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The Simulation of BLDC Motor Speed Control Based-Optimized Fuzzy PID Algorithm

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Abstract – **Fuzzy control and PID control are often used in control area. In recent years, a brushless DC motor (BLDCM) because of their good performance and low maintenance costs are more widely applied. Along with its control program is also rapid development. However, a single Fuzzy control or PID control can not satisfy the need of the rising complexity and precision of control systems. In this paper, with brushless DC motor (BLDCM) proposed a model based on PID speed control scheme, the use of brushless DC motor voltage equation and torque and speed equation adjust the PID parameters to achieve speed control. With the principle of fuzzy PID parameters , according to the changes in motor parameters PID parameters adjusted online, has made high-precision speed control. The simulation and experimental results show that the method of control of fuzzy PID for controlling a brushless DC motor, can achieve fast response, no overshoot, high control precision; and the system parameters and interference is high robust, as well dynamic and static performance are superior to the traditional PID control and only fuzzy control .**

Index Terms – Brushless DC Motort, Fuzzy PID control, PID control, Matlab / Simulink simulation

I. INTRODUCTION

Brushless DC motor is a permanent magnet motor, along with study of microelectronic devices and power electronic devices that emerged. In fact, it can be seen as a research study of the motor control system, the commutation of brushless motor is made of an external electronic circuitry. With don' t contact with the commutate or and brushes reduces generation of the spark, but also greatly reduces the motor losses and noise, it has been widely used in many demanding power drive. Permanent magnet brushless DC motor speed control system is a nonlinear, multivariable, time-varying system[1], and the parameter tuning is difficulty, a good set of tuning parameters only in a smaller scale have better control effect, when the parameter changes exceed a certain range, the effect become bad. and resulting in conventional PID control is difficult to meet the requirements.

While some of the new achievements of modern control theory, including pole placement and optimal control linear regulator based on precise feedback linearization, model reference adaptive control, are used to the control technology of motor to effectively improve the performance of brushless DC motor. but modern control theory is still dependent on the precise mathematical model of the motor, the motor performance parameters changes are impacted vulnerability by various uncertainties[2]. Since 1965, the University of California cybernetics expert Zadeh proposed fuzzy since its theories and methods of improving, just a few decades, the fuzzy control (Fuzzy Control) is widely used in the natural and social sciences and engineering control field [3]. Fuzzy logic has a natural language skills similar to the human brain, is very suitable for describing complex nonlinear systems. Fuzzy control does not depend on accurate mathematical model of controlled object [4], it is possible to overcome the influence of nonlinear factors on the adjustment object parameter changes have robust [5], but the summary of fuzzy rules and fuzzy membership tuning function rely mainly on experience, greater subjectivity. Simple fuzzy control certain steady-state error, steady precision low [6].

This paper presents a model that is based on fuzzy PID control of brushless DC motor speed control system. The model given its deviation and the rate of deviation change of between the actual speed and the change of speed act as the input parameters of the fuzzy control inference engine, with the fuzzy theory PID parameters online is adaptively adjusted and control system made simulation experiment in MATLAB . The simulation results show that the control system is fast response, small overshoot and robustness, and the dynamic characteristics is batter than traditional PID control and alone fuzzy control.

II. MATHEMATICAL MODEL OF BRUSHLESS DC MOTOR[7]

Brushless DC motor Consists of Three-phase stator windings, permanent magnet rotor, the inverter, the rotor magnetic pole position detector and other groups[8]. which its rotor used of shoe block and special magnetic circuit design, it can obtain a trapezoidal wave of gas gap magnetic field, the stator is used of the whole pitch concentrated winding, and the square wave current supplied by the inverter. The relations between Back-EMF and phase current of gap magnetic field sensor of BLDC , as shown in Fig1. Because the induced electromotive force of BLDC is trapezoidal wave comprising more high harmonics, and its inductance is nonlinear [9].Here, the use of induction motors d, q transform theory analysis method is not very effective, and in the analysis and simulation of BLDC control system, the direct use of phase variable method, according to the rotor position, represent induced electromotive force by the method of piecewise linear.

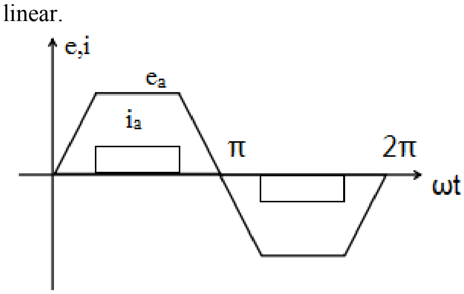

Fig. 1 The waveforms of A contrary EMF and current

In this paper, we make two-phase three-phase six star conduction state as a example to analysis BLDC characteristics of mathematical models and electromagnetic torque. For analysis, assume:

(1) Three-phase winding is completely symmetrical, the gap magnetic field is square-wave , the distribution of the stator current and rotor magnetic field are symmetrical [9].

(2) Ignore cogging, the process of phase change and the influence of the armature reaction.

(3) Armature windings in the stator surface is uniform continuous distribution.

(4) Magnetic circuit is not saturated, excluding eddy current and hysteresis losses.

According feature of BLDC ,we can create voltage, torque, and the equation of state and BLDC equivalent circuit.

A. Voltage equation

phase stator voltage balance equation of BLDC use the following state equation:

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_a & L_{ab} & L_{ac} \\ L_{ba} & L_b & L_{bc} \\ L_{ca} & L_{ab} & L_c \end{bmatrix} P \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{1}$$

In the formula, u_a, u_b, u_c is Three-phase stator voltage(V). e_a, e_b, e_c is the three-phase stator back electromotive force (V); i_a, i_b, i_c for the three-phase stator phase current (A); L_a, L_b, L_c for the three-phase stator self-inductance (H); L_{ab}, L_{ac}, L_{ba}, L_{bc}, L_{ca}, L_{cb} mutual inductance between the three-phase stator windings (H); R_a, R_b, R_c relative resistance (Ω) three-phase stator windings; P is the differential operator (d / dt).

The structure of the motor , by 360 ° in electrical angle, determines the rotor reluctance does not vary with the rotor position changes, and assuming symmetrical three-phase winding, there are: $L_a = L_b = L_c = L$, $L_{ab} = L_{ac} = L_{ba} = L_{bc} = L_{ca} = L_{cb} = M$, $R_a = R_b = R_c = R$.

Since the three-phase symmetrical motor, $i_a + i_b + i_c = 0$, and $Mi_b + M\,i_c = -Mi_a$, the formula (1) can be rewritten as:

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} P \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{2}$$

B. Torque equation

The electromagnetic torque equation of BLDC can be expressed as:

$$T_e = (e_a i_a + e_b i_b + e_c i_c) / \omega \tag{3}$$

Wherein, ω is the angular velocity of BLDC (rad / s).

The equations motion of BLDC can be expressed as:

$$T_e = T_l + B\omega + J\frac{d\omega}{dt} \tag{4}$$

Wherein, B is the damping coefficient (N · m · s / rad). J is the motor inertia (kg · m^2), T_l is load torque (N · m).

C. Equation of state

From (2) the voltage equation can be obtained equation of state of BLDC:

$$P\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \frac{1}{L-M} & 0 & 0 \\ 0 & \frac{1}{L-M} & 0 \\ 0 & 0 & \frac{1}{L-M} \end{bmatrix} \left\{ \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} - \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \right\} \tag{5}$$

III. Control Algorithm for BLDC

A.PID Control

With the rapid development of science and technology, The demand of control accuracy, response speed of automatic control system and stability of the system is higher, traditional PID control is mainly control the model of the linear process truly, and, in fact, most industrial processes are exist in different degrees of nonlinear, some process is difficult or can not established mathematical model at the same time, So the general PID control can not achieve precise control of such processes.

Classic PID control has been widely used because of its simple construction and good robustness. In project practice PID control still take the dominated place. The principle of PID control is to constitute a control with proportion, integration and differential, then choosing proper linear combination in order to control the target. As shown in Fig.2.

The feature of PID control is only change the controller parameters, can obtain satisfactory results. PID controller is a linear controller. For the control equation:

$$e(t) = x(t) - y(t) \tag{6}$$

The control law for PID controller is:

$$u(t) = k_p e(t) + k_i \int_0^t e(t)dt + k_d \frac{de(t)}{dt} \tag{7}$$

Where K_p is proportion gain coefficient, K_i is integration time coefficient, K_d is differential time coefficient.

(1) Proportion part: Proportion link is proportional to reflect the deviation signal, if the deviation produced, the controller reduce the deviation.

(2) Integral part: mainly used to eliminate static error, and improve the stability of the system.

(3) Differential part: can reflect the change trend of deviation signal (change rate), and before the value of the deviation signal become too large, the system introduced in an effective early correction signal, speed up the action of the system, reduce the adjusting time.

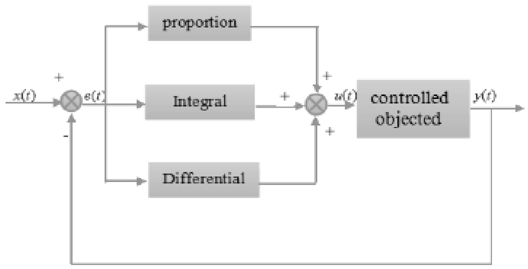

Fig.2 Schematic of a PID controller

B. Fuzzy control

Basic fuzzy control system including fuzzy, fuzzy reasoning and processing narrated. The basic structure of fuzzy control system is shown in Fig.3.

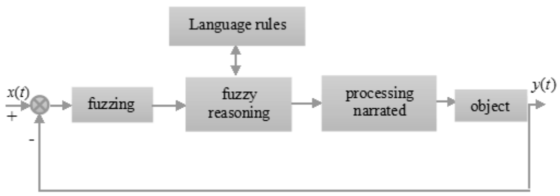

Fig. 3 Block diagram of Fuzzy control system

The processing of Fuzzy controller is to determine the value of the input in the process, at the same time, change the corresponding values of fuzzy language variables, the values of corresponding language variable are defined by the corresponding membership degree. Through such a theory that the input variables are mapped to the domain range with appropriate response process, accurate input data will transform into the appropriate language value or fuzzy set identifier. The general fuzzy controller uses the error and the error change as the input language variable.

Fuzzy reasoning commonly adopt the conditional sentences such as IF A THEN B to describe, including three parts: the major premise and minor premise and the conclusion. Major premise is multidimensional fuzzy conditional statements, which constitute a rule base, Adjustment and calibration of fuzzy rules is a key problem in fuzzy control.

Processing narrated is an important part of the fuzzy system, fuzzy reasoning is converted the fuzzy quantity into precise value. Common methods of the processing narrated have the maximum membership degree method, area average method, gravity method and maximum transferred to the average degree method.

Fuzzy control is the process of the interaction between these three links, it is key part is to choose suitable fuzzy membership function, use the reasonable reasoning method to come to a conclusion and adopt the appropriate methods of clear to restore the accurate quantity.

C. Fuzzy PID control

Fuzzy self-tuning PID controller with error e and error change rate ec as input, PID parameter K_p, K_i, K_d as output, *e* and *ec* can satisfy the self-tuning of the PID parameters. Using the fuzzy control rules to modify the PID parameters online, where we constitute a fuzzy self-tuning PID controller, the structure is shown in Fig. 4[10].

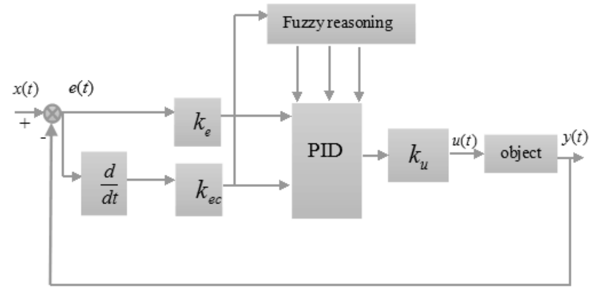

Fig.4 Block diagram of Fuzzy self-tuning PID control system

Where e is error and ec is error change rate, so K_e and K_{ec} are quantitative factors. K_u is the scaling factor.

From all aspects of stability, response speed, overshoot, and steady-state error of the system and other considerations, PID controller three parameters K_p, K_i, K_d role as follows [11]:

(1) The proportional coefficient K_p is to accelerate the response speed of the system and improve the regulation accuracy of the system. However, the more easily K_p larger system overshoot, or even make the system unstable. K_p value is too small, it will reduce the regulation accuracy, so that slow down the response, thereby extending the regulation time, static and dynamic characteristics of the system deteriorates.

(2) Integral coefficient K_i is to eliminate the steady-state error. Steady-state error K_i bigger, faster elimination system. But K_i is too large, early in the response process will produce integral saturation phenomenon, causing a large overshoot response process. However, if K_i is too small, the system is difficult to eliminate static error, regulation accuracy of the system.

(3) Differential coefficient K_d is to improve the dynamic characteristics of the system, mainly inhibit change deviation in any direction in response to the process, in advance of the forecast error. But K_d too large, it will advance the process of brake response, thereby extending the regulation time, reduce anti-jamming performance of the system.

The amount of the deviation e of input and error change rate ec and output ΔK_p, ΔK_i, ΔK_d make fuzzy processing, We take the fuzzy subset of fuzzy language variables are, representing a negative large, negative, the negative small, zero, positive small, positive large. Output here ΔK_p, ΔK_i, ΔK_d namely the amount of change K_p, K_i, K_d's. According to the actual situation, K_e, K_{ec} are quantized(-0.2 0.2), (- 0.05,0.05), (-2,2) region. Input and output variables are selected Gaussian membership functions. The use of MATLAB Gui design Mandani fuzzy controller, obtain the membership function of each fuzzy subset Fig.5 to7 [12].

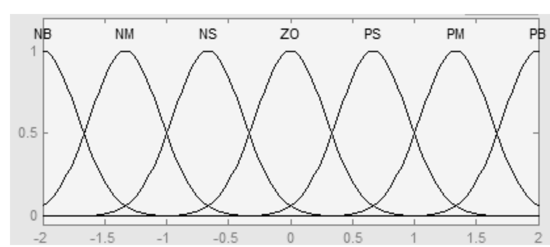

Fig 5 The membership functions of ΔK_d

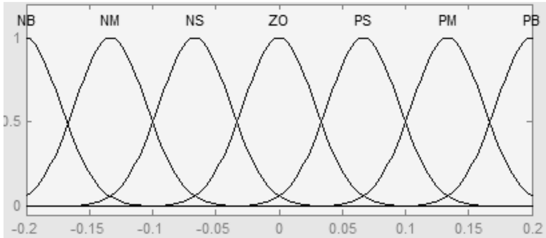

Fig 6 The membership functions of ΔK_p

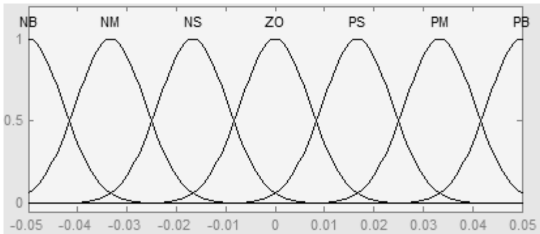

Fig 7 The membership functions of ΔK_i

For speed control system of brushless DC motor, taking into account the effect of contact time three different parameters and between[6], summarized based on actual operating experience, the establishment ΔK_p, ΔK_i, ΔK_d fuzzy control rules as shown in Table 1.

TABLE I

Fuzzy PID inference rules of Kp,Ki and Kd

e / ec	NB	NS	ZE	PS	PB
NB	NB PB PS	NB PB PS	PB NB ZB	PB NB ZE	ZE ZE PS
NS	PB NB NB	NS PS ZE	PS NS NS	ZE ZE ZE	NS PS ZE
ZE	PS NS NB	PS NS NB	ZE ZE NS	PS NS NB	NB PS PS
PS	PS NS NB	ZE ZE NS	NS PS NS	NS PS ZE	NB PB PS
PB	ZE ZE PS	NB ZE PS	NS PS ZE	PB NB ZE	PB NB PS

Controlled by the rule table, we can be drawn from a set of fuzzy control rules Fuzzy conditional constituted statements 49. Each fuzzy conditional statements to determine a fuzzy relation R_i, the "and" operator, the system can be drawn from the total 49 fuzzy relation fuzzy relations R_i of R. Made from different time input matrix synthesis and R op obtained three correction parameters ΔK_p, ΔK_i, ΔK_d fuzzy output, the amount of blur after clear processing (using the center area of the law) can be derived ΔK_p, ΔK_ii, the Δ Kd accurate output value, and then according to equation (5) can be calculated K_p, K_i, K_d output value and achieve self-tuning PID parameters online. Wherein, K_p ', K_i', K_d ' is three parameter of PID for the last sampling time.

$$\begin{cases} kp = kp' + \Delta kp \\ ki = ki' + \Delta ki \\ kd = kd' + \Delta kp \end{cases} \tag{8}$$

IV. Simulation and Results

Based on Matlab / Simulink establish a model of BLDC control system, and the model simulate BLDC dual closed-loop control system. In the simulation, the parameters of BLDC motor set: stator phase winding resistance R = 1 Ω, the stator phase winding inductance L = 0.02L, mutual inductance M = -0.061H, moment of inertia J = 0.005kg.m^2, damping coefficient B = 0.0002N · m · s / rad, rated speed n = 1000r / min, number of pole pairs p = 1,220V DC power supply. The basic use of system simulation module in MATLAB / Simulink built in a fuzzy PID controller and conventional PID simulation model, before simulation the first edited embedded fuzzy inference system Fuzzy Logic Controller module. Connect each module and modify the good of each module parameters. Show in Fig 8 [13].

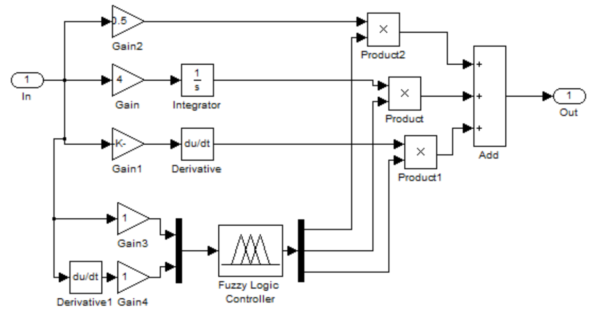

Fig .8 The simulation frame diagram of control system

A. The analysis results of simulation

After the system is running, you can see a virtual oscilloscope operating results, as shown in Fig. 9 to 12 that is the traditional PID control and fuzzy PID control. The results show that the fuzzy PID control than the traditional PID control, with higher control accuracy, small overshoot, control and regulate short time and good effect.

The following experiment is starting of motor without load and with load. The condition of simulation is staring without load and with load t=0 T=1.5N.m. t=0.6, T=4N.M. From the figures, we can see that when the motor star with a load, the torque have a fluctuations.

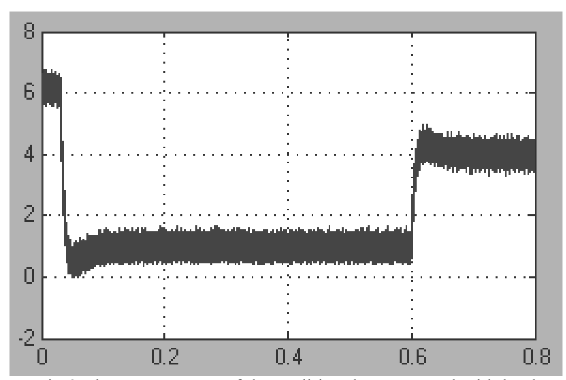

Fig.9 The torque curve of the traditional PID control with load

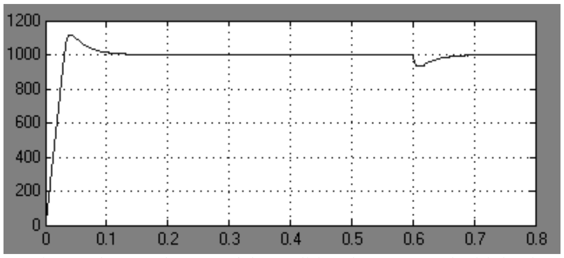

Fig.10 The speed curve of the traditional PID control with load

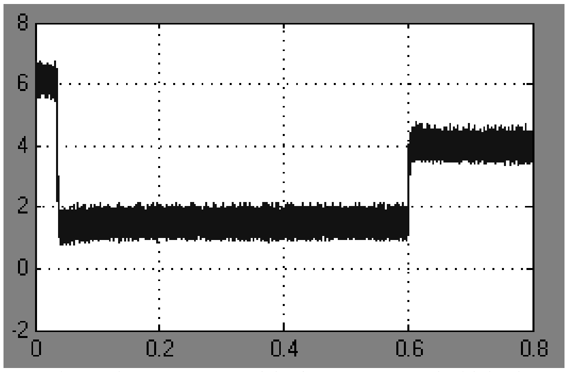

Fig.11 The torque curve of the fuzzy PID control with load

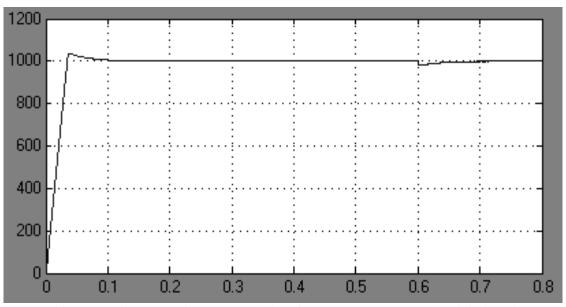

Fig.12 The speed curve of the fuzzy PID control with load

As it can be seen from these figures, For the conventional PID， when the motor star with load, the torque occur fluctuations , at same time, the speed occur little fluctuations. The time of adjustment become long. For the fuzzy PID, Compared with the traditional PID, The fuzzy PID control to this paper, the dynamic performance of torque and speed are improved significantly. The regulation time of torque and speed is shortened, the overshoot is reduced. It have a better robustness. As shown in Table 2, which are dynamic performance of the traditional PID and fuzzy PID with load and without operation.

TABLE I I
The speed of the traditional PID and fuzzy PID

With load	Adjustment time (t/s)	Overshoot (δ/%)
Traditional PID	0.18	15.8
Fuzzy PID	0.09	3.5

Here is the motor start-up and spin-down speed experiments. As shown in figure13 to 16.When at t=0.4s, the speed change from 1000 to 500. Then at t = 0.6s, when the load of the system mutate.

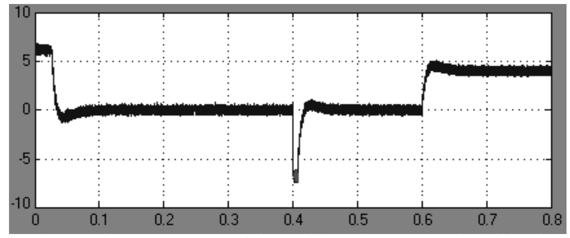

Fig.13 The torque curve of the traditional PID control with load

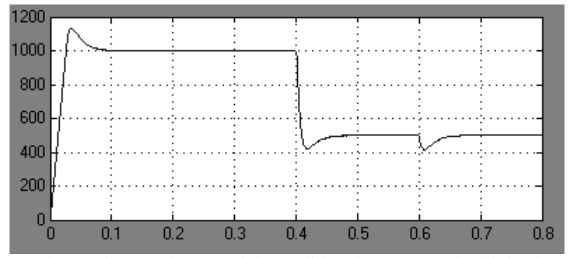

Fig.14 The speed curve of the traditional PID control with load

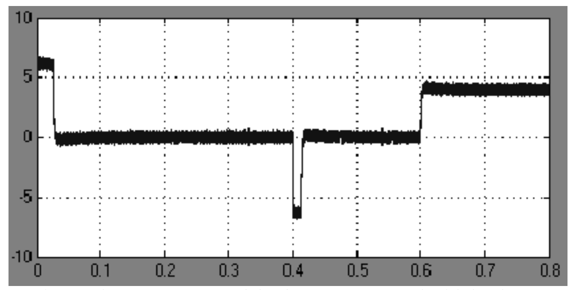

Fig.15 The torque curve of the fuzzy PID control with load

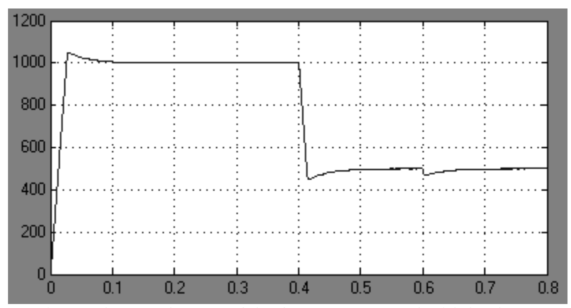

Fig.16 The speed curve of the fuzzy PID control with load

From the evident simulation curve and table we can obtain: The speed of fuzzy PID control of brushless DC motor is fast response and law overshoot; When at t=0.4s, the speed change from 1000 to 500. Then at t = 0.6s, when the load of the system mutate, the response curves less volatile, and quickly returned rated speed, the time of adjustment is short and strong anti-interference ability, the outcome show the system have good dynamic characteristics and greatly improve the robustness of the brushless DC motor speed control system. So that verify the proposed fuzzy PID controller can well suppress overshoot, load disturbance and speed fluctuations are robust and dynamic response capabilities, It can better control the motor speed.

V. CONCLUSIONS AND FUTURE WORK

This paper presented the design of control system of BLDC using the Fuzzy PID controller, which had a lot of great superiority for Brushless DC Motor Speed Control System. Compared with simple PID control or Fuzzy control, the controller which combined PID and Fuzzy had a better performance, including a small amount of overshoot and a fast response speed. Of course, the time of adjust is short. as we can see. The simulation results show that the fuzzy PID control scheme proposed is to improve the response speed of the brushless DC motor speed control system, overshoot suppression, improve control accuracy, enhance system robustness and dynamic and static performance, and its performance is superior to conventional control PID control.

At the same time, the controller combines PID and other methods, such as neutral network control will be considered in future work.

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REFERENCES

[1] Li Bin, Yongzhe Tang "The application of fuzzy PID algorithm in brushless DC motor control system", Micromotor, 14-15,2006.

[2] Guoyong Li, "Intelligent control and Its MATLAB realization", Beijing: Electronic Industry Press, 252-260,2005.

[3] Wang Ling, Weiguo Liu, "Brushless DC Motor Speed Control System Based on Fuzzy PI simulation", Computer Simulation, 186-189,2009.

[4] C. Yue, S. Guo, and M. Li, "ANSYS FLUENT-based modeling and hydrodynamic analysis for a spherical underwater robot", Proceedings of 2012 IEEE International Conference on Mechatronics and Automation, pp. 1577-1581, 2012.

[5] Junhong Li,Junlan Li, Wu Jiao Yang, "Brushless DC motor speed control system of adaptive neural network variable structure control ",Microcomputer Information,68-70,2010.

[6] Jingzhou Zhang,Weijing Yang,Anxiang Zhang,"The study and application of fuzzy adaptive PID Control Simulation ", Computer Simulation, 132-135,2009.

[7] Jicheng Chen，Yanxia Shen, Jianguo Jiang,"A Novel Method for Modeling and Simulation of BLDC SystemBased on Matlab" Journal of System Simulation,1745-1749, 2003.

[8] K. Kwan, D. Truongb, D. Namb, J. Yoonb, and S. Yokotac, "Position control of ionic polymer metal composite actuator using quantitative feedback theory", Sensors and Actuators A: Physical, Vol. 159, No.2, pp. 204-212, 2010.

[9] C. Bonomo, L. Fortuna, P. Giannone, S. graziani, and S. Strazzeri, "A nonlinear model for ionic polymer metal compositeds as actuators", Journal of Smart Material and Structures, Vol. 16, No. 1, pp. 1-12, 2007.

[10]MillerTJ E.Brushless Permanent-Magnet and Reluctance Motor Drives. Oxford， New York： Clarendon Press， 1989.

[11]Gengzhu Xie,Dezhi Wang,"Fuzzy control and PID control in the calcium carbide furnace applications",Chemical Industry Automation and Instrumentation,82-83,2004.

[12]Jicheng Chen，Yanxia Shen, Jianguo Jiang,"A fuzzy PI intelligent control, motor and Control new brushless DC motor speed control system", Electric Machines and Control,248-254,2003.

[13]Zhongsheng Wei,Yan Du,"The implementation of a paper machine Fuzzy-PID control system", Chemical Automation and Instrumentation, 79-80,2004.