Direct Torque Controlling of Permanent Magnet Synchronous Motor Based on the Adaptive Fuzzy Controller

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Abstract. This paper proposes a direct torque control system of permanent magnet synchronous motor based on fuzzy control. The stator flux linkage error, torque error and the stator flux vector angular position are used as fuzzy state variables. According to the settling fuzzy rules, the voltage vectors are selected to control the inverter. The zero voltage space vector is used to keep the steady state and reduce frequency of inverter. The simulation results show that the system can depress the torque ripple effectively and improve the startup response.

Keywords: Fuzzy control, permanent magnet synchronous motor (PMSM), direct torque controller (DTC), voltage vector.

1 Introduction

Based on fuzzy control of the direct torque control method, the fuzzy controller replaced the bang-bang controller used in the three-phase voltage inverter which can inhibit motor torque ripple, but the dynamic and static performances are not good enough. Using neural network technology for direct torque control parameters study, a large number of tests and off-line learning is needed, and the algorithm is also complicated. According to the non-linear and strong coupling of PMSM, adaptive fuzzy controlling is used as the direct torque controller of PMSM. Considering the big deviation in transient and tracking process, the flux region is fractionized, and a fuzzy rules table is acquired according to the effects of all voltage vectors. Adaptive fuzzy algorithm is applied to correct the voltage vectors, which can improve the controller performances. In this paper, a simulation model is built by using the fuzzy logic toolbox of MATLAB and Simulink tools. From the curve of simulation and performances, the adaptive fuzzy controller, can reduce the ultra-small of system response and accelerate the reaction velocity, and make the system have a better controlling effect than the conventional direct torque controller [1].

2 PMSM Mathematical Model

PMSM uses the electromagnetic torque which generated by the interaction of stator flux linkage and rotor flux linkage to drive the rotor rotation. If we ignore the impact

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of magnetic flux leakage and do not consider the magnetic saturation, assume that the stator windings completely symmetrical and the inductances are equal to each other, and the inductances have no relationship with the positions of rotors, rotor flux is a normal distribution in the air gap, then the equations of flux linkage, voltage and electromagnetic torque of PMSM on the rotor-based coordinate system (d-q shaft) are:

$$U_d = R_s i_d + p\phi_d - w_r \phi_q \tag{1}$$

$$U_q = R_s i_q + p\phi_q - w_r \phi_d \tag{2}$$

$$\phi_d = L_d i_d + \phi_f \tag{3}$$

$$\phi_q = L_q i_q \tag{4}$$

$$T = \frac{3}{2} p_n (\phi_d i_q - \phi_q i_d) \tag{5}$$

3 Adaptive Fuzzy Controller

Compared to the traditional controlling method, fuzzy control has better robust performance. But this method cannot eliminate static error completely, and the controlled resolution is not good. In order to improve the adaptive capacity of the fuzzy controller, we put fuzzy control technology and adaptive fuzzy control technology together which based on DTC technology, and solve the static error and improve the quality of dynamic. System block diagram is shown in Fig. 1.

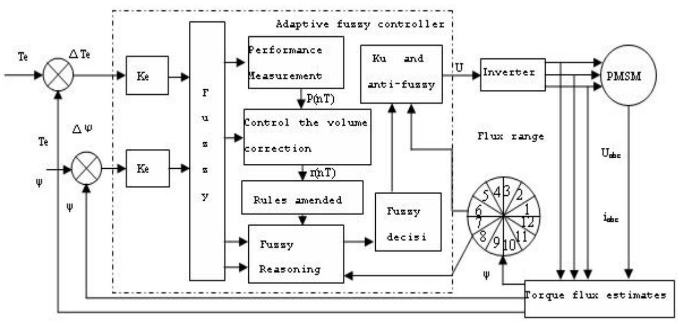

Fig. 1. Adaptive fuzzy control system block diagram

3.1 Traditional Direct Torque Control Mechanism

Based on the PMSM model, a hidden PMSM expression can be showed as:

$$T = \frac{3p_n}{2L_s} |\phi_s| \phi_f \sin\delta = \frac{3p_n}{2L_s} |\phi_s| \phi_f \sin(\delta_t + \delta_0) \tag{6}$$

The DTC control theory which PMSM is based on: to maintain the same amplitude of stator flux, and to control the angle between the stator flux and the rotor flux, thus the motor torque can be controlled and rapid torque response can be retained by changing the torque angle quickly. The control mechanism is: according to current and voltage value of three-phase chain, calculate the value of flux linkage and torque model, then calculate the sectors of stator flux linkage, then to choose the switching value of inverter according to the mistakes between specified values and true values. So that the electrical motor can adjust output torque with requirements [3] .

3.2 Based on Fuzzy Logic Direct Torque Control Technology

Traditional direct torque control separate the entire α-β plane into 6 regions, it is shown in Fig. 2.

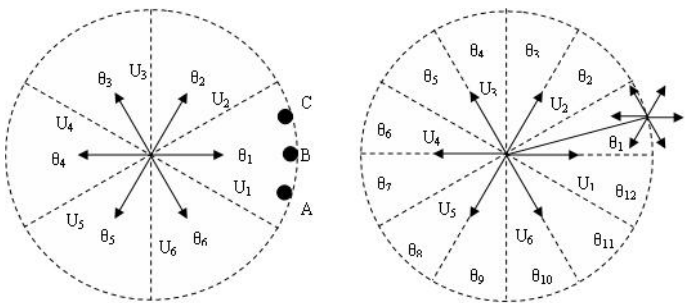

Fig. 2. DTC traditional system of 6 regions and 12 of the refining region

Ignoring the stator resistance, stator flux is the integral of the voltage vector, that is to say the change of flux linkage and the change of the voltage vector are the same direction. In the same region, to choose the voltage vector according to the flux and torque changes is needed. At present, the main method is to choose 4 non-zero vectors or 4 non-zero vectors to plus zero vector, for example, in the region of θ_1, to choose u_2, u_3, u_5, u_6 and u_0 (u_7). In fact, in the transient process of PMSM, the size and direction of the flux can be controlled according to the needs of changing. This article separates 6 regions into 12 smaller regions, and uses non-zero vectors and zero vectors in control method.

Rotate flux from point A to B, C point movement by anti-clockwise way. One point B is located on the axis vector u_1. Anti-clockwise turn the electrical motor, overlooking in the stator resistance, the same location on the flux and the role of torque are as follows:

u_1 voltage vector: from point A to point B, increases the flux linkage, at the same time increases the electromagnetic torque; from point B to point C, flux is increased, and the torque is reduced .

u_2 voltage vector: flux's amplitude is gradually increased, the capacity of increasing the torque slows down.

u_3 voltage vector: reduces the amplitude of flux, and increases the capacity of torque increment.

u_4 voltage vector: from point A to point B, the flux goes reversely point B, reducing the role of strengthening the role of torque weakened by conflict; from point B to point C so that the positive flux to reduce the role of the Weakened by the most powerful, torque increase to strengthen the role.

u_5 voltage vector: flux amplitude decreased gradually strengthen the role; increased torque capacity gradually weakened.

u_6 voltage vector: flux amplitude gradually increasing the role of the weaker; torque increase capacity to strengthen gradually.

u_0, u_7 voltage vector: flux amplitude will remain basically unchanged; torque decreased slightly.

In the same section, when the flux is in the different location, the size and the effection of voltage vector is changing continually. Therefore, the dividing line between the regions should not be very sure. This is conducive for integrating flux control and torque control to select the best vector control. So, using fuzzy control or other smart strategy with choosing the appropriate voltage vector is necessary. According to the above reasons, the α-β plane is divided into 12 regions, shown in Figure 2. The following is the Fuzzification treatment.

3.3 Direct Torque Control System

In PMSM, the statement of three-phase terminal voltage determines the statement of the stator flux. It is known that the three-phase six-pulse inverter can generate 8 voltage vectors (shown in Figure 3), the amplitude of the non-zero voltage vector is 2/3Vdc. The relationship of stator flux and the stator voltage vector is:

$$\Psi_s = \int (\upsilon_s - Ri_s)dt + \Psi_{s0} \tag{7}$$

in this function, R is for resistance of the stator, ψ_s is for the stator flux vector, ψ_{s0} is for the initial vector of stator flux, vs is for the stator voltage vector, is is for the stator current vector.

As the rotor of PMSM is the permanent magnet rotor, even the motor is not running, the stator can feel the sense of flux generated by rotor, that is, $\psi_{s0} = \psi_f$. Pay attention to these two values which have size of the volume and direction of the vector, so you should know the initial rotor position. Whether can determine the exact location of the rotor will be a direct impact on the performance of the system.

Fig. 3, the voltage vector is divided into 6 regions. When choosing the angle of voltage vector and the stator flux is less than π / 2, the amplitude of the stator flux will be increased, otherwise it will be decreased; when the voltage vector which is selected is ahead of the stator flux, the motor torque will increases, on the contrary it will decrease. Rotate motor on counter-clockwise, for example, assume that the current location of the stator flux at the District 3, you can choose voltage vector V_2, V_3 and V_6 to increase the magnetic ,and choose V_1, V_4 and V_5 to reduce the flux; choose V_1 and V_5 to increase torque, chooseV_6 and V_4 to reduce torque. In order to

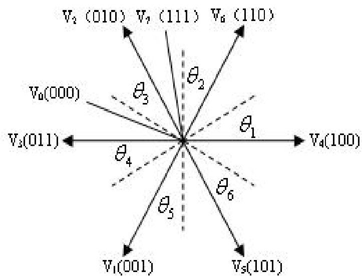

Fig. 3. Vector and the section of the division

Table 1. Choice of voltage vector table

$\Delta\psi$	ΔT	θ_1	θ_2	θ_3	θ_4	θ_5	θ_6
0	0	V 1	V 5	V 4	V6	V2	V3
0	1	V 2	V 3	V 1	V5	V4	V6
1	0	V 5	V 4	V6	V2	V3	V1
1	1	V 6	V 2	V3	V1	V5	V4

reduce the inverter's switch, just select the current flux in the neighbor region. For the above example, V_2 and V_5 will not be chosen. The specific choice of voltage vector in Table 1, $\Delta\psi$and ΔT mean electromagnetic and torque error, 0 and 1 is the electromagnetic and torque hysteresis output.

We analyze direct torque control in static $\alpha - \beta$ coordinates. The relationships in the static $\alpha - \beta$ coordinates are as follows:

$$i_s = i_\alpha + ji_\beta \tag{8}$$

$$\upsilon_s = \upsilon_\alpha + j\upsilon_\beta \tag{9}$$

$$\Psi_s = \Psi_\alpha + j\Psi_\beta \tag{10}$$

$$T_e = 1.5n_p(\Psi_\alpha i_\beta - \Psi_\beta i_\alpha) \tag{11}$$

Summing up the above, we can establish the diagram for direct torque control (Fig. 4). The specified value of speed and motor tachometer output can generate given torque by PI regulation. Stator flux value is slightly larger than or equal to the permanent magnets in the stator flux of the sensor.

3.4 Adaptive Institutions

The Fuzzy direct torque control is more "humane" than normal control and it can achieve strategy that adjustment big error and small error both well. But it is difficult to sum up a good fuzzy control rules for complex non-linear systems, thus making it difficult to get satisfactory control. In this paper, the above-mentioned fuzzy control

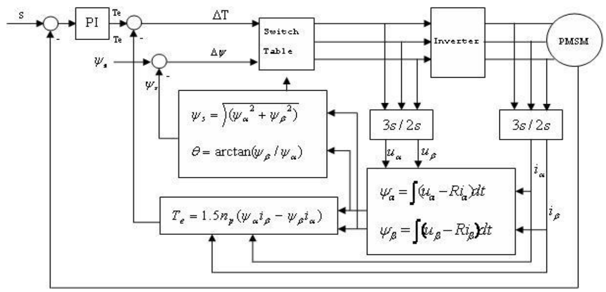

Fig. 4. Block diagram of Direct Torque Control

system have been added to a controller performance feedback. Through this feedback to adjust and improve the automatic control rules, it can achieve a better control statement. As shown in Fig. 1, it has 3 links more than a simple fuzzy controller. The 3 links are performance measurement, control volume amendments and control rules amendments.

1) Performance Measurement

In the session of Performance measurement, to measure the output characteristics of the system directly, and compare to pre-set values then calculate on the correct amount P (nT) of output. In this paper, the electromagnetic torque deviation E (Te) and changes in the rate of EC (Te) to represent the output characteristics. According to the two to measure the actual value of the output characteristics with the hope that the characteristics of bias. Methods used fuzzy sets out the rules of performance measurement, as shown in Table 2. For example, the rules of the table: if E (Te) = NS and EC (Te) = PS then P = PS, said that when the electromagnetic torque error E as a "small negative" error rate of change for the EC "is small", that is, output Properties rose more slowly, given the amount of correction for the P is small.

Table 2. Performance measurement correction table

P		E				
		NB	NS	Z	PS	PB
EC	NB	NB	NB	NB	NS	Z
	NS	NB	NS	NS	Z	PS
	Z	NB	NS	Z	PS	PB
	PS	NS	Z	PS	PS	PB
	PB	Z	PS	PB	PB	PB

2) Control the volume correction

Above the performance measurement are given to achieve the desired system performance required for amendments to the output volume. In order to achieve adaptive control, The need to amend the amount of output required to transform P amendments to control the amount r, but taking into account the AC servo systems and DC servo systems, fuzzy logic system output U_i for a single point of fuzzy

Table 3. Performance measurement of digital correction table

P		E				
		NB	NS	Z	PS	PB
EC	NB	-0.8	-0.8	-0.8	0.4	0
	NS	-0.8	-0.4	-0.4	0	0.8
	Z	-0.8	-0.4	0	0.4	0.8
	PS	-0.4	0	0.8	0.4	0.8
	PB	0	0.4	0.8	0.8	0.8

sets, two adjacent fuzzy sets no “Big” and “small” the relationship between the paper in the analysis of the fuzzy controller input and output relationship based on control by the correction read r fuzzy controller input volume amended, that is, r with amendments E (Te), a Pseudo-error E (Te)’, allowing the system to achieve the same output expectations towards the direction of change. Assuming that the system output characteristics look-up table to be 4 correction P = α, then enter the correct amount of fuzzy r = $\alpha \cdot \rho$, a revised system of fuzzy input E (Te) ’= E (Te) + r = E (Te) + $\alpha \cdot \rho$, which was adjacent to P membership function of the difference between the center position, as shown in Fig. 5.

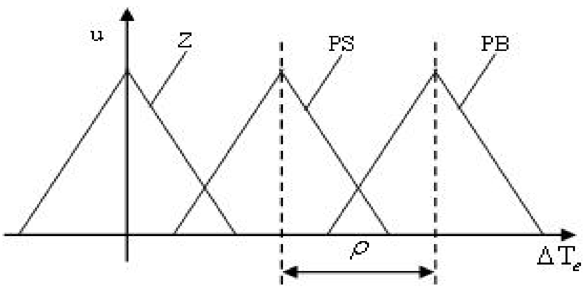

Fig. 5. Fuzzy language variables △ Te of the membership function

3) Amendment of the rules of fuzzy control

$E(k_T\text{-}d_T)$, $EC(k_T\text{-}d_T)$ and U $(k_r\text{-}d_T)$ represent torque bias, bias change and controlling which are before the d film. According to the above discussion, $E(Te)$ for the fuzzy logic controller input of the correction has been obtained, that is to say there is no need to amend the rules of fuzzy control as fuzzy controller input error “correction” in $(k-d)$ T time is $E(Te)$, the same response performance of system can be obtained in the k_T time [4].

4 System Simulation

Based on the above analysis, using fuzzy logic toolbox of MATLAB and Simulink simulation tool to build models of the conventional direct torque control and expansion of the adaptive fuzzy control technology of direct torque control for the simulation. The PMSM parameters are: stator resistance R_s = 311, straight-axis, cross-axis equivalent inductance $L_d = L_q = 8.5\ \ 10^{-3}$H, rotor flux $\Psi_f = 0.1$Wb, moment of inertia J=0.0008 kg · m^2, viscosity B=0, very few of P=4.

In this paper, only the simulations of electromagnetic torque wave are given which are shown in Fig. 6 and Fig. 7. The torque is begin 2 N · m, and at 0.15 S a given value turns 2 N · m into a 0.8 N · m. From the wave simulation, it can be seen that the torque overshoot σ of adaptive fuzzy control system in this paper reduced from 67% to 3%, and the regulation time ts reduced from 0.015S to 0.005S, The torque follow-up reaction speeds up, and static and dynamic performance becomes better.

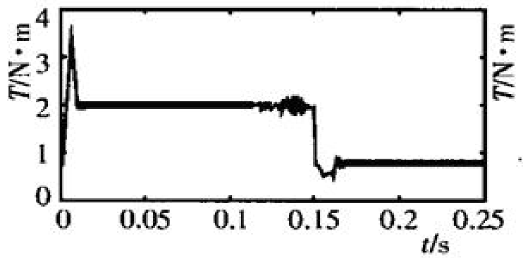

Fig. 6. Conventional direct torque control torque waveform

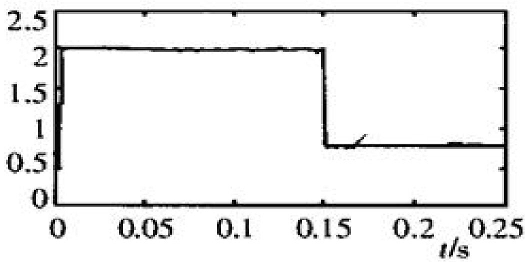

Fig. 7. Adaptive fuzzy control torque waveform

5 Conclusion

This paper make the PMSM as control target, and design adaptive fuzzy controller based on the direct torque control technology and propose an algorithm about optimizing the calculation efficiency and optimize the equivalent transformation of the fuzzy rules. The algorithm improves immediacy of real-time controller and simulates with Matlab7.0. It verifies the correctness of the theory. As a result, the expansion of adaptive fuzzy control technology on direct torque control can greatly increases the AC servo system dynamic and static performances.

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References

1. Feng, G.: A Survey on Analysis and Design of Model-Based Fuzzy Control Systems. IEEE Transactions on Fuzzy systems 14(5), 676–697 (2007)
2. Guo, X., Liu, J.: PMSM Direct Torque Control Research and Simulation. Small & Special Electrical Machines 40(4), 12–14 (2007)
3. Aguero, J.R., Vargas, A.: Calculating Functions of Interval Type-2 Fuzzy Numbers for Fault Current Analysis. IEEE Transactions on Fuzzy systems 15(1), 31–40 (2007)
4. Cheng, L., Li, G.: Adaptive fuzzy controller based on the permanent magnet synchronous motor direct torque control. Small & Special Electrical Machines 40(3), 26–29 (2007)