*EVS25*

*Shenzhen, China, Nov 5-9, 2010*

# The Comparison of Control Strategies for the Interior PMSM Drive used in the Electric Vehicle

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**Abstract—**The interior permanent magnet synchronous motor (PMSM) can offer many advantages, including high power-to-weight ratio, high efficiency, rugged construction, low cogging torque and the capability of reluctance torque, so it is widely used in electric vehicle (EV). Two control schemes, namely field oriented control (FOC) and direct torque control (DTC) are used in PMSM drive. In order to decrease current and torque ripple and fix switching frequency, an improved DTC scheme based on the control of stator flux, torque angle and torque was proposed, which used voltage vector selection strategy and the technology of space vector modulation (SVM) to generate the applied voltage vector instead of switching table. And this paper compared these three control schemes based on a 15-kW interior PMSM used in Honda Civic 06My hybrid electrical vehicle. Experimental results show for the FOC using the hysteresis current control, due to the lower sampling period, stator current is more sinusoidal. But it needs the continuous rotor position information and the switching frequency of the VSI is not constant. For the DTC using switching table, current ripple is higher and the switching frequency of the VSI is also not constant. But it does not need the rotor position information except for the initial rotor position. Compared with switching table, the proposed DTC can decrease current and torque ripple and fix switching frequency.

**Keywords—***electric vehicle, permanent magnet synchronous motor, field oriented control, direct torque control*

## 1. Introduction

Electric propulsion systems are the hearts of EV. They consist of electric motors, power converters and electronic controllers[1]. As the interior PMSM can offer many advantages, including high power-to-weight ratio, high efficiency, rugged construction, low cogging torque and the capability of the additional reluctance torque, it is widely used in the modern EV and hybrid EV. For the interior PMSM, there are two different high-performance control strategies, namely, the FOC and the DTC. Both of them are widely used in the industry application. The FOC is implemented in the rotor flux reference frame and needs the continuous rotor position information to implement the coordinate transformation. The DTC is implemented in the stationary reference frame, doesn't need the continuous rotor position information except for the initial rotor position. But it suffers from high current and torque ripples and variable switching frequency[2]-[8].

In order to decrease current and torque ripple and fix switching frequency, an improved DTC scheme based on the control of stator flux, torque angle and torque was proposed, which used voltage vector selection strategy and the technology of space vector modulation (SVM) to generate the applied voltage vector instead of switching table. And this paper compared these three control schemes based on a 15-kW interior PMSM used in Honda Civic 06My hybrid electrical vehicle.

## 2. The description of test bench

The tested electric drives used in this paper consist of three parts: the tested motor, the voltage source inverter (VSI) and the processor.

The tested motor is a 3-phase, 15-kW interior PMSM used in Honda Civic 06My hybrid electrical vehicle. Its parameters are shown in Tab. 1.

Table 1: The parameters of the tested motor

| | | |
|---|---|---|
| Pole pairs | p | 6 |
| Stator resistance | $R_s$ | 0.0142 Ω |
| d-axis stator inductance | $L_d$ | 0.6660mH |
| q-axis stator inductance | $L_q$ | 0.8745mH |
| Permanent flux | $\psi_f$ | 0.06Wb |

Three single-phase insulated gate bipolar transistor (IGBT) intelligent power modules (Semikron semix 202GB066HDs) are used for the VSI. SKYPER 32R is used to drive the power module. The cooling style of the inverter is forced water-cooling. The dc-link voltage and two-phase stator currents are sensed by isolated devices and fed back to the processor. AD 628 is used to measure the dc-link voltage and LEM HC2F-80s is used to measure stator current. An incremental encoder integrated into the motor is used to determine the rotor position. All the control schemes are implemented on a digital signal processor (DSP) TMS320F2812. The real time software is downloaded from Matlab/Simulink to the DSP directly.

The test bench is shown in Fig. 1. It consists of the tested motor, 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).

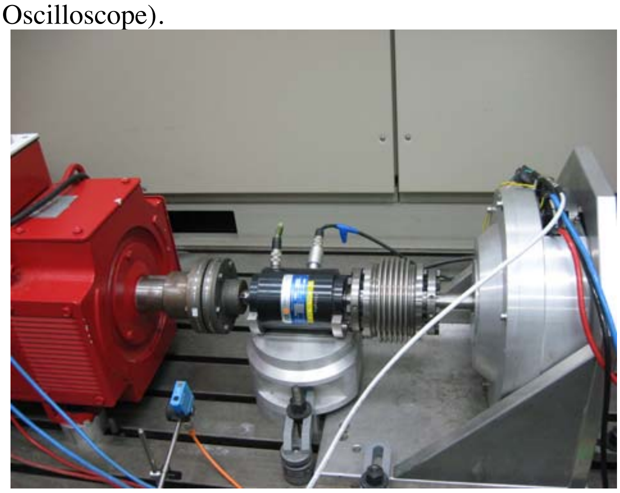

Figure 1: The test bench

## 3. The FOC

In the rotor flux reference frame, the torque of PMSM is shown in (1).

$$T_e = \frac{3}{2} p[\psi_f i_q + (L_d - L_q) i_d i_q] \quad (1)$$

And equ. (1) shows if the d-axis stator current is kept constant, the torque is proportional to the q-axis stator current. In this paper, the hysteresis current control is used to implement the FOC and the diagram of the FOC system is shown in Fig. 2. And Fig. 2 shows the implementation of the FOC needs the continuous rotor position information.

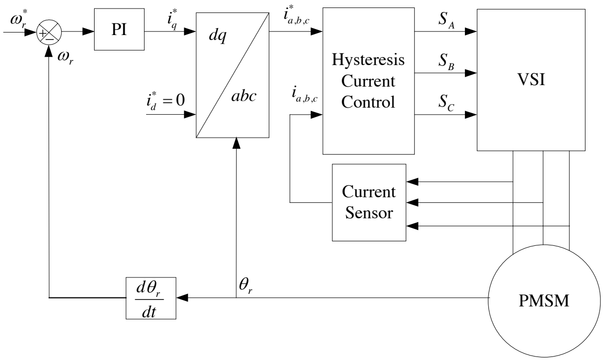


Figure 2: The diagram of the FOC system

The hysteresis bands for the control of three-phase stator currents are 0.02A. The sampling period for the speed control is 0.01s and the sampling period for the current control is 100μs. The reference speed is 100rpm and the d-axis reference stator current is 0A. When the speed of the motor is 100rpm, the a-phase stator current and stator voltage are shown in Fig. 3 and Fig. 4. Experimental results show under the control of the FOC stator current is sinusoidal, but the switching frequency of the VSI is not constant due to the use of the hysteresis control.

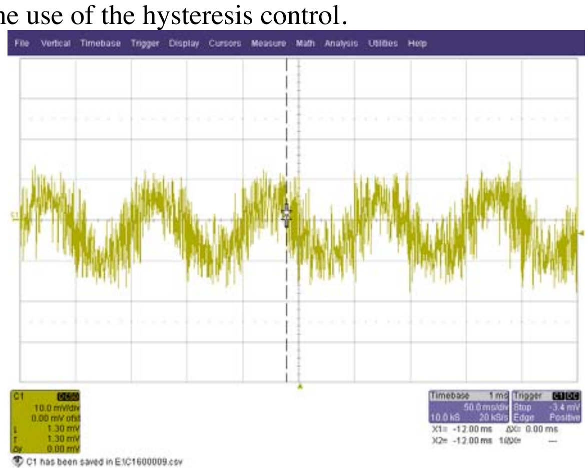

Figure 3: The a-phase stator current (5A/div)

Figure 4: The a-phase stator voltage (4V/div)

# 4. The DTC

In stator flux reference frame, the torque of PMSM in terms of the amplitude of stator flux and torque angle (the angle between stator and rotor flux vector) is shown in (2).

$$T_e = \frac{3p\hat{\psi}_s}{4L_d L_q}[2\psi_f L_q \sin\delta - \hat{\psi}_s (L_q - L_d)\sin 2\delta] \quad (2)$$

And equ. (2) shows if the amplitude of stator flux is kept constant, the torque of PMSM is determined by torque angle. Normally we apply a proper voltage vector to change the angular position of stator flux vector to change torque angle. And switching table is used as voltage vector selection strategy. The diagram of the DTC system using switching table is shown in Fig. 5. And Fig. 5 shows the implementation of the DTC doesn't need the continuous rotor position information. Switching table used in the DTC is shown in Tab. 2, where voltage vectors ($V_1$ to $V_6$) and stator flux sectors ($\theta_1$ to $\theta_6$) are shown in Fig. 6.

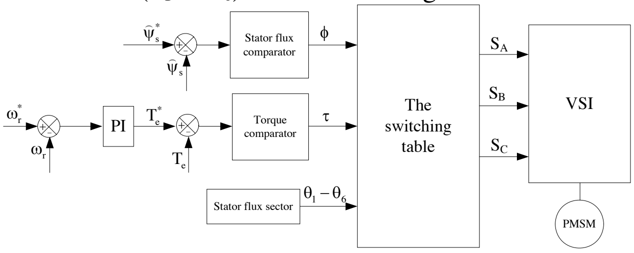


Figure 5: The diagram of PMSM DTC system using switching table

Table 2: Switching table used in the DTC for PMSM

| $\phi$ | $\tau$ | $\theta_1$ | $\theta_2$ | $\theta_3$ | $\theta_4$ | $\theta_5$ | $\theta_6$ |
|---|---|---|---|---|---|---|---|
| 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 | $V_5$ | $V_6$ | $V_1$ | $V_2$ | $V_3$ | $V_4$ |

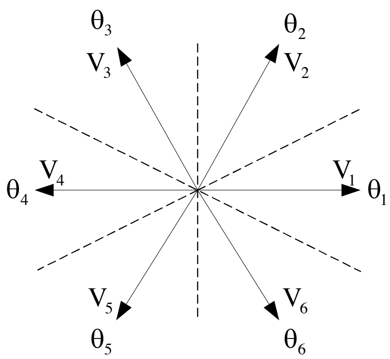


Figure 6: Voltage vectors and stator flux sectors

The hysteresis band for the amplitude of stator flux is 0.002Wb and the hysteresis band for torque is 0.002Nm. The sampling period for speed control loop is 0.01s and the sampling period for stator flux and torque control loop is 350 μ s. The reference speed is 100rpm and the reference amplitude of stator flux is 0.06Wb. When the speed of the motor is 100rpm, the a-phase stator current and stator voltage are shown in Fig. 7 and Fig. 8. Experimental results show under the control of the DTC stator current ripples are higher due to higher sampling period compared with the FOC. And the switching frequency of the VSI is also not constant due to the use of hysteresis control.

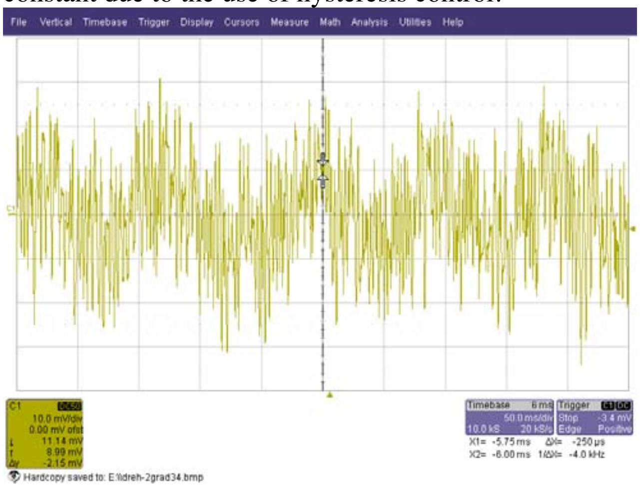

Figure 7: The a-phase stator current (5A/div)

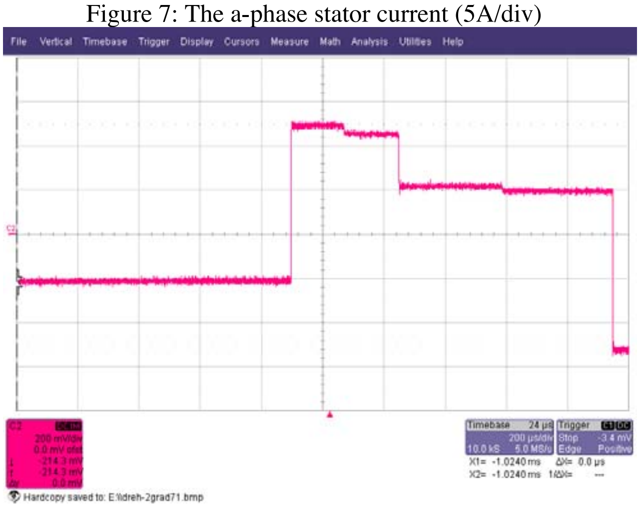

Figure 8: The a-phase stator voltage (4V/div)

# 5. Effects of voltage vector

In nature the DTC is the hysteresis control. The voltage vector selection strategy as the hysteresis control principle is critical to improve the control performance of the PMSM DTC drive.

Neglecting the voltage drop on stator resistance, after applying a voltage vector for a short period Δt, stator flux vector of the motor is presented in (3) and Fig. 9. And Fig. 9 implies the application of the voltage vector will change the amplitude and angular position of stator flux vector at the same time. And the latter will affect the change of torque angle.

$$\vec{\psi}_s' = \vec{\psi}_s + \vec{V}_s \cdot \Delta t - \vec{i}_s \cdot R_s \cdot \Delta t \approx \vec{\psi}_s + \vec{V}_s \cdot \Delta t \quad (3)$$

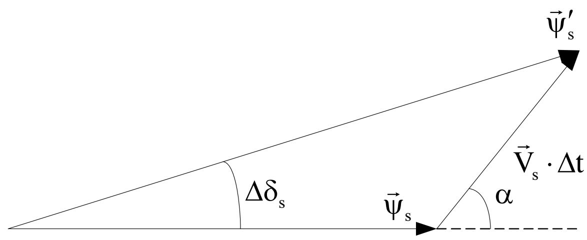


Figure 9: The move of stator flux vector due to the application of voltage vector

According the law of cosine and Fig. 9, after applying the voltage vector for Δt, the amplitude of stator flux can be expressed in (4).

$$\hat{\psi}_s' = \sqrt{\hat{\psi}_s^2 + (\hat{V}_s \cdot \Delta t)^2 + 2\hat{\psi}_s \cdot \hat{V}_s \cdot \Delta t \cdot \cos\alpha} \quad (4)$$

Here we define q as the following and equ. (4) can be rewritten into (6).

$$q = \hat{V}_s \cdot \Delta t / \hat{\psi}_s \quad (5)$$

$$\hat{\psi}_s' = \hat{\psi}_s \sqrt{1 + q^2 + 2q\cos\alpha} \quad (6)$$

Here we define f shown in (7) to represent the change of the amplitude of stator flux due to the application of the voltage vector. If f>0 means the voltage vector increases the amplitude of stator flux and if f<0 means the voltage vector decreases it. According to equ. (7), f versus α with the parameter 0<q<0.01 is shown in Fig. 10.

$$f = \sqrt{1 + q^2 + 2q\cos\alpha} - 1 \quad (7)$$

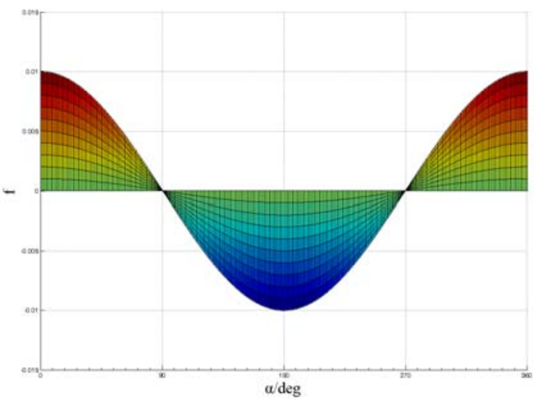

Fig. 10. f versus α with the parameter 0<q<0.01

Fig. 10 shows if the angle between stator flux vector and the applying voltage vector is within (-90°, 90°), the voltage vector increases the amplitude of stator flux and if the angle is within (90°, 270°), it decreases the amplitude of stator flux.

According the law of sine and equ. (5), neglecting the move of rotor flux vector, after applying the voltage vector for Δt, the change of torque angle can be expressed in (8).

$$\Delta\delta \approx \Delta\delta_s = \arcsin\frac{q\sin\alpha}{\sqrt{1 + q^2 + 2q\cos\alpha}} \quad (8)$$

According to equ. (8), Δδ versus α with the parameter 0<q<0.01 is shown in Fig. 11.

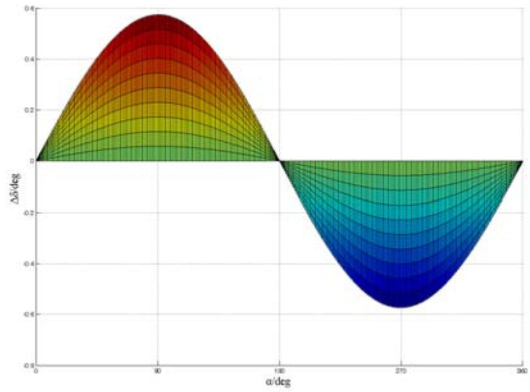

Fig. 11 Δδ versus α with the parameter 0<q<0.01

Fig. 11 shows if the angle between stator flux vector and the applying voltage vector is within (0°, 180°), the voltage vector increases torque angle and if the angle is within (180°, 360°), it decreases torque angle.

The change of torque is caused by the changes of the amplitude of stator flux and torque angle. Subsequently we discuss the effect of the voltage vector on torque.

Here we define k as the following and equ. (2) can be rewritten into (10).

$$k = \frac{(L_q - L_d)\hat{\psi}_s}{L_q \psi_f} \quad (9)$$

$$T_e = \frac{3p\psi_f \hat{\psi}_s}{2L_d}(\sin\delta - k\sin\delta\cos\delta) \quad (10)$$

According to the definition of k and equ. (9), after applying the voltage vector for Δt, the value of $k'$ is presented in (11).

$$k' = k\sqrt{1 + q^2 + 2q\cos\alpha} \quad (11)$$

Substituting (7), (8) and (11) into (10), we can get after applying the voltage vector for Δt, the torque of PMSM is shown in (12). Comparing (10) and (12), we can define M as (13) to represent the change of torque due to the application of the voltage vector. If M>0 means the voltage vector increases torque and if M<0 means the voltage vector decreases torque. Equ. (13) shows the change of torque due to the application of the voltage vector depends on k, δ and α.

$$\begin{aligned} T_e' = \frac{3p\psi_f \hat{\psi}_s}{2L_d}&\Big[\sqrt{1 + q^2 + 2q\cos\alpha}\,\sin\Big(\delta + \arcsin\frac{q\sin\alpha}{\sqrt{1 + q^2 + 2q\cos\alpha}}\Big) \\ &- k(1 + q^2 + 2q\cos\alpha)\sin\Big(\delta + \arcsin\frac{q\sin\alpha}{\sqrt{1 + q^2 + 2q\cos\alpha}}\Big)\cos\Big(\delta + \arcsin\frac{q\sin\alpha}{\sqrt{1 + q^2 + 2q\cos\alpha}}\Big)\Big] \end{aligned} \quad (12)$$

$$\begin{aligned} M &= \sqrt{1+q^2+2q\cos\alpha}\,\sin(\delta+\arcsin\frac{q\sin\alpha}{\sqrt{1+q^2+2q\cos\alpha}})-\sin\delta \\ &-k[(1+q^2+2q\cos\alpha)\sin(\delta+\arcsin\frac{q\sin\alpha}{\sqrt{1+q^2+2q\cos\alpha}})\cos(\delta+\arcsin\frac{q\sin\alpha}{\sqrt{1+q^2+2q\cos\alpha}})-\sin\delta\cos\delta] \end{aligned} \tag{13}$$

According to Tab. 1, when the amplitude of stator flux is 0.06Wb, k=0.238. According to equ. 13, M versus α with $0^\circ<\delta<90^\circ$ and k=0.238 is shown in Fig. 12.

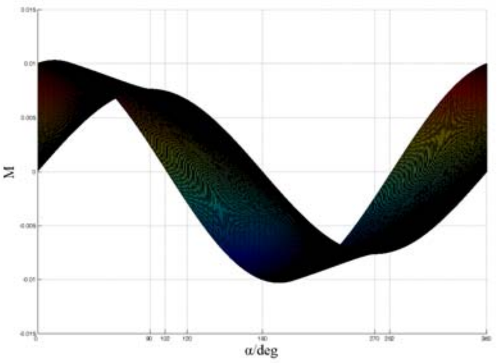


Fig. 12 M versus α with the parameter 0<q<0.01 and k=0.238

Fig. 12 shows if the angle between stator flux vector and the applying voltage vector is within (0°, 102°), the voltage vector must increase torque and if the angle is within (180°, 282°), it must decrease torque.

# 6. Voltage vector selection strategy

According to the effect of the voltage vector on the amplitude of stator flux, torque angle and torque of the tested motor, the selection area for $V_{11}$ (the voltage vector to increase the amplitude of stator flux, torque angle and torque) is ($\delta_s$, $\delta_s+90^\circ$), the selection area for $V_{01}$ (the voltage vector to decrease the amplitude of stator flux and increase torque angle and torque) is ($\delta_s+90^\circ$, $\delta_s+102^\circ$), the selection area for $V_{00}$ (the voltage vector to decrease the amplitude of stator flux, torque angle and torque) is ($\delta_s+180^\circ$, $\delta_s+270^\circ$), the selection area for $V_{10}$ (the voltage vector to increase the amplitude of stator flux and decrease torque angle and torque) is ($\delta_s+270^\circ$, $\delta_s+282^\circ$), where $\delta_s$ is the angular position of stator flux vector in the stationary reference frame.

According to Tab. 2 and Fig. 6, the angle between stator flux vector and $V_{11}$ is within (30°, 90°), the angle between stator flux vector and $V_{01}$ is within (90°, 150°), the angle between stator flux vector and $V_{00}$ is within (210°, 270°) and the angle between stator flux vector and $V_{10}$ is within (270°, 330°). Obviously, the switching table can always satisfy the control of the amplitude of stator flux and torque angle but can't always satisfy the control of torque.

According to voltage vector selection area, a simplified voltage vector selection strategy for the tested motor is proposed shown in (14), which can always satisfy the control of the amplitude of stator flux, torque angle and torque.

$$\begin{cases} \angle\vec{V}_{11} = \mathrm{mod}(\delta_s+60^\circ, 360^\circ) \\ \angle\vec{V}_{01} = \mathrm{mod}(\delta_s+100^\circ, 360^\circ) \\ \angle\vec{V}_{00} = \mathrm{mod}(\angle\vec{V}_{11}+180^\circ, 360^\circ) \\ \angle\vec{V}_{10} = \mathrm{mod}(\angle\vec{V}_{01}+180^\circ, 360^\circ) \end{cases} \tag{14}$$

Comparing equ. (14) and Tab. 2, we can know the angle between stator flux vector and the voltage vector determined by the switching table is variable. The angle between stator flux vector and the voltage vector determined by the voltage vector selection strategy is constant. The angle of the voltage vectors determined by the switching table is constant. The angle of the voltage vectors determined by equ. (14) is variable which depends on the angular position of stator flux vector. Both of them need the angular position of stator flux vector in the stationary reference frame.

As the angle of the voltage vector determined by the voltage vector selection strategy is arbitrary, the technology of space vector modulation (SVM) is used to generate the voltage vector. The diagram of the DTC system based on the voltage vector selection strategy is shown in Fig. 13.

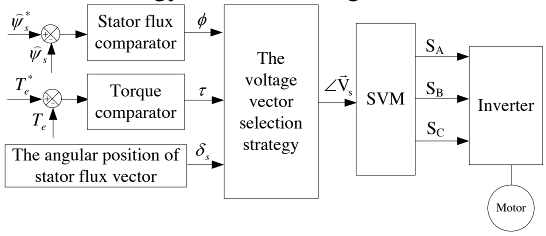


Figure 13: The diagram of the DTC system using voltage vector selection strategy

Fig. 13 shows compared with the DTC system using the switching table, the hysteresis comparators are still used to control the amplitude of stator flux and torque, but the voltage vector selection strategy and the SVM are used to generate the switching signals instead of the switching table. Thus the voltage vector selection strategy proposed in this paper can decrease torque ripple and fix the switching frequency.

The hysteresis band for the amplitude of stator flux is 0.002Wb and the hysteresis band for torque is 0.002Nm. The sampling period for speed control loop is 0.01s and the sampling period for stator flux and torque control loop is 350μs. The reference speed is 100rpm and the reference amplitude of stator flux is 0.06Wb. When the speed of the motor is 100rpm, the a-phase stator current (the yellow wave) and stator voltage (the red wave) are shown in Fig. 14 to Fig. 16.

Figure 14: The a-phase stator current (5A/div)

Figure 15: The a-phase stator voltage (4V/div)

Figure 16: The a-phase stator current ( 5A/div) and stator voltage (4V/div)

Experimental results show under the control of the voltage vector selection strategy current ripples are lower compared with the switching table. And the switching frequency of the VSI is constant due to the use of the SVM. Fig. 16 shows hysteresis comparators are still used in the DTC.

When the motor speed is 100rpm, a same negative load torque is applied on the PMSM. And the a-phase stator current (the yellow wave) and the load torque (the red wave) under the control of the switching table and voltage vector selection strategy are shown in Fig. 17 and Fig. 18, respectively.

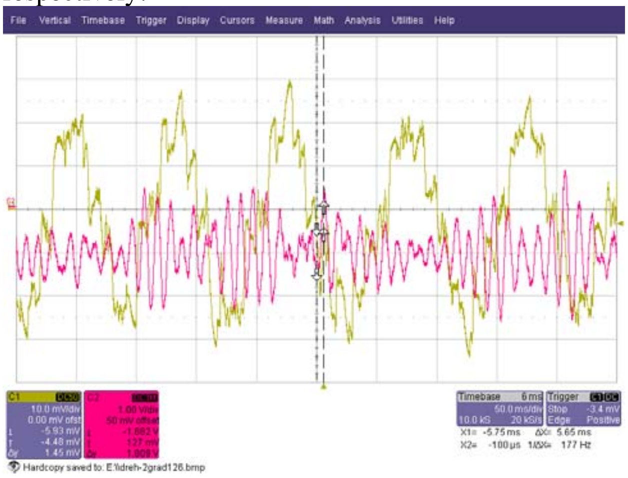

Figure 17: The a-phase stator current ( 20A/div) and the load torque (10Nm/div)

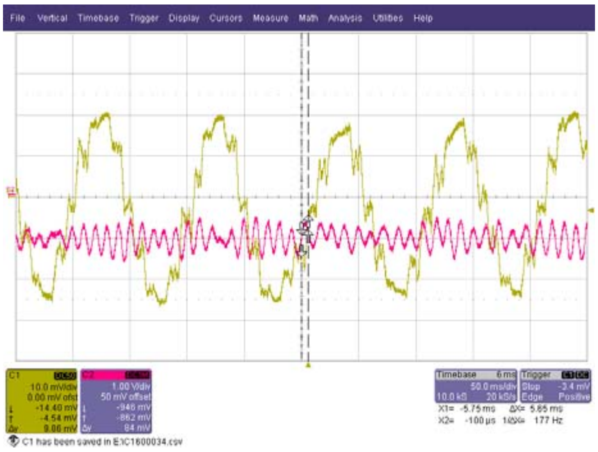

Figure 18: The a-phase stator current (20A/div) and the load torque (10Nm/div)

Comparing Fig. 17 and Fig. 18, we can get the voltage vector selection strategy can decrease stator current and torque ripples compared with the switching table.

## 7. Conclusion

Comparing the experimental results of the interior PMSM drive used in the electric vehicle under the control of the different control strategies, we can get conclusions as the following. For the FOC using the hysteresis current control, due to the lower sampling period, stator current is more sinusoidal. But it needs the continuous rotor position information and the switching frequency of the VSI is not constant. For the DTC using the switching table, current ripple is higher and the switching frequency of the VSI is also not constant. But it does not need the rotor position information except for the initial rotor position. Comparing with the switching table, the voltage vector selection strategy proposed in this paper can decrease current and torque ripple and fix switching frequency.

## Acknowledgments

This work was financially supported by China Postdoctoral Science Foundation funded project (20110491636) and Special Fund for Basic Scientific Research of Central Colleagues, Chang'an University funded project (CHD2011JC136).

## References

[1] Mehrada Ehsani, Yimin Gao, Sebastien E. Gay, Ali Emadi, "Modern electric, hybrid electric, and fuel cell vehicles". CRC Press, New York, 2005.

[2] L. Zhong, M. F. Rahman, W. Y. Hu, K. W. Lim, "Analysis of direct torque control in permanent magnet synchronous motor drives," IEEE Transactions on Power Electronics, Vol. 12, No. 3, pp. 528-536, May 1997.

[3] L. Zhong, M. F. Rahman, W. Y. Hu, K. W. Lim, "A direct torque controller for permanent magnet synchronous motor drives," IEEE Transactions on Energy Conversion, Vol. 14, No. 3, pp. 637-642, September 1999.

[4] M. F. Rahman, L. Zhong, K. W. Lim, "A direct torque-controlled interior permanent magnet synchronous motor drives incorporating field weakening," IEEE Transactions on Industry Application, Vol. 34, No. 6, pp. 1246-1253, November/Decmber 1998.

[5] L. X. Tang, L. Zhong, M. F. Rahman, "A novel direct torque controlled interior permanent magnet synchronous machine drive with low ripple in flux and torque and fixed switching frequency," IEEE Transactions on Power Electronics, Vol. 19, No. 2, pp. 346-354, March 2004.

[6] L. X. Tang, L. Zhong, M. F. Rahman, "A novel direct torque control for interior permanent-magnet synchronous machine drive with low ripple in torque and flux-a speed-sensorless approach," IEEE Transactions on Industry Application, Vol. 39, No. 6, pp. 1748-1756, November/December 2003.

[7] Yaohua Li, Dieter Gerling, Weiguo Liu "A Novel Switching Table to Suppress Unreasonable Torque Ripple for the PMSM DTC Drives," ICEMS 2008, pp. 972-977, 2008.

[8] Yaohua Li, Dieter Gerling, Weiguo Liu "The Control of Stator Flux and Torque in the Surface Permanent Magnet Synchronous Motor Direct Torque Control System," ICIEA 2009, pp. 2004-2009, 2009.

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