

Fuzzy PID control algorithm based on PSO and application in BLDC motor

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Abstract. A fuzzy PID control algorithm is studied based on improved particle swarm optimization (PSO) to perform Brushless DC (BLDC) motor control which has high accuracy, good anti-jamming capability and steady state accuracy compared with traditional PID control. The mathematical and simulation model is established for BLDC motor by simulink software, and the speed loop of the fuzzy PID controller is designed. The simulation results show that the fuzzy PID control algorithm based on PSO has higher stability, high control precision and faster dynamic response speed.

1 Introduction

BLDC motor has been widely used in the industry, transportation, military, aerospace, servo control and other fields. It has some advantages such as high efficiency, long life, high speed, low noise and good dynamic response. The control methods of optimization for BLDC takes an important roles for developing new controller and has bright application potential [1,2]. The traditional PID control which has been widely applied to the BLDC motor system is one of the earliest algorithm applied in industry. It has some advantage of simple structure, excellent performance, reliable operation, convenient maintenance. BLDC motor is a multivariable, nonlinear and strong coupling complex system, and has the disadvantage of PID control parameters which need to be strict setting. The traditional PID control is difficult to obtain ideal results [3-5], then the fuzzy control technology on BLDC motor is developed. Fuzzy control which directly used the language rules can not completely rely on the mathematical model of controlled object. It has advantages of fast response and good robustness and disadvantages of the online adjustment [6]. The fuzzy PID control algorithm of PSO is designed based on the analysis of the mathematical model of BLDC motor and use simulink software to set up the mathematical and simulation model in this paper. The simulation results show that using fuzzy PID control strategy of PSO which has better stability and anti-jamming compared with the traditional PID control, and has advantage of fast response, high control precision and no overshoot, etc.

2 Mathematical model of BLDC motor

BLDC motor stator is the three-phase Y connection, using two phase conduction and three phase six section operation mode sets up dynamic mathematical model of motor. The assumption base on the scope of structure allows aiming at analysing simply [7]: (1) The model ignore the motor armature reaction and the magnetic induction intensity of air gap is trapezoidal wave in space distribution; (2) Regardless of the influence of the magnetic saturation, the eddy current and hysteresis losses of the motor; (3) Ignore the cogging effect and the influence of commutation process, and the armature conductors distributes continuous and evenly on the surface of the armature; (4) Three-phase winding



of stator is symmetric and same parameters, and the current of stator and the magnetic field rotor are symmetric distribution. The damping winding on the rotor is ignored.

The voltage balance equation of two phase electric winding, the equation of counter electromotive force, the equation of electromagnetic torque and the equation of mechanical movement as follows:

$$u_d = E + i \cdot R(L - M) \cdot \frac{di}{dt} \quad (1)$$

$$E = C_n \cdot \omega \quad (2)$$

$$T_e = C_m \cdot i \quad (3)$$

$$T_e = J \frac{d\omega}{dt} + B \cdot \omega + T_L \quad (4)$$

where u_d and E are the voltage and the counter electromotive force of two phase winding on the certain current conditions; R is the resistance of each phase of the stator winding; L and M are the self-inductance of each phase winding and the mutual inductance between the two phase winding; C_n is the coefficient of counter electromotive force; ω is the mechanical speed of the motor; T_e is the electromagnetic torque of the motor; C_m is the torque coefficient; J is the moment of inertia of the motor; B is damping coefficient; T_L is the load torque including no-load torque of the motor.

When the Laplace transform derived, the transfer function of speed output and input voltage is got when the load torque of BLDC motor is zero input. It is shown in formula 5.

$$\frac{\omega(s)}{u_d(s)} = \frac{1}{J \cdot (L - M) / C_m \cdot s^2 + J \cdot R / C_m \cdot s + C_n} \quad (5)$$

3 Design of fuzzy PID controller based on PSO

3.1 Control principle of fuzzy PID based on PSO

The size and different relative between the quantitative factors of the fuzzy controllers' quantitative factor and scaling factor has great influence on control properties of fuzzy controller, and can fundamentally change the output characteristic of system [8]. Therefore, it must constantly adjust the fuzzy controller of running parameters to make the fuzzy control system has good dynamic and static characteristic after the change in the system characteristics [9], namely the weight coefficient of fuzzy controller became coefficient by optimizing the quantification factors Ke , Kec and scaling factor Ku . This system builds the two-dimensional fuzzy controller whose the input language variable is the error e and error change rate of e_c between a given speed n_e and BLDC motor speed n_s . Actual outputs variables are the correct amount ΔK_p , ΔK_i and ΔK_d of three parameters ΔK_p , ΔK_i and ΔK_d of PID. Its structure is shown in figure 1.

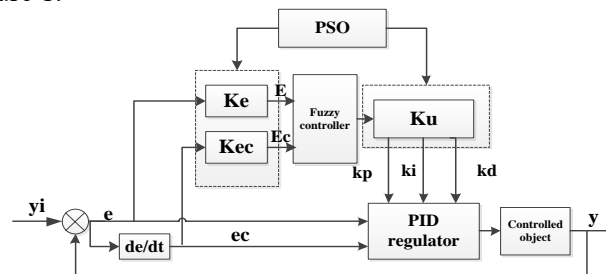


Figure 1: The structure of fuzzy PID controller.

It assumes that the parameters of selected conventional PID controller is K'_p , K'_i and K'_d , so three parameters K_p , K_i and K_d of PID controller is obtained from the formula:

$$\begin{aligned} K_p &= K'_p + \Delta K_p \\ K_i &= K'_i + \Delta K_i \\ K_d &= K'_d + \Delta K_d \end{aligned} \quad (6)$$

3.2 Improved PSO algorithm

PSO has some advantages such as simple concept, short core code, fast convergence rate, easy to implement, but also has shortcomings like low accuracy and disperse easily. If learning parameters or maximum speed is too large, the particle swarm is likely to miss the optimum solution and it can't convergence; Because of all the particles movement towards the direction to the optimal solution when convergence, particles tend to the same and the diversity is lack lead to the late convergence slow; And when the algorithm converges to a certain accuracy, it cannot continue to optimize [10]. So this paper uses inertia weight and piecewise time-dependent learning factor of PSO algorithm. Velocity updating formula is as follows:

$$V_{id}^{k+1} = \left(\omega_{\max} - \frac{\omega_{\max} - \omega_{\min}}{n_{\max}} \times n \right) V_{id}^k + \left((c_{1f} - c_{1i}) \times \frac{n}{n_{\max}} + c_{1i} \right) (p_{id}^k - x_{id}^k) + \left((c_{2f} - c_{2i}) \times \frac{n}{n_{\max}} + c_{2i} \right) (p_{gd}^k - x_{id}^k) \quad (7)$$

The time-varying weights expressed as:

$$\omega = \omega_{\max} - \frac{\omega_{\max} - \omega_{\min}}{n_{\max}} \times n \quad (8)$$

where ω_{\max} and ω_{\min} which are constant respectively are the maximum and minimum value of inertia weight. Piecewise time-dependent learning factor is expressed as:

$$c_1 = (c_{1f} - c_{1i}) \times \frac{n}{n_{\max}} + c_{1i} \quad (9)$$

$$c_2 = (c_{2f} - c_{2i}) \times \frac{n}{n_{\max}} + c_{2i} \quad (10)$$

where c_{1i} , c_{1f} , c_{2i} and c_{2f} are the initial value and final value of the c_1 and c_2 , and all of them are constant. n_{\max} is the maximum number of iterations. n is the current iteration number.

According to different optimization objects and adjust the particles' self-cognition and social experience very flexible, this algorithm uses the piecewise time-dependent learning factor to optimize the shortage of the PSO algorithm which is single inertia weight. Namely, one part of iteration range of PSO process uses fixed learning factor and the other part uses time-varying learning factor, so that the particles can not only have faster convergence, but also converge to the global optimal point more precisely.

3.3 Fuzzification and domain setting

The fuzzy controller uses two fuzzy controller as a simulation model which adopts the error E and error change rate E_c as two inputs and the correct amount of PID controller parameters ΔK_p , ΔK_i , ΔK_d as the output. Namely the form is the two inputs and three outputs.

The first is to get all the data becoming fuzzification in fuzzy control, so it can accept the processing of fuzzy rules. This system makes the two input amounts of error E and error change rate E_c and output of the PID parameters calibration ΔK_p , ΔK_i , ΔK_d into standard interval $[-6, 6]$, namely the theory domain of input E , E_c and output ΔK_p , ΔK_i , ΔK_d is $[-6, 6]$. Then these continuous accurate volume are made into discretization, and E , E_c , ΔK_p , ΔK_i , ΔK_d was divided into 7 levels {NB, NM, NS, ZO, PS, PM, PB} which respectively is negative big, negative middle, negative small, zero, positive small, positive middle, positive big. Each level uses a language to express.

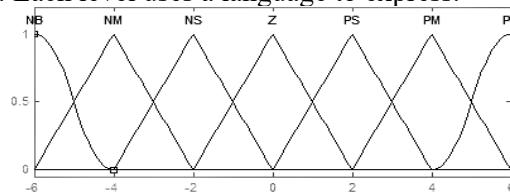


Figure 2: the membership function of E , E_c , ΔK_p , ΔK_i , ΔK_d .

These 7 levels correspond to seven fuzzy sets. This paper sets the membership function of the input E , E_c and the output ΔK_p , ΔK_i , ΔK_d to "Z", "triangle" and "S" form. Input and output fuzzy sets and domain is same, so its membership function diagram is the same, as shown in figure 2.

3.4 Establishment of the fuzzy control rules

Fuzzy rules are an important part of the fuzzy control accuracy. Proper fuzzy rules are established, and the principle is adjusted according to the different PID parameters. According to the fuzzy principle can get the rule table of output variable ΔK_p , ΔK_i , ΔK_d which is shown in table 1, table 2 and table 3.

Table 1: The fuzzy rule of ΔK_p .

E	E_c						
	NB	NM	NS	ZO	PS	PM	PB
NB	PB	PB	PM	PM	PS	ZO	ZO
NM	PB	PB	PM	PS	PS	ZO	NS
NS	PM	PM	PM	PS	ZO	NS	NS
ZO	PM	PM	PS	ZO	NS	NM	NM
PS	PS	PS	ZO	NS	NS	NM	NM
PM	PS	ZO	NS	NM	NM	NM	NB
PB	ZO	ZO	NM	NM	NM	NB	NB

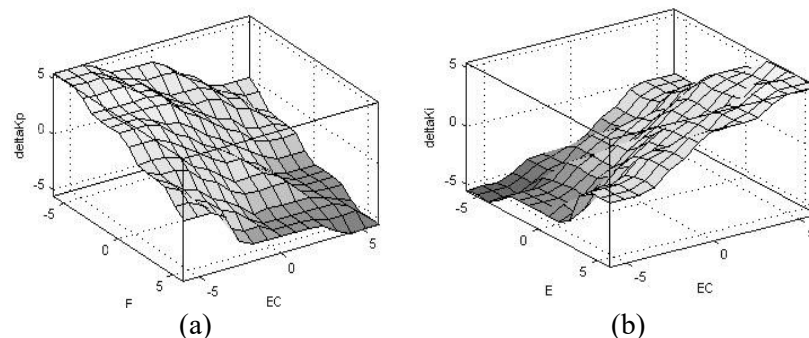
Table 2: The fuzzy rule of ΔK_i .

E	E_c						
	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NB	NM	NM	NS	ZO	ZO
NM	NB	NB	NM	NS	NS	ZO	ZO
NS	NM	NM	NS	NS	ZO	PS	PS
ZO	NM	NM	NS	ZO	PS	PM	PM
PS	NM	NS	ZO	PS	PS	PM	PB
PM	ZO	ZO	PS	PS	PM	PB	PB
PB	ZO	ZO	PS	PM	PM	PB	PB

Table 3: The fuzzy rule of ΔK_d .

E	E_c						
	NB	NM	NS	ZO	PS	PM	PB
NB	PS	NS	NB	NB	NB	NM	PS
NM	PS	NS	NB	NM	NM	NS	ZO
NS	ZO	NS	NM	NM	NS	NS	ZO
ZO	ZO	NS	NS	NS	NS	NS	ZO
PS	ZO	ZO	ZO	ZO	ZO	ZO	ZO
PM	PB	NS	PS	PS	PS	PS	PB
PB	PB	PM	PM	PM	PS	PS	PB

The control surface chart of three outputs with the member ship function of input and output variables is shown in figure3.



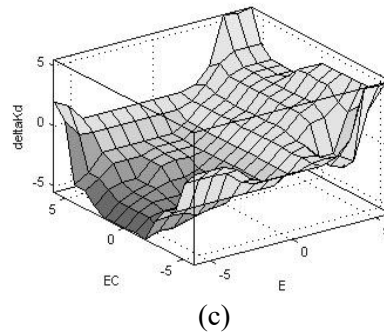


Figure 3: The output surface figure of ΔK_p , ΔK_i , ΔK_d at domain of discourse.

According to the above design, the fuzzy controller uses Matlab FIS editor to edit: the type of FIS selects Mamdani model, the way of ‘with’ is min, the way of ‘or’ is max, inference rules is min, synthetic rules is max and the defuzzification uses the method of “Centriod”. The window of Member Ship Function Editor and Rule Editor respectively completes the input and output variable membership functions and edits fuzzy control rules.

3.5 Defuzzification

This paper uses the “centroid method” to defuzzy the fuzzy set from fuzzy reasoning, its mathematical expression is as follow:

$$z_o = \frac{\int_a^b z u_c(z) dz}{\int_a^b u_c(z) dz} \quad (11)$$

where $u_c(z)$ is a membership function of variable z in the formula. The two input variables’ precision value $\{E, E_c\}$ of the fuzzy controller are got by formula (11), and calculate into the formula (12):

$$\begin{aligned} K_p &= K'_p + K_1 \{E, E_c\}_p \\ K_i &= K'_i + K_2 \{E, E_c\}_i \\ K_d &= K'_d + K_3 \{E, E_c\}_d \end{aligned} \quad (12)$$

In the formula, K'_p , K'_i , K'_d is the initial value of three parameters K_p , K_i , K_d . System determines the corrected value of three parameters K_p , K_i , K_d and realizes real-time setting through the real-time detection E , E_c and quantifying to the corresponding domain.

4 The simulation and analysis

This paper adopts BLDC motor is 57BL52-230. The rated voltage is $U=24V$. The rated power is $P=60W$. The rated speed is 3000r/min. each phase inductance is $L=1.19mh$. Each phase resistance is $R=0.488\Omega$. The torque coefficient is $C_m=0.0522Nm/A$. The counter electromotive force coefficient is $C_n=0.049Vs/rad$, the mutual inductance between the two phase winding is $M=0.057mh$. Making above data into formula (5) gets the transfer function is $1/(0.0039s^2+1.683s+0.049)$ When the rotating speed is $n=1r/s$ and $n=1000r/s$, the simulation results are shown in figure 4, 5.

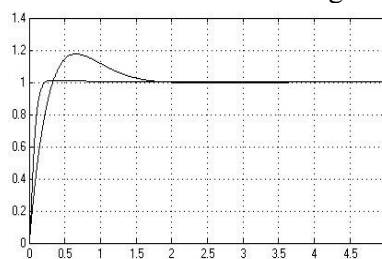


Figure 4: The speed response curve when $n=1$.

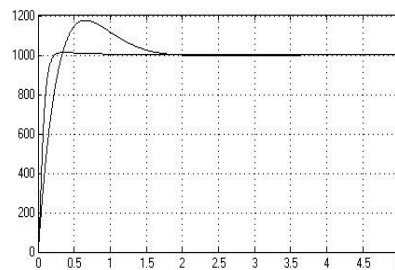


Figure 5: The speed response curve when $n=1000$.

The model under different rotational speed of response curve shows that when given speed is $n=1\text{r/s}$, the adjust time of traditional PID control is 1.72s, and overshoot is 17.7%. When using fuzzy PID based on PSO controls, the adjust time is 1.21s, and overshoot of system is 1.2%. When given speed is $n=1000\text{r/s}$, the adjust time of traditional PID control is 1.74s, and overshoot is 17.5%. When Using fuzzy PID based on PSO controls, the adjust time is 1.2s, and overshoot is 1%. When Controlled system makes sudden load in 3s, the response curve is shown in figure 6. From the figure we can see that when control system which uses the fuzzy PID based on PSO makes sudden load, the influence of speed is small, speed can use a short time into the steady state, and there is no steady-state error.

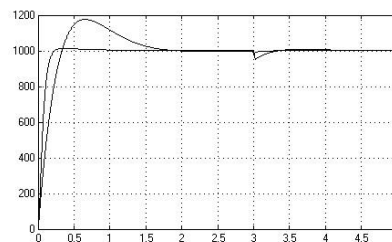


Figure 6: The speed response curve of changing load.

The simulation results show that compared with the traditional PID control, the fuzzy PID based on PSO control has higher accuracy, smaller overshoot, shorter adjusting time, and faster dynamic response.

5 Conclusion

The fuzzy PID control technology is introduced into BLDC motor speed control system. The fuzzy PID controller adjusts PID parameters in real time according to the actual speed of the system state in the process of control. Simulation results show that compared with the traditional PID control, using fuzzy PID based on PSO control strategy has higher stability and control precision and faster dynamic response speed. It improves the dynamic, static performance and robustness of the BLDC motor control system, and achieves a satisfactory control result.

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