PMSM Vector Control Based on Fuzzy PID Controller

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Abstract—The traditional motor speed control method is to use PID controller to adjust it, but the accuracy and anti-interference ability of its control effect are difficult to be guaranteed. Because the side effects of its error selection, "weighted sum" strategy may not be the best and integral feedback. In the case of motor load variation, this paper presents a control method based on Fuzzy PID controller. The simulation model of PMSM (permanent-magnet synchronous motor) is built in Matlab / Simulink. The simulation experiment shows that the fuzzy PID controller has higher accuracy and anti-interference ability than the classical double closed-loop PID vector control in PMSM vector control.

1. INTRODUCTION
PMSM is a multivariable, nonlinear and strongly coupled system, which is very sensitive to system parameter perturbation and external interference[1]. In the process of motor control, the parameters of motor are often dynamic variables and will be interfered by external factors. As the classical PID control belongs to linear control, it needs precise mathematical model, which leads to its limitations in motor control. So it is difficult to ensure the accuracy and robustness of the control. Fuzzy control is a computer digital control algorithm based on fuzzy set theory, fuzzy language variables and fuzzy logic reasoning. This algorithm transforms human experience into control strategy, and has good control effect for those time-varying, nonlinear and lagging high-order large inertia controlled objects[2].

In this paper, based on the double closed-loop PMSM vector control model of PI control, the fuzzy control and PID controller of speed loop are combined, and the feasibility of this method is verified by Matlab / Simulink simulation test.

2. VECTOR CONTROL PRINCIPLE OF PMSM
First, in order to simplify the voltage and magnetic linkage equations for theoretical analysis, several very important assumptions are made for PMSM, and some problems are idealized. The main assumptions are as follows:

(1) The magnetic field produced by the three-phase winding and permanent magnet of the stator is spatially sinusoidal, and the induction electromotive force waveform in the phase winding is sinusoidal when it runs stably;

(2) Ignoring the effect of stator slot on gap resistance and magnetic field distribution;

(3) The core permeability of the stator and the rotor is infinite, and the winding inductance of the motor does not change with the working condition. Based on the above assumption, the voltage equation of the motor in two-phase rotating d-q coordinate system is obtained as:
\[
\begin{align*}
    u_d &= R_s i_d + L_d \frac{di_d}{dt} - \omega_r L_q i_q \\
    u_q &= R_s i_q + L_q \frac{di_q}{dt} + \omega_r (L_q i_d + \psi_f)
\end{align*}
\] (1)

(2)

The motor's torque \(T_e\) equation is:

\[
T_e = \frac{3}{2} p [\psi_f i_q + (L_d - L_q) i_d]
\] (3)

In the above formula, \(u_d\) and \(u_q\) are the corresponding equivalent d-q axis voltage; \(i_d\) and \(i_q\) are the corresponding equivalent d-q axis current; \(\omega_r\) is the motor speed; \(\psi_f\) is the equivalent flux of PMSM; \(R_s\) is the equivalent stator resistance; \(L_d\) and \(L_q\) are the equivalent inductance of d-q axis; \(p\) is the pole pairs of motor.

The principle of vector control is that the permanent magnet synchronous motor is controlled according to the DC motor torque control method. By decoupling the stator current of the motor, it is decomposed into the excitation current component and the torque current component. These two components are 90 degree angle to each other in the coordinate system. They do not affect each other and remain independent. In this way, good control of the torque can be obtained by reasonably controlling the magnitude of the torque current and the excitation current\(^3\). The vector control model is shown in Figure 1:

![Vector control model](image)

3. PRINCIPLE OF FUZZY PID CONTROL

3.1 Principle of PID Control

PID control is literally to control by adjusting the three coefficients of proportional coefficient \((K_p)\), integral coefficient \((K_i)\) and differential coefficient \((K_d)\). PID controller is a kind of linear controller. The control deviation composed of the target value \(r(t)\) and the actual output value \(y(t)\) is its input value, and the input equation is:

\[
e(t) = rt - yt
\] (4)

The output equation of the controller is:

\[
u(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt}
\] (5)

Adjust the PID parameters to meet the system requirements, so that the controlled object has better dynamic and static response. The PID control model is shown in Figure 2:

![PID control model](image)

Proportional component: Controlling and reducing bias by adjusting the system control in proportion to the amount of bias. The role of the scale factor is to increase the speed of system response. The larger the scale factor, the faster the system response, but the system is prone to overshoot. If the scale factor is too small, the precision of system adjustment will be affected, the response time of the system will be longer, and the dynamic response of the system will be worse.
Integra component: It is used to eliminate the static error and improve the error degree of the system. The integral time constant determines the strength of the integral link, but if the integral action is too strong, it will affect the stability of the system.

Differential component: It will adjust the system control quantity according to the variation trend of deviation quantity. Before the deviation signal changes greatly, a correction signal is introduced in advance, which can speed up the system operation speed and reduce the regulation time. In order to adjust the differential parameters, it is necessary to note that too strong differential action may cause system oscillation.

It is not difficult to see that the parameter setting of PID controller is the core content of PID control, while the PID parameters of classical PID control are a set of fixed values. These parameters can not take into account the contradiction between the dynamic performance and static performance of the system and between the set value and disturbance suppression[4].

3.2 Fuzzy PID Control
First we need to know what fuzzy control is. Fuzzy control is to use the fuzzy set theory to quantify the control experience of human experts on a specific object, and transform it into a mathematical controller, so as to realize the control of the controlled object. The fuzzy control system consists of fuzzy data and rule base, fuzzifier, fuzzy inference engine and defuzzifier. A fuzzy control system is called a fuzzy controller when it is used as a controller[5].

The principle is to convert the state of the controlled object measured by the fuzzy controller into the fuzzy quantity described by human natural language, and then get the fuzzy value of the output control quantity by fuzzy inference according to human language control rules. The fuzzy value of the control quantity is transformed into the precise quantity that the actuator can receive by the defuzzifier.

Combined with the characteristics of PID control and fuzzy control, we can get the method of using fuzzy control to determine PID control parameters. In this way, the problem that PID parameters of dynamic system are fixed value can be solved. The deviation value \( e(t) = r(t) - y(t) \) and the change rate of the deviation value \( e'(t) \) (the exact value) are taken as the input of the fuzzy control, and then the fuzzy set is obtained by fuzzy processing. After fuzzy inference and anti fuzzy, the precise output \( K_P \), \( K_I \) and \( K_D \) is obtained[6]. Its structure is shown in Figure 3.
In this experiment, the fuzzy controller adopts the triangle membership function. All the membership functions are distributed symmetrically. And the weighted average method is used for anti fuzzy\[7\]. Fuzzy set is :\{NB,NM,NS,ZE,PS,PM,PB\}; all input domain are: {-3, 3}; Output domain( $K_p$, $K_i$ and $K_d$) are: {-0.3,0.3},{-0.06,0.06} and {-3,3}. At the same time, according to some principles summarized in reference [4], the reasoning rules of fuzzy control are formulated as follows Table 1 (Three control rules correspond to the control rules of $K_p$, $K_i$ and $K_d$ from top to bottom):

| $\dot{e}$ | $e$  | NB  | NM  | NS  | ZE  | PS  | PM  | PB  |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|
| $e$      | NB  | PB  | PB  | PM  | PM  | PS  | PS  | ZE  |
|          | NB  | NB  | NB  | NM  | NM  | ZE  | ZE  | ZE  |
|          | PS  | PS  | ZE  | ZE  | ZE  | ZE  | PB  | PB  |
| $e$      | NM  | PB  | PB  | PM  | PM  | PS  | ZE  | ZE  |
|          | NB  | NB  | NM  | NM  | NS  | ZE  | PS  | ZE  |
|          | NS  | NS  | NS  | NS  | ZE  | PS  | PM  | PM  |
| $e$      | NS  | PM  | PM  | PM  | ZE  | NS  | NS  | NM  |
|          | NM  | NM  | NS  | NS  | ZE  | PS  | PS  | PS  |
|          | NB  | NB  | NM  | NM  | ZE  | PS  | PS  | PM  |
| $e$      | ZE  | PM  | PS  | ZE  | NS  | NS  | NM  | NM  |
|          | NM  | NS  | NS  | ZE  | PS  | PS  | PM  | PM  |
|          | NB  | NM  | NM  | ZE  | PS  | PS  | PM  | PM  |
| $e$      | PS  | PS  | ZE  | NS  | NS  | NM  | NM  | NM  |
|          | NS  | NS  | ZE  | PS  | PS  | PM  | PM  | PM  |
|          | NB  | NM  | NS  | ZE  | PS  | PS  | PS  | PS  |
| $e$      | PM  | ZE  | ZE  | NS  | NM  | NM  | NM  | NB  |
|          | ZE  | ZE  | PS  | PM  | PM  | PB  | PB  | PB  |
|          | NM  | NS  | NS  | NS  | ZE  | PS  | PS  | PS  |
| $e$      | PB  | ZE  | NS  | NS  | NM  | NM  | NB  | NB  |
|          | ZE  | ZE  | PS  | PM  | PB  | PB  | PB  | PB  |
|          | PS  | ZE  | ZE  | ZE  | ZE  | ZE  | PB  | PB  |

When using the built-in fuzzy controller editor for MATLAB, the basic properties of the fuzzy inference system are: The “AND” operation uses a minimal operation; “Or” operation uses maximum operation; Fuzzy implication uses minimal operation; Fuzzy rule synthesis uses maximum operation; Fuzzy solution uses center of gravity method.

4. SIMULATION TESTE

In order to verify the superiority of the fuzzy PID controller, two PMSMs are selected to use the PID control method to debug, and the speed loop of one motor control system is improved to the fuzzy PID controller. Use Simulink to build the simulation model of the speed synchronous control system. The simulation model is shown in Figure 4 and Figure 5:
The simulation parameters are shown in Table 2:

| Parameter                              | Motor I     | Motor II    |
|----------------------------------------|-------------|-------------|
| Rated Speed (r/min)                    | 1000        | 1000        |
| Inductance Ld,Lq(mH)                   | 5.25/12     | 5.25/12     |
| Rotor Inertia (Kg*m2)                  | 0.003       | 0.003       |
| Stator Resistance Rs(Ω)                | 0.96        | 0.96        |
| polar numbers P                        | 4           | 4           |
| Damping coefficient B (N*M*S)          | 0.008       | 0.008       |
| magnetic linkage $\psi_f$ (wb)         | 0.182743    | 0.182743    |

Simulation conditions: DC side voltage: $U_{dc} = 311V$; PWM switching frequency: $f_{PWM} = 10Khz$;
sampling period: $T_s = 10 \mu s$; Variable step size ode23tb algorithm; relative error: 0.001; simulation time 0.4s.

The content of this experiment is to start and accelerate the two motors from 0rpm to 1000rpm at the same time, and change the load directly from 0 to $T = 5N*M$ after stable operation to 0.2S. The speed test results of the two motors are shown in Figure 6, 7 and 8:

5. CONCLUSION

From the simulation results, it is not difficult to see that the overshoot of fuzzy PID controller is smaller than that of classical PID controller, and it still has a faster dynamic response speed. When $t = 0.2S$ sudden load torque changes from 0 to $5N * m$, the motor can also quickly recover to the given reference speed value, while the classical PID control has relatively long delay. It can be seen that fuzzy PID control has good dynamic and static performance.

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