Direct Torque Control for Permanent Magnet Synchronous Motors Based on Novel Control Strategy

Sizhou Sun, Xingzhong Guo, Huacai Lu, and Ying Meng

Anhui Provincial Key Laboratory of Electric and Control,
Anhui Polytechnic University Wuhu, 241000, China
sszhou12345@163.com

Abstract. In high-performance servo applications a rapid and direct torque control (DTC) is desired. However, the conventional direct torque control based on the 60 degrees region used the position signal to select the proper space voltage vector, results in large torque and flux linkage ripple. In order to solve this problem, a novel DTC scheme for the permanent magnet synchronous motor (PMSM) is proposed, which based on voltage space vector and stator flux linkage sectors subdivision. In this scheme, the traditional six voltage vectors and six flux sectors are subdivided into 12 voltage vectors and 12 flux sectors method to find the optimal voltage vectors. The simulation results show that the presented method is superior to the conventional DTC, and DTC based on sectors subdivision can decrease the torque ripple drastically and enhance the control performance.

Keywords: Direct Torque Control (DTC), Permanent Magnet Synchronous Motor (PMSM), Vector Subdivision, Torque.

1 Introduction

Direct torque control (DTC) has many good features, such as simple implementation, insensitivity to motor parameters and fast torque response [1, 2]. Owing to its good torque control performance and research progressed on permanent magnetic synchronous motor (PMSM), the application on direct torque control strategy into the control of PMSM has become a research hotspot in motion control field [3-6]. However, Big torque and flux linkage ripples are a main problem associated with the conventional DTC method because of the use of two-value hysteresis controllers for the stator flux linkage and the torque and a 60°region based position signal for choosing the space voltage vector applied to the stator windings.

The ripples can be reduced if the errors of the torque and the flux linkage, and the angular region of the flux linkage are subdivided into several smaller subsections. So that a more accurate space voltage vector can be chosen and a more accurate torque and flux linkage control can be obtained. In this paper, to solve the problems associated with DTC of PMSM using conventional voltage space vector, a novel strategy based on voltage space vector and stator flux linkage sectors subdivision is proposed. The simulation results verify that the proposed control scheme can overcome the

K. Li et al. (Eds.): LSMS/ICSEE 2010, Part II, LNCS 6329, pp. 433–441, 2010.

drawbacks of DTC using conventional voltage space vectors selecting switch table and reduces the flux linkage and torque ripple.

2 DTC Theories for the PMSM

In order to simplify the analysis, a surface mounted non-salient permanent magnet synchronous motor is discussed in this paper. Using the *d–q* transformation, the voltage and flux linkage equations of a PMSM in the rotor reference frame are as follows:

$$\begin{cases} u_d = R_s i_d + \psi_d - \omega_r \psi_q \\ u_q = R_s i_q + \psi_q + \omega_r \psi_d \end{cases} \tag{1}$$

$$\begin{cases} \psi_d = L_d i_d + \psi_f \\ \psi_q = L_q i_q \end{cases} \tag{2}$$

Where L_d, L_q are the winding inductance of the *d* and *q* axis, respectively; ψ_d, ψ_q, i_d, i_q, u_d, u_q are the flux linkage, current, voltage of the *d* and *q* axis, respectively.

Using coordinate transformation, the electromagnet torque T_e of the non-salient PMSM is formulated as:

$$T_e = \frac{3n_p}{4L_d L_q}\psi_s\left[2\psi_f L_q \sin\delta - \psi_s (L_q - L_d)\sin 2\delta\right] \tag{3}$$

where *p* is the number of pole pairs; δ is the torque angle. The torque angle δ can be considered as the angle between the stator flux linkage vector ψ_s and rotor flux linkage vector ψ_r. It has been shown that the electromagnetic torque in a PMSM machine can be regulated by controlling the magnitude and angle of the stator flux linkage or load angle δ as seen in Fig. 1.

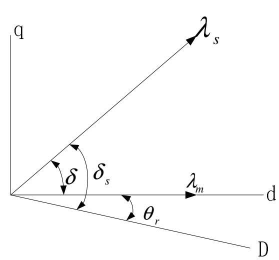

Fig. 1. Stator flux linkage vector diagram

Neglecting the resistance magnetic torque caused by the salient, namely $L_d = L_q = L_s$, the equation (3) can be expressed as:

$$T_e = \frac{3n_p}{2L_d}|\psi_s|\psi_f \sin\delta \tag{4}$$

From the formula (4), the relationship between change of torque angle and electromagnetic torque is shown as:

$$\frac{dT_e}{d\delta} = \frac{3n_p}{2L_d}|\psi_s|\psi_f \cos\delta \tag{5}$$

Equation (5) indicates that the electromagnetic torque T_e is controllable by adjusting the torque angle δ under the condition of keeping the amplitude of the stator flux linkage ψ_s constant.

Under the condition of keeping the stator constant and the torque angle within -90º ~ 90º, the torque increases with the torque angle. The prerequisite of the DTC application is that the changes of the torque is proportional to that of the torque angle, namely, the theory of the PMSM DTC is that the torque is controllable by controlling the stator flux rotation speed and direction to control the torque angle under the condition of keeping the stator flux linkage constant.

Table 1 indicates its VSV (Voltage Sectors Vector)switch table while the PMSM rotates counter clockwise. In the table, F_ψ and F_T are the output of flux and torque regulator respectively. $F_\psi = 1$ and $F_\psi = 0$ indicate the flux linkage increases and decreases respectively. $F_T = 1$ and $F_T = -1$ indicate the torque increases and decreases respectively. $F_T = 0$ denotes that the torque keeps unchanged.

Table 1. Permanent magnet synchronous motor direct torque control (including the zero vectors) switching table

F_ψ	F_T	S1	S2	S3	S4	S5	S6
	1	U_2	U_3	U_4	U_5	U_6	U_1
1	0	U_7	U_0	U_7	U_0	U_7	U_0
	-1	U_6	U_1	U_2	U_3	U_4	U_5
	1	U_3	U_4	U_5	U_6	U_1	U_2
0	0	U_0	U_7	U_0	U_7	U_0	U_7
	-1	U_5	U_6	U_1	U_2	U_3	U_4

In order to decrease the torque ripple, one way is to reduce the width of hysteresis loop, but this results in a higher switching frequency; another way is to increase the number of effective voltage vector that avoids a single vector working within the entire sampling time, so as to achieve the purpose of reducing torque ripple. In the traditional direct torque control system, only one of the six effective or two zero voltage vectors is effective each cycle, namely, a single vector working within the sampling period, that inevitably leads to a sharp increase or decrease in torque and torque ripple far beyond set hysteresis width. At the same time, there is no good use of space voltage vector modulation characteristics.

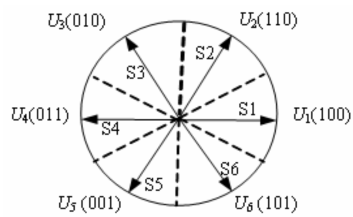

Fig. 2. 6 sector voltage space vector and sector map

At present, Bang-Bang control strategy is used in the direct torque control system mostly, namely, two-point hysteresis comparator is used in the flux controller and three-point hysteresis comparator is used in the torque controller, while the stator flux rotates counterclockwise, the torque increases if the torque hysteresis controller output is 1, and the voltage vector is selected to keep the stator flux linkage rotating at the same direction.

Similarly, the torque decreases if the torque hysteresis controller output is 0, and the voltage vector is selected to keep the stator flux linkage rotating at the reverse direction. The counter-clockwise rotation voltage vector U_1 to U_6 in the DTC is shown in Fig. 2.

3 A New Strategy for PMSM DTC

3.1 Synthesis of Voltage Vector

In order to improve system control performance and reduce the torque ripple, two vectors are used to synthesize any voltage vector direction and amplitude with the space vector pulse width modulation (SVPWM) method. Vector subdivision is that the two adjacent vectors are used to synthesize a new vector along the direction of their angle bisector. The original six voltage vectors are extended to 12 working vectors, namely, six original vectors and six synthetic vectors.

In practice, each VSV works within one T_s and its effects on the flux linkage are same. It can make the number of the effective voltage vector increase to 12 by the three-phase and two-phase alternative conduction mode. Fig.2 indicates three-phase voltage source inverter main circuit topology, S_A, S_B, S_C represent three-phase bridge output of the inverter respectively, S_n=1 indicates that the up bridge on and the down off, S_n=0 indicates that the up bridge off and the down on, S_n=-1 indicates that the up and the down bridges off all. U_d is the DC bus voltage of the voltage source inverter.

Tab. 2 shows the amplitude of the voltage vector in the two-phase conduction mode is 0.866 times of that in the three-phase conduction mode and it makes the voltage ripple reduce at the same time. Under the condition of the accurate parameter, 12 sectors flux linkage subdivision control system has a better torque and speed response than conventional DTC control. Distribution of voltage vector shown as Fig. 4 illustrates the voltage vector selection principle.

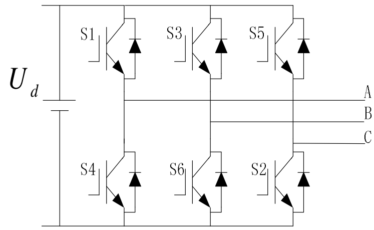

Fig. 3. Three-phase voltage source inverter main circuit topology

Table 2. Shows the three-phase inverter output effective voltage vector in the alternative conduction mode

	S_A	S_B	S_C	amplitude	phase angle
U_1	1	0	0	$2U_d/3$	0
U_2	1	-1	0	$\sqrt{3}U_d/3$	$\pi/6$
U_3	1	1	0	$2U_d/3$	$\pi/3$
U_4	-1	1	0	$\sqrt{3}U_d/3$	$\pi/2$
U_5	0	1	0	$2U_d/3$	$2\pi/3$
U_6	0	1	-1	$\sqrt{3}U_d/3$	$5\pi/6$
U_7	0	1	1	$2U_d/3$	π
U_8	0	-1	1	$\sqrt{3}U_d/3$	$7\pi/6$
U_9	0	0	1	$2U_d/3$	$4\pi/3$
U_{10}	-1	0	1	$\sqrt{3}U_d/3$	$3\pi/2$
U_{11}	1	0	1	$2U_d/3$	$5\pi/3$
U_{12}	1	0	-1	$\sqrt{3}U_d/3$	$11\pi/6$

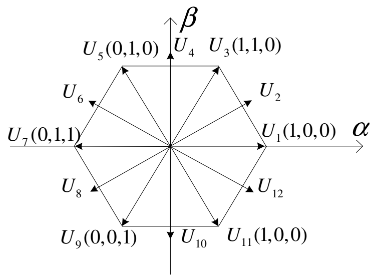

Fig. 4. Distribution and range of vector

Fig.5 illustrates that the flux linkage locates in the sector and the voltage U_4 make the amplitude of the flux linkage and torque increase simultaneously when the flux linkage rotates counterclockwise. Voltage vector U_5 make the flux amplitude reduce and torque increase. Voltage vector U_{11} makes the magnitude of the flux linkage increase and torque decrease, voltage vector U_{10} makes the amplitude of the flux linkage and torque to reduce simultaneously.

Zero-voltage vector makes the amplitude of the flux and torque remains unchanged in an instant. The voltage vector in other sectors is selected in the same way.

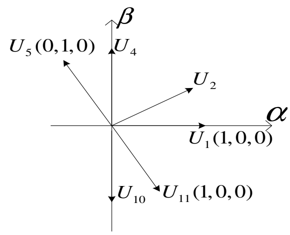

Fig. 5. The distribution of voltage vector (larea)

3.2 System Components

The system block diagram of the DTC speed control system based on vector subdivision is shown in Fig. 6. Permanent magnet synchronous motor is supplied by the three-phase voltage-type inverter, the measured stator three-phase currents i_a、 i_b、 i_c are used to Clark transform, and its output i_α、 i_β with the DC side voltage U_d are used to calculate in the flux and torque calculation unit ,then the appropriate switch is selected by the flux linkage subdivision unit.

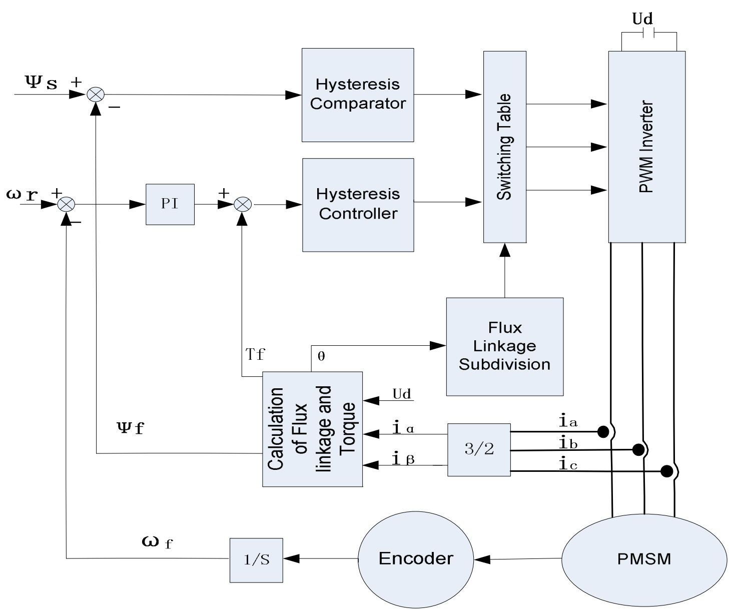

Fig. 6. System block diagram

4 Established System and Experimental Results

To verify the theory of the vector subdivision DTC for the PMSM system, Matlab/SIMULINK models were developed for the conventional and the vector subdivision PMSM DTC. The parameters of the PMSM used in the system are listed as the follows:

R_s=0.275Ω, L_d=L_q=8.5mH, n_p=4, J = 0.0012Kg•m^2, B=0.3, k_p = 2.4, k_i =3. Simulation has been done using Matlab7.0.

Fig. 7 and Fig. 8 show the steady state flux linkage waveforms under the control of traditional DTC and vector synthesis DTC, respectively, the flux linkage switching between the boundaries in six sectors is obvious under the control of the traditional DTC, which demonstrates that there is flux distortion on the sector boundaries. The flux linkage distortion on the sector boundaries reduce and the running track of flux linkage are improved significantly after the use of vector subdivision control.

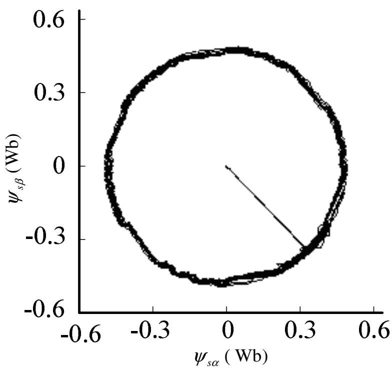

Fig. 7. The stator flux linkage waveforms of the conventional DTC

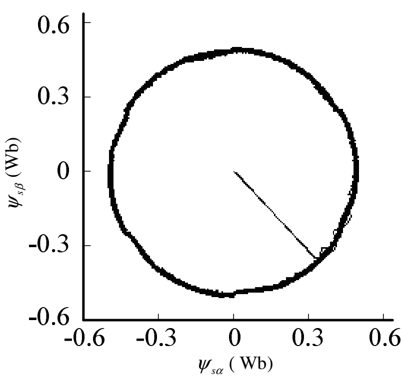

Fig. 8. Stator flux linkage waveforms based on the vector subdivision DTC

Fig. 9 to Fig. 10 are speed response and electromagnetic torque waveforms figure of permanent magnet synchronous motor at a given speed 500r/min based on the conventional DTC and the vector subdivision DTC respectively.

By contrast, it can be seen that vector subdivision DTC strategy can decrease the flux and torque ripple distinctively. In addition, it has faster tracking performance and maintains the fine traditional DTC robustness at the same time.

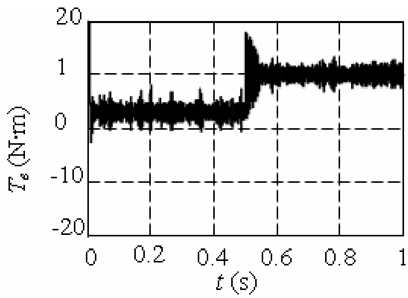

Fig. 9. Electromagnetic torque based on the conventional DTC algorithm

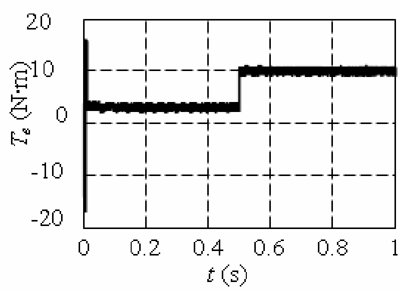

Fig. 10. Electromagnetic torque based on the vector subdivision DTC algorithm

5 Conclusions

In order to achieve good steady state and dynamic performance, a novel DTC strategy for PMSM is proposed in this paper, which based on voltage space vector and stator flux linkage sectors subdivision. In this scheme, the traditional six voltage vectors and six flux sectors are subdivided into 12 voltage vectors and 12 flux sectors method to find the optimal voltage vectors. And a new switching table is used to get high torque dynamics without increasing the computations incurred to calculate the optimal voltage vector. Theoretical analysis and simulations results show that the performance of the permanent magnet synchronous motor based on the vector subdivision DTC algorithm is superior to the traditional direct torque control method. And the vector subdivision DTC algorithm can decrease the torque ripple drastically and enhance the control performance.

Acknowledgments. The work was supported by Educational Commission of Anhui Province of China under grant KJ2007B079 and Scientific and Technological project of Anhui Province of China under grant 08010202120.

References

1. Liao, X.Z., Shao, L.W.: The Twelve-section Control Methods of Direct Torque Control. J. Proceedings of the CSEE 26(6), 167–173 (2006)
2. Sun, D., Jim, G.Z., He, Y.K.: Direct Torque Control Of Permanent Magnet Synchronous Motor Based On Fuzzy Logic. In: AUPEC 2002 (2002)
3. Li, L.B., Sun, H., Wang, X.J.: A high-performance direct torque control based on DSP in permanent magnet synchronous motor drive. In: Proceeding of 4th World Congress on Intelligent Control and Automation, Shanghai, China (2002)
4. Ghassemi, H., Vaez-Zadeh, S.: A very fast direct torque control for interior permanent magnet synchronous motors start up. J. Energy Conversion and Management. 46, 715–726 (2005)
5. Muhammed, F.R., Tang, L.X.: Problems Associated With the Direct Torque Control of an Interior Permanent-Magnet Synchronous Motor Drive and Their Remedies. IEEE Transctions on Industrial Electonics 51(4), 799–809 (2004)
6. Muhammed, F.R., Enamul, H.M., Tang, L.X., Limin, Z.: Problems associated with the direct torque control of an interior permanent magnet synchronous motor driver and their remedies. J. IEEE. Transaction on Power Electron. 51(4), 799–809 (2004)
7. Zhang, C., Liu, H., Chen, S.: Direct torque control of novel interior permanent magnet synchronous motor. J. Journal of System Simulation 19(9), 2037–2040 (2007)
8. Telford, D., Dunnigan, M.W., Williams, B.W.: A novel torque-ripple reduction strategy for direct torque control. J. IEEE Transactions on IE (S0278–0046) 48(4), 867–870 (2001)
9. Romeral, L., Arias, A., Aldabas, E., et al.: Novel direct torque control scheme with fuzzy adaptive torque-ripple reduction. J. IEEE Transactions on IE (S0278-0046) 50(3), 487–492 (2003)
10. Zolghadri, M.R., Roye, D.: A fully digital sensorless direct torque control system for synchronous machine. J. Elect. Mach. Power Syst. 26, 709–721 (1998)