

Fuzzy PID control brushless DC motor

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Abstract. Owing to its superior efficiency, power density, and reduced maintenance requirements, the brushless DC motor (BLDC) has found extensive applications in household devices, electric vehicles, and industrial automation systems. However, the nonlinear commutation characteristic and the torque pulsation caused by the trapezoidal wave of the back electromotive force make the traditional PID control have the defects of large overshoot and low speed jitter in the wide speed range. To enhance dynamic responsiveness and disturbance rejection capabilities, this study introduces a self-tuning fuzzy PID control framework that adaptively modifies the speed-loop PID parameters in real-time. Firstly, the mathematical model of BLDC motor is established, including voltage equation, back electromotive force characteristic and torque-motion equation, and a fuzzy controller is designed based on double closed-loop control architecture (outer loop fuzzy PID adjusting speed, inner loop PI controlling current). The controller takes speed error and error change rate as input, outputs PID parameter increment, and realizes parameter dynamic adjustment by fuzzy rule base and gravity center method. The proposed methodology establishes a foundational framework for high-precision BLDC motor control, demonstrating significant applicability in industrial motion control scenarios.

Keywords: Brushless DC motor; Fuzzy PID control; Parameter self-tuning.

1. Introduction

Compared with traditional brushless DC motors, brushless DC motors have the advantages of high efficiency, high power density and long life, and the maintenance cost and noise control difficulty of brushless DC motors are reduced, and they have a wide range of application prospects in many fields such as home appliances, new energy vehicles, and industrial sites[1]. Because BLDC itself has the defect of commutation nonlinear and reverse electrodynamic force trapezoidal wave leading to torque pulsation, the problem of overshoot and low-speed jitter will be caused when the parameters are fixed with traditional PID control in a wide speed range[2].

In order to solve the problem of overshoot caused by BLDC under traditional PID control, a fuzzy PID control strategy based on current feedback is proposed in this paper. By dynamically adjusting the PID parameters of the speed ring, smooth torque output is realized.

2. Establishment of brushless DC motor model

2.1 Model assumption

The mathematical modeling of the BLDC motor is grounded in the following premises: (1) perfect symmetry of three-phase windings, (2) negligible cogging effects, commutation transients, and armature's magnetic influence, (3) uniform stator winding distribution, and (4) exclusion of core losses including eddy currents and hysteresis.

2.2 Brushless DC motor system model

The electrical model of the BLDC motor is based on the voltage and current relationship of the three-phase windings (A, B, C). Assuming the motor is Y-connected, its voltage equation can be expressed as:

$$\begin{cases} V_a = Ri_a + L \frac{di_a}{dt} + e_a \\ V_b = Ri_b + L \frac{di_b}{dt} + e_b \\ V_c = Ri_c + L \frac{di_c}{dt} + e_c \end{cases} \quad (1)$$

The governing equations utilize these notations: V_a, V_b, V_c denote phase voltages (V), i_a, i_b, i_c represent phase currents (A), R and L correspond to per-phase resistance (Ω) and inductance (H), while e_a, e_b, e_c characterize back-EMF components (V).

The back electromotive force is a key characteristic of BLDC motors, and its waveform is a trapezoidal wave, which is related to the rotor position:

$$\begin{cases} e_a = k_e \cdot \omega \cdot f_a(\theta) \\ e_b = k_e \cdot \omega \cdot f_b(\theta) \\ e_c = k_e \cdot \omega \cdot f_c(\theta) \end{cases} \quad (2)$$

Symbol description: k_e is the back electromotive force constant; ω is the rotor angular speed; $f_a(\theta), f_b(\theta), f_c(\theta)$ are trapezoidal wave functions related to rotor position θ .

The relation between electromagnetic torque and current is:

$$T_e = K_t (i_a + i_b + i_c) \quad (3)$$

Rotor motion equation satisfies:

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

Symbol description: J is the moment of inertia; T_L is the load torque; B is the coefficient of viscous friction.

3. Fuzzy PID controller design

3.1 Control architecture design

This work elaborates on the structural design of a fuzzy PID controller for BLDC drives, emphasizing rule-based logic and adaptive parameter optimization to achieve enhanced speed tracking and robustness against disturbances.

This paper will use the double closed loop control structure. Outer ring: Input is the error $e = \omega_{ref} - \omega$ between the target speed ω_{ref} and the actual speed. Controller: fuzzy PID algorithm, output current reference value i_{ref} . Inner loop: Fixed parameter PI controller that generates PWM duty cycle signal to drive the inverter.

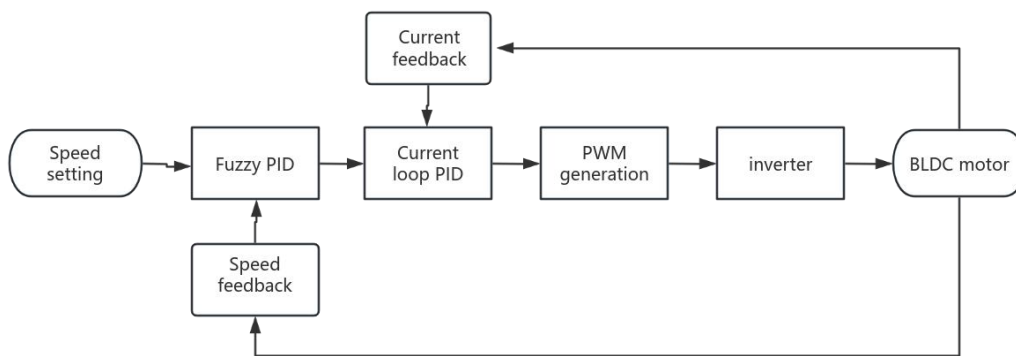


Fig.1 Double closed loop control structure diagram

3.2 Fuzzy logic design

The ΔKp , ΔKi , ΔKp parameters of the traditional PID controller can not be changed after

determining, so the traditional PID controller can not adapt to complex and changeable working conditions, and has many limitations in many fields. The fuzzy PID controller with parameter self-tuning type can realize the dynamic adjustment of PID parameters, so as to optimize the speed response and anti-interference ability.

The fuzzy system employs two inputs – speed deviation (e) and rate of error change (ec) – and three outputs (ΔKp , ΔKi , ΔKp). Linguistic variables are categorized into seven membership functions: {NB (Negative Big), NM (Negative Medium), NS (Negative Small), Z (Zero), PS (Positive Small), PM (Positive Medium), PB (Positive Big)}. Input adopts triangular membership function to ensure computational efficiency. The Gaussian membership function is output, as shown in Figure 2 and Figure 3.

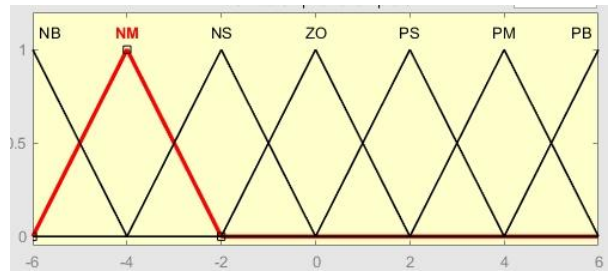


Fig.2 e, ec membership function graph

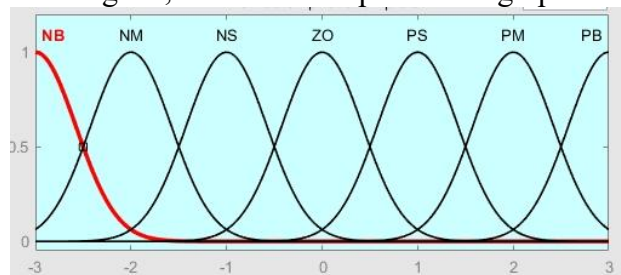


Fig.3 Membership function graph of ΔKp , ΔKi and ΔKp

Fuzzy rules are an important link that affects the precision of fuzzy control. This study establishes appropriate fuzzy inference rules for the controlled objects by citing expert experience[4]. The fuzzy rules are shown in Table 1.

Table 1 .Fuzzy rules for ΔKp , ΔKi ΔKp

$e \setminus ec$	NB	NM	NS	Z	PS	PM	PB
NB	PB,NB,PS	PB,NB,NS	PM,NM,NB	PM,NM,NB	PS,NS,NB	Z,Z,NM	Z,Z,PS
NM	PB,NB,PS	PB,NB,NS	PM,NM,NB	PS,NS,NM	PS,NS,NM	Z,Z,NS	NS,Z,Z
NS	PM,NM,Z	PM,NM,NS	PM,NS,NM	PS,NS,NM	Z,Z,NS	NS,PS,NS	NS,PS,Z
Z	PM,NM,Z	PM,NM,NS	PS,NS,NS	Z,Z,NS	NS,PS,NS	NM,PM,NS	NM,PM,Z
PS	PS,NM,Z	PS,NS,Z	Z,Z,Z	NS,PS,Z	NS,PS,Z	NM,PM,Z	NM,PB,Z
PM	PS,Z,PB	Z,Z,NS	NS,PS,PS	NM,PS,PS	NM,PM,PS	NM,PB,PS	NB,PB,PS
PB	Z,Z,PB	Z,Z,PM	NM,PS,PM	NM,PM,PM	NM,PM,PS	NB,PB,PS	NB,PB,PS

In the above design, in the first row ($e=NB$), when the error is large and the error change rate is

large, K_p is increased substantially to respond quickly, while K_i is kept at zero to avoid integral saturation. When the error is large but the error change rate is negative, keep K_p at zero and reduce K_i to suppress overshoot. In the middle row ($e=Z$), when the error is near zero and the error change rate is positive and small, K_i is increased slightly to eliminate the steady-state error.

To sum up, for a control system, the appropriate three parameters should be fully considered to ensure the dynamic and static performance of the system. After matlab simulation, three output control surfaces can be obtained, as shown in FIG. 4.

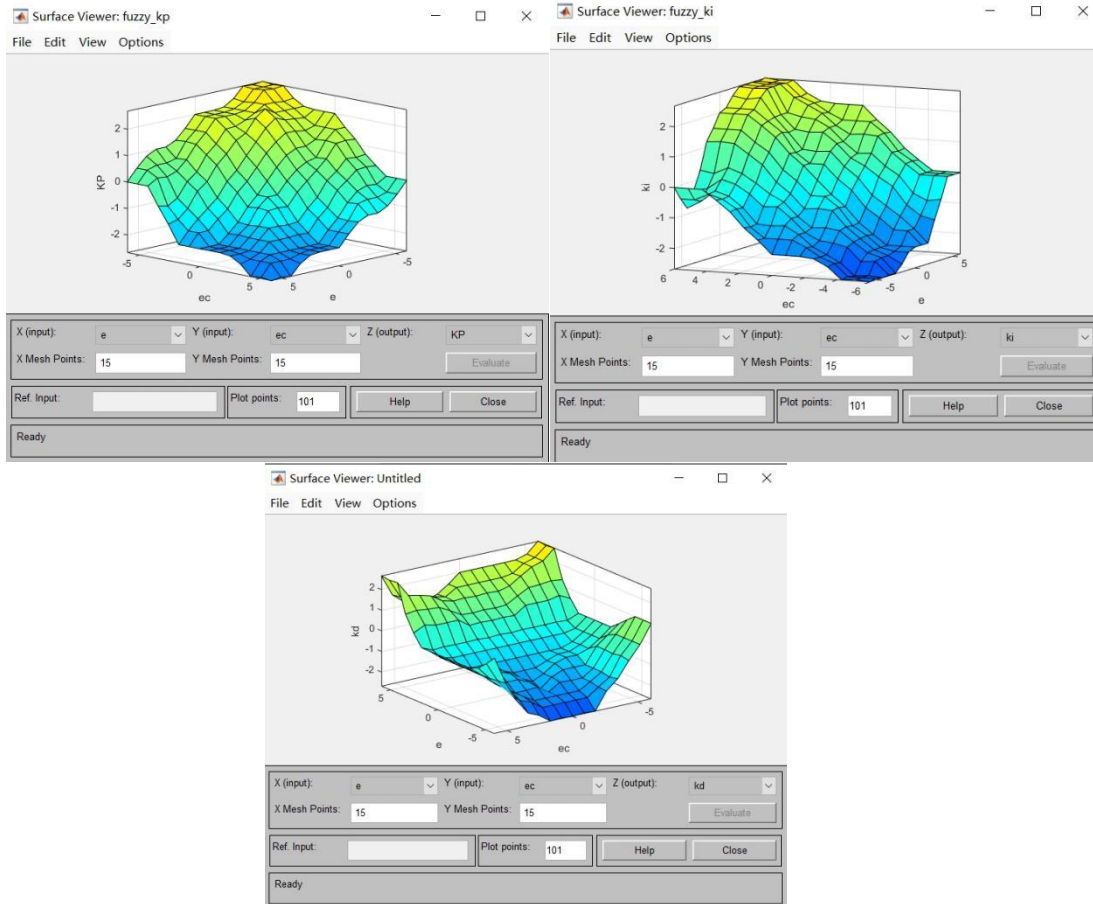


Fig.4 ΔK_p change ΔK_i change ΔK_d change

3.3 Fuzzy controller principle

The fuzzy controller takes input error e and error change rate ec as inputs, continuously detects e and ec during the motor operation, and constantly adjusts the three parameters of proportion, integral and differential in the PID controller to ensure that the controlled object can quickly, accurately and stably output according to the input[5]. Its control principle is shown in Figure5.

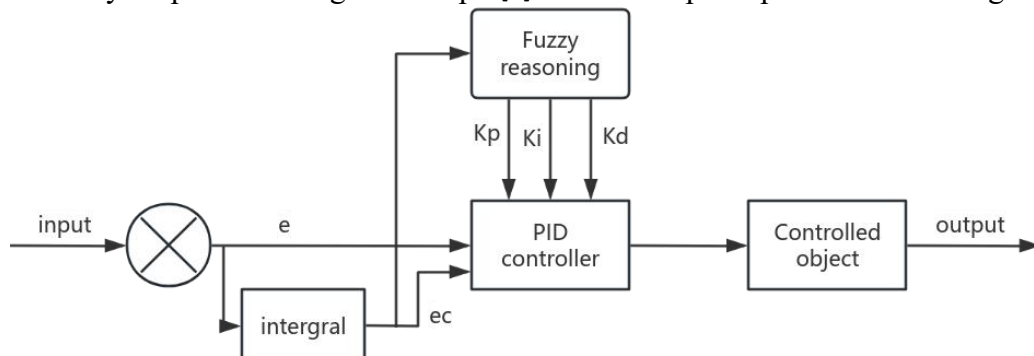


Fig.5 Fuzzy controller schematic diagram

3.4 The establishment of fuzzy PID simulation model

To mitigate speed overshoot challenges in BLDC control systems, a fuzzy PID architecture is implemented. This controller processes speed feedback errors and their derivatives through fuzzification, rule-based inference, and centroid defuzzification to generate precise current-loop commands. The Simulink-based implementation (Figure 6) rigorously adheres to electromechanical principles, with comparative analyses against conventional PID controllers validating performance enhancements.[6][7].

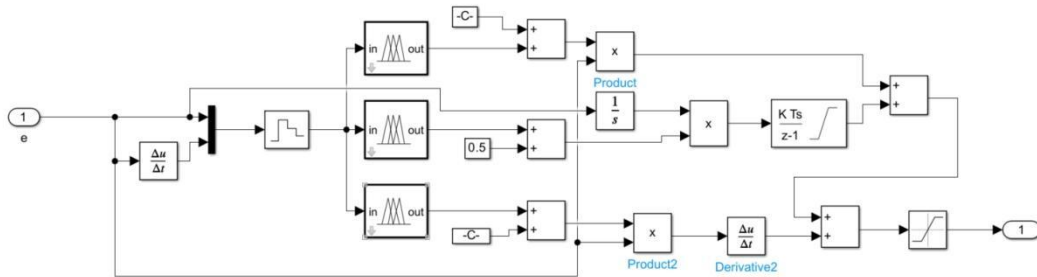


Fig 6. Fuzzy controller structure diagram

4. Simulation and analysis

Key motor parameters for simulation include: pole number $P_n=3$, inductance $L=0.0085\text{mH}$, stator resistance $R=0.011\text{ohms}$, moment of inertia $J = 6.33e^{-4}\text{kg} \cdot \text{m}^2$, damping coefficient $B = 0.000015\text{N} \cdot \text{M} \cdot \text{s}$, 300V DC power supply, sampling period $T_s = 10\mu\text{s}$.

As can be seen from FIG. 7, when the speed is set at 800r/min, the traditional PID control overshoot is larger and the speed stabilization time is longer. The speed overshoot of the brushless DC motor system under fuzzy PID control is small, and the speed stabilization time is short. The effect of fuzzy PID control is more stable than that of traditional PID control, and the adjustment time is smaller, indicating that this fuzzy control method has certain adaptability, thus shortening the development cycle of the project.

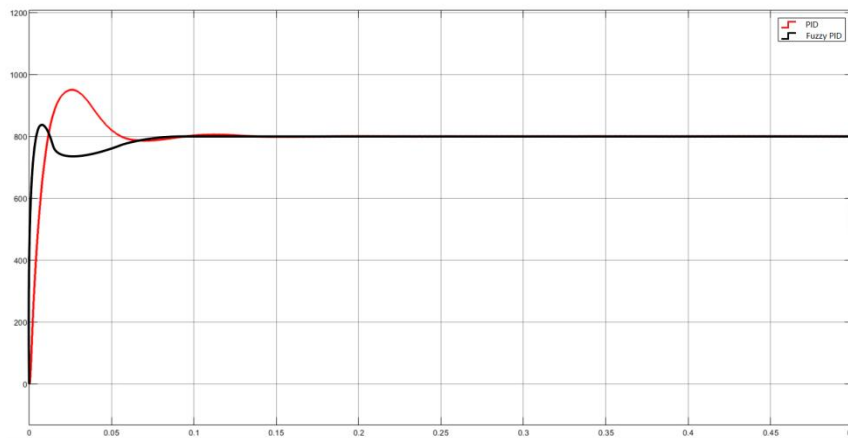


Fig.7 Simulation speed comparison between fuzzy PID control and traditional PID control

5. Conclusion

BLDC systems exhibit intricate multivariable dynamics with nonlinear coupling, posing greater control challenges than conventional DC motors. The developed fuzzy PID strategy demonstrates exceptional flexibility and precision in handling system nonlinearities and uncertainties, making it a superior candidate for industrial automation applications.

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