The fuzzy adaptive PID control of brushless DC motor

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Abstract. Brushless direct current motor (BLDCM) is a complicated system with multivariable, nonlinear and strong coupled. The present work devotes to design a fuzzy adaptive PID algorithm based on the speed loop so that it could crack the traditional PID problems which include bad parameter setting, poor adaptability, imprecise control and weak anti-interference so on. In this paper, the mathematical model and operating characteristics of BLDCM are analyzed. Then, the simulation platform is built by MATLAB/Simulink. Finally, the control effects of PI, PID and fuzzy adaptive PID are compared and analyzed. The results indicate that the fuzzy adaptive PID is better robustness, faster response, smaller overshoot and more stable operation than others.

1. Introduction

With the rapid development of modern power electronics and computer technology, BLDCM has been widely used in national defense, aerospace, robotics, precision machine tools, military and industrial fields due to their simple structure, good speed regulation and mechanical characteristics [1-4]. It is generally considered that the trapezoidal wave/square wave motor with a series-excited DC motor starting characteristic and a synchronous DC motor speed regulation characteristic is called as BLDCM [5]. A high-performance driver is the foundation for stable motor operation. The drive system not only needs to have fast speed response capabilities, but also has fast tracking capabilities when the motor parameters change or are subject to external disturbances [6]. In the field of motor control, conventional PID controllers are still widely used because of their simple structure, high reliability and easy engineering implementation. However, the algorithm for motor state estimation is based on linear model, while permanent magnet BLDCM is a multi-variable, strongly coupled nonlinear system, and it is difficult to achieve the ideal control effect by using conventional linear control method [7].

The traditional PID control parameter tuning effect is often not ideal, so how to tune the PID parameters is a hot spot in the research of BLDCM controller. In recent years, many domestic and foreign experts and scholars have proposed various advanced intelligent control methods to optimize the control of BLDCM. Such as neural network control [8], fuzzy control [9], ant colony algorithm control [10], adaptive control [11], sliding mode variable structure control [12] and other intelligent control algorithms [13-14]. Among them, fuzzy control technology has been widely used in motor control. Fuzzy control is a control theory based on linguistic rules and fuzzy reasoning, which is built on fuzzy set in modern control theory. It is an important branch of intelligent control. The concept of fuzzy sets was first proposed by the American scholar L A Zadeh in 1965 [15]. In 1973, Zadeh further
studied fuzzy language processing and gave the theoretical basis of fuzzy reasoning. And in 1974, Madani manufactured the first fuzzy controller for boilers and steam engines [16]. Fuzzy control theory and application technology have been developed for more than 30 years, although it has a short history but rapid development. Fuzzy control is an intelligent control technology that imitates human thinking [17]. Its advantage is that it does not require to master the mathematical model of the controlled object, but organizes the control decision table according to the artificial control rules, and then determines the size of the control amount [18]. Fuzzy control uses linguistic variables to describe the characteristics of the system, and makes inferences based on the system’s dynamic information and fuzzy control rules to obtain a suitable control amount, so it has strong robustness [19].

Therefore, in view of the characteristics of BLDCM system, such as time-varying parameters, strong interference, strong coupling, large inertia, etc, this paper combines the fuzzy adaptive control with the traditional PID control to design the fuzzy adaptive PID controller, which realizes the on-line self-tuning of PID parameters. The fuzzy adaptive PID control algorithm is applied to the speed loop control of the BLDCM. The reference speed value is set to observe the step function speed response of the motor under different control algorithms, and the parameters and performance of the motor under this condition are analyzed and compared. Finally, the advantages of the fuzzy adaptive PID control algorithm over the traditional PID control are obtained. The fuzzy adaptive PID control method not only inherits the advantages of traditional PID control, which is independent of object model, simple control structure, high reliability and easy to realize in engineering, but also overcomes the shortcomings of traditional PID controller in the case of strong interference or high nonlinearity and uncertainty, which greatly improves the performance of the controller. The system has the advantages of flexible control, simple control algorithm and wide parameter adaptability, and has better static and dynamic performance.

2. Mathematical of BLDCM

The stator winding of the two pole three-phase BLDCM is Y-connected concentrated full-distance winding, the rotor adopts a hidden pole inner rotor structure. And the three Hall elements are placed symmetrically in the space of 120°. Based on this structure, the following assumptions are made to simplify the analysis process:

(1) Ignore the saturation of motor core, excluding eddy current loss and hysteresis loss.
(2) Excluding the armature response, the distribution of air gap magnetic field is approximately considered as a trapezoidal wave with a flat top width of 120° electrical angle.
(3) Ignoring the cogging effect, the armature conductor is continuously and evenly distributed on the armature surface.
(4) The power tube and freewheeling diode of the inverter circuit of the drive system have ideal switching characteristics.

BLDCM has three stator windings and permanent magnets on the rotor. Due to the high resistivity of both the magnet and the stainless steel fixed sleeve, the rotor induced current can be ignored and there is no need to model the damping winding. Therefore, the differential equation mathematical model of the BLDCM can be composed of the following equations (1), (2), and (3) respectively.

\[
\begin{align*}
\begin{bmatrix}
U_A \\
U_B \\
U_C
\end{bmatrix}
&=
\begin{bmatrix}
R & 0 & 0 \\
0 & R & 0 \\
0 & 0 & R
\end{bmatrix}
\begin{bmatrix}
i_A \\
i_B \\
i_C
\end{bmatrix}
+
\begin{bmatrix}
L-M & 0 & 0 \\
0 & L-M & 0 \\
0 & 0 & L-M
\end{bmatrix}
\begin{bmatrix}
\frac{di_A}{dt} \\
\frac{di_B}{dt} \\
\frac{di_C}{dt}
\end{bmatrix}
+
\begin{bmatrix}
e_A \\
e_B \\
e_C
\end{bmatrix}
\end{align*}
\]

(1)

In the above equation, \(U_A, U_B, U_C\) refer to phase voltage, \(R\) refer to phase resistance of the stator, \(i_A, i_B, i_C\) refer to phase current, \(L\) refer to self-induction of three-phase winding, \(M\) refer to mutual inductance between three-phase winding, \(d/dt\) refer to differential operator, \(e_A, e_B, e_C\) refer to back EMF of three-phase winding.

The electromagnetic torque equation is shown in the following equation (2),

\[
T_e = (e_Ai_A + e_Bi_B + e_Ci_C)/\Omega
\]

(2)

Where \(T_e\) is the electromagnetic torque and \(\Omega\) is the mechanical angular velocity of the motor.
The motion equation of the motor is shown in the following equation (3),

$$T_e - T_L = J \frac{d\Omega}{dt} + B_v \Omega$$  \hspace{1cm} (3)

In the above equation, $T_L$ is the load torque, $J$ is the rotor inertia, and $B_v$ is the viscous friction coefficient. The phase diagram of square wave current and trapezoidal wave opposite electromotive force of phase A is shown in figure 1. In the figure, the abscissa $\theta$ represents the rotor position angle, and the ordinate represents the opposite electromotive force $e$ and phase current $i$.

![Figure 1. Phase A current and back EMF waveform.](image1)

3. **Fuzzy adaptive PID algorithm**

The fuzzy control algorithm designed in this study is a two-dimensional structure, in which the deviation $e$ and the deviation change rate $ec$ are taken as the input variables of the fuzzy control, and the PID parameter correction values $\Delta K_p$, $\Delta K_i$, $\Delta K_d$ adjusted by the fuzzy control rule table as output variables. PID parameters $K_p$, $K_i$, $K_d$ are adjusted online by fuzzy logic.

3.1. **Determination of membership function of linguistic variable**

The membership function of fuzzy variable is triangle, the fuzzy domain of input and output variable is [-6, 6], and the quantization levels are all 13, namely {-6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6}. Take the fuzzy subset of the input and output language variables as negative large, negative middle, negative small, zero, positive small, positive middle, and positive large, respectively represented by NB, NM, NS, ZO, PS, PM, PB. Five input and output variables select the same “triangle” membership function. The membership function of the input variable $e$ is selected for analysis, as shown in figure 2 below. The membership functions of the other four variables are the same.

![Figure 2. Membership function of input variable $e$.](image2)

3.2. **Establish the control rule table of fuzzy controller**

Fuzzy control rules are a set of fuzzy conditional statements summed up by the experience of experts and the skills of operators. As the core of the fuzzy controller, it is the key to determine the appropriate fuzzy control rules to achieve the desired dynamic and static characteristics of the system.
According to the principle of fuzzy PID parameter setting, the fuzzy rules of $\Delta K_p$, $\Delta K_i$ and $\Delta K_d$ are established as shown in Table 1 below.

**Table 1.** Table of fuzzy control rules.

| $e$   | $K_p$ | $K_i$ | $K_d$ |
|-------|-------|-------|-------|
| NB    | NM    | PS    | PB    |
| NM    | PB    | NS    | PS    |
| NS    | PM    | PS    | NZ    |
| ZO    | PM    | NS    | PS    |
| PS    | PS    | ZO    | ZO    |
| PM    | PS    | ZO    | PM    |
| PB    | ZO    | ZO    | PM    |

3.3. Fuzzy reasoning
Fuzzy inference is to make a set of fuzzy inference rules according to the input of the system, so as to get the corresponding output control quantity to drive the control object. In the paper, the max-min synthesis method is used in fuzzy reasoning, this is, according to the fuzzy implication relationship, the “maximum and minimum” synthesis operation is selected to get the fuzzy output value.

3.4. Defuzzification
The process of converting the fuzzy quantity into precise quantity is called defuzzification, which is also called clarity or fuzzy decision. In order to obtain an accurate control amount, it is required that the fuzzy method can output the calculation result of the membership function well. This research uses centroid method to perform the defuzzification operation. The centroid method is also called the center of mass method or area center method, which takes the center of gravity of the area enclosed by the fuzzy membership function curve and the abscissa as the representative point, that is, the center of gravity of a series of continuous points in the output range.

4. Simulation analysis and results discussion
For the BLDCM control system, a speed and current double closed-loop control model of the BLDCM system is established. The current loop adopts traditional PI algorithm to adjust the three-phase current separately, and the speed loop is designed with traditional PI, PID and fuzzy adaptive PID algorithms to adjust the parameters of the motor respectively. The simulation parameters of the motor are shown in Table 2 below.

**Table 2.** Parameters of BLDCM.

| Parameters                        | Value     |
|-----------------------------------|-----------|
| Phase resistance $R/\Omega$       | 4.765     |
| Phase inductance $L-M/mH$         | 8.5       |
| Rotor inertia $J/kg \cdot m^2$    | $1.501 \times 10^{-4}$ |
| Coefficient of viscous friction $B_v/N \cdot m \cdot s$ | $4.047 \times 10^{-5}$ |
| Pairs of poles $p$                | 2         |
| Torque constant $T_m/N \cdot m \cdot A_{peak}^{-1}$ | 0.7392    |
| PWM frequency $f/KHz$             | 1         |
| Nominal voltage $U/N$             | 100       |

The traditional PI, PID and fuzzy adaptive PID algorithms are used in the speed loop controller of the BLDCM, and the three phases of the current loop adopt traditional PI control, which finally generates 6 gate signals to drive the motor. The full-bridge control circuit topology of the BLDCM is shown in figure 3 below.
4.1. Speed step control of BLDCM

The following figure 4 is the speed step response curve of the BLDCM speed loop using the traditional PI, PID and fuzzy adaptive PID control algorithms. In the figure, the black dotted line represents the set reference speed value, the black solid line represents the PI control algorithm, the blue solid line represents the PID control algorithm, and the red solid line represents the fuzzy adaptive PID control algorithm. The abscissa represents the time s, and the ordinate represents the motor speed r/min. The reference speed of the motor is set to 1000r/min, so the performance parameters of the motor speed step response under different control algorithms can be obtained through data analysis, as shown in Table 3 below.

| Table 3. Comparative analysis of step response under different control algorithms. |
|---------------------------------|--------|---------|-----------|
|                                 | PI     | PID     | Fuzzy PID |
| Rise time $t_r$                 | 4.67 ms| 12.24 ms| 5.00 ms   |
| Adjustment time $t_s$           | 9.2 ms | 13.02 ms| 7.89 ms   |
| Overshoot $\sigma\%$            | 6.91 % | None    | 0.09 %    |
| Steady-state error              | 0.41 % | 0.16 %  | 0.14 %    |

Form table 3 above and figure 4 below, it can be concluded that the motor speed step response time is shorter, the overshoot and the steady-state error are smaller under the fuzzy adaptive PID control in the speed loop, which has a better overall control effect.

4.2. Response analysis of electromagnetic torque, phase current and back-EMF

The following figure 5 is the electromagnetic torque $T_e$ curve diagram of different control algorithms of the speed loop under the step function response with the set speed of 1000 r/min. It can be seen
from the figure that when the motor starts to run, it starts with the maximum electromagnetic torque, and then it balances with the load torque to enter the steady-state operation. After the motor runs stably, the electromagnetic torque $T_e$ of the motor under the speed loop PI control has obvious fluctuations, and compared with other two traditional control algorithms, the electromagnetic torque $T_e$ of fuzzy adaptive PID control can balance with the load torque at a faster speed, and there is almost no significant fluctuation after stabilization.

Figure 5. Curve of electromagnetic torque $T_e$.

Figure 6 below shows the change curve of phase-A current and back EMF of speed step response under different speed loop control algorithms. It can be seen from the figure that the phase A current increases rapidly when the motor starts, and then decreases rapidly to enter the stable operation state, it can be seen in the amplification area that compared with traditional PI and PID control, the fuzzy adaptive PID control can enter the stable operation at a faster response speed. After the motor runs stably, the speed loop PI control has obvious oscillation fluctuations, while the fuzzy PID control has faster response speed and smaller fluctuations than the other two algorithms.

Figure 6. Curve of phase A current $I_a$.

Figure 7 below shows the change curve of back electromotive force (EMF). It can be seen from the enlarged area on the upper left side of the figure that the fuzzy adaptive PID algorithm has faster response speed and smaller overshoot than traditional control. From the enlarged area on the lower right side of the figure, it can be seen that the motor under PI control in the stable operation stage has certain fluctuation in the width area of the flat top with an electrical angle of 120º, and the fuzzy PID control is more stable than the traditional control.
Through the above comparative analysis, it can be concluded that fuzzy adaptive PID control not only has the characteristics of high precision of traditional PID control, but also can take advantage of the flexibility and adaptability of fuzzy control. The fuzzy adaptive PID algorithm based on the speed loop is used to control the motor speed, which has the characteristics of fast response, no overshoot, small speed fluctuation, short regulation time and strong interference ability. Its performance is obviously better than traditional PID control, with excellent static and dynamic performance, which greatly improves the robustness of the BLDCM speed control system.

5. Conclusion

As a complex system with multiple variables, nonlinearity, strong coupling, and time-varying parameters, the characteristics and calculation of BLDCM are much more complicated than DC motors. Therefore, this paper presents a fuzzy adaptive PID control algorithm which can be used in BLDCM speed control systems. It combines the fuzzy control with the conventional PID control, taking advantage of each other’s weaknesses. It not only has the advantages of flexibility and adaptability of fuzzy control, but also has the characteristics of high precision of traditional PID control. This kind of fuzzy adaptive PID controller adjusts its control parameters online to effectively deal with the nonlinearity and uncertainty of its control system, improves the control performance of the system, and makes it have better anti-interference ability and robustness.

This paper mainly introduces the BLDCM mathematical model and fuzzy adaptive PID control algorithm, then compares and analyzes the step response at a set reference speed of 1000r/min and the trend of various parameters of the motor under the same conditions. The results show that compared with traditional control algorithms, the fuzzy adaptive PID controller not only has a certain anti-interference ability, but also has small overshoot, short adjustment time, stable operation and strong robustness, and the dynamic performance of the system is also improved.

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