Direct Torque Control of PMSM with Torque Ripple Reduction Based on Fuzzy Logic Control

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Abstract. This paper is presented to examine and improve the performance of the torque ripple suppression for direct torque controlled permanent magnet synchronous motor by using fuzzy control method. On the basis of analyzing the torque ripple of the direct torque control in details, the fuzzy controllers are designed for two parts. Since the errors of the torque and flux could not assess accurately in hysteresis structure, the hysteresis controllers of the conventional DTC method are replaced by the fuzzy controller which could select the optimal voltage vector by judging the deviation degree of the torque and flux errors according to the fuzzy logic inference. Then the action time of the selected optimal voltage vector is determined by using the fuzzy duty ratio control method, the ripples of torque and flux can be attenuated effectively. The comprehensive simulation experiment is exhibited to reveal the excellent response performance of the system and verify the feasibility of the proposed fuzzy control scheme.

Keywords: Permanent magnet synchronous motor (PMSM) · Direct torque control (DTC) · Torque ripple · Fuzzy control

1 Introduction

The direct torque control (DTC) and field oriented control (FOC) which have made the outstanding contributions to the electric drive development are the most commonly used control method in motor control as we know nowadays [1]. DTC is firstly applied to induction motor and then is extended to PMSM which has high motion performance and the simple structure [2,3].

Unlike field oriented control, the direct torque control is based on stationary frame and focuses on controlling torque and flux directly. Therefore some parts like the transformation of coordinate, current regulation and pulse width modulator are eliminated. In this way the DTC presents some merits as fast torque dynamic response with the simple control structure. Meanwhile the concept of space voltage vector is applied in the DTC. In practical application, the applied voltage vector is obtained according to the outputs of the hysteresis controllers and the location of the stator flux. However the fixed hysteresis width could

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not assess the actual error values accurately, in addition usually only one-state voltage vector is fed by voltage-source inverter (VSI) in a sampling period, the actual controlled torque and flux often exceed the set values of the hysteresis controllers. It thus that DTC has some weakness include large flux and torque ripples, high current distortions [4].

In recent years, many researchers have paid much attention to improve the above shortcomings to utilize the DTC more widely. Some useful methods have proposed, among which the multilevel method and the DTC combined with space vector modulation (SVM-DTC) methods are effective to perfect the DTC performance [5–8]. However multilevel method may increase the complexity of the system on the hardware and the control design, and some SVM-DTC methods may weaken the control simplicity and robustness. In addition the duty ratio method which is similar to SVM method to some extent is also used to attenuate the ripple of the torque [9–13]. The basic concept of duty ratio is that in every sampling time the active vector is only chosen to work a part time of the period and the rest time a zero vector is chosen. The duty ratio method uses the concept of combining vectors and it is easier to implement than the SVM method. Several kinds of schemes have been proposed according to the different optimized targets of minimizing the torque ripple to determine the duty ratio. These schemes have shown the better performance to weaken the torque ripple significantly compared with conventional DTC scheme. However they often depend on the motor parameters and need a series of complicated computations [11–13].

Fuzzy control which is also known as fuzzy logic control is a kind of intelligent control technology. The most major feature of fuzzy control is that it designs the rules based on imitating the human experience to control the system. Fuzzy control does not depend on the exact object model and it can deal with nonlinear problems. Fuzzy control has been applied to control DTC systems to handle the different problems [14–18]. In [14], the fuzzy control method is used to design the outer speed loop of DTC system to obtain the excellent dynamic and steady state performance and improve the robustness of the system when external disturbance and the parameter variations are encountered. The authors in [15] focus on implementing the fuzzy controller of the DTC on FPGA by using the VHDL language. In [16], the widths of hysteresis controllers are adjusted on-line based on fuzzy control, the torque ripple is decreased as well as the dynamic response is improved.

In this paper, the fuzzy control is applied to DTC PMSM system to decrease the ripple of torque and improve the system performance. The fuzzy controller is designed for two parts. First of all, the conventional hysteresis controllers are replaced by the fuzzy controller, and the optimal voltage vector could be selected by judging the deviation degree of the torque and flux errors. Since the actual system is controlled discretely by sampling time, the controlled torque and flux may exceed the command values even though the optimal voltage vector is selected. Then after the optimal voltage vector is obtained, the action time of the selected voltage vector is taken into account by drawing on the experience of duty ratio method. The fuzzy control is also used to determining the duty ratio. At last, the comprehensive simulation experiment is carried out to show the proposed system has the less torque ripple than the conventional DTC method, the test results verify the feasibility of the proposed scheme.

2 The Principle of PMSM DTC

To simplify the analysis, take the typical surface mounted PMSM for example. The stator flux equation of PMSM could be described by complex vector form as

$$\boldsymbol{\psi_s} = \int (\boldsymbol{u_s} - R_s \boldsymbol{i_s}) dt \tag{1}$$

where $\boldsymbol{\psi_s}$ is the stator flux vector, $\boldsymbol{u_s}$ is the stator voltage vector, R_s is the stator resistance, $\boldsymbol{i_s}$ is the stator current vector. If the stator resistance is neglected, the stator flux is mainly affected by the applied voltage vector. The change direction of the stator flux is as same as the direction of the voltage vector, thus the voltage vector could change the amplitude of the stator flux.

The electromagnetic torque expression is described as follows

$$T_e = \frac{3n_p}{2L_s} \psi_f \left| \boldsymbol{\psi_s} \right| \sin \delta \tag{2}$$

where T_e is electromagnetic torque, n_p is the number of pole pairs, L_s is the stator inductance, ψ_f is the permanent magnet flux, δ is the torque angle.

In above torque equation, the number of pole pairs, stator inductance and permanent magnet flux are regarded as the constant values. The torque is only affected by the torque angle if the amplitude of the stator flux is remained unchanged. It thus the torque could be controlled when the torque angle is changed by applying the different voltage vectors.

In DTC method, the six non-zero voltage vectors (V_1-V_6) and two zero voltage vectors (V_0, V_7) are generated by the VSI with the help of voltage space vector concept. Meanwhile the stationary $\alpha - \beta$ plan is divided into six sectors (S_1-S_6) according to the location of stator flux. All voltage vectors and sectors are presented as Fig. 1 The appropriate vector is selected to output by VSI on the basis of the signs of the torque and flux errors and the sector of the stator flux. As Fig. 1 shows, when the stator flux is located at sector $S_k (k = 1, ..., 6)$, the controlled torque will be increased if vector V_{k+1} or V_{k+2} is applied, whereas the controlled torque will be decreased if vector V_{k-1} or V_{k-2} is applied. The amplitude of stator flux will be increased if vector V_{k+1} or V_{k-1} is selected, and the amplitude of stator flux will be decreased if vector V_{k+2} or V_{k-2} is selected. In this way, the appropriate vector is selected to control the torque and stator flux every sector when the signs of hysteresis controllers are determined.

In hysteresis controllers, only the signs of torque and flux errors are considered rather than the amplitudes of their errors. It thus the current vector is changed only if the amplitudes of the torque and flux exceed the boundary of the hysteresis. And the same vector will be applied no matter the errors are large

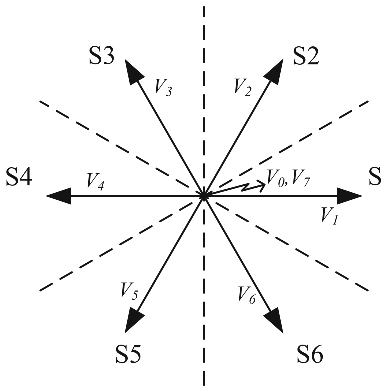


Fig. 1. Voltage vector and sector distribution

or small due to the two digital value outputs of the hysteresis controllers when the signs of errors are not changed. Moreover the control process is discrete by sampling time rather than continuous, the ripples of torque and flux are higher than the limit of the hysteresis. The conventional DTC presents the large torque and flux ripples due to these reasons.

3 The Analysis of Torque Ripple

The electromagnetic torque equation is rewritten in rotor $d-q$ frame as

$$T_e = \frac{3}{2} n_p \psi_f i_q \tag{3}$$

Since n_p and ψ_f are constant values, the variation of the torque is described as

$$\frac{dT_e}{dt} = \frac{3}{2} n_p \psi_f \frac{di_q}{dt} \tag{4}$$

For the typical surface mounted PMSM, the variation of the q-axis current is given as

$$\frac{di_q}{dt} = -\frac{R_s}{L_s} i_q - \frac{\omega_{re}(L_s i_d + \psi_f)}{L_s} + \frac{u_q}{L_s} \tag{5}$$

Where ω_{re} is rotor electrical angular velocity, u_q is the q-axis voltage, i_d and i_q are d-axis and q-axis current respectively. Then the following expression is obtained

$$\frac{dT_e}{dt} = -\frac{3}{2} n_p \psi_f \frac{R_s}{L_s} i_q - \frac{3}{2} n_p \psi_f \frac{\omega_{re}(L_s i_d + \psi_f)}{L_s} + \frac{3}{2} n_p \psi_f \frac{u_q}{L_s} \tag{6}$$

It can be seen that the change of torque is consisted of three parts from the above expressions. Since the motor is only controlled by the voltage vector fed by VSI, the voltage vector will directly affect the torque. When the zero vector is selected, the change of torque is different from the ones when active vector is selected. In the real discrete control application, using one active vector in whole period could make the torque change bigger and fail to fulfill the desired requirement of the system. If the combination of the active vector and zero vector is used in every sampling period, the ripple of torque could be decreased significantly.

4 Fuzzy Control of PMSM DTC

In this part, the fuzzy controllers are designed for two parts. As discussed above, the fuzzy controller will be designed firstly to replace the hysteresis controllers which could not distinguish the amplitudes of the torque and flux errors. The errors of the torque and flux could be differentiated in fuzzy method, so the optimal vector is selected by assessing the deviation degrees of the errors. Then after the optimal vector is obtained by fuzzy control method, using one vector during the whole period may cause the larger torque ripple in the discrete control process, the fuzzy duty ratio control is designed.

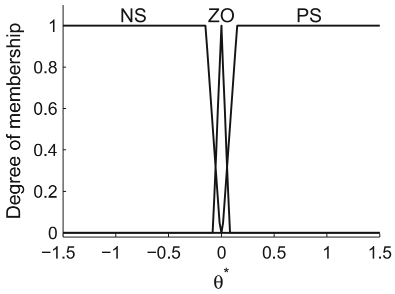
4.1 Fuzzy Controller Designer of Vector Selection

As is well known, the fuzzy controller generally consists of four parts: fuzzification, knowledge base, fuzzy inference, defuzzification. The torque error E_T, flux error E_ψ and stator flux angle θ_s are chosen as the fuzzy input variables of controller, and the controller output variable V is the voltage vector generated by the VSI. The flux angle in the whole plan could be mapped to the range of $(-\pi/6, \pi/6)$ by the following expression since the symmetry of the sector.

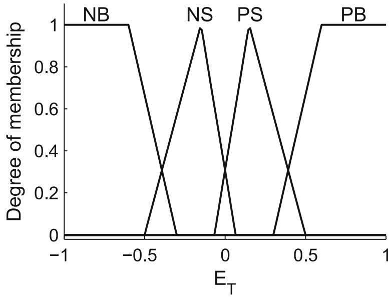
$$\theta_s^* = \theta_s - \frac{\pi}{3}\left\lceil \frac{\theta_s - \pi/6}{\pi/3} \right\rceil \tag{7}$$

Where θ_s is the actual flux angle, and θ_s^* is the flux angle input of the fuzzy controller after mapping. The operator $\lceil\ \rceil$ is on the behalf of rounding to the nearest bigger integer. The design process is simpler as the decreased fuzzy rules through this step. The fuzzy set of the flux angle is defined as NS, ZO, PS in view of controlling the vector accurately, and the membership function is shown as Fig. 2a. The fuzzy sets of the torque and flux errors are both included four components as NB, NS, PS, PB due to the reason that it could distinguish the variation accurately, the membership functions are shown as Fig. 2b and Fig. 2c. The above elements NB, NS, ZO, PS, PB represent negative big, negative small, zero, positive small, positive big respectively. The fuzzy set of the output variable is the singleton set in order to obtain the voltage vector, as shown in Fig. 2d. The fuzzy rules which are acquired by analysis and trial are designed as the Table 1.

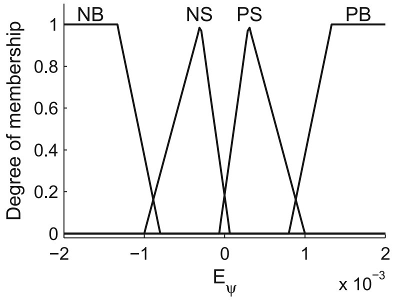
The fuzzy inference operator is based on Mamdani method by using above fuzzy rules, and the maximum criterion is adopted to obtain the exact voltage vector. Finally, the output voltage vector of the controller needs to be converted to the whole plan due to the above mapping process.



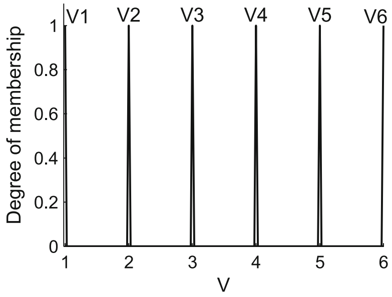
(a) Flux angle θ_s



(b) Torque error E_T



(c) Flux error E_ψ



(d) Vector V

Fig. 2. The membership function of three input variables and the output variable

4.2 Fuzzy Controller Designer of Duty Ratio

The fuzzy controller of duty ratio is designed as single input single output structure. Since the torque variation is affected by duty ratio, the input variable of the controller is torque error which is represented as ΔT here. The controller output variable is the duty ratio represented as Δd. The fuzzy sets of them both have five language sets as NB, NS, ZO, PS, PB. The membership function is presented as Fig. 3. The fuzzy rules are designed as the following IF-THEN expressions according to the analysis and trial.

Table 1. Fuzzy control rules

θ_s^*		NS				ZO				PS			
		E_ψ				E_ψ				E_ψ			
		NB	NS	PS	PB	NB	NS	PS	PB	NB	NS	PS	PB
E_T	NB	V_4	V_5	V_5	V_6	V_5	V_5	V_6	V_6	V_5	V_5	V_6	V_6
	NS	V_4	V_5	V_6	V_6	V_5	V_5	V_6	V_6	V_4	V_5	V_1	V_1
	PS	V_3	V_2	V_1	V_1	V_3	V_3	V_2	V_2	V_4	V_3	V_2	V_2
	PB	V_3	V_2	V_2	V_1	V_3	V_3	V_2	V_2	V_3	V_3	V_2	V_2

Rule1: If ΔT is NB, then Δd is NB;
Rule2: If ΔT is NS, then Δd is NS;
Rule3: If ΔT is ZO, then Δd is ZO;
Rule4: If ΔT is PS, then Δd is PS;
Rule5: If ΔT is PB, then Δd is PB;

The Mamdani method is applied in the fuzzy inference process by using above fuzzy rules and the exact duty ratio is obtained by the gravity method in defuzzification process. Based on above two fuzzy controllers, the active vector and the zero vector are alternatively output by VSI to control the PMSM.

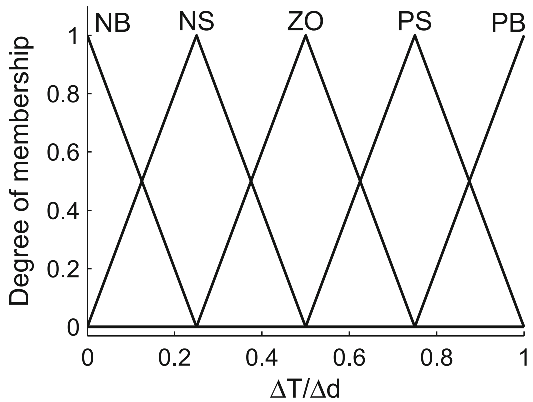


Fig. 3. The membership function of the variables ΔT and Δd

5 Simulation Results

To verify the validity of the proposed fuzzy DTC control method, the comprehensive simulation tests are carried out in the Matlab/Simulink environment. The block diagram of simulation is shown as Fig. 4, where two fuzzy controllers are used to choose the appropriate vector and determine the duty ratio respectively. The hysteresis controllers and lookup table in the conventional DTC are eliminated, and the action times of the active vector and zero vector are allocated through the duty ratio. The parameters of the PMSM for simulation are shown in Table 2. The fixed sample time of the simulation is set as 50 μs for the two control methods.

The various responses of the conventional DTC method and the proposed fuzzy DTC method, included the speed, torque, stator flux and the current performances, are shown and compared as Figs. 5, 6, 7 and 8, respectively. The motor starts up with rated load of 4 Nm, and the load decreases to 50 % rated value at 0.2 s. The simulation tests of the two methods are both under the same situation. The speed responses of the two methods are compared as Fig. 5, the interesting

Table 2. PMSM parameters

Parameter	Value	Unit
Mechanical inertia(J)	0.000828	kg·m^2
Magnet flux linkage(ψ_f)	0.09428	Wb
Stator resistance(R_s)	0.779	Ω
Stator inductance(L_s)	0.003026	H
Number of pole pairs(n_p)	4	-
Rated torque(T_N)	4	N·m
Rated voltage(U_N)	220	V
Rated speed(n_N)	3000	r/min

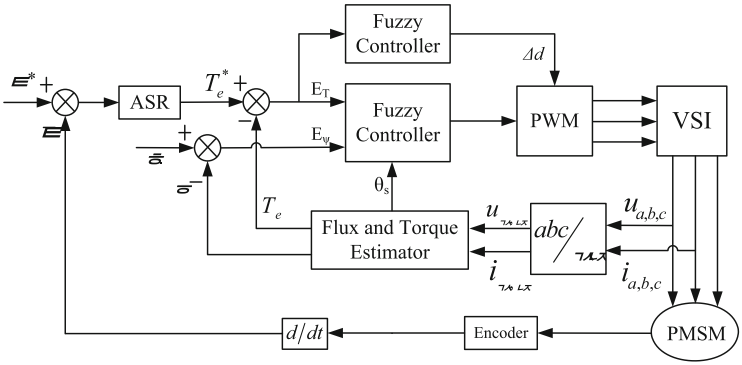
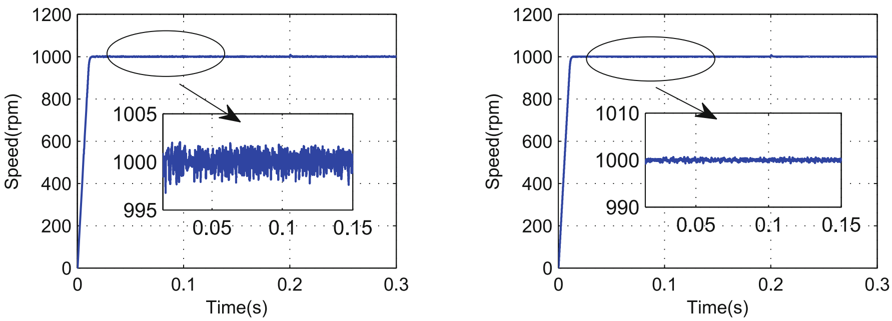


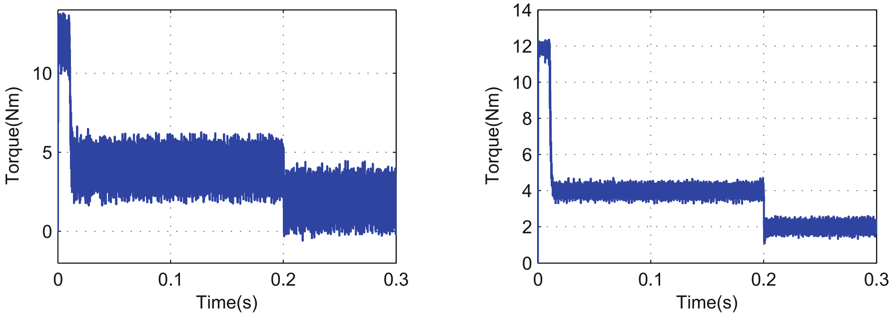
Fig. 4. Control schematic diagram of the proposed fuzzy PMSM DTC system



(a) Conventional DTC (b) Fuzzy DTC

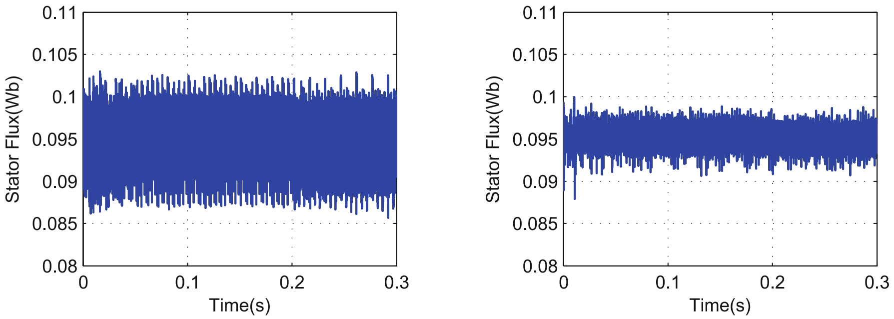
Fig. 5. The simulation results of the speed response

details of the steady state response are partial enlarged clearly. The proposed fuzzy DTC method also show the excellent dynamic response as the conventional one, and its steady state speed ripple is smaller compared to the conventional



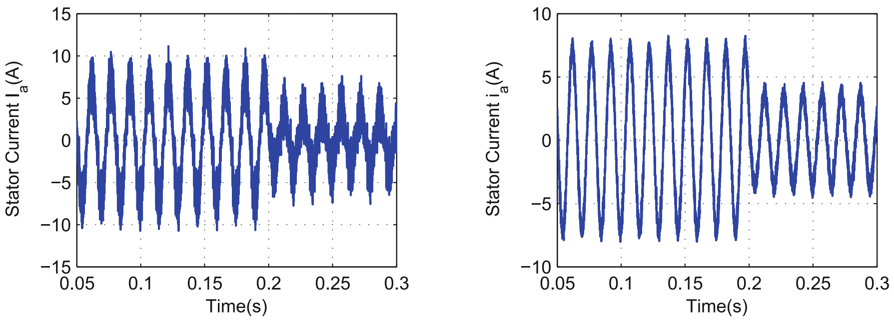
(a) Conventional DTC (b) Fuzzy DTC

Fig. 6. The simulation results of the torque response



(a) Conventional DTC (b) Fuzzy DTC

Fig. 7. The simulation results of the flux response



(a) Conventional DTC (b) Fuzzy DTC

Fig. 8. The simulation results of the stator current response

one. Figure 6 shows the torque performances of two methods, it can be seen that the conventional DTC method shows the large torque ripple. The torque ripple of approximate 4 Nm in the conventional DTC is decreased significantly to about 1 Nm in the proposed method, it means that the torque ripple of the proposed DTC has been reduced by 75 %. In addition, the torque dynamic performance of the proposed method is as quick as the conventional one. The stator flux responses of the two methods are compared as Fig. 7, the flux ripple of the conventional DTC is about 0.015 Wb. At the same time, the proposed method, where the flux ripple has a 50 % reduction compared with the convention one, presents less ripple. Figure 8 shows the stator current performances of the two methods, it can be seen that the stator current presents smooth and smaller fluctuation, which verifies the superiority of the proposed method.

6 Conclusion

This paper has presented the fuzzy PMSM DTC scheme due to the disadvantages of the conventional DTC such as large torque and flux ripples. The fuzzy method is used to select the voltage vector conveniently and then determine the duty ratio. The design processes of the fuzzy controllers are discussed in detail. The simulation is carried out to examine the performance of the proposed fuzzy DTC method, tests results show the proposed method could decrease the ripples of the torque and flux without deteriorating dynamic response of the torque, which verifies the validity of the proposed method.

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