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Study on Control Strategy of Permanent Magnet Synchronous Motor for Electric Vehicle

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Abstract: Permanent magnet synchronous motors have been widely used in electric vehicles because of their good performance and high energy conversion efficiency. mathematical models of permanent magnet synchronous motors in different coordinate system are built in the paper . Based on the vector control method of permanent magnet synchronous motor, a double closed-loop control system of permanent magnet synchronous motor is constructed. Combining fuzzy control theory and traditional PID control method, control rules are design according to control experience, PID parameters is set, and a new fuzzy self-adaptive PI control system are design in order to realize precise control of permanent magnet synchronous motor. The simulation models of traditional digital PID control and fuzzy PID control are built using Matlab/Simulink software, and the simulation experiment of the control system is carried out. The simulation results show that the proposed fuzzy PID control scheme can effectively improve the speed response speed and control accuracy, and has good stability and dynamic performance.

1. Introduction

Under the trend of global warming, countries all over the world are making more and more efforts to protect the environment, and electric vehicles, as an important tool for energy saving and emission reduction, are becoming more and more important in daily life. The electric motor is the key component of electric vehicles, and the permanent magnet synchronous motor has better performance compared with other motors, and it has a series of advantages such as small size, high power density, wide speed range, etc. Therefore, choosing the permanent magnet synchronous motor as the electric vehicle drive motor is the inevitable trend of electric vehicle drive system development.

2. Mathematical Model of Permanent Magnet Synchronous Motor

Under ideal condition, the stator voltage equation of three-phase winding is as follows[1].

$$\begin{bmatrix} U_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & Rs & U \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + P \begin{bmatrix} \psi_a \\ \psi_b \\ \psi_c \end{bmatrix} \tag{1}$$

Where, u_a,u_b,u_c,i_a,i_b,i_c are voltage and current in three-phase stationary coordinate system are ; ψ_a、ψ_b、ψ_c are the flux linkage of winding ; Rs is resistance of stator winding; P is a differential operator.

The stator flux equation is as follows[2].

$$\begin{bmatrix} \psi_a \\ \psi_b \\ \psi_c \end{bmatrix} = \begin{bmatrix} L_{aa}(\theta) & M_{ab}(\theta) & M_{ac}(\theta) \\ M_{ba}(\theta) & L_{bb}(\theta) & M_{bc}(\theta) \\ M_{ac}(\theta) & M_{bc}(\theta) & L_{cc}(\theta) \end{bmatrix} + \begin{bmatrix} cos\,\theta \\ cos(\theta - 120) \\ cos(\theta + 120) \end{bmatrix} \psi \tag{2}$$

Where,L_{aa},L_{bb},L_{cc} are the self-sensing coefficients of the three-phase windings, respectively ; M_{ab}, M_{ac},M_{ba},M_{bc},M_{ac},M_{bc} are stator mutual inductance coefficients; ψ_a、ψ_b、ψ_c are stator three-phase winding flux linkage; ψ is the excitation flux linkage of rotor ; θ is the angle between axis direction and ψ direction of A phase winding.

The mathematical model of permanent magnet synchronous motor in two-phase rotating coordinate system is obtained by Park transformation as follows.

The stator voltage equation is shown in formula 3.

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{d}{d_t} \begin{bmatrix} \psi_d \\ \psi_q \end{bmatrix} + \begin{bmatrix} -\omega_e \psi_q \\ \omega_e \psi_p \end{bmatrix} \tag{3}$$

The stator flux equation is in formula 4.

$$\begin{bmatrix} \psi_d \\ \psi_q \end{bmatrix} = \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \psi \begin{bmatrix} 1 \\ 0 \end{bmatrix} \tag{4}$$

The motion equation is in formula 5.

$$J \frac{d_\omega}{d_t} = T_e - T_L - B_\omega \tag{5}$$

Because of $L_d = L_q$, formula 5 can be written as formula 6.

$$T_e = P_n \psi i_q \tag{6}$$

The current state equation of permanent magnet synchronous motor can be obtained by solving the equation (3) (4) (5) (6) ,it is shown in formula 6

$$\begin{cases} \frac{di_d}{dt} = -\frac{R_s}{L_d} i_d + \frac{1}{L_d} u_d + P_n \omega i_q \\ \frac{di_q}{dt} = -\frac{R_s}{L_q} i_q + \frac{1}{L_q} u_q - P_n \omega i_d - \frac{P_n \psi}{L_q} \omega \\ \frac{d\omega}{dt} = \frac{P_n \psi}{J} i_q - \frac{B}{J} \omega - \frac{T_L}{J} \\ \frac{d\theta}{dt} = \omega \end{cases} \tag{7}$$

Where, θ is the mechanical angle, $\theta_e = P_n \times \theta$.

From the formula 7, it can be seen that the expression representing the d-axis and q-axis current components does not contain θ, so it is not necessary to consider the problem of mutual coupling between flux linkages in motor current, so that the independent control of torque and flux linkage simplifies the control system.

3. Building Fuzzy Control model

3.1. Fuzzy Control Theory

Fuzzy PID is a computer digital control technology based on fuzzy set theory, fuzzy logic, and fuzzy language variables. It is the application of fuzzy mathematical theory to control. It is based on the experience accumulated to control what needs to be controlled[3]. Objects are often summarized with "if" statement and “then” statement.

The fuzzy PID control system uses the deviation e and the deviation change rate e_c as the output of the fuzzy PID control, and uses the fuzzy control rules to modify the PID parameters in real time, which greatly improves the control accuracy[4]. Its control system is shown in Figure 1.

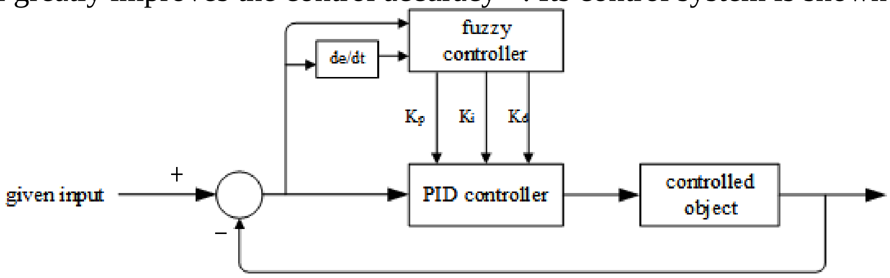


Figure 1. Schematic diagram of fuzzy PID control system

3.2. Design of Fuzzy PI Controller

The fuzzy control system is mainly composed of three modules. They are the fuzzification module, the fuzzy inference module and the defuzzification module[5]. The main function of the fuzzification module is to divide the input data into different levels of membership according to size and type. The relevant modules of fuzzy reasoning mainly formulate fuzzy control rules using the knowledge and experience accumulated by experts, and then perform fuzzy reasoning on the input data. Defuzzification is to solve the fuzzification equation according to the membership degree obtained by fuzzification and the fuzzy rules obtained by fuzzy reasoning, and obtain the required fuzzy quantity.

3.2.1. Determining the input and output quantities and threshold values of the system

The two-dimensional fuzzy PI controller is established in this paper, and the deviation of the system target quantity and the feedback quantity and the deviation change rate are selected as the input quantities, which are represented by e and e_c respectively; the k_p compensation amount and k_i compensation amount are used as the output quantities, respectively Δk_p and $\Delta \mathrm{k_i}$ represent.

In this study, the fuzzy controller language variables are divided into seven levels, which are represented by word sets {NB, NM, NS, ZO, PS, PM, PB}. Defining the discussion domain of deviation e and e_c as {-3,-2,-1,0,1,2,3}, then the domain of discussion of output quantities Δk_p and $\Delta \mathrm{k_i}$ is {-0.3,-0.2,-0.1, 0,0.1,0.2,0.3}.

3.2.2. Membership function selection and sharpness fuzzification

In this paper, the triangular membership function, which is easy to calculate, is selected as the fuzzy controller function. The input of the fuzzy controller is a clear quantity, so it needs to be fuzzified firstly, so that the fuzzy quantity conforms to the universe of discourse. Assuming that the given area variable is $\{-x_e, x_e\}$, and the range of the fuzzy area variable is $\{-n, n\}$, the quantization factor and scale factor are determined according to formula (8).

$$\begin{cases} K_1 = \frac{n_e}{x_e} \\ K_2 = \frac{n_{ec}}{x_{ec}} \end{cases} \tag{8}$$

3.2.3. Making fuzzy rule

In order to better control the permanent magnet synchronous motor, according to the existing experience, the fuzzy control rule table of the output parameters is formulated, it is shown in Table 1 and Table 2. [6]

Table 1. Table of Δk_p fuzzy rules

	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 Table of Δk_i fuzzy rules

	NB	NM	NS	ZO	PS	PM	PB
NB	ZO	PB	PB	PS	PM	PS	ZO
NM	ZO	PM	PM	PM	PS	PS	ZO
NS	ZO	PS	PM	PS	ZO	ZO	ZO
ZO	ZO	ZO	PS	ZO	NS	ZO	ZO
PS	ZO	ZO	ZO	NM	NM	ZO	ZO
PM	ZO	NS	NS	NM	NM	NM	ZO
PB	ZO	NS	NM	NB	NB	NB	ZO

3.2.4. Defuzzification

After the given input is adjusted by fuzzy control and fuzzy control rules, it is necessary to inverse fuzzy to get the accurate amount, so as to control permanent magnet synchronous motor. The accurate output can be obtained by using the gravity center method for inverse fuzzy operation.

$$\boldsymbol{\mu} = \frac{\sum_{m=1}^{7} \mu_i \mu(m)}{\sum_{i=1}^{7} \mu_{(m)}} \tag{9}$$

Where, μ is the output clarity, and μ_i is the weight of each group of elements.

4. Modeling and Simulation Analysis

4.1. Simulation Design

Using the idea of modularization and SIMULINK simulation tools, according to the system's anti-load disturbance requirements, the control strategy is simulated, and the control principle is shown in Figure 2.

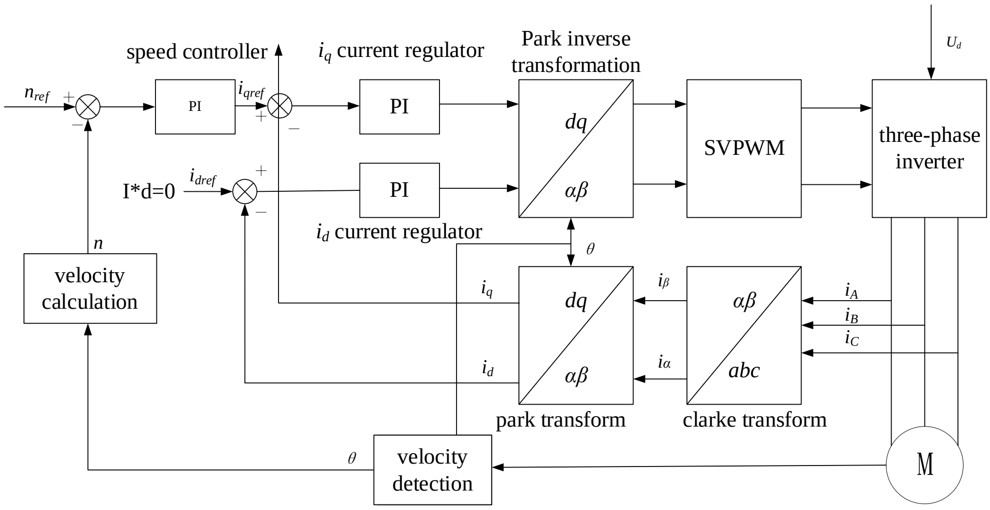


Figure 2. Principle diagram of vector control

The motor data used in the study are shown in Table 3.

Table 3. Simulation motor parameters

Nominal power P	Number of pole-pairsn_p	Stator resistance R_s	d-axis inductanceL_d	q-axis inductanceL_q	Magnetic flux φ_f	Rated speed ω
$3kW$	4	0.958Ω	$5.25mH$	$12mH$	$0.1827wb$	$1200rpm$

In order to verify the effectiveness of fuzzy PI control, the simulation model of speed control system is established in MATLAB/Simulink . The simulation model is shown in Figure 3.

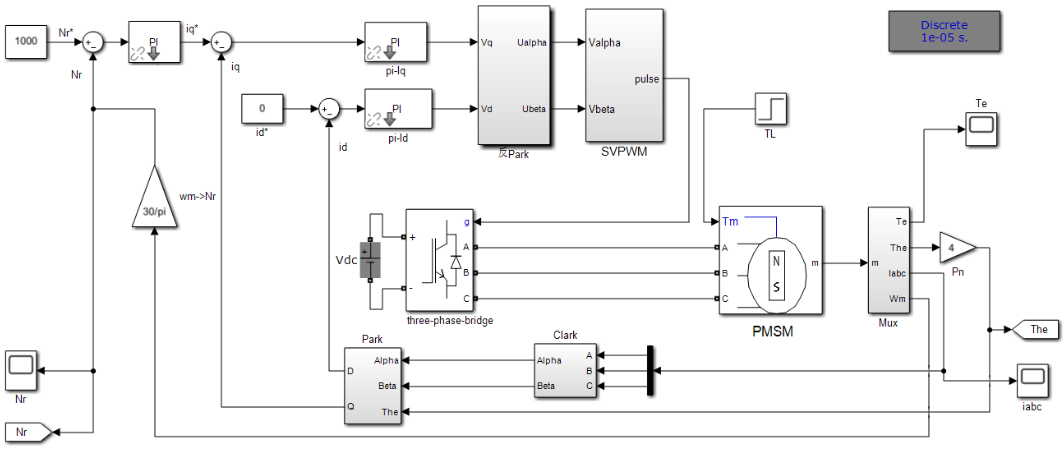


Figure 3. Model permanent of magnet synchronous motor control system

The simulation model includes permanent magnet synchronous motor model, coordinate transformation module, SVPWM module and PI adjustment module. Among them, PI adjustment module includes fuzzy control module and traditional control module. The simulation model of fuzzy control module is shown in Figure 4.

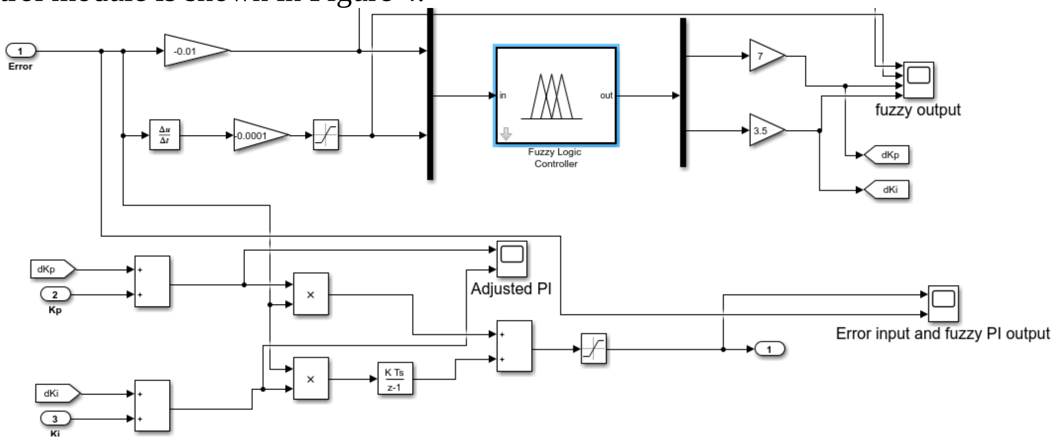
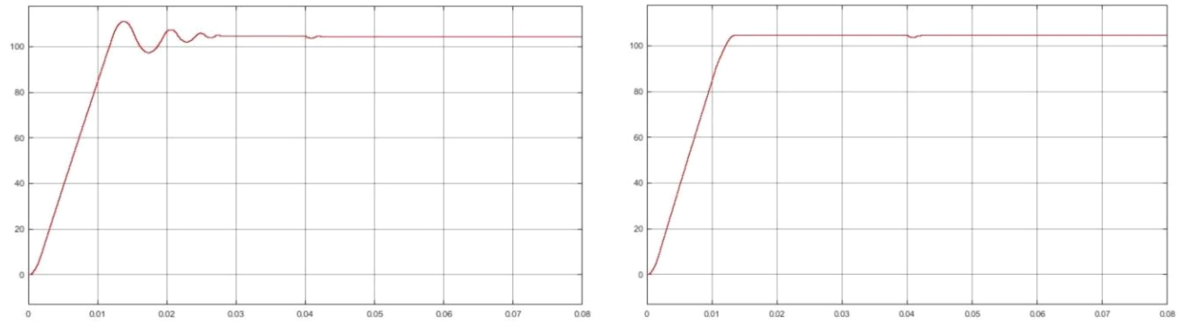


Figure 4. Fuzzy PID Control

4.2. Analysis of simulation results

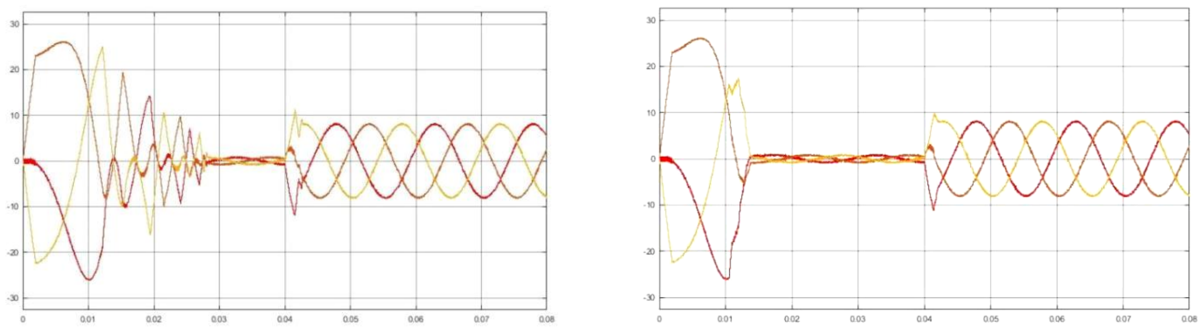
The speed waveform, three-phase winding current waveform and torque waveform of the two control methods are obtained by simulation experiments, they are shown in Figure 5, Figure 6 and Figure 7.



(a) (b)

Figure 5. Speed simulation waveform

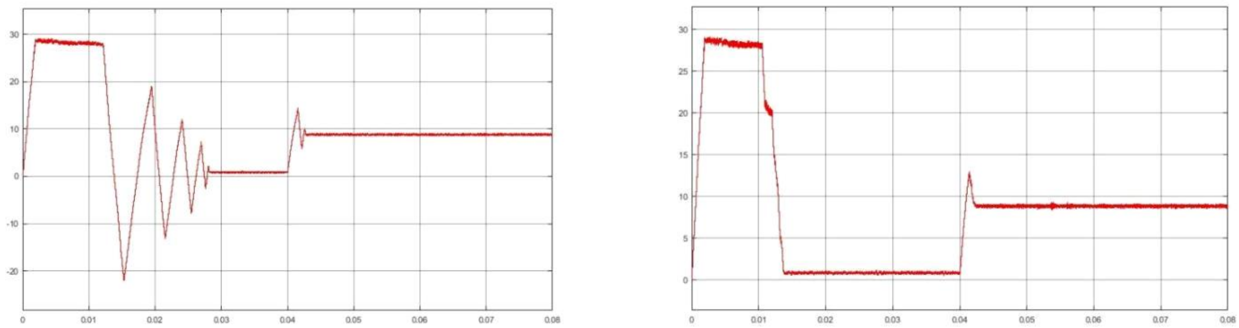
a.traditional PI,b.Fuzzy PI



(a) (b)

Figure 6. Current current simulation waveform

a. traditional PI, b.Fuzzy PI



(a) (b)

Figure 7. Torque simulation waveform

a.traditional PI, b.Fuzzy PI

From simulation curve, it can be seen that for the speed regulation, the fuzzy control system is obviously faster, and the speed is more stable. The current output of the fuzzy control is relatively stable in the regulation process. The regulation effect of the torque is also better than that of the traditional PID regulation, and the regulation process is more stable. Moreover, the load is increased in 0.02 seconds, and the ability of Fuzzy PID which is adapt to the load is also better than that of traditional PID regulation.

5. Conclusion

According to the characteristics of electric vehicles, the PID control method and the fuzzy control principle of current and speed double closed-loop control system for permanent magnet synchronous motor are analyzed, and the differences and respective characteristics of digital PID control and fuzzy PID control methods are compared. The simulation models of the two control systems are built based on Matlab/Simulink software. Through the analysis and comparison of simulation experiments, it is proved that the control system combining vector transformation and fuzzy PID control has high stability and anti-interference ability, which can make permanent magnet synchronous motor operate efficiently and stably.

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