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Direct Torque Control of Permanent Magnet Synchronous Motor

ZHANG Tao, LIU Baolian, ZHANG Huiping

Faculty of Electronic and Electrical Engineering, Huaiyin Institute of Technology, Huaian 223003, P,R.China
E-mail: zhangtaohyit@126.com

Abstract: Direct torque control (DTC) is a method to control motor with utilizing torque and flux. But the torque and current ripples are occurred in the conventional DTC. Reason of undesired torque and current ripples is low number of voltage vectors applied to the motor controlled by the conventional DTC technique. In this paper, DTC of the PMSM has been analyzed. The stator flux and voltage space vectors are studied and the simulation of the DTC is realized. Base on the analysis of basic DTC of permanent magnet synchronous motor (PMSM), a new DTC technology based on flux error vector (FEV-DTC) is proposed to reduce torque and flux ripples in this paper. Simulation and experimental results from the conventional DTC and FEV-DTC are presented and compared. Result shows that the torque and flux ripples are decreased in new DTC.

Key Words: Direct Torque Control, Stator Space Vectors, Permanent Magnet Synchronous Motor

1 INTRODUCTION

Permanent magnet synchronous motors (PMSM) are widely used in high-performance drives such as industrial robots and machine tools for their advantages high power density, high-torque, and free maintenance and so on. In recent years, the magnetic and thermal capabilities of the PM have been considerably increased by employing the high-coercive PM materials.

Direct Torque Control (DTC) method has been first proposed for induction machines. This concept can also be applied to synchronous drives. The DTC technique is different from the conventional vector control method, where torque is controlled in the rotor reference frame via current control loops. But the conventional DTC strategy has serious ripples of the electromagnetic torque and flux linkage inevitably, so its steady state performance is poor, and the inverter has variable switching frequency. Many researchers have devoted to the improvement of the steady state performance of the basic DTC, especially for induction machine since the first industrial product has been produced in 1996[2-5]. In the late 1990s, DTC method has been proposed for permanent magnet synchronous motor[8], as well as the advantages for induction motor. However, new problems appear regarding application of zero vectors. This is especially true at a low speed, when the zero voltage vectors application on the PMSM holds the torque rather than decreases it. As well as improving dynamics, deletion of zero vectors also causes more significant torque and flux ripples in steady state, and complicates the control of the motor smoothly in the low speed range. Therefore, the way of minimizing torque ripples becomes the main research subject in a DTC of PMSM.

Space vector modulation DTC is a technique to reduce the ripples of the electromagnetic torque and flux linkage. Space vector modulation techniques have several advantages that are offering better DC bus utilization, lower torque ripples, lower total harmonic distortion in the AC motor current, lower switching loss, and easier to implement in the digital systems.

In this paper, the principle of FEV-DTC is introduced and an algorithm to estimate the flux error is proposed. The voltage vectors in FEV-DTC system is calculated by the error of current stator flux vector and reference stator flux vector and is realized by the method of space vector modulation. The simulation results shows the proposed DTC system having less flux linkage and torque ripples while it maintains as good torque response as the conventional DTC. At the same time the complexity of the power circuit does not increase.

2 MATHEMATIC MODEL OF PMSM

The voltage and flux equations for a PMSM in the *d*-*q* coordinates can be expressed as:

$$\begin{aligned} u_{sd} &= r_s i_{sd} + \frac{d\psi_{sd}}{dt} - p\omega_m \psi_{sp} \\ u_{sq} &= r_s i_{sq} + \frac{d\psi_{sq}}{dt} + p\omega_m \psi_{sd} \\ \psi_{sd} &= L_d i_{sd} + \psi_m \\ \psi_{sq} &= L_q i_{sq} \end{aligned} \quad (1)$$

The electromagnetic torque equation is

$$T_e = \frac{3}{2} p(\psi_m i_{sq} - (L_d - L_q) i_{sq} i_{sd}) \quad (2)$$

Where p is the number of pole pairs, r_s is the stator winding resistance, ω_m is the angular frequency, u_{sd}, u_{sq} and i_{sd}, i_{sq} are the d, q components of the stator winding voltage and current, ψ_{sd}, ψ_{sd} are d, q components of the stator flux linkage, L_d, L_q are d and q axis inductances, ψ_m is the PM rotor flux linkage,

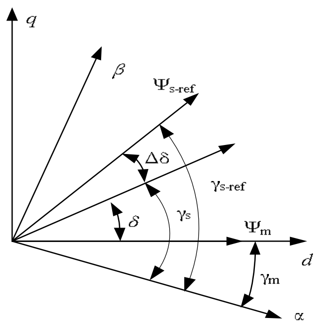


Fig.1 Vector diagram

From the vector diagram we can get following relationship:

$$T_e = \frac{3}{2} p \frac{\psi_{s-ref}}{L_d L_q} [\psi_m L_q \sin\delta + \frac{1}{2}\psi_{s-ref}(L_d - L_q)\sin 2\delta] \quad (3)$$

From equation (3) we can see that for constant stator flux amplitude and flux produced by permanent magnet, the electromagnetic torque can be changed by control of the torque angle. This is the angle between the stator and rotor flux linkage, when the stator resistance is neglected. The torque angel δ, in turn, can be changed by changing position of the stator flux vector in respect to PM vector using the actual voltage vector supplied by PWM inverter. In the steady state, δ is constant and corresponds to a load torque, whereas stator and rotor flux rotate at synchronous speed. In transient operation, δ varies and the stator and rotor flux rotate at different speeds.

3 DTCSYSTEMBASED ON FLUX ERROR VECTOR

In the conventional DTC PMSM scheme, two stator currents (i_α and i_β) and DC-bus voltage V_{dc} are sampled. The magnitude of stator flux and torque calculated are compared with their reference values in the hysteresis comparators and then the outputs of the comparators are fed to a switching table to select an appropriate inverter voltage vector. But the traditional DTC causes the torque and flux linkage ripple because of its basic Bang-bang control principle. And the control system can only choose one of eight voltage vectors to supply for the PMSM in a control period. That is a non-continuous voltage vectors.

In order to reduce the ripples of electromagnetic torque and flux linkage, this paper introduced the FEV-DTC strategy. Fig.2 shows the FEV-DTC system scheme.

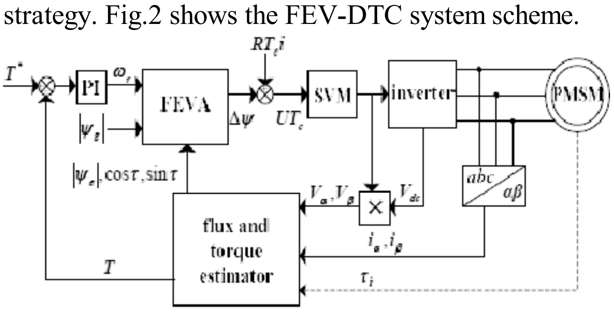


Fig 2 FEVA-DTC system scheme

For the reduction of torque and flux ripples, the reference stator flux vector is employed in FEV-DTC system. There is error between the given torque and actual observed torque. In order to make the actual torque follow the given torque and eliminate the errors, phase angle of stator flux linkage is needed to increase Δτ, which can determine the reference stator flux vector. The error between the reference stator flux vector and the estimated stator flux vector can be calculated by the unit of FEV. The component of stator voltage used to compensate the error can be obtained by voltage space vector calculation model SVM, and then control signal of inverter is outputted. The reference stator flux vector and the estimated stator flux vector can be calculated as

$$\begin{aligned} \psi_r &= |\psi_g|\cos\tau_r + j|\psi_g|\sin\tau_r \\ \psi_e &= |\psi_e|\cos\tau + j|\psi_e|\sin\tau \end{aligned} \quad (4)$$

Where $|\psi_g|$ is the given stator flux vector, τ_r is the reference flux angle, τ is estimated flux angle

$$\tau_r = \omega_r T_c + \tau \quad (5)$$

ω_r is the angular velocity of ψ_r, T_c is the sampling period.

$$\begin{aligned} \Delta\psi &= \psi_r - \psi_e \\ &= [|\psi_g|\cos(\omega_r T_c) - |\psi_e|)\cos\tau - |\psi_g|\sin(\omega_r T_c)\sin\tau] \\ &+ j[|\psi_g|\cos(\omega_r T_c) - |\psi_e|)\sin\tau - h|\psi_g|\sin(\omega_r T_c)\cos\tau] \end{aligned} \quad (6)$$

The Δτ is small, the flux error can be expressed as follow

$$\begin{aligned} \Delta\psi &== (|\psi_g| - |\psi_e|)\cos\tau - |\psi_g|(\omega_r T_c)\sin\tau \\ &+ j[|\psi_g| - |\psi_e|\sin\tau - j|\psi_g|(\omega_r T_c)\cos\tau \end{aligned} \quad (7)$$

It is easy to achieve the difference between the reference stator flux vector and the estimated stator flux vector. cosτ and sinτ can be calculated by the predictor of flux linkage of rotor. When the reference flux linkage is set to per unit 1, the values of cosτ and sinτ are the same as ψ_α and ψ_β, which simplify the calculation of flux linkage error.

The voltage space vectors U are then determined by the following equation

$$UT_c = \Delta\psi + RT_c i. \quad (8)$$

R and i are stator resistance and stator current vector respectively.

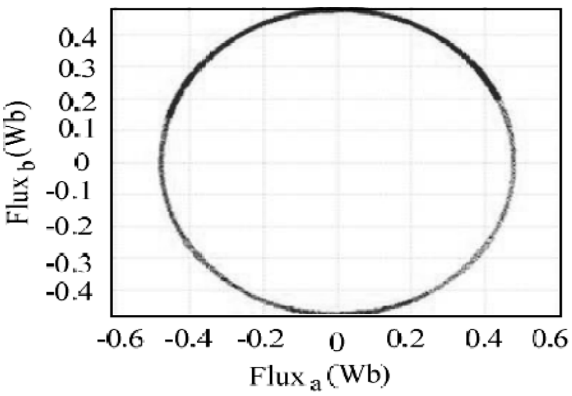
4 SIMULATION AND EXPERIMENTAL RESEARCH

In order to verify the performance of the FEVA-DTC system, two simulation models based simulink were developed to compare the different control algorithm. It is supposed that the permanent magnet synchronous motor used in the simulation is ideal. The magnetic saturation and any other nonlinear factors are neglected. The power devices are ideal switch component. The parameters of the experimental permanent magnet synchronous prototype motor are shown in Tab.1. The steady state flux linkage permanent magnet synchronous motor with the conventional DTC and FEV-DTC are shown in Fig.3. The torque is shown in Fig.4. In the simulation system, load torque is 3.5 Nm, given speed is 1450 r/min, the sampling period of the conventional DTC is chosen as 55 μs, the sampling period of the FEV-DTC is chosen as 110 μs.

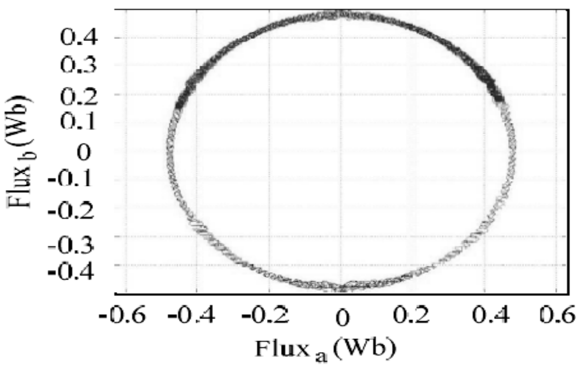
Tab. 1 Parameters of PMSM

Parameters	value
Rated power	1.2Kw
Rated line voltage	220V
Number of pole pairs	2
Rated speed	1450r/min
Rated torque	3.5Nm
Stator resistance	0.057Ω
Stator inductance	2.57mH
inertia	0.143kgm^2
Rotor flux linkage	0.132Wb

Torque PI controller is employed in the FEV-DTC system, torque response is more ideal and torque ripples is reduced. Compared with the conventional DTC, ripples of electromagnetic torque of FEV-DTC are almost reduced by 90%, ripples of flux linkage are almost reduced by 95%. The simulation results indicate that the ripples in both the flux linkage and the torque are greatly reduced in EFV-DTC and the performance of the control system is improved.



(a) Stator flux linkage of FEV-DTC



(b) Stator flux linkage of FEV-DTC

Fig.3 stator flux linkage

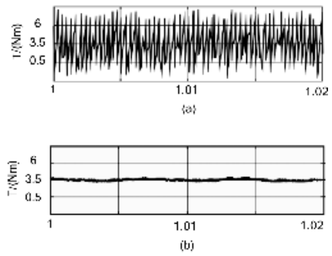
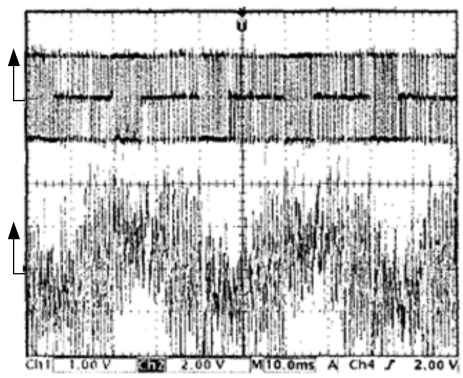


Fig.4 stator flux linkage

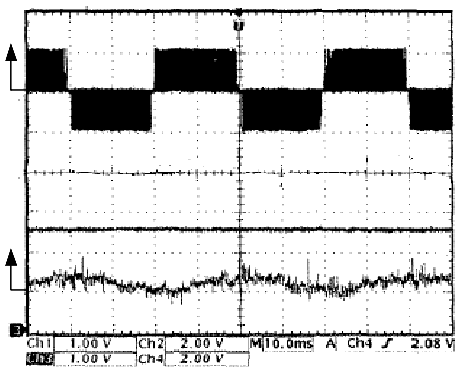
To verify the proposed FEV-DTC concept, a laboratory setup with 1.2kW permanent magnet synchronous motor drive with dSPACE laboratory control board was constructed. The system is based on TMS320F240 DSP. The main processor implements the FEV-DTC control and flux and torque estimation algorithm, whereas the second provides the space vector modulation. The board is equipped with A/D converters, D/A converters, and the input for an encoder. A PC is used for software development and results visualization. The experimental steady state operation at no load is presented in Fig.5a,bare the line to line voltage and motor torque of no load experimental steady state of traditional DTC and FEV-DTC respectively.

5 CONCLUSIONS

The paper presents a new DTC based on flux error vector for PMSM that achieves constant switching frequency and reduced torque ripples control. The simulation and experimental researches have been carried out showing the advantages of the FEV-DTC system compared with the conventional DTC system.



(a)



(b)

Fig.5 Experimental results

The experimental results indicate that the dynamic performance based on FEV-DTC system that the FEV-DTC scheme has lower harmonic current, and consequently lower torque ripple than conventional DTC system..

REFERENCES

[1] Qian Kun, Xie Shousheng, Gao Meiyan, Improved direct torque control method for induction motor applications, Proceedings of the CSEE, 210-214, 2004.

[2] M. Jin, J. Qiu, C. Shi, R. Lin, A fuzzy DTC method with a SVM defuzzification to permanent magnet synchronous machine, The 30th Annual Conference of the IEEE Industrial Electronics Society, 3196-3199, 2004.

[3] D.Sun, J.G.Zhu, and Y.K.He, A space vector modulation direct torque control for permanent magnet synchronous motor drive systems, PEDS2003, 692-697, 2003.

[4] Lai Y S, Chan J H, A new approach to direct torque control of induction motor drives for constant inverter switching frequency and torque ripples reduction, IEEE Trans. Energy. Vol. 16, pp. 220-227, 2001.D. Z. Cheng. Controllability of switched bilinear systems. IEEE Trans. on Automatic Control, 2005, 50(4): 511-515.

[5] A.F. Bakan, H. Bodur, M.H. Sarul, and I. Aksoy, "A Study of Induction Motor DTC Driver's Switching," X. National Conference on Electrical Electronics Computer Engineering, Istanbul, Turkey, pp.183-186, September 2003.

[6] S. Ozcira, N. Bekiroglu, and E. Aycicek, "Simulation of Direct Torque Controlled Permanent Magnet Synchronous Motor Drive," Eleco 2007 Proc., 5th International Conference on Electrical Electronics Engineering, Bursa, Turkey, pp. 272-276, December 2007.

[7] S. Ozcira, N. Bekiroglu, and E. Aycicek, "Sensorless Speed Control of Permanent Magnet Synchronous Motor Based on Direct Torque Control Method," SPEEDAM 2008, Proc., 19th International Symposium.