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Direct Torque Control System and Sensorless Technique of Permanent Magnet Synchronous Motor

HU Yu-wen[1], TIAN Cun[1], YOU Zhi-qing[1], Tang Li-xin[2], M. F. Rahman[2]
(1. Aero-Power Sci Tech Center, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China)
(2. School of Elec. Eng. And Tele., The University of New South Wales, Sydney Australia)

Abstract: The direct torque control theory has achieved great success in the control of induction motors. However, in the DTC drive system of Permanent Magnet Synchronous Machine (PMSM) proposed a few years ago, there are many basic theoretical problems that must be clarified. This paper describes an investigation about the effect of the zero voltage space vectors in the DTC system of PMSM and points out that if using the zero voltage space vectors rationally, not only can the DTC system be driven successfully but also the torque ripple is reduced and the performance of the system is improved. This paper also studies the sensorless technique in the DTC system of PMSM and configures the DTC system of PMSM with sensorless technique including zero voltage space vectors. Numerical simulations and experimental tests have proved the theory correct. In the condition of sensorless, the DTC system of PMSM is wide-rangely speed adjusting, and the ratio of speed adjustment is 1∶100.

Key words: power electronics; direct torque control; permanent magnet motors; sensorless; stator flux linkage

无速度传感器永磁同步电机直接转矩控制系统. 胡育文, 田淳, 游志青, 汤立新, M. F. Rahman. 中国航空学报(英文版), 2003, 16(2): 97- 102.

摘　要: 详细阐述了零矢量在永磁直接转矩控制系统中的作用, 指出如果合理应用零矢量, 不仅能使永磁电机(PMSM)的DTC系统正常运行, 而且能减少转矩脉动的频率和改善系统的性能。还研究了PMSM的DTC系统的无速度传感器技术, 构建了包含零矢量在内的无速度传感器PMSM的DTC系统。仿真和实验都证明了理论的正确性。在无速度传感器的条件下, PMSM的DTC系统实现了宽范围调速, 调速比达到了1∶100。

关键词: 电力电子; 直接转矩控制; 永磁电机; 无速度传感器; 定子磁链
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The DTC for induction machines proposed in the middle of 1980′s has been used in many applications already. In 1990′s, many attempts have been made to implement the idea of the DTC of induction to PMSM, however, the current controllers were not eliminated in these strategies and could not control the torque directly by voltage space vectors[1]. Only the DTC theory of PMSM proposed in 1997 has the same advantages as the DTC of an induction machine[2]. Not just so, many potential advantages were found in this scheme: for example, the field-weakening control becomes easier because the stator flux linkage can be controlled directly in the DTC system of a PMSM[3]; sensorless control becomes possible because the method does not need accurate rotor position information. In recent years, the modified strategy of the DTC system of PMSM, which is named Space Vector Modulation (SVM), has been studied further to reduce the torque ripple[4]. This

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is a strategy to produce multiple voltage space vectors in the sampling interval. For convenience, this strategy is called SVM-DTC, and the traditional strategy, which produces only one voltage space vector, is called Basic DTC. However, the DTC system of PMSM has many basic theoretical problems that have not been clarified yet. For example, what kind of role exactly do the zero voltage space vectors play on the DTC system of PMSM? It shows clearly in Ref. [2] that zero voltage space vectors should not be used in the DTC system of PMSM when Basic DTC is adopted; otherwise, the system cannot work properly. So, there are no zero voltage space vectors in the corresponding switch table but six other voltage space vectors. However, for the SVM-DTC, why does the system run in order when using the zero voltage space vectors? Certainly, some abnormal status could be emerged while debugging the SVM-DTC control program. Is it because of the zero voltage space vectors? Therefore, what the zero voltage space vectors act as in the DTC system of PMSM is one important theoretical problem. If this problem is not solved, it cannot be said that a perfect theory on the DTC of a PMSM is established.

The sensorless control is an important technique. In the Field Oriented Control system of PMSM, the sensorless control scheme has been shown up in literature, while, in the DTC system, it has just began to be studied. DTC does not need accurate rotor position information, which leads to much easier implement of sensorless control in the DTC than in the Field Oriented Control of PMSM.

This paper will carry out deeply research from the aspects of basic theory of DTC of PMSM and the sensorless control, *etc*; at the same time, a ratio of wide-range speed adjustment of 1∶100 is realized in the experiment device.

1　Basic Theory of DTC of PMSM

If controlling φ_s, let $|\varphi_s|$ = constant, and neglecting the stator resistance, the torque of the PMSM and its differential coefficient can be derived[2]

$$T = \frac{3}{2}p[\varphi_D(i_x\sin\delta + i_y\cos\delta) - \varphi_Q(i_x\cos\delta - i_y\sin\delta)] = \frac{3}{2}p|\varphi_s|i_y \tag{1}$$

$$\frac{\mathrm{d}T}{\mathrm{d}t} = \frac{3p|\varphi_s|}{4L_DL_Q}[2\varphi_fL_Q\dot{\delta}\cos\delta - 2|\varphi_s|(L_Q - L_D)\dot{\delta}\cos2\delta] = \frac{3p|\varphi_s|}{4L_D}[2\varphi_f\cos\delta - 2|\varphi_s|(1 - L_D/L_Q)\cos2\delta]\dot{\delta} \tag{2}$$

where p is the Number of pole pairs; φ_s and φ_f are the stator flux linkage and rotor flux linkage; φ_D and φ_Q are the components of the stator flux linkage on the axis of D and Q; i_x and i_y are the components of the axis of x and y. The load angle δ is the angle between the stator flux φ_s and φ_f. Here, $|\varphi_f|$ = constant, because the rotor is PM excited. L_D, L_Q are D-axis and Q-axis inductance respectively.

Eq. (2) implies that the torque increases with the increase in δ subject to some conditions. By changing δ quickly, the torque can be changed quickly too.

In fact, any change $\Delta\delta$ consists of two parts: angular change $\Delta\delta_s$ of φ_s and angular change $\Delta\delta_f$ of φ_f.

$$\Delta\delta = \Delta\delta_s + \Delta\delta_f \tag{3}$$

$\Delta\delta_s$ can be controlled by selecting the proper voltage space vectors. $\Delta\delta_s = 0$, when zero voltage space vectors are selected.

$\Delta\delta_f$ is due to the motion of the rotor. The faster the rotor rotates, the larger the $\Delta\delta_f$ is. If the rotating speed is zero, $\Delta\delta_f = 0$.

2　Effect of the Zero Voltage Space Vectors

$$\Delta\delta = \Delta\delta_s + \Delta\delta_f = \mathrm{ang}(\boldsymbol{U}_iT_s) - \omega_rT_s \tag{4}$$

where $\boldsymbol{U}_i$ is a voltage space vector; T_s is sampling interval. If zero voltage space vectors are selected, then it is seen that $\Delta\delta = \Delta\delta_f = -\omega_rT_s$. This means that δ will decrease and hence the developed torque will be reduced, which is exactly the same as in the induction machine system. Thus, it should be accepted naturally that if the control mode of the induction machine is adopted, the system would also work properly. And then, the control switch table for the positive direction operation is shown in Table 1. Ref.[2] indicates that the system will be often in a protected condition and operates out of order if PMSM is under the control of this table. Only when zero voltage space vectors are eliminated, can the motor work properly, that is to replace Table 1 with Table 2. The condition of the negative direction is similar to that of the positive direction, which has been discussed above.

Table 1 The switch table for the positive direction operation

$\Psi, \tau, \theta_{(N)}$		$\theta_{(1)}$	$\theta_{(2)}$	$\theta_{(3)}$	$\theta_{(4)}$	$\theta_{(5)}$	$\theta_{(6)}$
$\Psi = 1$	$\tau = 1$	U_2(1 1 0)	U_3(0 1 0)	U_4(0 1 1)	U_5(0 0 1)	U_6(1 0 1)	U_1(1 0 0)
	$\tau = 0$	U_7(1 1 1)	U_0(0 0 0)	U_7(1 1 1)	U_0(0 0 0)	U_7(1 1 1)	U_0(0 0 0)
$\Psi = 0$	$\tau = 1$	U_3(0 1 0)	U_4(0 1 1)	U_5(0 0 1)	U_6(1 0 1)	U_1(1 0 0)	U_2(1 1 0)
	$\tau = 0$	U_0(0 0 0)	U_7(1 1 1)	U_0(0 0 0)	U_7(1 1 1)	U_0(0 0 0)	U_7(1 1 1)

The table is exactly the same as the one in the induction motor[5].

Table 2 The switch table for the positive direction operation without using zero voltage space vectors

$\Psi, \tau, \theta_{(N)}$		$\theta_{(1)}$	$\theta_{(2)}$	$\theta_{(3)}$	$\theta_{(4)}$	$\theta_{(5)}$	$\theta_{(6)}$
$\Psi = 1$	$\tau = 1$	U_2(1 1 0)	U_3(0 1 0)	U_4(0 1 1)	U_5(0 0 1)	U_6(1 0 1)	U_1(1 0 0)
	$\tau = 0$	U_6(1 0 1)	U_1(1 0 0)	U_2(1 1 0)	U_3(0 1 0)	U_4(0 1 1)	U_5(0 0 1)
$\Psi = 0$	$\tau = 1$	U_3(0 1 0)	U_4(0 1 1)	U_5(0 0 1)	U_6(1 0 1)	U_1(1 0 0)	U_2(1 1 0)
	$\tau = 0$	U_5(0 0 1)	U_6(1 0 1)	U_1(1 0 0)	U_2(1 1 0)	U_3(0 1 0)	U_4(0 1 1)

In Table 1 and Table 2, Ψ and τ are the outputs of the hysteresis controller for the flux linkage and torque, respectively. If $\Psi = 1$, then the actual flux linkage is smaller than the reference value. The same is true for the torque. $\theta_{(1)}$-$\theta_{(6)}$ are region numbers for the stator flux linkage positions[2,5]. U_0-U_7 are the voltage space vectors.

Therefore, Ref.[2] concludes that zero voltage space vectors work differently in the induction machine and PMSM, and zero voltage space vectors cannot be used in the PMSM. Explanation cannot be given at that time, but experiment shows it clearly.

However, in recent years, zero voltage space vectors have been used again naturally with satisfying experimental results when SVM-DTC strategy is studied further. Why do both the experiments come to the contradictory conclusion? For the sake of the improvement of the DTC theory in PMSM, it is necessary to make clear what role zero voltage space vectors play on the DTC system of PMSM.

$\Delta\delta_s$ and $\Delta\delta_f$ should have to be calculated carefully in order to make clear the role of the zero voltage space vectors in synchronous motors. It can be seen that when the rotor speed is less than, say, 5000 r/min, $\Delta\delta_f$ is so small that it can be neglected. For example, if $\omega = 3000$ r/min, $T_s = 100\mu s$, $\Delta\delta$ only equals $-1.8°$. If driving a heavy load, δ is about 90°, so that $\Delta\delta_f/\delta = 2\%$, therefore, change of δ is very small. If $\omega_f = 300$ r/min, $\Delta\delta_f/\delta = 0.2\%$ only. Due to this reason, the change of torque caused by $\Delta\delta_f$ is also very small.

On the other hand, according to the experimental result, average change of δ set off by the non-zero voltage space vectors in sampling interval T_s, i.e. $\Delta\delta_s$, becomes about 9°-18°, which is 10-100 times that of $\Delta\delta_f$. Thus, the zero voltage space vectors in the DTC system of a PMSM hold the torque rather than decrease it. This is true only in the case that the rotating speed is not too high. If the speed exceeds 10 000 rev/min, decreased torque contributed by the zero voltage space vectors will cause more than 6° of change in δ during T_s of $100\mu s$. Therefore the decrease in torque contributed by the zero voltage space vectors should be considered.

3 A Novel Control Strategy of DTC of PMSM

Considering that the zero voltage space vectors have the ability to hold the function holding torque. This novel strategy including zero voltage space vectors is shown below

$$\text{if } \tau = \begin{cases} 1 & T_e^* - T_e > \Delta T/2 \\ 0 & |T_e^* - T_e| \leq \Delta T/2 \\ -1 & T_e^* - T_e < -\Delta T/2 \end{cases}$$

where ΔT is the range of the allowed torque ripple; T_e^* is torque reference; T_e is the real torque. Then the switch table can be obtained as Table 3.

Table 3 The switch table for the positive direction operation using zero voltage space vectors

$\Psi, \tau, \theta_{(N)}$		$\theta_{(1)}$	$\theta_{(2)}$	$\theta_{(3)}$	$\theta_{(4)}$	$\theta_{(5)}$	$\theta_{(6)}$
$\Psi = 1$	$\tau = 1$	$\boldsymbol{U}_2$(1 1 0)	$\boldsymbol{U}_3$(0 1 0)	$\boldsymbol{U}_4$(0 1 1)	$\boldsymbol{U}_5$(0 0 1)	$\boldsymbol{U}_6$(1 0 1)	$\boldsymbol{U}_1$(1 0 0)
	$\tau = 0$	$\boldsymbol{U}_7$(1 1 1)	$\boldsymbol{U}_0$(0 0 0)	$\boldsymbol{U}_7$(1 1 1)	$\boldsymbol{U}_0$(0 0 0)	$\boldsymbol{U}_7$(1 1 1)	$\boldsymbol{U}_0$(0 0 0)
	$\tau = -1$	$\boldsymbol{U}_6$(1 0 1)	$\boldsymbol{U}_1$(1 0 0)	$\boldsymbol{U}_2$(1 1 0)	$\boldsymbol{U}_3$(0 1 0)	$\boldsymbol{U}_4$(0 1 1)	$\boldsymbol{U}_5$(0 0 1)
$\Psi = 0$	$\tau = 1$	$\boldsymbol{U}_3$(0 1 0)	$\boldsymbol{U}_4$(0 1 1)	$\boldsymbol{U}_5$(0 0 1)	$\boldsymbol{U}_6$(1 0 1)	$\boldsymbol{U}_1$(1 0 0)	$\boldsymbol{U}_2$(1 1 0)
	$\tau = 0$	$\boldsymbol{U}_0$(0 0 0)	$\boldsymbol{U}_7$(1 1 1)	$\boldsymbol{U}_0$(0 0 0)	$\boldsymbol{U}_7$(1 1 1)	$\boldsymbol{U}_0$(0 0 0)	$\boldsymbol{U}_7$(1 1 1)
	$\tau = 0$	$\boldsymbol{U}_5$(0 0 1)	$\boldsymbol{U}_6$(1 0 1)	$\boldsymbol{U}_1$(1 0 0)	$\boldsymbol{U}_2$(1 1 0)	$\boldsymbol{U}_3$(0 1 0)	$\boldsymbol{U}_4$(0 1 1)

4 Sensorless Control Technique

4.1 Orientation of the rotor pole initial position

In the DTC control, only by the acquisition of which region where the initial position of the pole lies among the six regions, can the space voltage vectors be selected. Therefore, compared with the Field Oriented Control strategy, DTC strategy requests much less accuracy of the initial position, which is the advantage of DTC strategy. Under the situation that the load is not affected by the initial rotating direction strictly, the initial position will be orientated easily by using the following method.

Switch on the lower IGBT of the phase B and C, and at the same time, control both the upper and the lower transistors of the phase A in way of Chopping control (the duty is 0.1). Then the flux linkage φ_s will be formed in the direction of axis A in the motor, which causes the rotor pole to turn to the phase A of the motor, and the initial position of the rotor pole is orientated simultaneously.

4.2 Sensorless control scheme

In the stable condition, the stator flux linkage of synchronous motors rotates at the same speed as the rotor, that is $\omega_s = \omega_r$. In the static axis of the stator, there is

$$\omega_s = \frac{d\theta_s}{dt} = \frac{d}{dt}\left(\arctan\frac{\varphi_Q}{\varphi_D}\right) = \frac{\dot{\varphi}_Q\varphi_D - \dot{\varphi}_D\varphi_Q}{\varphi_D^2 + \varphi_Q^2}$$

for

$$\dot{\varphi}_D = U_D - i_D R_s$$

$$\dot{\varphi}_Q = U_Q - i_Q R_s$$

then

$$\omega_r = \omega_s = \frac{(U_Q - i_Q R_s)\varphi_D - (U_D - i_D R_s)\varphi_Q}{\varphi_D^2 + \varphi_Q^2}$$

where U_Q and U_D are the components of the terminal voltage U on the axis of Q and D, respectively, which can be calculated by the U_{DC} on the DC side and the space vectors in the sample interval; φ_D and φ_Q are the controlling variables in the DTC strategy and have been calculated during the control. According to the formula above, the rotor rotating speed can be easily obtained. However, it should be noted that the formula only applies to calculating the rotating speed in the stable condition. Because ω_s is not equal to ω_r totally in the dynamic condition, some modulation should have to be done.

5 Simulation and Experimental Test

The parameters of the PMSM are given in the appendix. The block diagram of a PMSM drive with DTC is shown as Fig 1, where the flux estimator can be expressed as

$$\varphi_D(k) = \varphi_D(k-1) + (U_D(k-1) - Ri_D)T_s$$

$$\varphi_Q(k) = \varphi_Q(k-1) + (U_Q(k-1) - Ri_Q)T_s$$

$$|\varphi_{(k)}| = \sqrt{\varphi_{D(k)}^2 + \varphi_{Q(k)}^2}$$

$$|\varphi_{(k)}| = \sqrt{\varphi_{D(k)}^2 + \varphi_{Q(k)}^2}$$

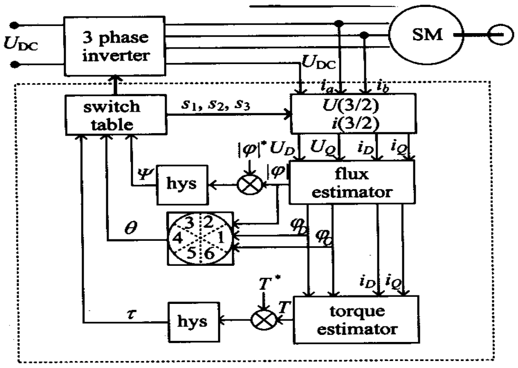
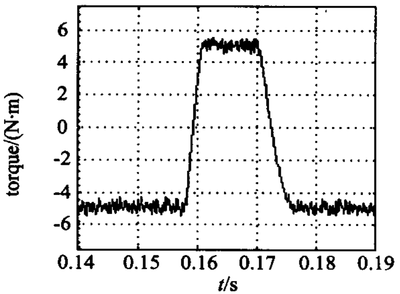


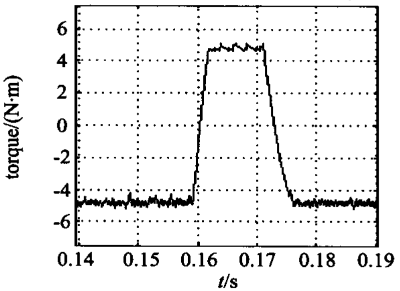
Fig. 1 The block diagram of a PMSM drive with DTC

DSP TMS320C32 is used for real time control of the PMSM.

Fig. 2 is the simulation results of the torque ripple under the control strategy including and excluding zero voltage space vectors, that is, Fig. 2 (a) corresponds to the control method in Table 2 and Fig. 2(b) to that in Table 3.



(a)torque ripple without using zero voltage vectors



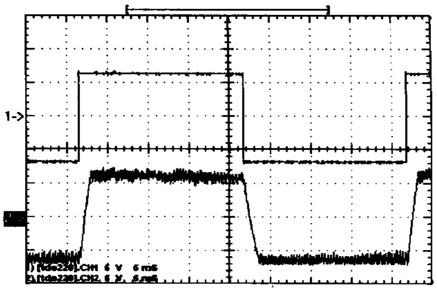
(b)torque ripple with using zero voltage vectors

Fig. 2 Simulation results of torque ripple

It can be seen in the figure that the torque ripple is much more in the strategy without using zero voltage space vectors than the one with using zero voltage space vectors, which means that the zero voltage space vectors exactly have the ability to hold the function holding torque. In this way, the switching times of the transistor will be reduced sharply, and the consumption will be decreased with lower disturbance.

It also shows some simulation results of the dynamic response under the control strategy including zero voltage space vectors. It can be observed that the response time of torque change from 5N·m to − 5N·m is 2ms only, which is the same as that in the control without using zero voltage space vectors, and therefore, the dynamic response will not be worsened by using zero voltage space vectors.

Fig. 3 is the experimental results of the dynamic response under the control strategy including zero voltage space vectors. It is proved correct that the response time of a torque change from 5N·m to − 5N·m is only 2ms, which is thoroughly similar to the results of simulation.



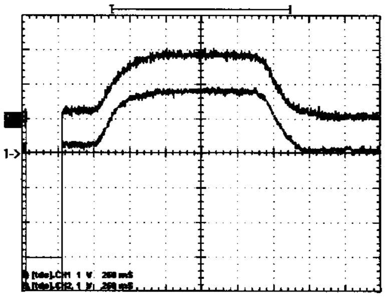
Ch1: torque reference

Ch2: torque response 1div= 4N·m

torque response(− 5N·m to 5N·m)

Fig. 3 The experimental results

Fig. 4 shows the speed-tracking curve of the DTC system of PMSM including the zero voltage space vectors with using sensorless technique.



Ch1: speed reterence 1div= 500r/min

Ch2: speed response 1div= 500r/min

Fig. 4 Speed-tracking curve in the sensorless condition

It can be derived from this figure that although the formula to estimate the speed, which is adopted in the sensorless control, is relatively simple, it contributes to a good performance when tracking the speed reference.

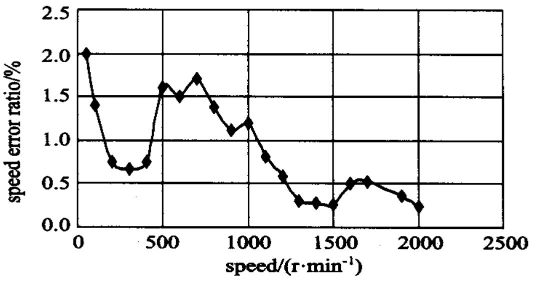


Fig.5 Speed error in the sensorless condition

Fig. 5 indicates the speed error in the DTC system of PMSM with using sensorless control.

This motor's rated speed is 1500 r/min. It can reach the maxim speed 2000 r/min with the aid of the field-weakening control, and can fall to the minimum speed 20 r/min by using novel filter technique when the motor rotates at low speed. In the motion control of this system, the ratio is up to 1∶100, the error ratio is less than 2% and below 1% when the motor is running at high speed.

6 Conclusions

(1) By dividing the control scheme of the torque to include regimes of increase, decrease and hold, and using the zero voltage space vectors to hold the torque, the DTC system of PMSM can not only work properly, but also improve the performance of the system. Therefore the zero voltage space vectors should be used and should not be forsaken, in the DTC system of PMSM. Thus, one can draw the conclusion that zero voltage space vectors should be used in the control of both Basic DTC and SVM-DTC, which will solve the previous contradiction.

(2) With the help of the filter, the sensorless Basic DTC strategy including the zero voltage space vectors can decrease largely the frequency of the torque ripple and decelerate to 20r/min at low speed. The ratio in the motion control can reach 1∶100.

Appendix

Parameters of the machine used in simulation

Voltage U_n:	220 V	Rated power P_n:	1 kW
Rated speed W_r:	1500 r/min	Rated current I:	2 A
D-axis inductance L_D:	0.1133H	Q-axis inductance L_Q:	0.1295H
Stator resistance R_s:	20.51Ω	Magnet flux linkage φ_f:	0.6115Wb
Rated torque T	5 N·m	Number of pole pairs p:	2

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Biographies:

HU Yu-wen Born in 1944, a professor in the Department of Electrical and Electronic Engineering. Tel: (025) 4892867, E-mail: huyuwen@nuaa.edu.cn.

TIAN Chun Born in 1973, she received Ph. D. from Nanjing Univ. of Aero. & Astro. in 2001. Her research interest is directed towards electricity and electronics technology, modern technology of speed regulation, *etc*.

YOU Zhi-qing Born in 1977, she received B. S. from Nanjing Univ. of Aero. & Astro. in 2000. She is now studying for master degree.

Tang Li-xin He is now pursuing Doctor degree in School of Elec. Eng. & Tele of University of New South Wales, Australia.

M. F. Rahman He is a vice professor in School of Elec. Eng. & Tele of University of New South Wales, Sydney Australia.