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A Novel Direct Torque Control Permanent Magnet Synchronous Motor Drive used in Electrical Vehicle

Li Yaohua, Ma Jian, Yu Qiang, Liu Jiangyu
School of Automobile of Chang'an University
Nan Er Huan Lu Zhong Duan, Xi'an, China, 710064
e-mail: nuaaliyaohua@126.com

Abstract

In this paper, a modified direct torque control (DTC) scheme for permanent magnet synchronous motor (PMSM) is investigated, which enables low torque ripple by using an improved voltage vector selection strategy instead of switching table used in conventional DTC. Based on the control of stator flux, torque angle and torque, voltage vector selection strategy of PMSM DTC drive is proposed. In the proposed voltage vector selection strategy, the applied voltage vector is determined according to outputs of hysteresis comparators for stator flux and torque, angular position of stator flux and torque angle, which is finally synthesized by space vector modulation (SVM). Modeling and experimental results for an interior PMSM used in Honda Civic 06My Hybrid electrical vehicle are given. Simulation and experimental results show torque ripple is reduced and the total harmonics of stator current is decreased when compared those of conventional DTC. And a fixed switching frequency is obtained with the help of SVM. In addition, the proposed DTC doesn't need any additional PI controller, which maintains the simplicity in conventional DTC.

***Keywords**: direct torque control, permanent magnet synchronous motor, electrical vehicle, torque ripple, switching frequency*

1. Introduction

With the development of automobile industy, air pollution, global warming and the rapid depletion of the earth's petroleum resoucese are becoming serious. Electrical vehicle (EV) which inclused battery EV, hybrid EV and fuel cell EV has drawn increasing interests [1]-[2].

Electric propulsion systems are the hearts of EV, which functions as internal combustion engine in conventional vehicle. They consist of electric motors, power converters and electronic controllers. As permanent magnet synchronous motor (PMSM) can offer many advantages, including high effieciency, high power/torque density and high reliability, it is widely used in the modern EV [3]-[4]. For EV application which requires high dynamic performance, field oreinted control (FOC) is often employed. Recently, another high-performance control technique, named direct torque control (DTC) has also been invistegated in PMSM drives [5]-[7]. Compared with FOC, DTC has the advantages of faster torque and flux regulation, elimination of current regulators and PWM generators, robustness to rotor parameters variation. Furthermore, all calculations are implemented in stationary reference frame, therefore, the coordinate transformation and continuous rotor position information are not required and the structure of DTC is simple [8]-[9].

Despite the merits mentioned above, DTC also presents some drawbacks, including large torque ripple and variable switching frequency [10]-[11]. In nature DTC is hysteresis control and voltage vector is the final output variable. Conventional DTC uses switching table as hysteresis control principle to select proper voltage vectors. But switching table can't always satisfy the control of torque [12]-[13]. Thus to get proper voltage vector selection strategy is critical to suppress torque ripple. Some voltage vector selection strategies were proposed in [14]-[16]. But they can only be used for surface PMSM which can't produce reluctance torque or the motor whose parameters are known. In this paper, a universal voltage vector selection strategy for PMSM is proposed. In the proposed DTC, the applied voltage vector is determined according to outputs of hysteresis comparators for stator flux and torque, torque angle and angular position of stator flux, which is finally synthesized by space vector modulation (SVM). Modeling and experimental results for an interior PMSM used in Honda Civic 06My Hybrid electrical vehicle show torque ripple is reduced and the total harmonics of stator current is decreased when compared those of conventional DTC. And a fixed switching frequency is obtained with the help of SVM. In addition, the proposed DTC doesn't need any additional PI controller, which maintains the simplicity in conventional DTC.

2. Control of stator flux, torque angle and torque

Neglecting voltage drop on stator resistance, after applying a voltage vector for a short period Δt, stator flux is presented in Figure 1. According to Figure 1, the change of the amplitude and angular position of stator flux can be expressed in (1) and (2), where ψ_s is stator flux, V_s is the applied voltage vector, α is the angle between stator flux and the applied voltage vector.

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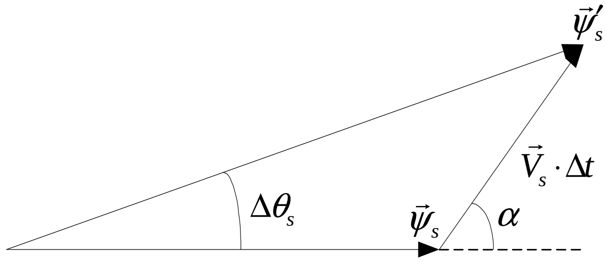

Figure 1. The move of stator flux vector

$$\Delta \hat{\psi}_s = \sqrt{\hat{\psi}_s^2 + (\hat{V}_s \cdot \Delta t)^2 + 2\hat{\psi}_s \cdot \hat{V}_s \cdot \Delta t \cdot \cos\alpha} - \hat{\psi}_s \tag{1}$$

$$\Delta\theta_s = \arcsin \frac{\hat{V}_s \cdot \Delta t \cdot \sin\alpha}{\sqrt{\hat{\psi}_s^2 + (\hat{V}_s \cdot \Delta t)^2 + 2\hat{\psi}_s \cdot \hat{V}_s \cdot \Delta t \cdot \cos\alpha}} \tag{2}$$

Here we define q shown in (3). Substituting (3) into (1) and (2) and neglecting the move of rotor flux, we can use f and Δδ to show the change of stator flux and torque angle due to the application of voltage vector.

$$q = \frac{\hat{V}_s \cdot \Delta t}{\hat{\psi}_s} \tag{3}$$

$$f = \sqrt{1 + q^2 + 2q\cos\alpha} - 1 \tag{4}$$

$$\Delta\delta = \arcsin \frac{q \sin\alpha}{\sqrt{q^2 + 1 + 2q\cos\alpha}} \tag{5}$$

According to (4) and (5), when $0<q<0.1$ and $0<\alpha<360^{\circ}$, the change of stator flux and torque angle are shown in Figure 2 and Figure 3, resepectively.

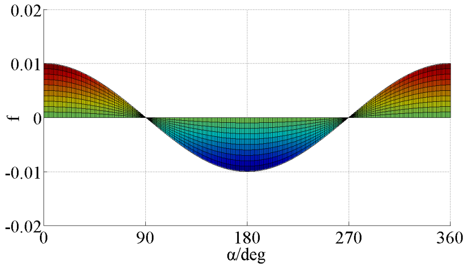

Figure 2 The change of stator flux

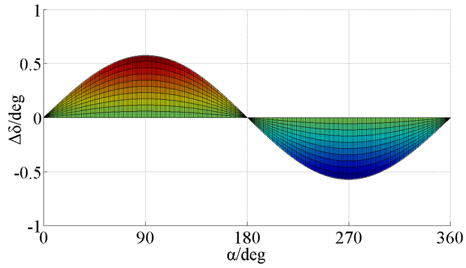

Figure 3 The change of torque angle

Figure 2 and Figure 3 show the control of stator flux and torque angle are dependent on the angle between stator flux and the applied voltage vecotr. If α is within (-90°, 90°), the applied voltage vector increases the amplitude of stator flux and if α is within (90°, 270°), it decreases the amplidue of stator flux. If α is within (0°, 180°), the applied voltage vector increases torque angle and if α is within (180°, 360°), it decreases torque angle.

In stator flux reference frame, torque of the PMSM in terms of the amplitude of stator flux and torque angle is presented in (6), where L_d and L_d are d- and q-axis stator inductances, ψ_f is permanent magnet flux, p is number of pole paris, δ is torque angle.

$$T_e = \frac{3p\psi_f \hat{\psi}_s}{2L_d}(\sin\delta - k\sin\delta\cos\delta), \quad k = \frac{(L_q - L_d)\hat{\psi}_s}{L_q \psi_f} \tag{6}$$

Thus we can define M shown in (7) to represent the change of torque due to the application of voltage vector.

$$M = \sqrt{1+q^2+2q\cos\alpha}\,\sin(\delta+\arcsin\frac{q\sin\alpha}{\sqrt{1+q^2+2q\cos\alpha}})-\sin\delta$$
$$-k[(1+q^2+2q\cos\alpha)\sin(\delta+\arcsin\frac{q\sin\alpha}{\sqrt{1+q^2+2q\cos\alpha}})\cos(\delta+\arcsin\frac{q\sin\alpha}{\sqrt{1+q^2+2q\cos\alpha}})-\sin\delta\cos\delta] \quad (7)$$

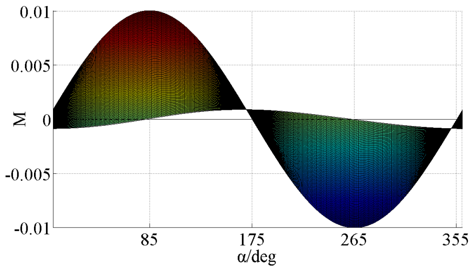

Figure 4 The change of torque @ δ=5°

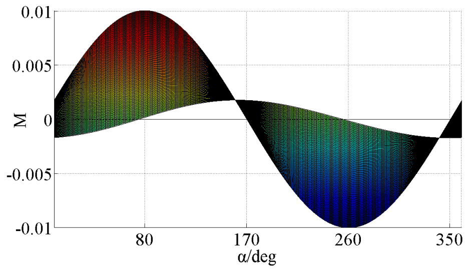

Figure 5 The change of torque @ δ=10°

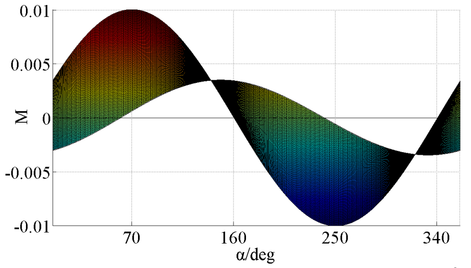

Figure 6 The change of torque @ δ=20°

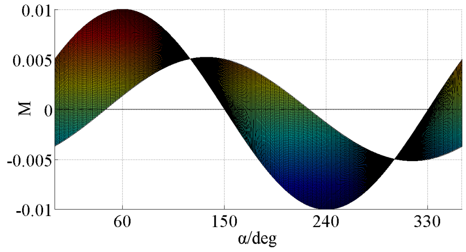

Figure 7 The change of torque @ δ=30°

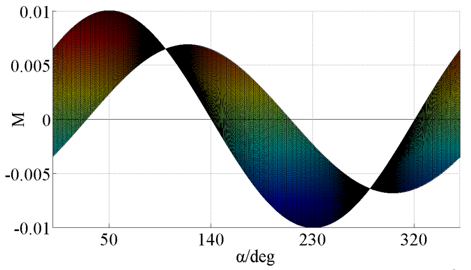

Figure 8 The change of torque @ δ=40°

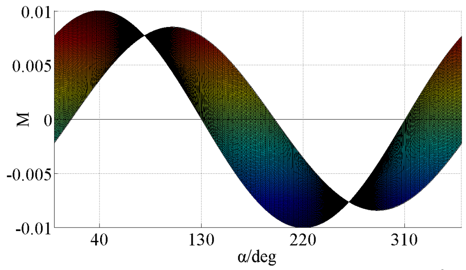

Figure 9 The change of torque @ δ=50°

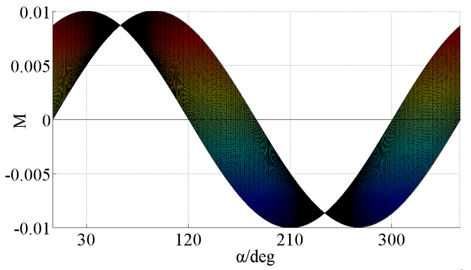

Figure 10 The change of torque @ δ=60°

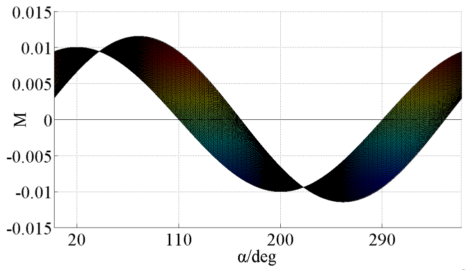

Figure 11 The change of torque @ δ=70°

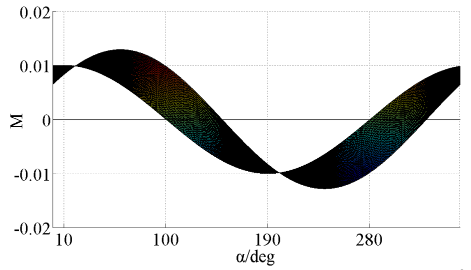

Figure 12 The change of torque @ δ=80°

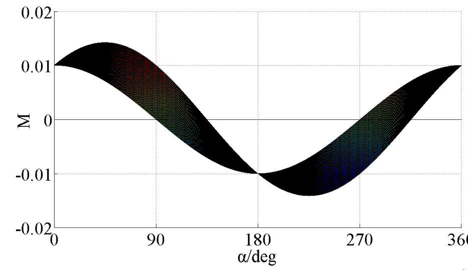

Figure 13 The change of torque @ δ=90°

The equation of M shows the change of torque is dependent on k, δ and α. When q=0.1, 0<k<1 and $0^{\circ}<\alpha<360^{\circ}$, the change of torque at different torque angle are shown in Figute 4 to Figure 13. Figure 4 to Figure 13 show when torque angle is less than 90°, if α is within (90°-δ, 180°-δ), the applied voltage vector must increase torque and if α is within (270°-δ, 360°-δ), it must decrease torque.

3. Voltage vector selection strategy

According to the control of stator flux, torque angle and torque, selection area for voltage vector V_{11} to increase stator flux and torque is (θ_r+90°, θ_s+90°), selection area for voltage vector V_{01} to decrease stator flux and increase torque is (θ_s+90°, θ_r+180°), selection area for voltage vector V_{00} to decrease stator flux and torque is (θ_r+270°, θ_s+180°), selection area for voltage vector V_{10} to increase stator flux and decrease torque is (θ_s+180°, θ_r+360°), where θ_s and θ_r are angular position of stator and rotor flux in stationary referece frame.

Any voltage vector in selection area can be used to control stator flux and torque, so there are unlimited voltage vector selection strategies. Here a voltage vector selection strategy is proposed as an example, which is shown in (8).

$$\begin{cases} \angle\vec{V}_{11} = \mathrm{mod}(90^{\circ} + \theta_s - \dfrac{\delta}{2},\ \ 360^{\circ}) \\ \angle\vec{V}_{01} = \mathrm{mod}(90^{\circ} + \theta_s + \dfrac{90^{\circ} - \delta}{2},\ \ 360^{\circ}) \\ \angle\vec{V}_{00} = \mathrm{mod}(\angle\vec{V}_{11} + 180^{\circ},\ \ 360^{\circ}) \\ \angle\vec{V}_{10} = \mathrm{mod}(\angle\vec{V}_{01} + 180^{\circ},\ \ 360^{\circ}) \end{cases} \tag{8}$$

According to (8), the angle of applied voltage vector is arbitrary. A voltage source inverter (VSI) can only generate a limited number of discrete voltage vectors with fixed amplitude and angle, so the SVM must be used to synthestize the applied voltage vector. In the SVM, the amplitude of applied voltage vector is constant which is the radius of the inscribed circle of the hexagon shown in Fig. 14. Assuming the angle of applied voltage vector V_s is within (0°, 60°), V_1, V_2 and V_0 are used to synthesize V_s. The principle of SVM is shown in Fig. 15, where λ is the angle between V_1 and V_s.

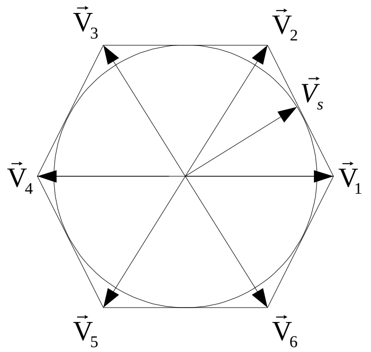

Figure 14 The amplitude of applied voltage vector

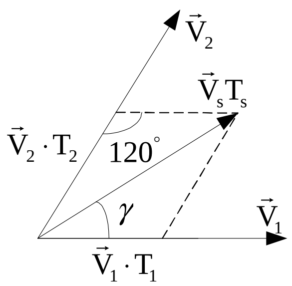

Figure 15 The SVM

According to Fig. 15 and the law of sine, we can get (9), where U_{dc} is dc-link voltage of VSI and T_s is the sampling period.

$$\frac{2U_{dc}T_2}{3\sin\gamma} = \frac{2U_{dc}T_1}{3\sin(60^{\circ}-\gamma)} = \frac{\sqrt{3}U_{dc}T_s}{3\sin 120^{\circ}} \tag{9}$$

Thus in a sampling period T_s, the applying periods of V_1, V_2 and V_0 are shown in (10).

$$\begin{cases} T_1 = \sin(60^{\circ} - \gamma)\cdot T_s \\ T_2 = \sin\gamma \cdot T_s \\ T_0 = T_s - T_1 - T_2 \end{cases} \tag{10}$$

The diagram of PMSM DTC drive using proposed voltage vector selection strategy is shown in Fig.16, where equ. (8) is used as voltage vector selection strategy, a look-up table is used to determine torque angle, ϕ and τ are outputs of hysteresis comparators for stator flux and torque and S_A, S_B and S_c are switching signals of VSI.

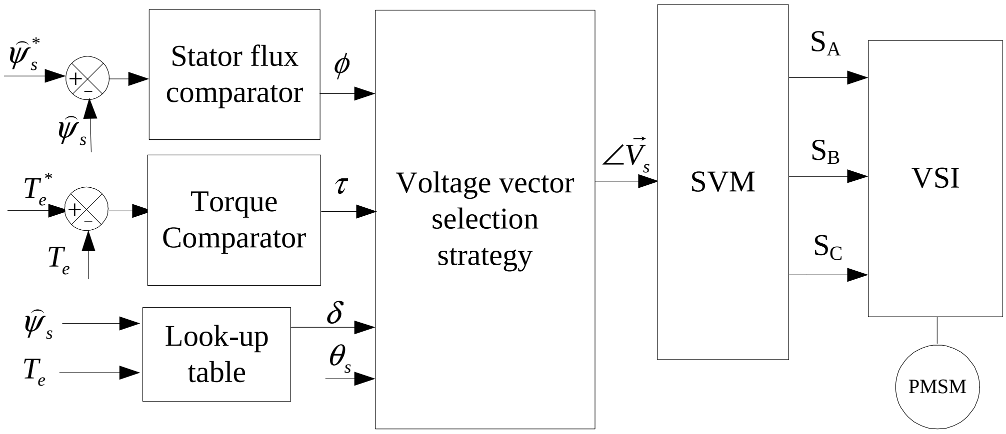

Figure 16 The interior PMSM DTC drive using voltage vector selection strategy

Fig. 16 shows voltage vector selection strategy is used to determine the applying voltage vector instead of switching table, which ensures applied voltage vectors can always satisfy the control of stator flux, torque angle and torque. The proposed DTC still uses hysteresis comparators to control stator flux and torque and doesn't require any additonal PI controllers, which maintains the simplicity in conventional DTC. In additon, as the SVM is used to generate switching signals, which fixes switching frequency of VSI.

4. Simulation results

In this section, PMSM DTC drive simulation model based on Matlab/Simulink is built to testify theoretical analysis. The simulation model is the continuous system with open loop speed control. The motor used in simulation is an interior PMSM used in Honda Civic 06My Hybrid electrical vehicle, whose parameters are shown in Table. 1. The reference amplitude of stator flux is 0.06Wb. The reference torque is 44.02Nm and its corresponding torque angle is 75°. The hysteresis band for the amplitude of stator flux is 0.002Wb and the hysteresis band for torque is 0.02Nm. Simulation results of PMSM DTC drive under the control of switching table and voltage vector selection strategy shown in (8) are given as follows. Switching table used in PMSM DTC drive is shown in Table. 2.

Table 1. The Performance of test motor

Pole pairs (p)	Stator resistance (R_s/ Ω)	d-axis stator inductance (L_d/mH)	q-axis stator inductance (L_q/mH)	Permanent magnet flux (ψ_f/Wb)
6	0.0142	0.6660	0.8745	0.06

Table 2. Switching table of PMSM DTC drive

ϕ	τ	θ_1	θ_2	θ_3	θ_4	θ_5	θ_6
1	1	V_2	V_3	V_4	V_5	V_6	V_1
1	0	V_6	V_1	V_2	V_3	V_4	V_5
0	1	V_3	V_4	V_5	V_6	V_1	V_2
0	0	V_5	V_6	V_1	V_2	V_3	V_4

4.1. Switching table

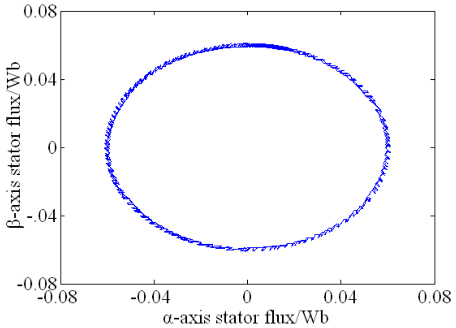

Figure 17 Stator flux circle

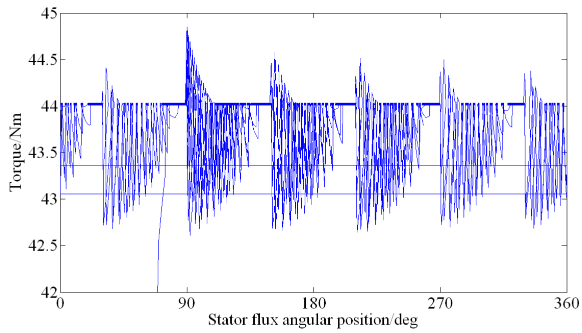

Figure 18 Torque versus stator flux angular position

4.2. Voltage vector selection strategy

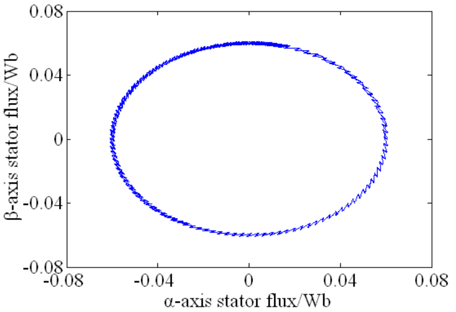

Figure 19 Stator flux circle

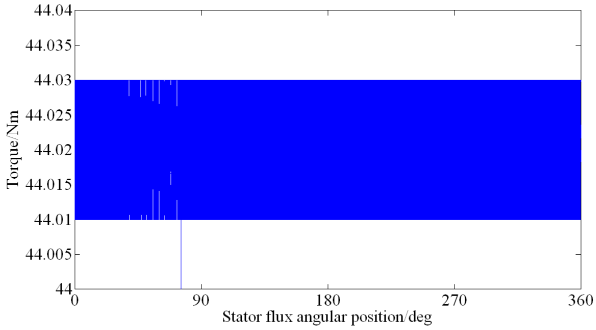

Figure 20 Torque versus stator flux angular position

4.3. Analysis

Comparing simulation results of PMSM DTC drive using switching table and voltage vector selection strategy, we can know switching table can always satisfy the control of the amplitude of stator flux, but it can't always satisfy the control of torque and causes torque ripple. And the proposed voltage vector selection strategy can always satisfy the control of stator flux and torque.

5. Experimental results

5.1. Test bench

The test bench is shown in Fig. 21. It consists of the tested motor (the interior PMSM used in Honda Civic 06My Hybrid electrical vehicle), a controlled DC motor used to load the PMSM and a torque meter (Vibro-Meter TG-10BP-M3). All time-dependent functions (current, voltage, torque and speed) presented in this thesis are recorded by an oscilloscope (LeCroy wave Surfer 44Xs Oscilloscope).

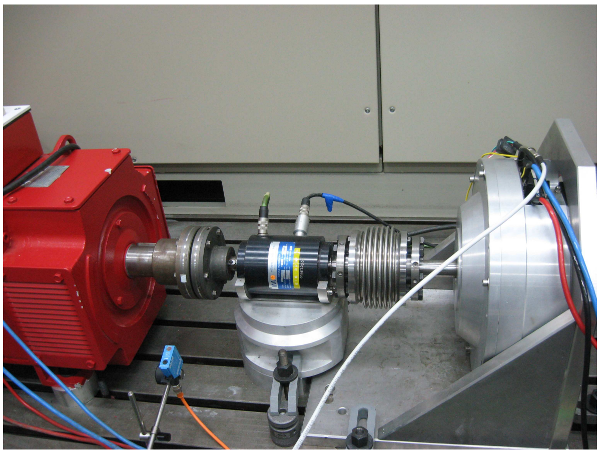
Figure 21 Test bench

The reference speed is 100rpm. The reference amplitude of stator flux is 0.06Wb. The widths of hysteresis band for stator flux and torque are 0.02Wb and 0.02Nm. Experimetnal results of PMSM DTC drive under the control of switching table and voltage vector selection strategy shown in (8) are given as follows.

5.2. Switching table

Figure 22 The a-phase stator current (yellow wave, 5A/div), motor speed (green wave, 50rpm/div) and load torque (red wave, 10Nm/div) @ no-load

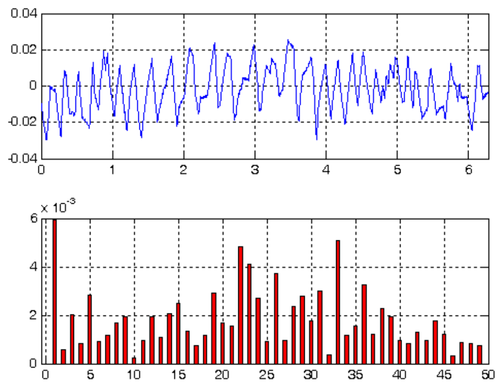

Figure 23 FFT of a-phase stator current @ empty load

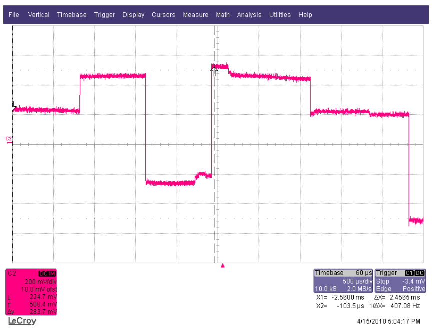

Figure 24 The a-phase stator voltage (40V/div) @ no-load

Figure 25 The a-phase stator current (yellow, 20A/div), motor speed (green, 50rpm/div) and load torque (red, 10Nm/div) @ load

Figure 26 FFT of a-phase stator current @ load

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5.3. Voltage vector selection strategy

Figure 28 The a-phase stator current (yellow, 5A/div), motor speed (green, 50rpm/div) and load torque (red, 10Nm/div) @ no-load

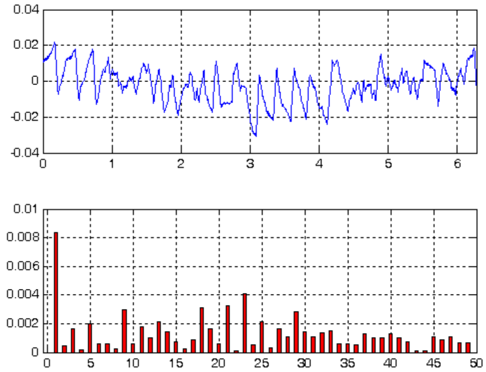

Figure 29 FFT of a-phase stator current @ empty load

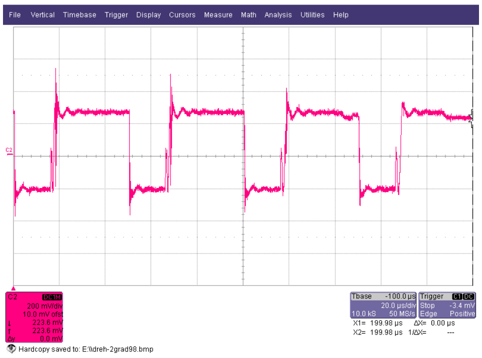

Figure 30 The a-phase stator voltage (40V/div) @ no-load

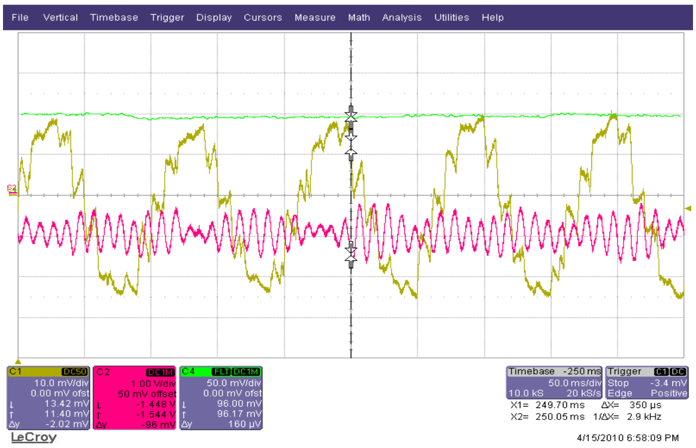

Figure 31 The a-phase stator current (yellow, 20A/div), motor speed (green, 50rpm/div) and load torque (red, 10Nm/div) @ load

Figure 32 FFT of a-phase stator current @ load

5.4. Analysis

Comparing experimental results of PMSM DTC drive under the control of switching table and voltage vector selection strategy, we can know the proposed voltage vector selection strategy can reduce the total harmonics of stator current and decrease current and torque ripples compared with switching table. In addition, switching frequency is fixed in PMSM DTC drive using voltage vector selection strategy due to the use of SVM compared with using switching table.

6. Conclusion

In this paper, the control of stator flux, torque angle and torque in PMSM DTC drive is investigated. The angle between stator flux and the applied voltage vector (α) determines the control of stator flux and torque angle. If α is within (-90°, 90°), the applied voltage vector increases stator flux and if α is within (90°, 270°), it decreases stator flux. If α is within (0°, 180°), the applied voltage vector increases torque angle and if α is within (180°, 360°), it decreases torque angle. When torque angle is less than 90°, if α is within ($90^{\circ}-\delta$, $180^{\circ}-\delta$), the applied voltage vector must increase torque and if α is within ($270^{\circ}-\delta$, $360^{\circ}-\delta$), it must decrease torque. Thus selection area for V_{11} is (θ_r+90°, θ_s+90°), selection area for V_{01} is (θ_s+90°, θ_r+180°), selection area for V_{00} is (θ_r+270°, θ_s+180°), selection area for V_{10} is (θ_s+180°, θ_r+360°). A voltage vector selection strategy is proposed which uses stator flux position and torque angle information to determine the applied voltage vector and uses SVM to generate it. Simulation and experimental results prove the proposed voltage vector selection strategy can decrease stator current and torque ripples and fix switching frequency compared with switching table.

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Bibliography of authors

Li Yaohua, received the B.E. degree in autocontrol from Nanjing University of Aeronautics and Astronautics, Nanjing, China, in 2002, the M. E. degree in control theory and control engineering from Shaan'xi Univerisy of Sciense and Technology, Xianyang, China, in 2005 and Dr.-Ing degree in electrical engineering from Unveristy of Federal defense, Munich, Germany, in 2010.
He is currently lectuer of School of automobile of Chang'an University, Xi'an, China.
His research interests include electrical vehicle, high-performance motor control and advanced digital control with real-time implementation.

Ma Jian, received the B.E. degree, the M. E. degree and Dr.-Ing degree in vehicle engineering from Chang'an University, China.
He is currently professor of School of automobile of Chang'an University, Xi'an, China.
His research interests include electrical vehicle, high-performance motor control and advanced digital control with real-time implementation.

Yu Qiang, received the B.E. degree, the M. E. degree and Dr.-Ing degree in vehicle engineering from Chang'an University, China.
He is currently prefessor of School of automobile of Chang'an University, Xi'an, China.
His research interests include electrical vehicle, high-performance motor control and advanced digital control with real-time implementation.

Liu Jingyu received the B.E. degree, the M. E. degree and Dr.-Ing degree in vehicle engineering from Chang'an University, China.
She is currently prefessor of School of automobile of Chang'an University, Xi'an, China.
Her research interests include electrical vehicle, high-performance motor control and advanced digital control with real-time implementation.