Speed Control Study of Brushless DC motor Based on Fuzzy Optimization PID

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Abstract. Targeting at the problems of response lag and poor control effect of traditional PID speed control system for brushless DC motor, a novel PID speed regulation system based on fuzzy optimization was proposed in this paper. On the basis of analyzing basic working principle of brushless DC motor, the new fuzzy self-tuning PID optimal controller is introduced, the controller output switches power MOSFET devices by changing the duty ratio of PWM control signal, thus the speed control of brushless DC motor was realized. Both the fuzzy optimized PID control introduced in this paper and the traditional PID control are respectively simulated and compared under the Matlab/Simulink environment. The results show that with the fuzzy optimized PID control system has better performance than traditional PID control.

1. Introduction

Brushless DC motor features large torque, small size, high efficiency, long service life and environmental protection. It is widely used in industrial equipment and many other equipments [1]. Traditional PID controller is usually employed for the speed control in brushless DC motor, but the PID controller is over-sensitive to the change of target’s parameters. Only when the controller is carefully tuned and a suitable parameter group is found, can good performance be obtained. If the plant parameters vary, the traditional PID controller usually failed to work properly. In these cases, the traditional PID controller will show poor performance and lead to slow response, low control accuracy and difficult to ensure good process quality[2].

The fuzzy control method was suggested by L.A. Zadeh at first, based on the theory of fuzzy sets, fuzzy linguistic variables and fuzzy logic inference[3]. Like the popular PID controller, fuzzy control algorithm does not need accurate mathematical model of target plant, moreover, it can deal with non-linear problems simply and effectively and improve the robustness and agility of the control system. This paper presents a fuzzy-PID control scheme, in which a fuzzy logic block observes the error and error change to correct traditional PID controller in real time. The results indicate that the control algorithm suggested in this paper has satisfactory static and dynamic performance, as well as strong robustness.
2. Basic Brushless DC Motor Principles

The main components of brushless DC motor are motor body, position sensor, motor driver and controller. Most stator windings take the form of three-phase symmetrical star connection, shown in Fig. 1. This paper assumes the motor is three-phase six-state, where \( L_r \), \( R \), \( e_a \), \( e_b \) and \( e_c \) are three-phase equivalent circuits of motor. Q1, Q2, Q3, Q4, Q5 and Q6 are six power transistors. Hall sensors A, B, C are arranged on the stator symmetrically with 120 degrees interval. As motor rotates, the three Hall sensors generate 120 degrees difference position square wave signals. The controller takes the Hall signal as input, compute the motor speed, outputs three-phase commutation signals to drive MOSFET power transistor. The motor can output continuous torque through the inverter.

![Figure 1. Brushless DC motor driving diagram.](image)

By ignoring hysteresis loss and eddy current loss, the model of brushless DC motor can be divided in three parts: voltage differential equation, electromagnetic torque equation and motor motion equation[4]. Assuming eddy current, hysteresis loss, cogging and electromagnetic interference in commutation process can be ignored, the three motor windings are symmetrical, the voltage equation of the three-phase stator windings of the brushless DC motor can be derived as\[5\]:

\[
\begin{bmatrix}
    u_a \\
    u_b \\
    u_c \\
\end{bmatrix} = \begin{bmatrix}
    y_r & 0 & 0 \\
    0 & y_r & 0 \\
    0 & 0 & y_r \\
\end{bmatrix} \begin{bmatrix}
    i_a \\
    i_b \\
    i_c \\
\end{bmatrix} + \begin{bmatrix}
    L_r & M_r & M_r \\
    M_r & L_r & M_r \\
    M_r & M_r & L_r \\
\end{bmatrix} \frac{d}{dt} \begin{bmatrix}
    i_a \\
    i_b \\
    i_c \\
\end{bmatrix} + \begin{bmatrix}
    e_a \\
    e_b \\
    e_c \\
\end{bmatrix} \tag{1}
\]

in which \( u_a \), \( u_b \) and \( u_c \) stand for three phase voltages; \( i_a \), \( i_b \) and \( i_c \) denote three phase currents; \( e_a \), \( e_b \) and \( e_c \) are three-phase back-EMF; \( L_r \) are self-inductance of three-phase windings; \( M_r \) denotes mutual inductance between two-phase windings, and star connection is used for three-phase motor. According to Kirchhoff's Law, if there is \( i_a + i_b + i_c = 0 \), there is \( M_i_a + M_i_b + M_i_c = 0 \), so formula (1) would be put into:

\[
\begin{bmatrix}
    u_a \\
    u_b \\
    u_c \\
\end{bmatrix} = \begin{bmatrix}
    y_r & 0 & 0 \\
    0 & y_r & 0 \\
    0 & 0 & y_r \\
\end{bmatrix} \begin{bmatrix}
    i_a \\
    i_b \\
    i_c \\
\end{bmatrix} + \begin{bmatrix}
    L_r - M_r & M_r & M_r \\
    M_r & L_r - M_r & M_r \\
    M_r & M_r & L_r - M_r \\
\end{bmatrix} \frac{d}{dt} \begin{bmatrix}
    i_a \\
    i_b \\
    i_c \\
\end{bmatrix} + \begin{bmatrix}
    e_a \\
    e_b \\
    e_c \\
\end{bmatrix} \tag{2}
\]

For the convenience of analysis, it is assumed that the viscous coefficient and the inductance of armature winding are not taken into account when the motor rotates. The motor output electromagnetic torque equation will be put into:

\[
T_e = \frac{(i_a e_a + i_b e_b + i_c e_c)}{\omega} \tag{3}
\]

The equation of motion can be obtained as follows:

\[
T_e - T_L = J \frac{d\omega}{dt} \tag{4}
\]

where \( \omega \) is the speed of the motor, \( T_L \) denote the load torque, \( J \) is the inertia of the system.

3. Design of the Fuzzy-PID Controller for BLDC

The brushless DC motor control system take the approach of Pulse Width Modulation(PWM) to govern the speed of the brushless DC motor. Traditional proportional-integral(PI) and proportional-
integral-differential(PID) controllers are extensively used in motor control applications for the sake of benefits like simple structure, easy engineering implementation and good robustness[6]. The speed PID controller can be expressed as:

\[ u(k) = K_p e(k) + K_i \sum_{j=0}^{k} e(i) + K_D e(k) \]  

Among the formula, e(k) is the input error and u(k) is computed outputs of the PID controller. Symbol \( K_p, K_i, K_D \) signify the gains of proportional, integral and the differential channels respectively. The total control output is the sum of all these three channels. Generally, the parameters of PID control should be carefully tuned before the system runs, it does not have the adaptive online tuning function[7].

Fig. 2 demonstrates the structure of the fuzzy PID controller. Comparing to traditional PID control, it has an additional fuzzy self-tuning block, the input are error signal e and the change of error, the PID correction parameters (\( \Delta K_p, \Delta K_i, \Delta K_D \)) are inferred from the fuzzy logic rule and output. While the system works, the fuzzy logic block will monitor the error and error change, dynamically adjust the three gains of PID controller.

![Figure 2. Principle and Structure of Fuzzy-PID Controller.](image)

The input signal flows into fuzzy logic block will be fuzzified first, then the output s are computed with the fuzzy logic rules, finally the computed result are defuzzified and output to driver circuit. The fuzzy sets of input error e and error change ec and \( K_p, K_i, K_D \) are as follows: \{L~N (Large Negative), M~N (Medium Negative), S~N (Small Negative), Z~Z (Zero), S~P (Small Positive), M~P (Medium Positive), B~L (Large Positive)\}; The range of values of input variables e and ec, as well as output variables \( \Delta K_p, \Delta K_i \) and \( \Delta K_D \), are pre-defined according to actual motor control application. Input and output parameters range in this paper are defined as Table 1, and the membership functions are symmetrically distributed triangular membership functions.

| Parameter Name | Domain |
|----------------|--------|
| e              | \{-3, -2, -1, 0, 1, 2, 3\} |
| \( e \)        | \{-3, -2, -1, 0, 1, 2, 3\} |
| \( \Delta K_p \)| \{-3, -2, -1, 0, 1, 2, 3\} |
| \( \Delta K_i \)| \{-0.9, -0.6, -0.3, 0, 0.3, 0.6, 0.9\} |
| \( \Delta K_D \)| \{-0.6, -0.4, -0.2, 0, 0.2, 0.4, 0.6\} |

The design principle of the fuzzy controller is mainly to sum up the engineering experience[8]. In order to establish a suitable fuzzy rule table, we should learn from the experience of tuning process for traditional PID control. The principles are as follows:
1) When $e$ is large, to increase the response speed of the system, it is necessary to choose a large $K_P$ and a small differential coefficient $K_D$ to reduce the differential overflow caused by the error, and a small $K_I$ to prevent integral windup.

2) When $e$ and $ec$ are moderate, $K_P$ is reduced to decrease excessive system overshoot. $K_I$ and $K_D$ should be moderate.

3) When $e$ is very small, $K_P$ and $K_I$ should be large enough to reduce the residual error of $e$. When error change $ec$ is large, $K_D$ can be too small, and when $ec$ is small, $K_D$ can be larger[9][10]. If $e$ and $ec$ are moderate, $K_P$ should be decreased to restrain system overshoot. $K_I$ and $K_D$ should be moderate.

According to the above principles, such fuzzy control logic rule tables are setup as Table 2 to Table 4. Adaptive tuning will be executed based on $K_P$, $K_I$, $K_D$.

**Table 2. Fuzzy Rule Table of $K_P$.**

| $e$  | L~N | M~N | S~N | Z~O | S~P | M~P | P~L |
|------|-----|-----|-----|-----|-----|-----|-----|
| L~N  | P~L | P~L | M~P | M~P | S~P | Z~O | Z~O |
| M~N  | P~L | P~L | M~P | S~P | S~P | Z~O | S~N |
| S~N  | M~P | M~P | M~P | Z~O | S~N | S~N |
| Z~Z  | M~P | M~P | S~P | Z~Z | S~N | M~N | M~N |
| S~P  | S~P | S~P | Z~Z | S~N | S~N | M~N | M~N |
| M~P  | S~P | Z~Z | S~N | M~N | M~N | L~N |
| P~L  | P~L | Z~Z | M~N | M~N | M~N | L~N | L~N |

**Table 3. Fuzzy Rule Table of $K_I$.**

| $e$  | L~N | M~N | S~N | Z~Z | S~P | M~P | P~L |
|------|-----|-----|-----|-----|-----|-----|-----|
| L~N  | L~N | L~N | M~N | M~N | S~N | Z~Z | Z~Z |
| M~N  | L~N | L~N | M~N | S~N | S~N | Z~Z | Z~Z |
| S~N  | L~N | M~N | S~N | S~N | Z~Z | S~P | S~P |
| Z~Z  | M~N | M~N | S~N | Z~Z | S~P | M~P | M~P |
| S~P  | M~N | S~N | Z~Z | S~P | M~P | P~L | P~L |
| M~P  | Z~Z | Z~Z | S~P | M~P | P~L | P~L |
| P~L  | Z~Z | Z~Z | S~P | M~P | P~L | P~L |
Table 4. Fuzzy Rule Table of Kd.

| e   | ec  |
|-----|-----|
| L~N | S~P |
| M~N | S~N |
| S~N | Z~Z |
| Z~Z | M~P |
| P~L | P~L |

4. Simulation Experiment and Analysis

Like many other motor speed control applications, the brushless DC motor control system usually employs the double closed-loop control scheme of speed and current. In this paper, the system structure follows the continuous-time model. The inner current ring which control the average current through the circuit, while the outer speed loop track the given speed input value and reach the closed-loop speed control. Under ideal conditions, the simulation experiment is built in Matlab/Simulink environment. The model of BLDCM is established as shown in Fig. 3.

![Figure 3. Matlab/Simulink model of Brushless BLDC Motor drive.](image)

The motor is powered by 40V DC power supply and three-phase IGBT inverter. In order to visually present the result of the improved speed controller, the drive system is composed of only speed closed-loop. The selected parameters of the motor are shown in Table 5.

Table 5. BLDC Motor Parameter.

| Parameters          | Value         |
|---------------------|---------------|
| Nominal-voltage     | 40 V          |
| Stator-resistance Rs | 18.7 Ω        |
| Stator-inductance Ls | 8.5e-3 mH     |
| Torque-constant     | 2.2725        |
| Rated-Speed         | 3000 rpm      |
| Inertia             | 2.6e-3 kgm²   |

The arrangement of the fuzzy speed controller is shown in the Fig. 4. The input error signal e and the error change ec are feed into fuzzy reasoning block, the optimized PID parameters are derived according to the fuzzy rules.
With a given the speed input to the system, the output control voltage is generated by the speed regulator, and the control square wave is generated by the PWM conversion module. According to the Hall commutation table, the PWM signal is generated to drive MOSFET device, and then the speed of the DC brushless motor is controlled. External disturbance factors are also considered in the experimental simulation to observe the tuning effect of the speed controller. The effectiveness of the new control algorithms is verified by comparing the tuning time and performance under the disturbance.

Fig. 5 shows the change curve of load torque under the control mode of traditional PID controller and fuzzy optimization controller. It can be seen that the stability time of motor's torque depends on the stability time of motor's speed.

By observing Figs. 6, 7 and 8, the response speed of the three controllers in the initial stage is similar. From the fluctuation point of view, the traditional PI controller has overshoot compared with the traditional PID controller and the fuzzy PID controller, and the settling time is 14ms. The speed curve of traditional PI controller fluctuates greatly when the load is suddenly added at 30ms.
Figure 6. Speed response in traditional PI control.

The traditional PID controller has trivial overshoot and the speed curve is relatively stable compared with the PI controller after sudden load, but the speed settling time is 15ms.

Figure 7. Speed response in traditional PID control.

The speed settling time of the fuzzy PID controller is 13ms, and the speed curve is stable under sudden load. Through the above observation, it can be concluded that the stability of the fuzzy PID controller is better than that of the traditional PI controller and the PID controller. Under the load disturbance of 30ms, there is a slight torque ripple, but the steady state can be quickly restored.

Figure 8. Speed response in fuzzy-PID control.
5. Conclusion
This paper analyses the driving structure of BLDC motor, reveals the relationship between the fuzzy controller and the PID controller based on the analysis of the structure of the fuzzy controller, and simulates it under the environment of Matlab/Simulink. The results show that the control scheme has fast response speed, good stability and robustness.

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