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Adaptive Control for Brushless DC Motor Based on Fuzzy Inference

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Abstract

Due to the nonlinearity of brushless direct current (BLDC) motor, it is difficult to obtain satisfied control characteristics using proportional integral derivative (PID) controller. A novel adaptive fuzzy control method based on high performance speed control is proposed in this paper, which combines an adaptive parameter adjustment mechanism with fuzzy controller to solve the problems of non-linearity, parameter variations and load excursions that occur in the BLDC motor drive system. The adaptive parameter adjustment mechanism can give better quantization and proportion factors of the fuzzy controller when there are variations in motor parameters or load, hence the fuzzy control rules are changed. The adaptive fuzzy control system is simulated in matlab with the changes of motor parameters and load, the control performance of the traditional PID controller is compared with the adaptive fuzzy controller. The comparison results indicate that the adaptive fuzzy control system has stronger robust and self-adaptive ability, faster response time, and zero overshoot and steady state error, which can satisfy the request of the BLDC motor control system.

Keywords: *brushless DC motor, adaptive control, fuzzy control, simulation*

1. Introduction

With the development of power electronics technique, BLDC motor has been widely used in motion control applications such as aerospace, electric vehicles, robotics, numerically controlled machine tools, medical equipments, and so on. Since the BLDC motor doesn't use the physical contact between the mechanical brush and commutator, instead, it is electronically commutator; the BLDC motor has the advantages of higher power/weight, higher efficiency, higher reliability, and small size, etc. But compared with the DC motors, the BLDC motors yield a more complicated control problem.

PID controller is usually employed in a BLDC motor control system because it is simple in algorithm and realization. But PID control parameters depend on accurate mathematical model of the controlled system, and it isn't change automatically when the operating condition of controlled system changes such as disturbances and load changes, besides, it is difficulty to obtain a sufficient high performance in the nonlinear system using PID controller. It is, however, known that the BLDC motor is a nonlinear system with multi-variables. It is very difficult to gain an accurate mathematical model of the BLDC motor. Furthermore, some parameters of the motor are usually time-varying and uncertain. Thus the PID controller fails to obtain optimal performance with the requirements that BLDC motor control system should be more accurate, faster, and more efficient [1-5].

Recently, many new control methods are adopted to the BLDC motor control system such as fuzzy control, adaptive control, neural control, and sliding model control, etc [6-10]. Reference [7] combines a model reference adaptive system with artificial neural network to solve the problems of nonlinear, parameter variations and load excursions that occur in BLDC motor drive systems. In [8], in order to achieve high performance speed tracking, an adaptive backstepping controller is designed to obtain the reference voltage for the pulse width modulation in the BLDC motor control system. In [9], XIA Chang-liang et al. present an auto-tuning method for fuzzy logic controller based on genetic algorithm for the BLDCM control.

Both fuzzy control and adaptive control are nonlinear control methods, have advantages of the robust, self-adaptive ability, simple structure, and so on, they can be a very good deal with uncertainty, non-linearity, time variability and coupling of system, and they are very suitable

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for the BLDC motor system [11-17]. In this paper, it is proposed for BLDC motor system that an adaptive fuzzy controller combines fuzzy controller and adaptive controller, the proposed controller can adjust the controller parameters on-line, keeps simple structure, and has robust performance against disturbances and load variations. The performance of the proposed controller was compared with PID controller using MATLAB SIMULINK software. Simulation results prove that the adaptive fuzzy controller shows much higher static and dynamic performance than PID controller.

2. Mathematic Model of BLDC Motor

A three-phase BLDC motor is adopted in this paper, the BLDC motor consists of a permanent magnet rotor and stator windings, which are sinusoidally distributed in the “Y” connection, and the current always passes through two phase windings. Under the assumption of linear magnetic structure, the three-phase stator windings are completely equal, the self- and mutual inductances are constant, and the effect of alveolus, commutation and the armature reaction are ignored, the mathematical model of BLDC motor can be described by the following equations [18]:

$$u_a = R_a i_a + L_a \frac{di_a}{dt} + e_a \tag{1}$$

$$u_b = R_b i_b + L_b \frac{di_b}{dt} + e_b \tag{2}$$

$$u_c = R_c i_c + L_c \frac{di_c}{dt} + e_c \tag{3}$$

$$T_e = \frac{P_2}{\omega} = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega} \tag{4}$$

$$T_e - T_L = J\frac{d\omega}{dt} + B\omega \tag{5}$$

Where u_a, u_b, u_c are the per phase voltage of phase a, b and c respectively, i_a, i_b, i_c are the per phase current of phase *a*, *b* and *c* respectively, R_a, R_b, R_c are the per phase resistance of phase *a*, *b* and *c* respectively, L_a, L_b, L_c are the per phase inductance of phase *a*, *b* and *c* respectively, e_a, e_b, e_c are the per phase back electromotive force of phase *a*, *b* and *c* respectively, ω is the rotor speed, T_e and T_L are electromagnetic torque developed by the motor and load torque, *J* and *B* are inertia and friction coefficients.

Through analyzed the mathematical model of the BLDC motor, we can obtain the dynamic structure [19-20], as shown in Figure 1. In the Figure 1, U_d is direct current voltage, *R* is stator winding resistance and $R=R_a=R_b=R_c$, *L* is stator winding inductance and $L= L_a=L_b=L_c$, C_T is torque constant, C_e is voltage constant, GD^2 is flywheel moment of inertia.

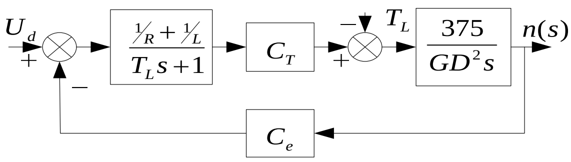


Figure 1. The BLDC Motor Dynamic Structure

The transform function of BLDC motor control system can be derived from the Figure 1, as shown in Equation (6),

$$n(s)=\frac{1/C_e}{\frac{LGD^2}{375}s^2+\frac{RGD^2}{375C_eC_T}s+1}U_d(s)-\frac{\frac{L}{C_eC_T}s+\frac{R}{C_eC_T}}{\frac{LGD^2}{375}s^2+\frac{RGD^2}{375C_eC_T}s+1}T_L(s) \tag{6}$$

3. Adaptive Fuzzy Controller of BLDC Motor

3.1. BLDC Motor Control System Structure

To improve the accuracy and dynamic performance, the BLDC motor control system adopts double closed loop control scheme of speed and current, the control system block is shown in Figure 2. Outer loop is speed loop to adjust the speed using adaptive fuzzy strategy, and inner loop is current loop to directly control current using PI controller.

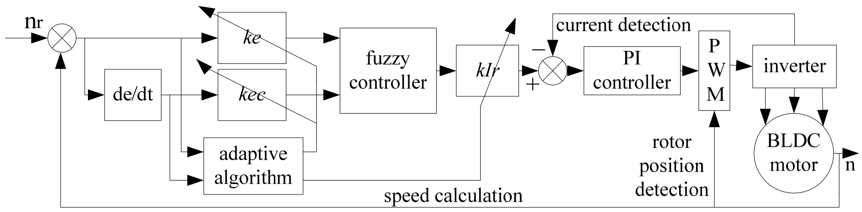


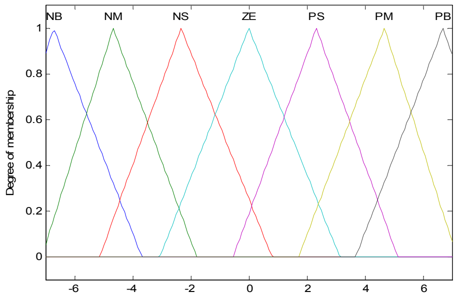
Figure 2. Control System Structure of the BLDC Motor

Adaptive fuzzy controller is consisted of fuzzy controller and parameters tuner of proportion and quantization factors. Parameters tuner continuously adjusts on-line the proportion and quantization factors of fuzzy controller based on speed error and its rate of change, the fuzzy control rules are changed too, and the control variable are adjusted automatically. Thereby, the proposed BLDC motor control system has good static and dynamic performance, self-adaptive ability, and stronger robustness when the BLDC motor operating condition changes such as disturbances and load changes, and so on.

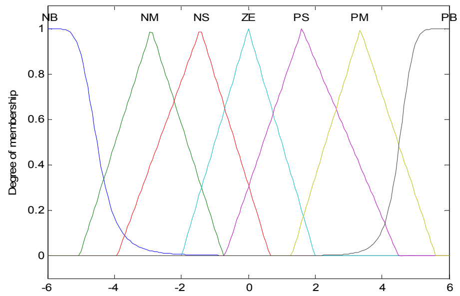
3.2. Design of Fuzzy Controller

The fuzzy controller is selected a two-dimensional structure with a dual-input and single output, the inputs of adaptive fuzzy controller are speed error *e* and error change rate *ec*, the output is reference current i_r .

The fuzzy domain of inputs (E, EC) are taken as [-6, 6], and the output (Ir) fuzzy domain are taken as [-7, 7]. Both inputs fuzzy subsets of linguistic variable and output's are selected as {NB, NM, NS, ZE, PS, PM, PB}. For the sake of simplicity, the membership function of E, EC and Ir are taken trigonometric function, as shown in Figure 3.



(a) E and EC membership function



(b) Ir membership function

Figure 3. Membership Function of E, EC and Ir

Fuzzy control rules are a series of fuzzy conditional statements based on the knowledge and experience of an experienced operator as well as an expert. In the BLDC motor control system, the fuzzy controller plays a role that system output is in fast response to system input and uncertain disturbances as soon as possible. Based on the principles and the previous experience in the BLDC motor control, the fuzzy control rules are obtained, as shown in Table 1.

Table 1. Fuzzy Control Rules

Ir		***EC***						
		NB	***NM***	***NS***	***ZE***	***PS***	***PM***	***PB***
	NB	PB	PB	PB	PB	PM	PS	ZE
	NM	PB	PB	PB	PM	PM	PS	ZE
	NS	PB	PB	PM	PM	PS	ZE	NS
E	***ZE***	PB	PM	PS	ZE	NS	NM	NB
	PS	PM	PS	ZE	NS	NM	NM	NB
	PM	PS	ZE	NS	NM	NB	NB	NB
	PB	ZE	NS	NM	NB	NB	NB	NB

The Mamdani inference reasoning algorithm is adopted as fuzzy inference method in this paper. According to fuzzy control rules in Table 1, a fuzzy set of output can be obtained using Mamdani inference reasoning algorithm when inputs are given. This fuzzy set of output must be defuzzification. Defuzzification of output information adopts weighted average method, the formula is:

$$\mathrm{Ir} = \frac{\sum_{i=1}^{n} \mathrm{Ir}_i \cdot \mu(\mathrm{Kr}_i)}{\sum_{i=1}^{n} \mu(\mathrm{Kr}_i)} \tag{7}$$

3.3. Design of Parameters Adaptive Tuning

Fuzzy controller is a controller using fuzzy linguistic variables. Among which, the input variables domain is transformed into the fuzzy domain by the quantization factors (ke, kec), while the output domain is transformed into the fuzzy domain by the proportion factor (kIr). The values of the proportion and quantization factors affect the static and dynamic performance of the BLDC motor control system, which will be adjusted by adaptive tuner according to the error and disturbance of system consequently.

As *e* and *ec* are all larger, the main task of adaptive tuner is to eliminate error. Thus the size of *ke* and *kec* should be smaller to reduce influence of *e* and *ec*, and the value of *kIr* should be bigger to decrease the response time and ensure stability of control system. When *e* and *ec* are all smaller, the control system is close to steady state. The system's main task is to stabilize as quickly as possible. The weight of *ke* and *kec* should be bigger to increase the influence of *e* and *ec*. and the value of *kIr* should be smaller to avoid over-shoot. Combined the above principle with the BLDC mathematic model, the functions below is chosen as performance functions of the *ke*, *kec* and *kIr*.

$$ke(m) = f(e(m), ec(m), T_L(m)) \tag{8}$$

$$kec(m) = g(e(m), ec(m), T_L(m)) \tag{9}$$

$$kIr(m) = y(e(m), ec(m), T_L(m)) \tag{10}$$

The value of *ke, kec* and *kIr* can be continuously adjusted by the performance index function J which can be expressed as:

$$J = E\left\{\left[P(m)e(m) + S(m)ec(m)\right]^2 + \left[Q(m)T_L(m)\right]^2\right\} \tag{11}$$

Where assume that:

$$\begin{cases} \dfrac{\partial J}{\partial e(m)} = 0 \\ \dfrac{\partial J}{\partial ec(m)} = 0 \\ \dfrac{\partial J}{\partial T_L(m)} = 0 \end{cases} \tag{12}$$

Calculate Equation (12), P(m), S(m), Q(m) would be obtained, and *ke, kec* and *kIr* can be expressed as Equation (13).

$$\begin{cases} ke(m) = \dfrac{P(m)}{\sum_{i=1}^{m} P(m)} \\ kec(m) = \dfrac{S(m)}{\sum_{i=1}^{m} S(m)} \\ kIr(m) = \dfrac{Q(m)}{\sum_{i=1}^{m} Q(m)} \end{cases} \tag{13}$$

Equation (13) shows that the value of ke, kec and kIr can be changed continuously and adaptively according to the error and disturbance of system, so the adaptive fuzzy controller can easily adapt to the nonlinear BLDC motor control system.

4. Simulation and Analysis

To test the performance of the adaptive fuzzy controller, we carried out a series of simulation experiments using Matlab/Simulink software. The adaptive fuzzy controller and the PID controller are simulated respectively. The parameters of the BLDC motor are: DC voltage U = 500V, rated power P=3000W, the resistance of stator winding R = 2.875Ω, inductances of the stator L = 8.5mH, moment of inertia J = 0.0012kg.m2, rated speed n = 3000r/min, number of pole pairs p = 2.

4.1. Simulation

The BLDC motor control system simulation experiments were carried on different operating conditions such as change in reference speed, change in load torque and change in moment of inertia, the response curves of the adaptive fuzzy controller and the PID controller were shown in Figure 4-Figure 7.

Figure 4 shows the speed response compared adaptive fuzzy controller with PID controller for a step change in reference speed. It can be seen that the BLDC motor system with adaptive fuzzy controller takes 40ms to reach steady state with zero overshoot and steady state error, while the PID control system takes 60ms to reach steady state with a percentage overshoot of 9% and zero steady state error.

Figure 5 shows the speed response of adaptive fuzzy controller and PID control system for a step change in load torque. It can be seen that the BLDC motor system with adaptive fuzzy controller takes 40ms to reach steady state with zero overshoot and steady state error, and the PID control system takes 70ms to reach steady state with a percentage overshoot of 7.5% and zero steady state error.

Figure 6 shows the speed response compared adaptive fuzzy controller with PID controller for a step change in reference speed as J is 0.0012Kg.m2. As shown in the Figure 6, the adaptive fuzzy control system takes 40ms to reach steady state with zero overshoot steady

state error, and the system with PID controller takes 80ms to reach steady state with a percentage overshoot of 6% and zero steady state error.
Figure 7 shows the speed response using adaptive fuzzy controller and PID controller for a step change in reference speed when J is 0.002Kg.m2. It can be seen that the BLDC motor system with adaptive fuzzy controller takes 40ms to reach steady state with zero overshoot and steady state error, and the PID control system takes 90ms to reach steady state with a percentage overshoot of 10% and zero steady state error.

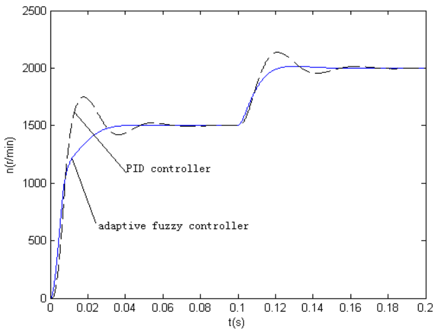


Figure 4. Speed Response with Step Change in Reference Speed

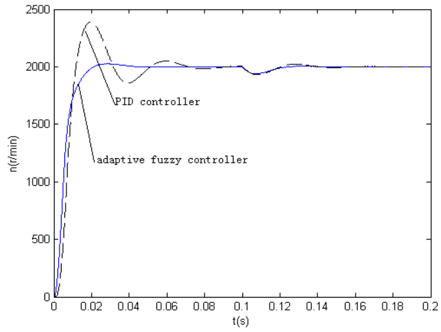


Figure 5. Speed Response with Step Change in Load Torque

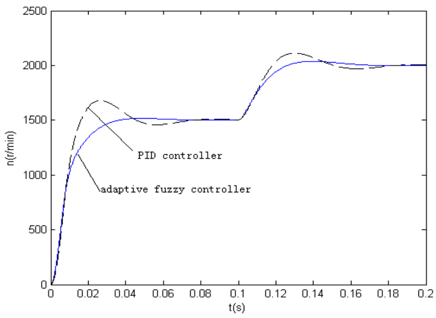


Figure 6. Speed Response with Step Change in Reference Speed (J=0.0012kg.m2)

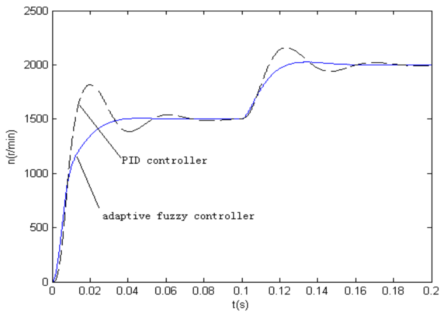


Figure 7. Speed Response with Step Change in Reference Speed (J=0.002kg.m2)

4.2. Simulation Results Analysis

Table 2. Performance Parameters of Adaptive Fuzzy and PID Controller

Simulation experiment: Changes in operating conditions	Controller	Response time(s)	Overshoot (%)
Change in reference speed	Adaptive fuzzy	0.04	0
	PID	0.06	9
Change in load torque	Adaptive fuzzy	0.04	0
	PID	0.07	7.5
J=0.0012 Kg.m^2	Adaptive fuzzy	0.04	0
	PID	0.08	6
J=0.002 Kg.m^2	Adaptive fuzzy	0.04	0
	PID	0.09	10

The simulation results of the BLDC motor control system compared the adaptive fuzzy controller with the PID controller are shown in Table 2. The simulation results clearly show that the steady and dynamic performance of adaptive fuzzy controllers is better than the PID controller during reference speed, load torque and inertia changes. The BLDC motor with adaptive fuzzy controller is able to respond with smaller response time, zero steady state and overshoot.

5. Conclusion

In this paper, we consider the adaptive fuzzy control algorithm for the BLDC motor system with parameters' uncertainty and nonlinearity, and the fuzzy controller and adaptive controller are nonlinear in nature. It is proposed that fuzzy control and adaptive algorithm can be combined based on the BLDC motor mathematics model. From the comparison simulation results of adaptive fuzzy controller and PID controller, four main contributions of this research are concluded:

(1) The adaptive fuzzy controller can achieve good steady and dynamic performance;
(2) The adaptive fuzzy controller has stronger robust and self-adaptive when the motor parameters changes and load disturbs;
(3) The adaptive fuzzy controller is easy to implement;
(4) The performance of the adaptive fuzzy controller is superior to the PID controller.

In summary, the adaptive fuzzy controller can conquer the problem such as nonlinear and parameter variety of the BLDC motor, and is a good proposal for the BLDC motor control system.

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