input variables or explicit values, which makes it more application friendly.The T-S type fuzzy model can be described by the following statement:

$$\begin{aligned} &R_i \text{ IF } x_1 \text{ is } A_1^1 \text{ AND } x_2 \text{ is } A_2^1 \text{ AND } \cdots x_m \text{ is } A_m^1, \text{ then } y = f_1(x_1, x_2, \cdots, x_m) \\ &R_2 \text{ IF } x_1 \text{ is } A_1^2 \text{ AND } x_2 \text{ is } A_2^2 \text{ AND } \cdots x_m \text{ is } A_m^2, \text{ then } y = f_2(x_1, x_2, \cdots, x_m) \\ &\vdots \\ &R_n \text{ IF } x_1 \text{ is } A_1^n \text{ AND } x_2 \text{ is } A_2^n \text{ AND } \cdots x_m \text{ is } A_m^n, \text{ then } y = f_n(x_1, x_2, \cdots, x_m) \end{aligned} \tag{27}$$

For localized linear systems, segmented control systems and nonlinear time lag systems, T-S type controllers provide better control.

II. C.Fuzzy fractional order PID controller

II. C. 1) Fractional Order PID Controller

The main content of the study of fractional order calculus is how to design the fractional order controller, the common typical fractional order controllers are CRONE controller, $PI^{\lambda}D^{\mu}$ controller, fractional order overrun a lag compensator, fractional order differential equations in the time domain is shown in the following expression:

$$b_0 D^{\beta_0}{}_{y(t)} + b_1 D^{\beta}{}_{y(t)} + \cdots + b_m D^{\beta_n}{}_{y(t)} = a_0 D^{\alpha_0}{}_{u(t)} + a_1 D^{\alpha_1}{}_{u(t)} + \cdots + a_n D^{\alpha_n}{}_{u(t)} \tag{28}$$

In this equation, ${}_0D_t^{\alpha_n}$ defines the difference differential operator. At the initial state, the transform Laplace transform is performed on the above equation:

$$G(s) = \frac{Y(s)}{U(s)} = \frac{a_0 D^{\alpha_0} + a_1 D^{\alpha_1} + \cdots + a_n D^{\alpha_n}}{b_0 D^{\beta_0} + b_1 D^{\beta_1} + \cdots + b_m D^{\beta_m}} = \frac{\sum_0^n a_i D^{\alpha_i}}{\sum_0^n b_j D^{\alpha_j}} \tag{29}$$

Negative feedback control mechanism:

$Gc(s)$ denotes the transfer function of the controller, $Gs(s)$ denotes the transfer function of the controlled object, $W(s)$ denotes the input signal, and $Y(s)$ denotes the output of the closed-loop system:

$$G(s) = \frac{Y(s)}{W(s)} = \frac{G_c(s)G_s(s)}{1 + G_c(s)G_s(s)} \tag{30}$$

$$Y(s) = G(s)W(s) \tag{31}$$

The output of the negative feedback control system in the time domain is:

$$y(t) = L^{-1}[G(s)W(s)] \tag{32}$$

To determine a specific output system expression, an inverse transformation of Eq. (30) is required:

$$G(s) = \frac{Y(s)}{U(s)} = \frac{a_0 D^{\alpha_0} + a_1 D^{\alpha_1} + \cdots + a_n D^{\alpha_n}}{b_0 D^{\beta_0} + b_1 D^{\beta_1} + \cdots + b_m D^{\beta_m}} = \frac{\sum_0^n a_i D^{\alpha_i}}{\sum_0^n b_j D^{\alpha_j}} \tag{33}$$

For partial PID controllers, the time expression is:

$$u(t) = k_p e(t) + k_t D^{\lambda} e(t) + k_d D^{\mu} e(t) \tag{34}$$

The fractional order PID controller [25] can be regarded as a special type of filter. Its design principle is similar to that of a full PID controller. The difference is that the fractional controller PID adjusts five controller parameters based on the system performance specification. The performance specification adjusts the five parameters of the controller - Kp, Ki, Kd, λ, μ, and performs a Laplace transform of the time-domain expression of fractional-order calculus to obtain the following equation:

$$L\{{}_a^cD_t^\alpha f(t)\} = s^\alpha F(s) - \sum_{k=0}^{N-1} S^{\alpha-k-1} f^{(k)} \tag{35}$$

Under zero initial conditions the above equation can be expressed as:

$$L\{{}_a^cD_t^\alpha f(t)\} = s^\alpha F(s) \tag{36}$$

The PID controller local transfer function is modeled:

$$G_c(s) = K_p + \frac{K_i}{s^\lambda} + K_d s^\mu, (\lambda, \mu > 0) \tag{37}$$

In the above equation, s^λ it is the integral term associated with the steady state error of the system. The slope of the s^λ phase frequency is -20 λ dB/dec. The partial order PID controller has been increased by λ data compared to the full order PID controller.

II. C. 2) Components and working mechanism of fuzzy fractional order control system

The theoretical basis of this system of fuzzy mathematics, which converts expert knowledge into an automatic control strategy, is centered on fuzzy control rules formed based on practical experience. This part presents the results of fuzzy fractional order PID [26] controller using fuzzy rules to adjust the partial parameter PID controller, fuzzy fractional order PID controller is essentially on the basis of the above fractional order PID control, adding fuzzy inference link to realize the fractional order PID controller parameter connection, and to achieve the partial sequence.

II. C. 3) Fuzzy fractional order PID controller

(1) Determination of affiliation function and control rules

The fuzzy control rule is the most important of all the links, here take the fuzzy controller's input is the cooling water temperature and temperature deviation e and its rate of change e., the output variables are $\Delta Kp, \Delta Ki, \Delta Kd, \Delta\lambda, \Delta\mu$, in the thesis domain of the inputs and outputs, except for $\Delta\lambda, \Delta\mu$ is [-0.1, 0.1], the rest are taken as [-3, 3], and the fuzzy subsets are {NB, NM, NS, Z, PS, PM, PB}, which stand for negative large, negative medium, zero, positive medium, positive large, and five affiliation functions, respectively.

(2) Fuzzy variation rules for Kp, Ki, Kd, λ and μ

For different errors and their degree of change, the fuzzy fractional order PID control parameters Kp fraction, Ki, KD, into and μ size can be varied according to the following rules:

When e is large, a larger value of Kp and a smaller value of Kd should be used; Kp enhances the system response rate, and a smaller Kd reduces the effect of interfering signals;

When e is moderately large, the system operates at a fast rate, as well as good stability and tracking performance, a smaller Kp and appropriately sized Ki and Kd should be taken;

When e is small, in order to make the system have excellent response speed, smaller overshooting amount, should take a smaller Kp and appropriate size of Ki, Kd;

The parameters $\Delta\lambda, \Delta\mu$ affect the integration conditions and control derivatives by changing the values of λ and μ . The λ mainly affects the accuracy of the system state and the adjustment time. For different errors and error change rates, the size of the control parameter $\Delta\lambda, \Delta\mu$ can be varied according to the following rules:

When e is large, take a larger λ to reduce the systematic error;

When e is moderately large, take appropriate values of entry and μ to maintain system stability;

When e is small, the value of λ, μ should be adjusted appropriately according to the rate of change of error e, in order to maintain a smaller system. The system error at the same time, improve the stability of the system; by the fuzzy logic rules to rectify the parameter expression is as follows:

$$\begin{cases} K_p = K_{p0} + \Delta K_p \\ K_i = K_{i0} + \Delta K_i \\ K_d = K_{d0} + \Delta K_d \\ \lambda = \lambda_0 + \Delta\lambda \\ \mu = \mu_0 + \Delta\mu \end{cases} \tag{38}$$

In the above equation $K_{p0}, K_{i0}, K_{d0}, \lambda_0, \mu_0$ is the initial value of each parameter of the controller, $\Delta Kp, \Delta Ki, \Delta Kd, \Delta\lambda, \Delta\mu$ is the increment of the parameter obtained after fuzzy reasoning, in this paper, the center of gravity method is used to generate the fuzzy reasoning output value.

III. Analysis of the effect of fan speed regulation based on fuzzy fractional-order PID controller

III. A. Verification of the effect of fuzzy fractional order PID controller

In Simulink software, according to the deviation of the required air volume and the current air volume predicted by the BP neural network and its rate of change, the rotational speed of the coal mine fan is controlled by the fuzzy fractional-order PID controller and the PID controller, respectively, and the control effect of different controllers is shown in Fig. 1. As can be seen from the figure, the 2 control methods can quickly make the fan speed to reach a stable state. Compared with the PID controller, the proposed fuzzy fractional-order PID controller controls the fan speed to a steady state faster, and after a delay of 10s, the fan speed reaches a steady state, and the overshooting amount decreases by about 15%. This shows that the fan speed can be regulated more quickly with the fuzzy fractional-order PID controller, which has good adaptive ability and shows good dynamic performance.

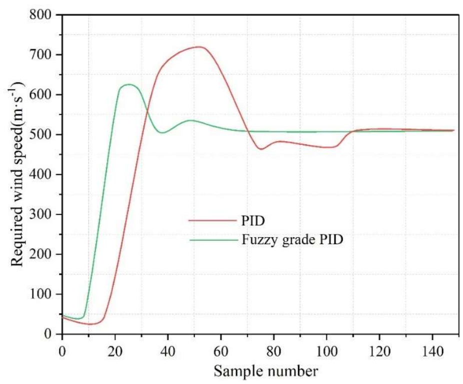


Figure 1: Control effect of different controllers

In order to verify the superiority of the proposed fuzzy fractional-order PID controller, based on Simulink software, the control effect of the designed fuzzy fractional-order PID controller, the improved particle swarm optimization algorithm optimized PID controller (PSO-PID) and the improved genetic algorithm optimized PID control (GA-PID) on the rotational speed of the wind turbine is analyzed, and the control effect of the different controllers is shown in Figure 2. As can be seen from the figure, compared with PSO-PID controller and GA-PID controller, the proposed fuzzy fractional-order PID controller has a better control effect on the fan speed, which can quickly control the fan speed to reach a steady state, and almost no overshooting phenomenon; while the other controllers under the control of the fan speed to reach a steady state for a longer period of time, and overshooting phenomenon has occurred. This shows that the fuzzy fractional-order PID controller has a certain superiority for fan speed control, which can improve the precision of fan speed control and shorten the time of fan speed control.

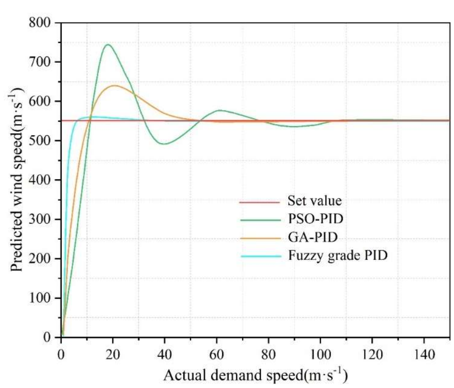
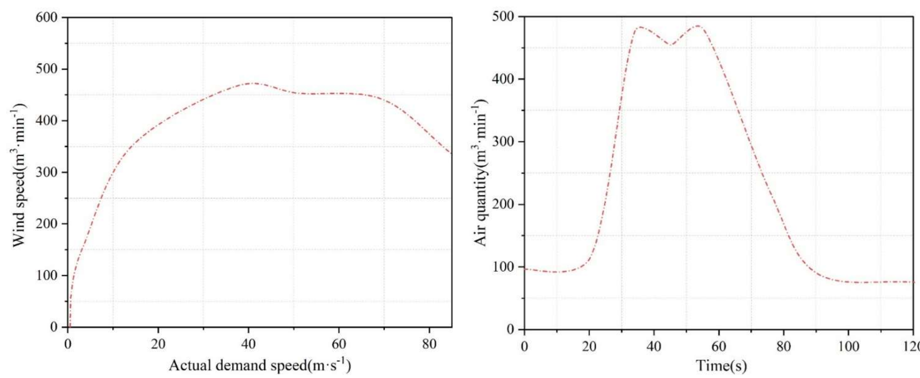


Figure 2: Control effect of different controllers

To further verify the effectiveness of the fuzzy fractional-order PID controller, the experiment was based on Simulink and Fluent software, and based on the deviation and change rate between the required air volume predicted by the BP neural network and the current air volume. The joint simulation results of the fuzzy fractional-order PID controller are shown in Figure 3. Among them, (a) and (b) respectively represent the curve of air volume varying with the actual required wind speed and the curve of air volume varying with time. As can be seen from Fig. (a), from 0 to 40s, the fan air volume rises rapidly; from 41 to 70s, the fan air volume is more stable; from 71 to 85s, the fan air volume decreases slowly. From Figure (b), it can be seen that from 0 to 20s, the fan air volume is lower; from 20 to 35s, the fan air volume rises rapidly; from 54 to 91s, the fan air volume decreases gradually; from 92 to 120s, the fan air volume is lower.

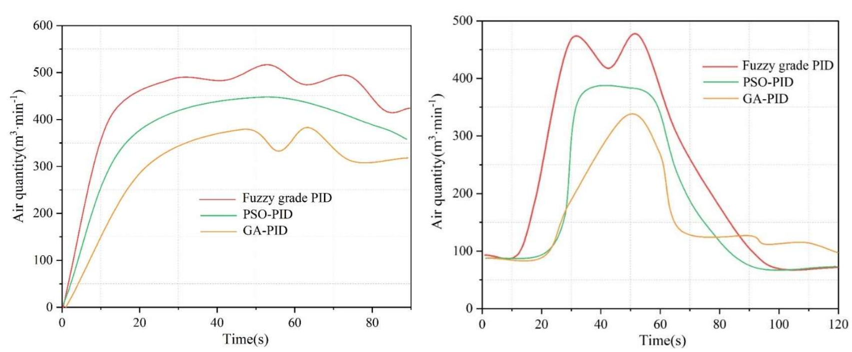
Analyze the reason, 0 ~ 40s, the mine in the harmful gas volume fraction is higher, the need for more air, and BP neural network predicted fan air volume and the actual air volume there is a significant difference, this time the need to quickly increase the air volume, increase the speed of the fan; 40 ~ 70s, BP neural network prediction of the fan air volume and the actual air volume is relatively close to the air volume, at this time the fan air volume is basically stable, the fan air speed to maintain stable; 70 ~ 85s, the volume fraction of harmful gases in the mine has decreased to the safety zone, the air volume decreases, and the fan speed should be reduced at this time.

Overall, the use of BP neural network and fuzzy fractional order PID controller for fan air speed control, there is no violent control fluctuations, and the control effect is good, speed regulation is smooth, overshooting is small, and can quickly realize the fan air speed control.



(a)The wind volume is the curve of the wind speed (b)The volume of the wind changes at any time

Figure 3: The joint simulation results of the fuzzy fractional PID controller



(a)The wind volume is the curve of the wind speed (b)The volume of the wind changes at any time

Figure 4: The different controllers are simulated by simulink and fluent

In order to verify the superiority of the proposed fuzzy fractional-order PID controller for fan speed control in Simulink and Fluent software, the control effects of fuzzy fractional-order PID controller, PSO-PID controller, and GA-PID control on the fan speed were experimentally compared based on the deviation of the predicted and current air demand and the rate of change of the air demand predicted by the BP neural network. The joint simulation results of different controllers in Simulink and Fluent are shown in Fig. 4, where (a) and (b) represent the variation curves of air volume with actual required air speed and air volume with time, respectively. As can be seen from the figure, compared with PSO-PID controller and GA-PID controller, the fuzzy fractional-order PID controller has better control performance, can quickly adjust the fan speed in real time according to the volume fraction of harmful gases, and then increase or decrease the airflow in real time, which can quickly maintain the volume fraction of harmful gases in a safe range, and it has the advantages of good control effect, smooth speed regulation, and small overshooting amount. This shows that the designed fuzzy fractional-order PID controller has certain superiority in the simulation environment.

III. B. System simulation and result analysis

Main parameters of mine explosion-proof type press-in counter-rotating axial local ventilation fan: P_n=25kW, U_n=370V, I_n=25.5A, f=55Hz, n_n=2500r/min, the number of pole-pairs p=4, and the permissible overload multiplier is 2.5, and the frequency inverter is used. VFD-460F is selected, main parameters: rated frequency 60Hz, externally set analog input voltage signal 1~15 V. Simulation study of local ventilation fan air volume regulation system is carried out by using Simulink and Fuzzy toolbox in Matlab.

III. B. 1) Effect of Fractional Order on the Control System

According to the established ventilation system model and the improved Oustaloup algorithm, the system is simulated, due to the existence of hysteresis in the system, the delay is taken as 2s, the input air volume is taken to be 300m³/min, λ=0.6, μ is chosen as 0.2, 0.4, 0.6, 0.8, and 1, respectively, and the step responses under different differential orders are shown in Fig. 5. From the figure, it can be seen that as the value of μ increases, the system oscillation is reduced, the dynamic quality is improved, the regulation time becomes shorter and the overshoot is reduced.

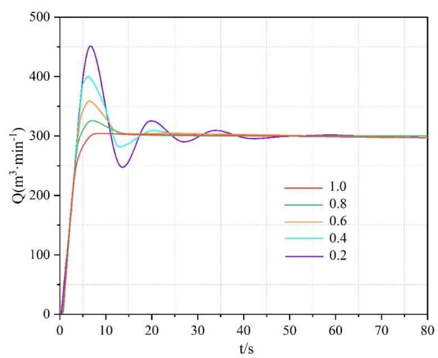


Figure 5: The step response of different derivatives

Taking μ=1 and λ is taken as 0.1, 0.3, 0.5, 0.7 respectively, the step response curves obtained from simulation with different integration orders are shown in Fig. 6. From the figure, it can be seen that as λ increases, the performance of the fuzzy fractional-order PID controller is improved, and the system has an overshoot, but it is relatively reduced, and at the same time, the order is too small or too large, which reduces the steady-state accuracy of the system.

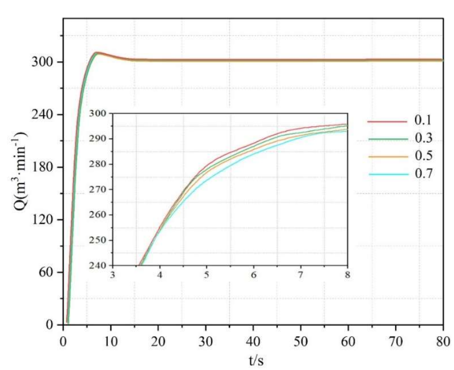


Figure 6: The step response of different integrals

III. B. 2) Normal ventilation comparison test

From the above analysis, the fuzzy fractional-order PID order is μ=1, λ=0.5, and the initial value of the fuzzy fractional-order PID controller can be obtained by the conventional PID controller parameter tuning method. The comparison results of the system order response curve are shown in Fig. 7. The control parameters of conventional PID are kp=0.001, ki=0.001, kd=0.001 and the simulation results are compared. Under the fuzzy fractional-order PID control, the system reaches the stabilization time of 6.97s, and the overshoot of the system is very small, which is 0.01%, while under the conventional PID control, the system reaches the stabilization time of 37.03s, which shows that the rapidity of the fuzzy fractional-order PID control is significantly better than that of the fractional-order PID and conventional PID control.

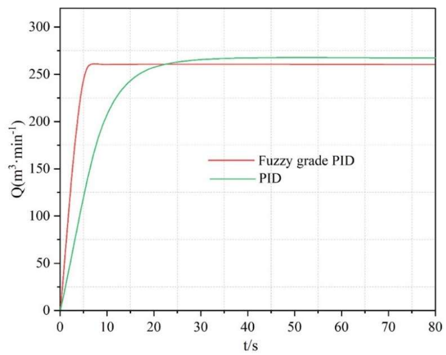


Figure 7: The comparison of the system step response curve

III. B. 3) Anti-interference tests

Conventional PID controllers have more obvious control qualities under ideal conditions (no disturbances), but do not achieve good control results under non-ideal conditions. However, the fuzzy fractional-order PID controller has the ability of online parameter tuning, which can deal with the disturbances appearing in the system and enhance the system's anti-disturbance ability. The comparative results of the step response curve under perturbation are shown in Fig. 8. When the given wind volume step response is stabilized, a disturbance signal with a time of 1s and 5% of the set value is added at 58s. It can be seen that when the sudden addition of external disturbances, the use of fuzzy fractional-order PID control, the rapidity and stability of the system is significantly better than the conventional PID control of the two control methods, and the disturbance is eliminated, it can be restored to a stable state more quickly.

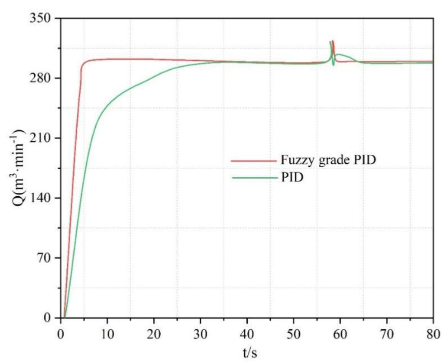


Figure 8: The comparison of the response curve of the disturbance

IV. Conclusion

For the fan speed regulation system, a control method based on fuzzy fractional-order PID is designed, and the effectiveness of the method is verified through theoretical analysis and simulation experiments. The fuzzy fractional-order PID controller utilizes fuzzy rules to adaptively adjust the control parameters, which improves the dynamic performance of the system. The simulation results show that the fuzzy fractional-order PID controller exhibits superior control with almost no overshooting compared with the PSO-PID controller and GA-PID controller. In the normal ventilation test, the system under fuzzy fractional-order PID control reaches the steady state in 6.97 s, and the overshooting amount is only 0.01%, while the stabilization time under the traditional PID control reaches 37.03 s. In the anti-jamming test, the fuzzy fractional-order PID controller restores the steady state faster when the system adds the disturbance signal with a time of 1 s and a set value of 5%. Fractional order parameter analysis shows that the differential order μ increases so that the system oscillation is reduced and the dynamic quality is improved; the integral order λ takes 0.5 when the system performance is optimal. The fuzzy fractional-order PID control strategy enhances the anti-interference ability of the system through online parameterization, and provides a feasible technical solution for the control of wind turbine speed.

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