Fuzzy Direct Torque Control of Six Phase Induction Machine Based on Torque Prediction

Shan Li and Dan-ping Qi

Department of Electronics Information and Automation,
Chongqing Institute of Technology, Chongqing 400050, China
lishan@cqit.edu.cn, qidanping@cqit.edu.cn

Abstract. In the paper, direct torque control (DTC) and fuzzy control are combined. The scheme of fuzzy DTC of multiphase based on torque prediction was presented. The errors of stator flux linkage and magnetic torque were fuzzified by using fuzzy controller. Expected voltage vector and flux linkage angle were determined by using fuzzy decision. The value of the expected voltage vector was confirmed through torque prediction. Simulation results verified the performance of the proposed method.

Keywords: Direct torque control, fuzzy control, torque prediction, multiphase induction machine.

1 Introduction

Multiphase induction machine has many advantages such as higher reliability 、 lower torque pulsation. All of these depend on its applications. But multiphase induction machine has many variable parameters, which needs simple control algorithm when the motor needed performances are satisfied.

First concept of DTC was developed in 1986 by M. Depenbrock [1]. This method has not only faster torque response 、 insensitivity of parameter but also lower switching frequency、robust against machine parameter variations. Because multiphase induction machine and three phase induction machine have the same theoretical basis. The control strategy of three phase induction machine can be used in multiphase induction machine.

The algorithm of conventional DTC was used in five phase induction machine [2]. In [3][4], the same algorithm was used in dual three-phase induction machine and simulation results were obtained. They were simple extension of three phase system and didn't consider the feature of multiphase induction machine and the rejection of stator harmonics current. Inverter voltage vector were selected by looking up table.

However, there are many defects such as torque、flux linkage and current ripples、the on-off period of inverter indeterminacy [5][6]. Otherwise, the performances of DTC depend on torque observer and magnetic flux observer. The numbers of space voltage vector are increased in geometric series when the phases

B. Cao, T.-F. Li, C.-Y. Zhang (Eds.): Fuzzy Info. and Eng., Volume 2, AISC 62, pp. 1209–1218.
springerlink.com

of multiphase induction machine are increased. It is obvious that this scheme can't be extended in variable frequency speed adjustable system of multiphase.

The outputs of conventional fuzzy DTC are almost discrete space voltage vector whose phase and angle can't be changed following the errors change of flux linkage and torque. The features of space voltage vector modulation are not sufficiently used. The predictive DTC based on mathematic model [7] can efficiently decrease the torque ripple and increase steady-state behavior. But its computations are complex and the computation courses use many parameters of electric machine. In this case, the parameters of electric machine have important influence on induction machine.

The six-phase induction motor is a representative scheme. Usually it divides 60° electrical angle belt winding of three-phase motor to two parts equally, so it has two sets stator winding which has 30° electrical angle and has isolated midpoint, shown in Fig. 1, the rotor adopts standard squirrel-cage structure the same as three-phase induction motor.

In this paper, a scheme of fuzzy direct torque control of six phase induction machine based on torque prediction is presented, which has high robust and decreases torque ripple. The performance of this system is obviously improved.

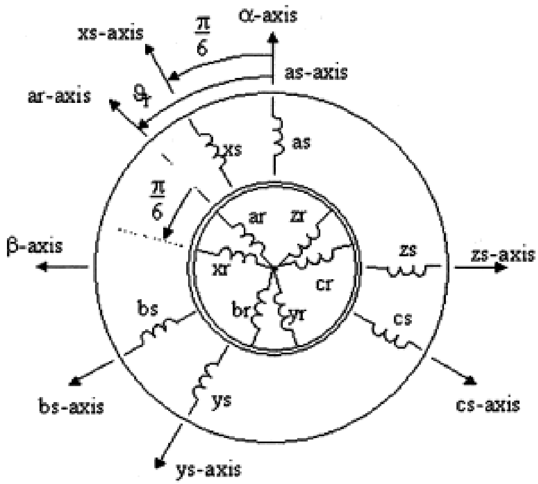


Fig. 1. The physical model of six-phase induction machine

2 6PIM Theoretical Analysis and Model

The six-phase induction machine is a six-dimensional system. The voltage equations in the original phase coordinates can be described as in the literatures [8][9].

$$\begin{aligned}[V_s] &= [R_s]\cdot[i_s] + p[\psi_s] \\ &= [R_s]\cdot[i_s] + p([L_{ss}]\cdot[i_s] + [L_{sr}]\cdot[i_r])\end{aligned} \tag{1}$$

$$\begin{aligned}[0] &= [R_r]\cdot[i_r] + p[\psi_r] \\ &= [R_r]\cdot[i_r] + p([L_{rr}]\cdot[i_r] + [L_{rs}]\cdot[i_s])\end{aligned} \tag{2}$$

where, L_{ss} , L_{rr} is stator and rotor inductance matrix respectively, L_{sr} , L_{rs} is stator and rotor mutual inductance matrix respectively, $p = d/dt$.

According to the Vector Space Decomposition, the original six dimensional system of the machine can be decomposed into three orthogonal sub-spaces (α, β), (μ_1, μ_2) and (z_1, z_2) introducing a 6×6 transformation matrix [T_6] [9] having the following properties:

$$[T_6] = \frac{1}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} & 0 \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} & \frac{1}{2} & \frac{1}{2} & -1 \\ 1 & -\frac{1}{2} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} & 0 \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} & \frac{1}{2} & \frac{1}{2} & -1 \\ 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 \end{bmatrix} \tag{3}$$

1) The fundamental components of the machine variables and the harmonics of order $k = 12n \pm 1$, ($n = 1,2,3,\cdots$) are mapped in the (α, β) subspace. These components contribute to the air-gap flux.

2) The harmonics of order $k = 6n \pm 1$, ($n = 1,3,5,\cdots$) are transformed in the (μ_1, μ_2) subspace. These harmonics do not contribute to the air-gap flux, will increase current loss of stator.

3) The zero-sequence components are mapped in the (z_1, z_2) subspace.

When the motor has two sets stator windings with isolated neutral points, it can be demonstrated that no current components flow in the subspace (z_1, z_2). So the machine model only need decompose to (α, β) and (μ_1, μ_2) sub-space.

In the (α, β) subspace, the state equations of six-phase induction motor are:

$$\begin{cases} \overline{v}_s = R_s \cdot \overline{i}_s + p \cdot \overline{\psi}_s \\ 0 = R_r \cdot \overline{i}_r + p \cdot \overline{\psi}_r - j\omega_r \cdot \overline{\psi}_r \end{cases} \tag{4}$$

$$\begin{cases} \overline{\psi}_s = L_s \cdot \overline{i}_s + L_m \cdot \overline{i}_r \\ \overline{\psi}_r = L_r \cdot \overline{i}_r + L_m \cdot \overline{i}_s \end{cases} \tag{5}$$

$$\begin{cases} \overline{v}_s = v_{s\alpha} + jv_{s\beta} & \overline{\psi}_s = \psi_{s\alpha} + j\psi_{s\beta} \\ \overline{i}_s = i_{s\alpha} + ji_{s\beta} & \\ \overline{i}_r = i_{r\alpha} + ji_{r\beta} & \overline{\psi}_r = \psi_{r\alpha} + j\psi_{r\beta} \end{cases} \tag{6}$$

where ψ_s and ψ_r are stator and rotor flux respectively, L_s and L_r are stator and rotor inductance respectively, ω_r is rotor speed and $p = d/dt$.

Electromagnetic torque is

$$T_e = 3\cdot\frac{P}{2}\cdot\left(\psi_{s\alpha}\cdot i_{s\beta} - \psi_{s\beta}\cdot i_{s\alpha}\right) = 3\cdot\frac{P}{2}\cdot(\overline{\psi}_s \otimes \bar{i}_s) \tag{7}$$

where, P is the number of poles.

3 Flux and Torque Control

The voltage space vector of multiphase is :

$$\left\{ V_s = \frac{1}{m}U_d\begin{bmatrix} 1 & e^{j2\pi/m} & e^{j4\pi/m} & \cdots & e^{j2(m-1)\pi/m}\end{bmatrix}\times S_k \right. \tag{8}$$

where m is the phase of multiphase motor, U_d is DC busbar voltage of inverter, V_s is space voltage vector of stator, S_k is switching function of inverter.

The relationship between stator voltage vector and flux linkage vector is:

$$\frac{d}{dt}\boldsymbol{\psi}_s = \mathbf{u}_s - r_s\mathbf{i}_s \approx \mathbf{u}_s \tag{9}$$

The (9) can be written:

$$\Delta\psi_s = u_s\cdot\Delta t \tag{10}$$

where Δt is the operation time of u_s.

When L_σ is very small in the stationary state, the variable value of torque in adjacent on-off state is:

$$\Delta T_e = \frac{P\cdot\psi_s \otimes u_s}{L_\sigma}\Delta t \tag{11}$$

where $L_\sigma = (L_s L_r - L_m^2)/L_m$.

From (10), and (11), the angle between voltage vector and flux linkage depend on the alternation of torque and flux linkage when the amplitude of nonzero voltage vector is determined. Torque will increase when voltage vector of stator flux linkage is in advance. As for flux linkage, the angle between voltage vector and flux linkage will decrease when the errors of flux linkage are increasing. The inputs of the proposed Fuzzy DTC controller are flux linkage error E_φ and torque error E_T. The outputs are the angle θ_g between voltage vector and flux linkage.

4 Fuzzy Controller

The flux linkage error E_φ and torque error E_T all choose five language variables. They are PL、PS、ZO、 NS and NL. The membership functions are shown in Fig.2.

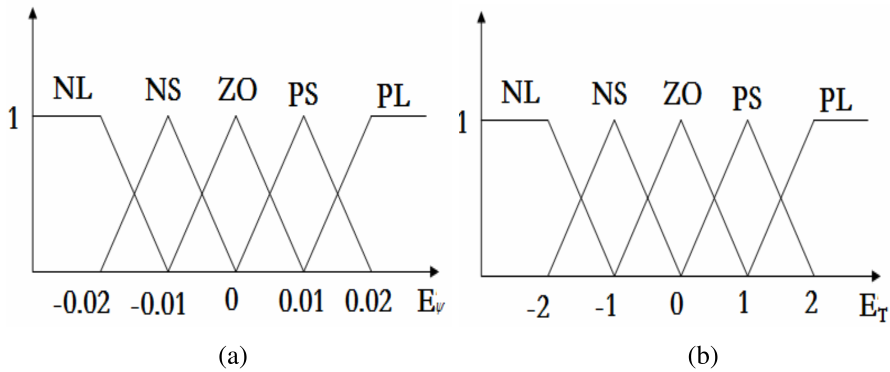


Fig. 2. The membership function of the errors of flux linkage and torque (a) flux linkage (b) torque

The fuzzy rules are depended on the influence of torque and flux linkage which are affected by voltage vector. When torque and flux linkage increase or decrease, the selected voltage vector is not the original one and exists in given areas. These areas are shown in Fig.3. The fuzzy rules are deduced in Table 1.

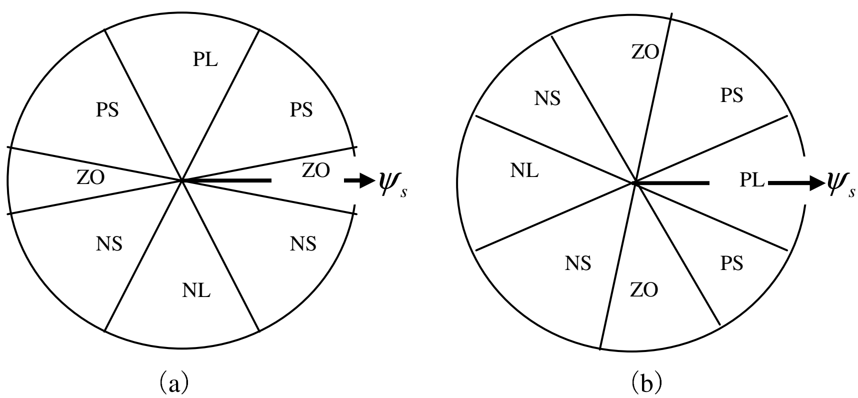


Fig.3. Influence of voltage vector on flux linkage and torque (a) torque (b) flux linkage

Table 1. Fuzzy rule table

E_ψ \ E_T	NL	NS	ZO	PS	PL
NL	$-\frac{5\pi}{6}$	$-\frac{11\pi}{12}$	π	$\frac{11\pi}{12}$	$\frac{5\pi}{6}$
NS	$-\frac{2\pi}{3}$	$-\frac{3\pi}{4}$	$-\frac{11\pi}{12}$	$\frac{3\pi}{4}$	$\frac{2\pi}{3}$
ZO	$-\frac{\pi}{2}$	$-\frac{2\pi}{3}$	0	$\frac{2\pi}{3}$	$\frac{\pi}{2}$
PS	$-\frac{\pi}{3}$	$-\frac{\pi}{4}$	$-\frac{\pi}{12}$	$\frac{\pi}{4}$	$\frac{\pi}{3}$
PL	$-\frac{\pi}{6}$	$-\frac{\pi}{12}$	0	$\frac{\pi}{12}$	$\frac{\pi}{6}$

Defuzzification uses the weighted average method:

$$\theta_g = \frac{\sum_{i=1}^{N} W_i C_i}{\sum_{i=1}^{N} W_i} \tag{12}$$

W_i is operational intensity of the rule of i and C_i is the controlled output of the rule of i. In (12), the angle between expected voltage vector and flux linkage is determined. In $\alpha-\beta$ subspace, the angle of voltage vector needs to add θ_Ψ. As in shown in Fig.4.

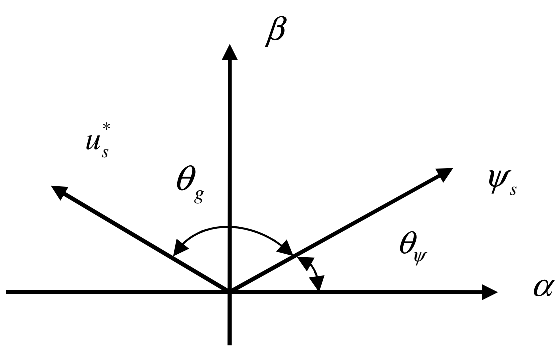


Fig. 4. The angle between desired voltage vector and flux linkage

In $\alpha-\beta$ subspace, the expression of expected voltage vector is:

$$\begin{aligned} u_{s\alpha}^{*} &= V\cos(\theta_g+\theta_\psi) \\ u_{s\beta}^{*} &= V\sin(\theta_g+\theta_\psi) \end{aligned} \tag{13}$$

The angle of voltage vector is determined through fuzzy DTC. Torque changing depends on the amplitude of voltage vector. Assume that the difference between given torque and feedback torque is ΔT_e and the predictive difference of given torque is ΔT_e^*. The amplitude of voltage vector is confirmed by (14):

$$V=\frac{|\Delta T_e|}{\Delta T_e^*\sin\theta_g}\frac{U_d}{\sqrt{3}} \qquad (V_{\max}=\frac{U_d}{\sqrt{3}}) \tag{14}$$

The reference voltage vector of the inverter output is the certained voltage vector. After combining by SVPWM based on zero order balance vector, the voltage vector can suppress harmonics current. The block diagram of control system can be seen in Fig.5.

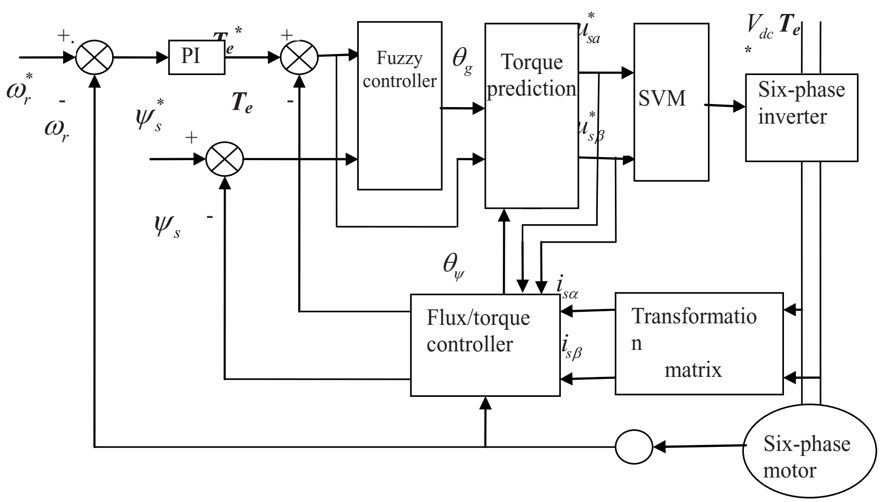


Fig. 5. Block diagram of fuzzy DTC based on torque prediction

5 Experiment Results

The simulation model parameters [10] of six phase induction machine are listed in Table2:

Given speed are $10r/\min$ and $800r/\min$. Firstly starting with no-load, then in 0.5s, the load $40N\cdot m$ is added. Zero order balance vector are combined by long vector.

Table 2. The parameters of six-phase induction machine

Six phase Induction machine	Value
Rated power	5.5KW
Rated phase voltage	86V
Frequency	50Hz
Number of pole pairs	3
Total shaft inertia	$0.116\,kg \cdot m$
Stator resistance	$0.22\,\Omega$
Rotor resistance	$0.47\,\Omega$
Stator and rotor inductance	$0.0395\,H$
Mutual inductance	$0.0364\,H$
Controlled period	$200\,\mu s$

As is shown in Fig.6, Fig.7 and Fig.8, compared with conditional DTC, the proposed method dramatically decrease the amplitude of flux linkage and torque impulse. The flux linkage pulse is $\pm 0.01wb$ and torque pulse is $\pm 1N \cdot m$.

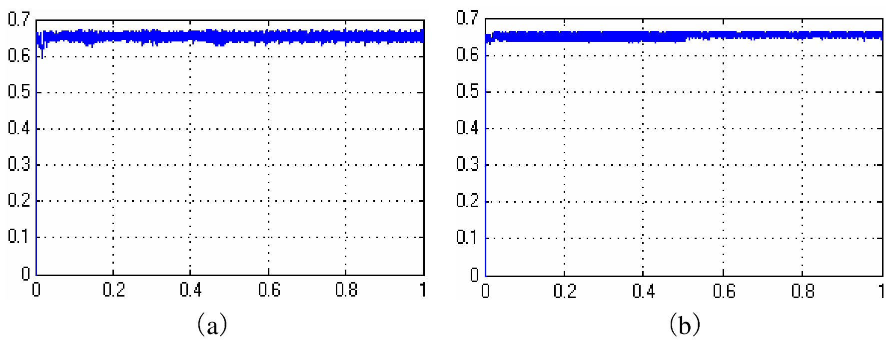


Fig. 6. Simulation waves of stator flux linkage (a) conventional DTC (b)Fuzzy DTC

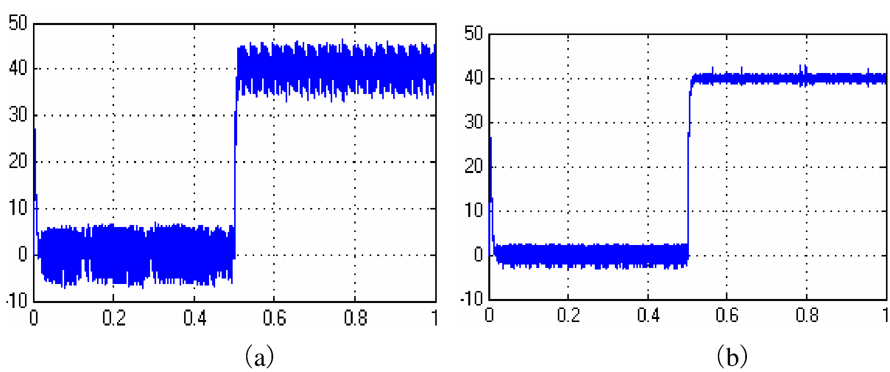
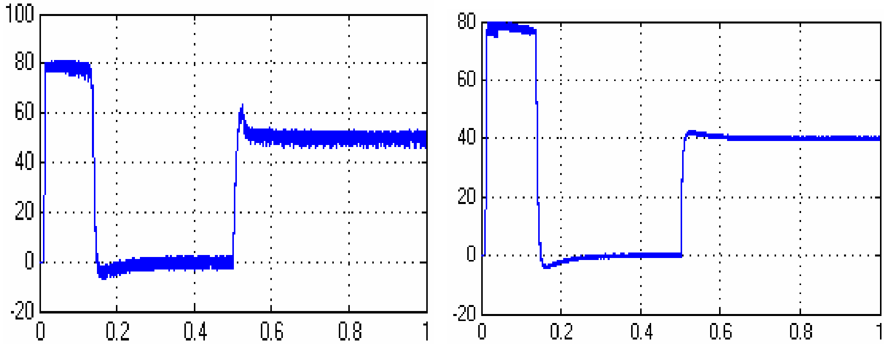


Fig. 7. Simulation waves of low speed torque (a) conventional DTC (b)Fuzzy DTC



(a) (b)

Fig. 8. Simulation waves of high speed torque (a) conventional DTC (b) Fuzzy DTC

6 Conclusions

In this paper, a novel fuzzy DTC of multiphase induction machine based on torque prediction has been proposed to improve the dynamic performance. The parameters of motor aren't almost used in calculated course. The merits of conventional DTC are kept and inherited in the proposed scheme. The simulation results verify the proposed scheme.

Acknowledgements

The work was supported by the Natural Science Foundation of Chongqing (No. 8662).

References

1. Depenbrock, M.: Direkte sslbstregelung (DSR) fuhrhochdy-nanische Drehfeldantri-ebe mit Stromrichterspeisung ETZ Archiv, bd 7(7), 211–218 (1985)
2. Toliyat, H.A.: A Novel Direct Torque Control (DTC) Method for Five-Phase Induction Machines. In: IEEE APEC, pp. 162–168 (2000)
3. Chen, L., Fang, K.L.: A novel direct torque control for dual-three-phase induction motor. In: Proceedings of the Second International Conference on Machine Learning and Cybernetics, Xi'an, pp. 876–881 (2003)
4. Chen, L., Zhu, H., Fang, K., Xiong, Y.: Fuzzy direct torque control for dual-three-phase induction motor. IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences E86-A(6), 1458–1465 (2003)
5. Habetler, T.G., Profumo, F., Pastorelli, M., et al.: Direct torque control of induction motor using space vector modulation. IEEE Trans. Ind. Application 28(5), 1045–1053 (1992)

6. Li, Y.D.: Direct torque control of induction motors for low speed drives considering discrete effects of control and dead-time of inverters. In: Int. Conf. Rec. on Industry Applications, vol. 1, pp. 781–788 (1997)
7. Yadong, L., Xuezhi, W., Lipei, H.: SVPWM method for performance improvement of direct torque control. Journal of Tsinghua University 44(7), 869–872 (2004)
8. Bojoi, R., Lazzari, M., Profumo, F., Tenconi, A.: Digital field oriented control for dual three-phase induction motor drives. IEEE Transactions on Industry Applications 39(3), 752–760 (2003)
9. Zhao, Y., Lipo, T.A.: Space vector PWM control of dual three-phase induction machine using vector space decomposition. IEEE Trans. Ind. Appl. 31(5), 1100–1108 (1995)
10. Hou, L., Su, Y.: Research on Winding Structure and Simulation for Six-phase Induction Machines. S&M Electric Machines 31(2), 5–9 (2004)