Direct Torque Control for Dual Three Phase Induction Machine Using Fuzzy Space Voltage Modulation

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Abstract. Conventional hysteresis control schemes for direct torque control (DTC) of dual-three-phase induction machine (DTPIM) usually result highly distorted current waveforms. In this paper, fuzzy space voltage modulation technique is presented for DTPIM. Using two fuzzy controllers, amplitude and space angle of desired stator voltage vector, are obtained dynamically. Combined with unified pulse width modulation method, direct torque control is applied to DTPIM. Simulation results show that fast dynamic responses are achieved. The ripple of torque and the harmonics of stator current in steady state can be reduced remarkably compared with conventional DTC method.

Keywords: Fuzzy Control, Direct Torque Control, Space Voltage Modulation, Dual-Three-Phase Induction Machine.

1 Introduction

The main advantage of multi-phase drives is the possibility to divide the controlled power on more inverter legs, and reduce the current stress of each switch, compared with a three-phase converter. For this reason, multi-phase drives are convenient in high-power and/or high-current applications, such as ship propulsion, aerospace applications, and electric/hybrid vehicles, etc. [1]. A very interesting and discussed multi-phase solution is the dual three-phase induction machine having two sets of three-phase windings spatially shifted by 30 electrical degrees with isolated neutral points.

Direct torque control has become one of the most popular methods of control for three-phase induction motor drives. Common disadvantages of conventional DTC are high torque ripple in steady state. Several techniques have been developed to improve the torque performance. One method is to use Pulse-Width Modulation based DTC (PWM-DTC) techniques to obtain a constant switching frequency of the inverter. The reference voltages for the PWM modulator can be obtained by methods like predictive algorithms [2-5]. Coming to the DTC for dual-three phase drives, the literature reports only a few references [6-7]. Hysteresis Control based DTC (HC-DTC) techniques are applied to DTPIM. The simulation and experimental results show fast dynamical performances of torque and flux are reached. But as shown in [7], HC-DTC schemes usually result highly distorted current waveforms. To combine PWM with DTC, the main problem is how to obtain the required space voltage

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vector. In Ref. [7], each cycle period, the required voltage space vector is synthesized using PWM technique. The performance of DTPIM is significantly improved and switching frequency is maintained constant. However, it requires calculating several complicate equations online to get expected voltage vector, and it depends on more machine parameters. Fuzzy control does not need the accurate mathematic model of the process to be controlled, and uses the experience of people's knowledge to form its control rules. In this paper, fuzzy logic technique and PWM are used in DTC of DTPIM. According to the torque error and stator flux error, required space voltage vector, including its amplitude and space position is predicted on fuzzy controllers. Using unified PWM [8], DTC for DPTIM is realized. Fast dynamic responses of torque and flux are achieved. The harmonics of current waveform is reduced. The simulation results are shown.

2 Direct Torque Control Principles

In stationary reference frame, space voltage vectors of both stator and rotor of the DTPIM are represented as follows:

$$\vec{u}_s = r_s \vec{i}_s + \frac{d\vec{\psi}_s}{dt} \tag{1}$$

$$\vec{u}_r = r_r \vec{i}_r + \frac{d\vec{\psi}_r}{dt} - j\omega\vec{\psi}_r \tag{2}$$

Where r_s and r_r are stator and rotor resistances, $\vec{u}_s$ and $\vec{u}_r$ are stator and rotor space voltage vectors, $\vec{\psi}_s$ and $\vec{\psi}_r$ are stator and rotor flux respectively. ω is the angular speed of the rotor.

The torque could be expressed in term of stator flux, rotor flux and the angle γ between stator flux and rotor flux.

$$T_e = c\,\psi_s \psi_r \sin\gamma \tag{3}$$

In formula (3), c is a constant [2]. If for simplicity, it is assumed the stator voltage drop r_s is small and neglected, then the stator flux variation can be expressed as:

$$\Delta\vec{\psi}_s \approx \vec{u}_s \cdot \Delta t \tag{4}$$

In general, rotor flux changes much more slowly than that of the stator. If sampling period is short enough, and the magnitude of stator flux is assumed to be constant, the torque can be rapidly changed by turning angle γ in the required direction. The angle γ can be easily changed by the appropriate space voltage vector. As shown in formula (4), the stator flux variation is nearly proportional to voltage vector, as the sampling period Δt is constant. Stator flux space vector will move fast and angle γ increase, if non-zero switching vectors are applied.

3 Fuzzy Logic Controller for Desired Voltage Vector

The goal of DTC of DTPIM is to maintain the stator flux error and torque error within the limits of flux and torque hysteresis bands by proper selection of the stator space

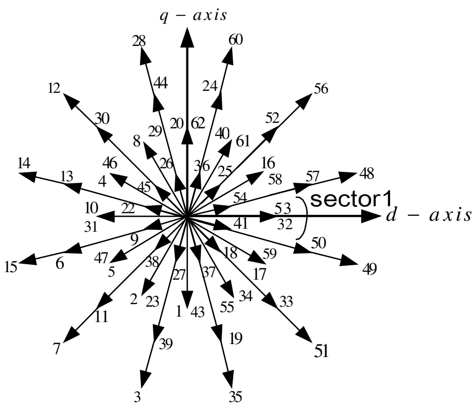


Fig. 1. Inverter voltage vectors projected on d-q subspace

voltage vectors during a sampling period. Differing from three-phase system, there are $2^6 = 64$ space voltage vectors for dual-three phase system. The vectors are located on the boundary of four 12-side polygons. The ratio of amplitudes of the voltage vectors is 1:1.932:2.732:3.732 from the smallest one to the largest one respectively. There are different ways to select space voltage vector in DTC of DTPIM, which is benefit for control torque and flux more preciously than that in three-phase machine drive.

As mentioned above, space angle θ^* and amplitude of voltage reference vector influences the variation of torque, flux, and current. Voltage vectors are nonlinear to flux or flux. In this paper, Fuzzy logic method is introduced to obtain voltage reference vector. To simplify the problem, both amplitude of vector and deflection angle are determinate by fuzzy controllers respectively. The influence of space angle and amplitude of voltage reference vector on torque and flux is considered in each

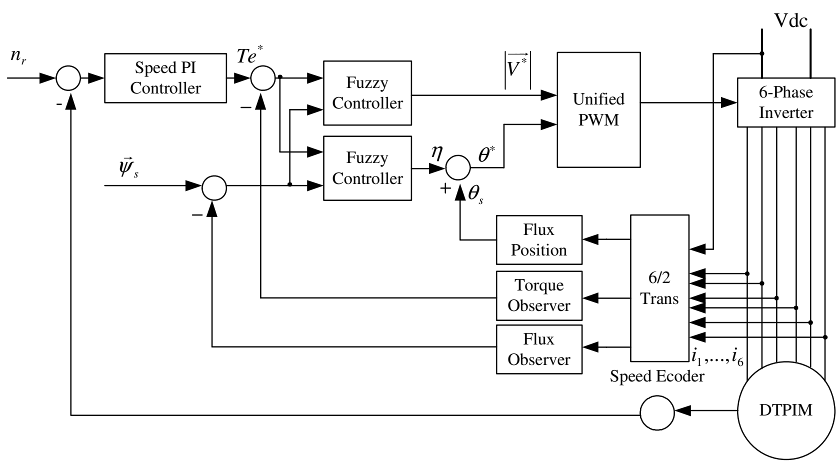


Fig. 2. Block diagram of fuzzy control for DTPIM

fuzzy controller. Unified pulse modulation method is used to form required voltage vector. As in Fig. 1, when the voltage reference vector $\vec{V}^*$ is located in sector 1, it can be easily synthesized by six adjacent effective vectors ($\vec{V}_{48}, \vec{V}_{49}, \vec{V}_{57}, \vec{V}_{50}, \vec{V}_{54}, \vec{V}_{41}$) and two zero vectors on the basis of unified pulse width modulation. Because there are three kinds of amplitude vectors are applied to DTPIM in a sampling period, ripples of torque and flux are reduced. The harmonics of stator current is also obviously depressed [8]. The block diagram of DTC for DTPIM is shown in Fig. 2. The details are as follows.

3.1 Fuzzy Controller for Angle of Voltage Vector

As shown in Fig. 3, in stationary reference frame, the stator flux variation can be resolved in two perpendicular components $\Delta\vec{\psi}_{sf}$ and $\Delta\vec{\psi}_{st}$, where $\Delta\vec{\psi}_{sf}$ affects the stator flux magnitude, and $\Delta\vec{\psi}_{st}$ influences on torque magnitude. Synthesized space voltage vector is in the direction of $\Delta\vec{\psi}_s$, and affects on both $\Delta\vec{\psi}_{sf}$ and $\Delta\vec{\psi}_{st}$. In this paper, both magnitude and angle θ^* of expected voltage reference vector $\vec{V}^*$ are the controlled variables. If magnitude of $\vec{V}^*$ is determined, the proper angle θ^* will change $\Delta\vec{\psi}_{sf}$ and $\Delta\vec{\psi}_{st}$, i.e., torque and flux in expected way. Since space position θ_s of stator flux can be calculated, the space angle of $\vec{V}^*$ is able to be determined by predicting the angle of η and practical stator flux angle θ_s, i.e.

$$\theta^* = \theta_s + \eta \tag{5}$$

In formula (5), θ_s is the angle between stator flux vector and d axis, which stand for actual position of stator flux. η is called deflection angle.

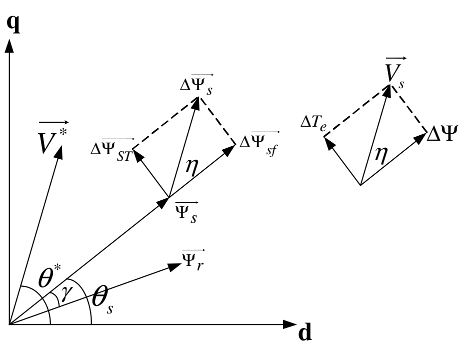
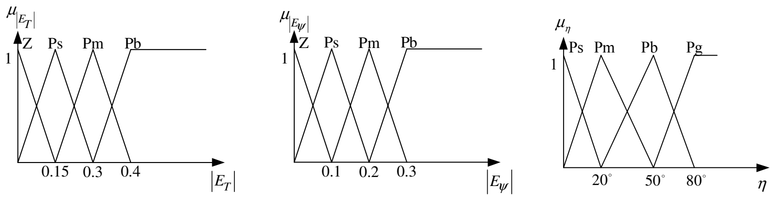


Fig. 3. Space voltage vector and stator flux vector in stationary reference frame

In the fuzzy controller, there are two input variables, which are absolute torque error $|E_T|$, stator flux error $|E_\Psi|$. One output variable is the deflection angle η of synthesized voltage vector. Torque error and flux error are normalized with the rated torque and rated flux. Each universe of discourse of the torque error, flux error, and deflection angle is divided into four fuzzy sets. Triangle membership functions have been used. All the membership functions (MF) are shown in Fig. 4 respectively.



a.: MF of torque b.: MF of stator flux c.: MF of angle η

Fig. 4. Membership functions of torque error $|E_T|$, stator flux error $|E_\psi|$, and angle η in fuzzy control of η

There are total of 16 rules as listed in table 1. Each control rule can be described using the input variables $|E_T|$, $|E_\psi|$ and control variable η. The i^{th} rule R_i can be expressed as:

$$R_i\text{: If } |E_T| \text{ is } A_i\text{ , } |E_\Psi| \text{ is } B_i \text{ then } \eta \text{ is } V_i$$

Where A_i, B_i and V_i denote the fuzzy subsets. In table 1, linguistic variable Z, Ps, Pm, Pb, or Pg represent that value of the variable is zero, positive small, positive middle, positive big, or positive great respectively. If the flux error is large, the control of flux is prior to that of torque. If flux error is small, then torque control is prior.

Table 1. Fuzzy rule base with 16 rules for angle η

η ($|E_T|$ \ $|E_\psi|$)	Z	Ps	Pm	Pb
Z	Pm	Pm	Ps	Ps
Ps	Pb	Pm	Pm	Ps
Pm	Pb	Pm	Ps	Ps
Pb	Pg	Pb	Pm	Ps

The inference method used in this paper is Mamdani's procedure based on min-max decision. The firing strength α_i for i^{th} rule is given by

$$\alpha_i = \min(\mu_{A_i}(|E_T|), \mu_{B_i}(|E_\psi|)) \tag{6}$$

$$\mu'_{V_i}(\eta) = \min(\alpha_i, \mu_{V_i}(\eta)) \tag{7}$$

Where μ_{Ai}, μ_{Bi} and μ_{Vi} are membership functions of sets A, B and V of the variables $|E_T|$, $|E_\psi|$ and η, separately. Thus, the membership function μ_V of the output η is given by

$$\mu_V(\eta) = \max_{i=1}^{16}(\mu'_{V_i}(\eta)) \tag{8}$$

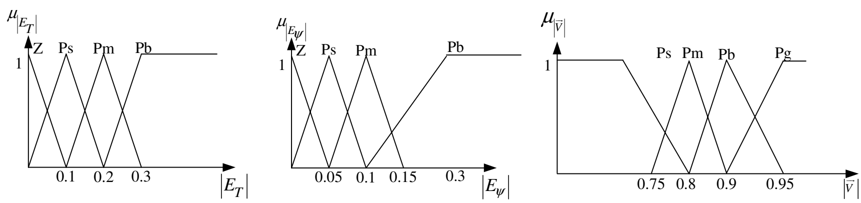
Central weight method is used for defuzzification, and output variable η is obtained. If torque error and flux error are not all the positive, in those cases, the angle η can be derived simply as follows:

If $|E_T|\geq 0$ and $|E_\psi|\leq 0$, then $\eta=\pi-\eta$;
If $|E_T|<0$ and $|E_\psi|<0$, then $\eta=\pi+\eta$;
If $|E_T|<0$ and $|E_\psi|\geq 0$, then $\eta=2\pi-\eta$

Finally, as stator flux vector angle is estimated on line, the space angle of required space voltage vector can be calculated by formula (5).

3.2 Fuzzy Controller for Amplitude of Voltage Vector

Besides the angle of voltage vector, amplitude is another factor influencing dynamic responses of torque and flux. It is similar to that in section 3.1. The torque error $|E_T|$, and stator flux error $|E_\psi|$ are selected as input variables, and one output variable is amplitude of voltage vector in fuzzy controller. The membership functions of input and output variable are in shown in Fig. 5. There are 16 rules listed in table 2.



a.: MF of torque b.: MF of stator flux c.: MF of vector's amplitude

Fig. 5. Membership functions of torque $|E_T|$, stator flux $|E_\psi|$, and amplitude of $\vec{V}^*$

Table 2. Fuzzy rule base with 16 rules for amplitude of $\vec{V}^*$

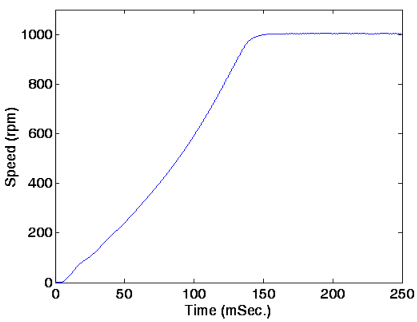
$\lvert E_T \rvert$ \ $\lvert E\psi \rvert$ \ $\lvert \vec{V} \rvert$	Z	P s	P m	P b
Z	P s	P s	P m	P b
P s	P s	P m	P b	P g
P m	P m	P b	P b	P g
P b	P b	P g	P g	P g

In table 2, if flux error or torque error is big, the output is positive great to control flux and torque. Only both flux error and torque error is small, output is positive small.

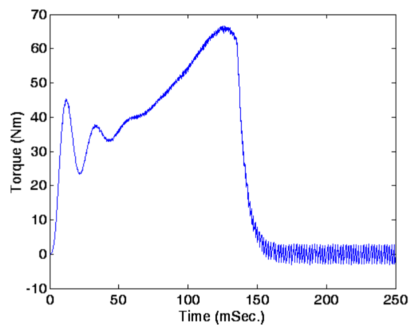
The Mamdani's inference method is the same as applied in section 3.1 to get amplitude of voltage reference vector.

4 Simulation Results

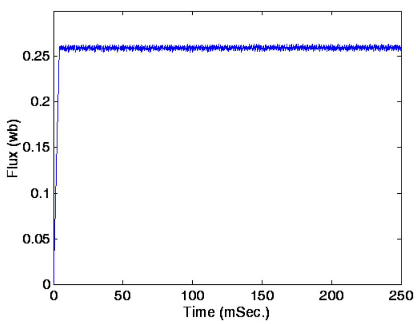
To verify the technique proposed in this paper, digital simulations based on Matlab/Simulink have been implemented. The DTPIM used for the simulations has the following parameters: $Rs = 0.22\Omega$, $Rr = 0.47\Omega$, $q = 2$, $Ls = Lr = 39.5mH$, $M = 36.4mH$. To compare with conventional DTC, both proposed DTC and conventional DTC of DTPIM are simulated. The sampling period of the system is 100 μs for conventional DTC, and 200 μs for new method. In two cases, the dynamic



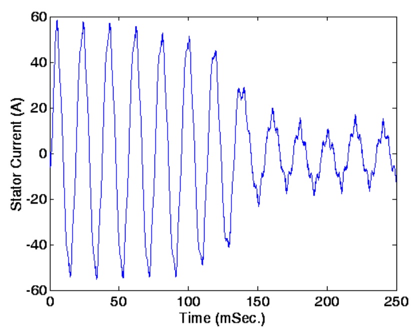
a.: Speed response



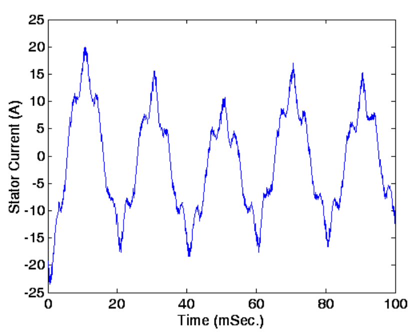
b.: Torque response



c: Flux response

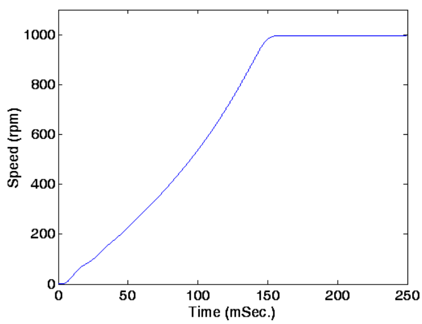


d.: Stator current response

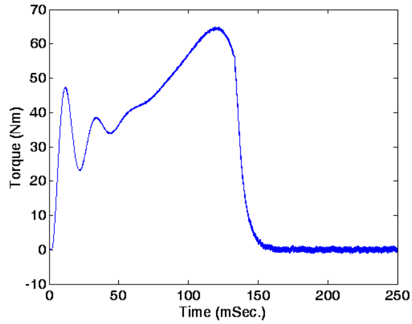


e.: Steady stator current

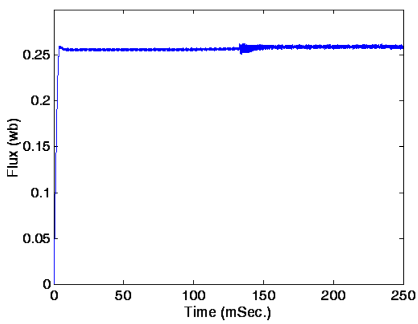
Fig. 6. Dynamic responses of DTPIM with conventional DTC method



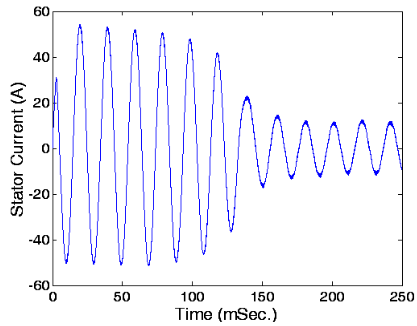
a.: Speed response



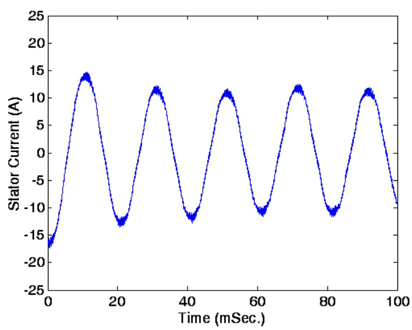
b.: Torque response



c: Flux response



d.: Stator current response



e.: Steady stator current

Fig. 7. Dynamic responses of DTPIM with proposed DTC method

responses of speed, flux, torque and stator current for the starting process are shown in Fig. 6 and Fig. 7, respectively.

The simulation results show that flux and torque responses are very rapid for two DTC methods. By novel DTC technique, though sampling period is doubled, the ripple of torque in steady state is reduced clearly from ± 3Nm to ± 1.2Nm compared with conventional DTC. Stator current harmonics is also evidently depressed.

5 Conclusions

In this paper, a direct torque control scheme using fuzzy space voltage modulation technique is presented. Using fuzzy controllers, the reference space voltage vector, including its amplitude and space angle, can be obtained dynamically. The simulation results suggest that DTC of dual-three-phase induction machine can achieve precise control of the stator flux and torque. Compared to conventional DTC, steady performance of torque is considerably improved, and harmonics of stator current is obviously depressed using presented method.

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