Front. Electr. Electron. Eng. China 2010, 5(1): 91–99
DOI 10.1007/s11460-009-0067-1

RESEARCH ARTICLE

F. HEYDARI, A. SHEIKHOLESLAMI, K. G. FIROUZJAH, S. LESAN

Predictive field-oriented control of PMSM with space vector modulation technique

Abstract This paper is concerned with two popular and powerful methods in electrical drive applications: field-oriented control (FOC) and space vector modulation (SVM). The proposed FOC-SVM method is incorporated with a predictive current control (PCC)-based technique. The suggested method estimates the desirable electrical torque to track mechanical torque at a fixed speed operation of permanent magnet synchronous motor (PMSM). The estimated torque is used to calculate the reference current based on FOC. In order to improve the performance of the traditional SVM, a PCC method is established as a switching pattern modifier. Therefore, PCC-based SVM is employed to further minimize the torque ripples and transient response. The performance of the controller is evaluated in terms of torque and current ripple and transient response to step variations of the torque command. The proposed method has been verified with MATLAB-Simulink model. Simulation results confirm the ability of this technique in minimizing the torque and speed ripples and fixing switching frequency, simultaneously. However, it is sensitive to parameter changes.

Keywords permanent magnet synchronous motor (PMSM), predictive current control (PCC), field-oriented control (FOC), space vector modulation (SVM), constant switching frequency

1 Introduction

In recent years, permanent magnet synchronous motors (PMSMs) have gained an increasing popularity in a variety of industrial applications [1]. In addition, many researchers have tried to reduce the torque pulses and harmonics in PMSM. There are many ways to use power converters to fix the voltage or current in a PMSM driver to desired set point. There are two popular modulation methods for inverter voltage control. One is voltage control (such as six-step, sinusoidal, and space-vector modulation), and the other is current control (such as hysteresis and delta modulation) [2]. Since important improvements have been made regarding the control techniques of the special machines, adequate operation for any industrial application is obtained with the appropriate supplying-motor assembly. In the same way, two of the control techniques, which are called field-oriented control (FOC) and direct torque control (DTC), respectively [3], are widely used in this industrial environment. These control strategies are different on the operation principle but their objectives are the same. They both aim to control effectively the motor torque and flux in order to force the motor to accurately track the command trajectory regardless of the machine and load parameter variation or any extraneous disturbances. Both control strategies have been successfully implemented in industrial products [4].

DTC is able to produce very fast torque and flux control, if the torque and the flux are correctly estimated, and will be robust with respect to motor parameters and perturbations. By controlling stator current by FOC, it reduces torque ripple for quieter motor operation. The supporters of FOC and DTC claim the superiority of their strategy versus the other. The question of which strategy is superior has not been clearly answered [5]. Nonetheless, the DTC-based controllers are very little sensible to the parameters detuning in comparison with FOC, and operation with variable switching frequency and large torque ripple (due to the hysteresis comparators) are the disadvantages of these controllers [6].

The idea of combining the advantages of DTC and PMSMs into a highly dynamic drive appeared in the literature in the late 1990s [7,8]. In the past decade, several authors have proposed ways to adapt DTC to work with

Received April 28, 2009; accepted July 14, 2009

F. HEYDARI, A. SHEIKHOLESLAMI, K. G. FIROUZJAH (✉), S. LESAN
Faculty of Electrical and Computer Engineering, Noshirvani University of Technology, Babol 47135-484, Iran
E-mail: kgorgani@stu.nit.ac.ir

PMSMs [9]. In 1989, Ref. [10] presented the PMSM, which was one of several types of permanent magnet (PM) alternating current (AC) motor drives available in the drives industry. They did not consider the damper windings and designed the motor drive system in FOC. Reference [11] developed FOC in PMSM and presented a microprocessor-based FOC for PM hysteresis synchronous motor. Recently, some researches have been devoted on the torque and flux ripple reduction and fixing the switching frequency of the DTC system [12–17]. In the literature, a modified DTC scheme with fixed switching frequency and low torque and flux ripple was introduced in Refs. [14–17]. With this design, however, two proportional integral (PI) regulators are required to control the flux and torque, and they need to be tuned properly. To reduce the torque ripples, Ref. [18] proposed a fuzzy logic algorithm to refine the selection of the voltage vectors. By using the space vector modulation (SVM), the torque and flux ripples can be more significantly reduced [19].

With mentioned in literature, the high current and torque ripple in DTC are due to the presence of hysteresis comparators together with the limited number of available voltage vectors [20]. Due to this disadvantage of conventional current control, the current control of a PMSM by a predictive current control (PCC) technique based on SVM was presented in Ref. [21]. Other references applied predictive current control technique to PMSM drive system and voltage source inverter in Refs. [21–24] and Refs. [25–27], respectively. Reference [23] proposed a technique to reduce the current errors that exist due to the inaccuracies in the system parameters and the nonideal behavior of the inverter. In addition to these, Ref. [22] discretized the PMSM module to improve transient and steady state, which is better than the conventional predictive current controllers.

The significant advantages of SVM are the ease of microprocessor implementation [28]. Also, one advantage of FOC is that it increases efficiency, letting smaller motors replace larger ones without sacrificing torque and speed. Another advantage is that it offers higher and more dynamic performance in the case of speed and torque controlled AC drives [29]. Therefore, in order to utilize the capabilities of FOC and SVM techniques and eliminate the problems of variable switching frequency, a predictive current control-based method (compatible with both FOC and SVM methods) is proposed. In addition to the constant switching frequency, the proposed predictive technique is employed to reduce speed and torque ripple (by predicting the proper vector of the applied voltage at the PMSM terminal). The method uses the d-q form of motor equations and discretizes the equations to have controlled torque with lower error. The discretizing process in constant time period (T), leads to operate the proposed PMSM driver with constant switching frequency ($1/T$ Hz). The electromechanical relations of PMSM are used to estimate the desired currents and proper voltage vectors in synchronous speed terms.

2 Analytic mode of PMSM

Permanent magnet synchronous motor has widely been studied in the last two decades. The majority of devoted methods on PMSM are a set of equations depending on rotor position. By representing the motor equations in rotor reference frame, there is a set of equations independent of rotor position. The d and q axis currents will be obtained from two transformations. The first part transfers the three phases (a,b,c) to two phases (α,β). The second part is the quantities at stationary frame to rotational frame:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}, \tag{1}$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}, \tag{2}$$

where θ represents the rotor position, i_α and i_β are the stator currents at stationary reference frame, and i_d and i_q are the stator currents at rotational reference frame.

Electromechanical behavior of the PMSM in the d-q frame is as follows:

$$V_q = Ri_q + \omega_r\lambda_d + \frac{d\lambda_q}{dt}, \tag{3}$$

$$V_d = Ri_d - \omega_r\lambda_q + \frac{d\lambda_d}{dt}, \tag{4}$$

$$V_o = Ri_o + \frac{d\lambda_o}{dt}, \tag{5}$$

$$\lambda_q = L_q i_q, \tag{6}$$

$$\lambda_d = L_d i_d + \lambda_m, \tag{7}$$

$$\lambda_o = L_o i_o, \tag{8}$$

$$T_e = \frac{3}{2}p(\lambda_m i_q + (L_d - L_q)i_d i_q), \tag{9}$$

$$\frac{d\omega_r}{dt} = \frac{p}{J}(T_e - B\omega_r - T_m), \tag{10}$$

where R represents stator resistance, V_d and V_q represent stator voltages at rotational reference frame, ω_r represents rotor electrical speed, i_o represents zero-sequence components of stator current, λ_d and λ_q represent stator flux at rotational reference frame, λ_m represents stator flux linkages due to the permanent magnet, T_e represents electrical torque, p represents the number of pole pairs, J represents rotor inertia, T_m represents mechanical load torque, and L_d and L_q represent stator inductance.

If the angle between stator and rotor field flux is kept at 90°, then

$$i_d^* = 0, \tag{11}$$

where i_d^* represents stator reference currents at rotational reference frame.

By this assumption and considering that $i_o = 0$, we can determine i_q, which leads to controlling the electrical torque:

$$T_e = \frac{3}{2} p \lambda_m i_q. \tag{12}$$

It should be mentioned that a predictive process will be present to have constant motor speed accompanied with low error torque tracking procedure.

3 Traditional SVM

SVM for three phase voltage source inverters is based on the representation of the three phase quantities as vectors in a two-dimensional ($\alpha\beta$) plane. The reference voltages are given by space voltage vector, and the output voltages of the inverter are considered as space vectors. There are eight possible output voltage vectors: six active vectors $\boldsymbol{V}_2 - \boldsymbol{V}_7$, and two zero vectors $\boldsymbol{V}_1$, $\boldsymbol{V}_8$ (Fig. 1). The reference voltage vector is realized by the sequential switching of active and zero vectors. According to the SVM method, the inverter will switch between switching vectors ($\boldsymbol{V}_1 - \boldsymbol{V}_8$) with consideration of angle of desirable voltage (θ). However, a disadvantage of SVM is that it requires complex online computation that limits the inverter switching frequency [30].

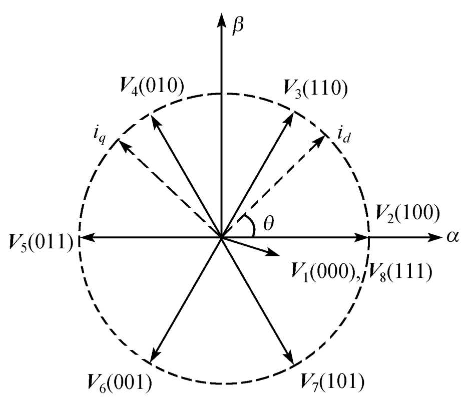

Fig. 1 Output voltage represented as space vectors

4 Proposed predictive FOC-SVM method

PMSM control techniques can be divided into scalar and vector control. The problem with scalar is that motor flux and torque, in general, are coupled. The vector control theory provides a control strategy to regulate the instantaneous rotational torque in electrical machines. In this control technique, the magnitude of stator and rotor flux and their mutual angle are considered.

The vector control of currents and voltages results in the control of the spatial orientation of the electromagnetic fields in the machine, and it has led to the field, called orientation-field. Oriented control usually refers to controllers that maintain a 90° orientation, referred to as field angle control or angle control.

To have an independent controlled orthogonal special angle (electrical) between stator and rotor flux, the angle between stator and rotor field flux should be kept at 90°, which leads to

$$\begin{cases} i_d = 0 \rightarrow i_d^* = 0, \\ i_q = i_s, \end{cases} \tag{13}$$

where i_s is stator current. In other words, the desired value of i_d is zero. Therefore, the d axis reference current is taken as zero, $i_d = 0$. In order to calculate the q axis reference current, the following relations are suggested. Eq. (10) can be represented in discrete state:

$$\begin{aligned} \frac{\mathrm{d}\omega_r}{\mathrm{d}t} &= \frac{p}{J}(T_e - B\omega_r - T_m) \\ \rightarrow \frac{\omega_r(n+1) - \omega_r(n)}{T} &= \frac{p}{J}(T_e(n) - B\omega_r(n) - T_m(n)), \end{aligned} \tag{14}$$

where B represents damping coefficient, T represents sample time in discretizing process, $\omega_r(n)$ represents rotor speed at the existing sample, and $\omega_r(n+1)$ represents rotor speed at the next sample.

By considering this fact that the synchronous motor has a fixed speed, then, we would have $\omega_r(n+1)$ as a known parameter of the next sample condition. The desired value of $T_e(n)$ will be derived as follows:

$$\omega_r(n+1) = \omega_r^*, \tag{15}$$

$$T_e^*(n) = B\omega_r(n) + T_m(n) + \frac{J}{p}\left(\frac{\omega_r^* - \omega_r(n)}{T}\right), \tag{16}$$

where ω_r^* represents rated speed (rpm).

With regards to Eqs. (12) and (16), the q axis reference current can be obtained as

$$i_q^* = \frac{2}{3p\lambda_m}\left(B\omega_r(n) + T_m(n) + \frac{J}{p}\left(\frac{\omega_r^* - \omega_r(n)}{T}\right)\right), \tag{17}$$

where i_q^* represents stator reference currents at rotational reference frame.

Substitute Eqs. (6), (7) in Eqs. (3), (4), respectively, we can represent the equations of PMSM in *d*-*q* frame as

$$V_q = Ri_q + L_d\omega_r i_d + \lambda_m\omega_r + L_q\frac{\mathrm{d}i_q}{\mathrm{d}t}, \tag{18}$$

$$V_d = Ri_d - L_q\omega_r i_q + L_d\frac{\mathrm{d}i_d}{\mathrm{d}t} + \frac{\mathrm{d}\lambda_m}{\mathrm{d}t}. \tag{19}$$

We can write Eqs. (18) and (19) in discrete time, considering the concept of derivation in discrete time:

$$V_d(n) = Ri_d(n) - L_q\omega_r(n)i_q(n) + L_d\frac{i_d(n+1) - i_d(n)}{T}, \tag{20}$$

$$V_q(n) = Ri_q(n) + L_d\omega_r(n)i_d(n) + \omega_r(n)\lambda_m + L_q\frac{i_q(n+1) - i_q(n)}{T}, \tag{21}$$

where $i_d(n)$ and $i_q(n)$ represent stator *d*-*q* axis currents at the existing sample, and $i_d(n+1)$ and $i_q(n+1)$ represent stator *d*-*q* axis currents at the next sample.

The subscript *n* represents the present time values and $n+1$ represents the values in the next sample. Note that the duration between two samples is equal to *T*. With regards to Eqs. (20) and (21), the estimated values of i_d and i_q at the next sample ($i_d(n+1)$ and $i_q(n+1)$) can be obtained as

$$i_d(n+1) = i_d(n) + \frac{T}{L_d}(V_d(n) - Ri_d(n) + L_q\omega_r(n)i_q(n)), \tag{22}$$

$$i_q(n+1) = i_q(n) + \frac{T}{L_q}(V_q(n) - Ri_q(n) - L_d\omega_r(n)i_d(n) - \omega_r(n)\lambda_m). \tag{23}$$

According to Eqs. (22) and (23), by keeping the existing voltage vectors (V_d, V_q), the *d*-*q* currents at the next sample are obtained.

In order to reduce the speed error and torque ripple, the estimated *d* and *q* axis currents ($i_d(n+1)$ and $i_q(n+1)$) must track the reference *d* and *q* axis currents (i_d^* and i_q^*) accurately. The error between the references and $n+1$ state current (calculated currents in Eqs. (13), (17) and Eqs. (22), (23), respectively) motor are defined as

$$\begin{cases} \Delta i_d = i_d^* - i_d(n+1), \\ \Delta i_q = i_q^* - i_q(n+1), \end{cases} \tag{24}$$

where Δi_d and Δi_q represent stator *d*-*q* axis current errors.

With the above definition, we can establish the SVM technique in the proposed predictive FOC method. With regards to Fig. 1, by having the rotor angle (θ), Δi_d, and Δi_q, the proper switching state (correspondingly the proper voltage vector) will be chosen.

As a matter of fact, the negative amounts of Δi_d and Δi_q indicate that the proper vector must increase i_d and i_q through the next sample. Also, the positive amounts of Δi_d and Δi_q indicate that the proper vector must decrease i_d and i_q through the next sample. As an example, for $\theta = 45°$, the switching pattern is shown in Fig. 2. As shown in Fig. 2, the proper voltage vector is selected in terms of probable values of Δi_d and Δi_q. In the mentioned example, there are two possible switching vectors (110, 010 and 001, 101,

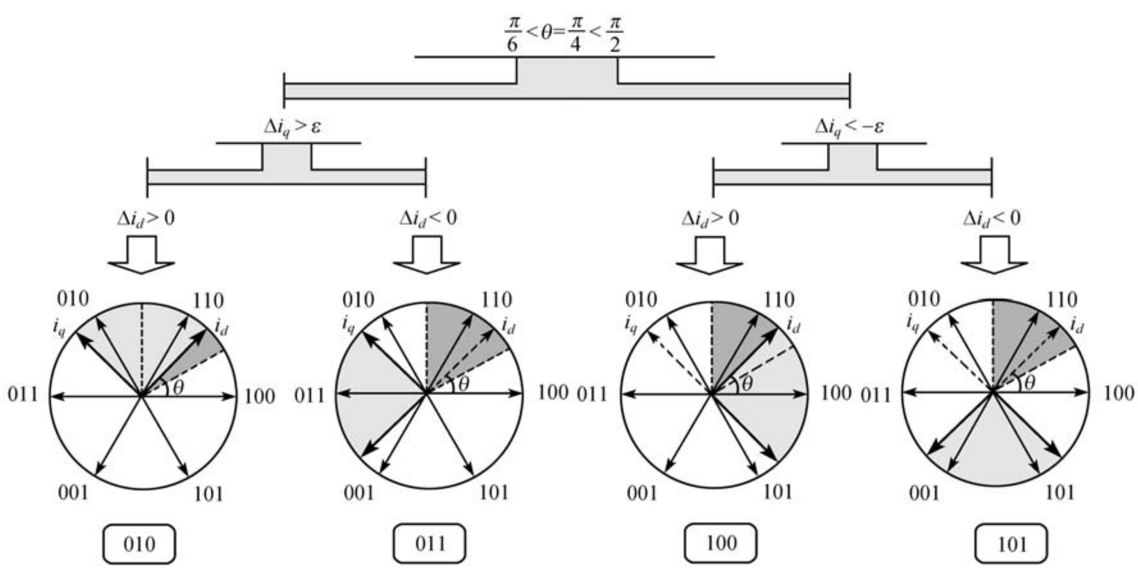

Fig. 2 Switching pattern in terms of probable values of Δi_d, Δi_q, and rotor angle

Table 1 Selecting pattern of proper voltage vectors

voltage vectors	$\Delta i_q > \varepsilon$		$-\varepsilon < \Delta i_q < \varepsilon$		$\Delta i_q < -\varepsilon$	
	$\Delta i_d > 0$	$\Delta i_d < 0$	$\Delta i_d > 0$	$\Delta i_d < 0$	$\Delta i_d > 0$	$\Delta i_d < 0$
$-\pi/6 < \theta < \pi/6$	110	010	111	000	101	001
$\pi/6 < \theta < \pi/2$	010	011	111	000	100	101
$\pi/2 < \theta < 5\pi/6$	011	001	111	000	110	100
$5\pi/6 < \theta < 7\pi/6$	001	101	111	000	010	110
$7\pi/6 < \theta < 3\pi/2$	101	100	111	000	011	010
$3\pi/2 < \theta < 11\pi/6$	100	110	111	000	001	011

respectively). In this situation, the desirable vector is selected in terms of greater increase or decrease of i_q (when $\Delta i_d > 0$ and $\Delta i_q > \varepsilon$, the 010 switching vector leads to increase of i_d; and when $\Delta i_d < 0$ and $\Delta i_q < -\varepsilon$, the 010 switching vector leads to the increase of i_q). In the similar way, the switching pattern, in terms of $0 < \theta < 2\pi$, can be presented in Table 1.

It should be mentioned that the obtained switching vectors are applied through a sample (T). Due to this scheme, the switching frequency is fixed in $1/T$ Hz. Therefore, the constant switching frequency reduces the switching looses.

5 Simulation Result

The block diagram of the proposed PMSM drive is shown in Fig. 3. As shown in Fig. 3, the SVM technique is incorporated with the proposed predictive field-oriented controller. The d-q axis currents and voltages, speed, and mechanical load of the PMSM are applied to the predictive FOC. Thereupon, the difference between estimated and reference d-q currents is utilized to the SVM rules (established in Table 1). Consequently, the obtained switching vectors are applied to the voltage source inverter through a constant switching period. It is clear that the high switching frequency leads to proper operation of the proposed drive. Simulation parameters (such as PMSM, voltage source inverter) are listed in Table 2.

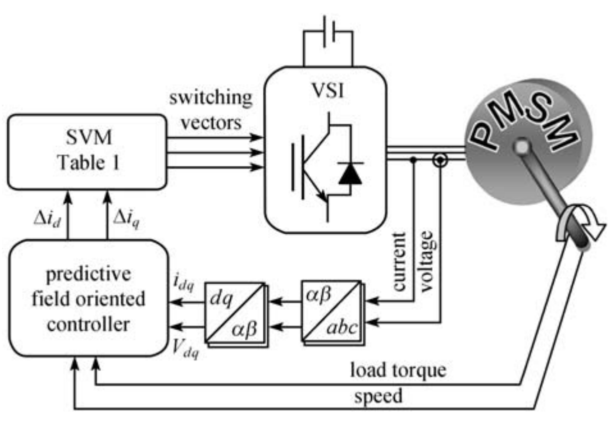

Fig. 3 Block diagram of proposed PMSM drive

Table 2 PMSM parameters in simulation model

parameter	description	value
p	number of pole pairs	2
R/Ω	stator resistance	1
L_d, L_q/mH	stator inductance	6
λ_m/Wb	rotor magnet flux	0.2
$J/(\mathrm{kg \cdot m^2})$	rotor inertia	0.001
B	damping coefficient	0.0004
V_{DC}/V	DC voltage	300
ω_r/rpm	rated speed	2000
$T_N/(\mathrm{N \cdot m})$	rated torque	10
f_r/kHz	switching frequency	20
–	power switches	IGBT

As mentioned in Table 2, the reference speed is set in 2000 rpm. In order to show the performance of the proposed controller, a sudden load change is applied to the PMSM. With regards to Fig. 4, the electrical torque tracks the mechanical load torque properly. Figure 4 depicts that the electrical torque response has minimum error (mechanical torque changes: 5 to 8 N·m at 0.8 s). Furthermore, the electrical speed in terms of the arbitrary reference speed (exhibited in Fig. 5) has minimum ripple, error. Also, according to Fig. 5, the fast transient response of electrical torque is a result of the proposed method. In fact, a considerable step up in mechanical load will cause a considerable speed reduction. Therefore, the duty of a controller is reducing motor speed drop at minimum transient time. Furthermore, the motor drive must keep the speed error in the steady-state at admissible range. According to Fig. 4, the error of the electromagnetic torque produced by the motor in steady-state is around 2% and 1.25% at 5 N·m and 8 N·m of the mechanical load torque, respectively. Therefore, the electrical torque of PMSM can be tunable in a tolerable range of mechanical torque with fast transient response and low error at steady-state. The rotor electrical angle is shown in Fig. 6.

The current and voltage waveforms for transient state and steady state operations of the proposed method are shown in Figs. 7 and 8, respectively. It can be seen that the three phase motor currents are symmetric with low ripple. Also, the output of the voltage source inverter (VSI) is a unipolar square waveform voltage. The switching statuses during an arbitrary observation window (with length of 6 ms as shown in Fig. 9) demonstrate the reduction of switching loses properly. For example, in the considered observation window (as shown in Fig. 9), the vectors $\boldsymbol{V}_5$ and $\boldsymbol{V}_6$ are repeater than $\boldsymbol{V}_1$ and $\boldsymbol{V}_8$, whereas the vectors $\boldsymbol{V}_1$ and $\boldsymbol{V}_8$ are repeaters as compared to the others. According

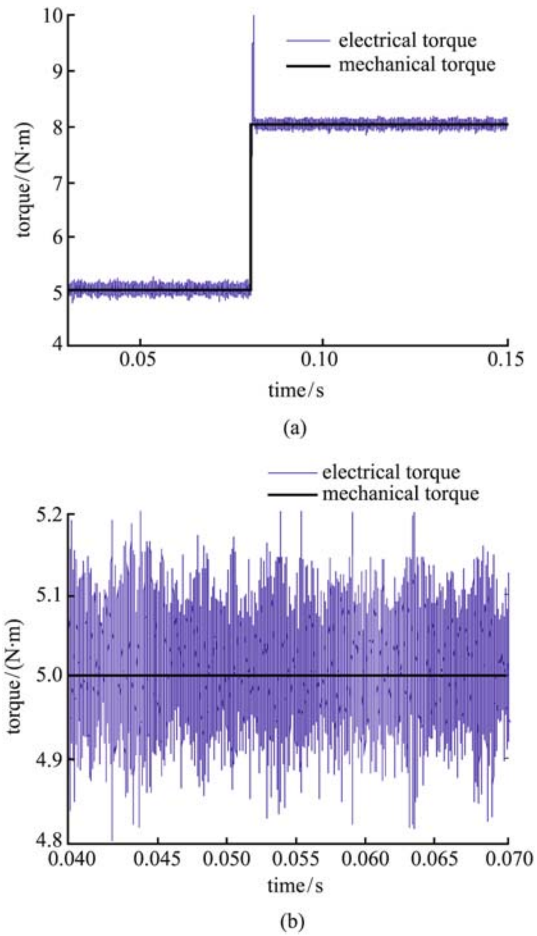

Fig. 4 Dynamic change in load torque: electrical and mechanical torque. (a) Displaying of entire torque signal; (b) displaying a specified part of torque signal around 5 N·m

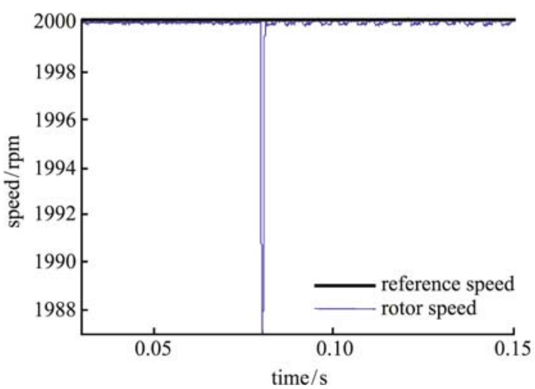

Fig. 5 Electrical speed of PMSM during a dynamic change in load torque

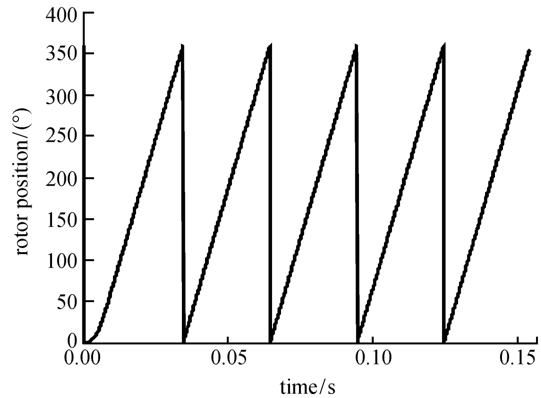

Fig. 6 Rotor position obtained in simulation

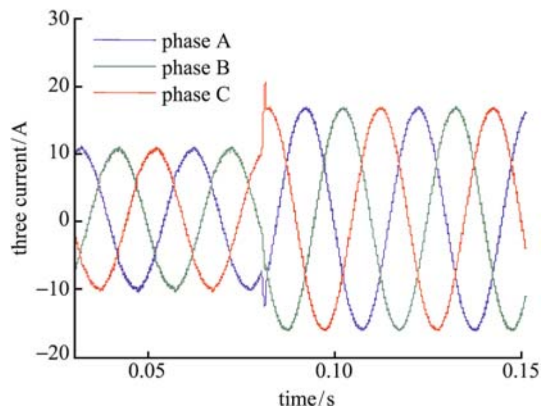

Fig. 7 Three phase stator currents of PMSM

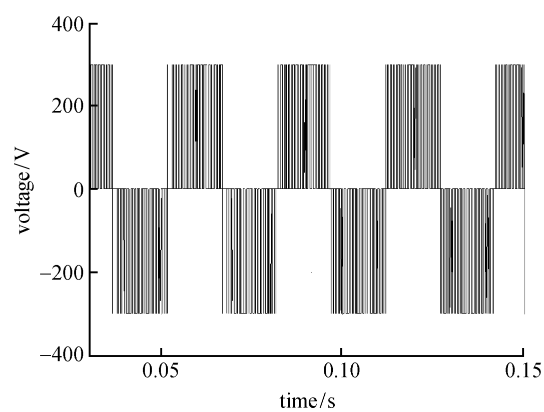

Fig. 8 Output voltage of voltage source inverter (VSI): phase A (applied to PMSM)

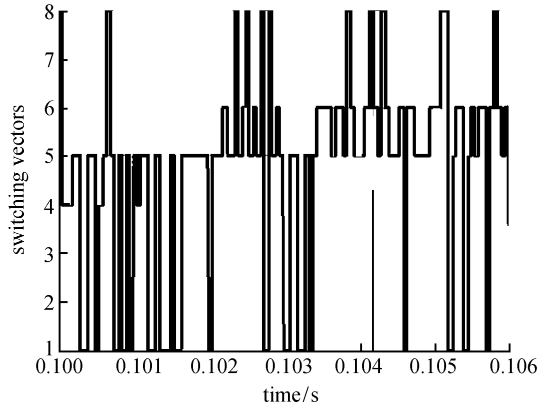

Fig. 9 Switching statuses during an arbitrary observation window (with length of 6 ms)

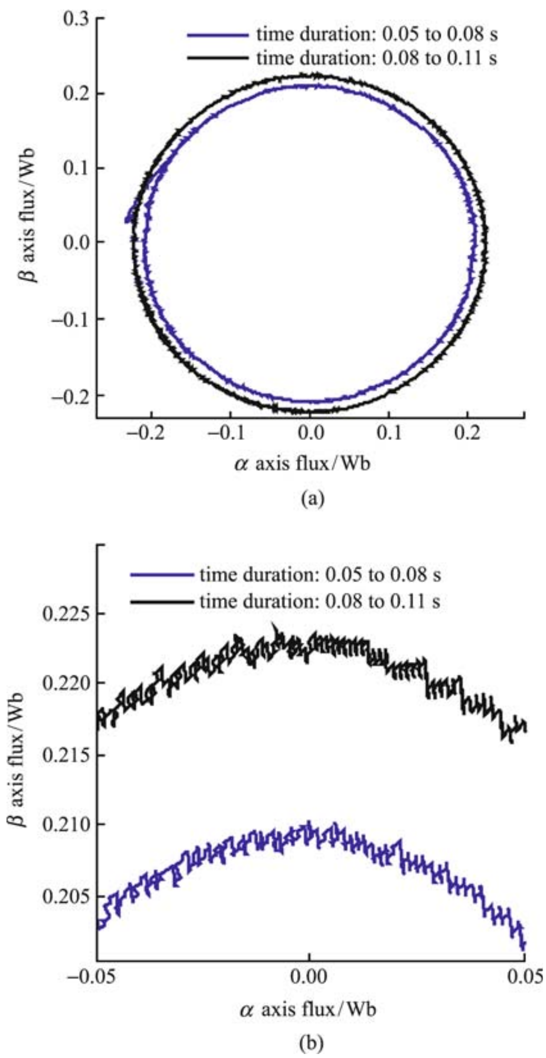

Fig. 10 Stator flux in $\alpha\beta$ reference frame during an abrupt mechanical torque change at 0.08 s. (a) Displaying of entire flux signal; (b) displaying of a specified part of flux signal around 0.21 Wb

to Fig. 10, the proposed predictive FOC-SVM-based technique is able to reduce the transient state of stator flux at torque variation times 0.08 s. Also, Fig. 10 shows that the stator flux has minimum error and variation.

In order to make comparison of the proposed method in this paper with a recent work on the PMSM drive field, we chose Ref. [31].

Reference [31] proposed a filter topology to reduce the torque ripple and harmonic noises in a PMSM controlled by FOC composed with a hysteresis current controller. The proposed method used to generate the voltage reference signals is related to the control algorithm of the motor, which uses the motor model in the rotor *d*-*q* reference frame and the rotor FOC principles with monitored rotor position/speed and monitored phase currents [31]. The motor performances before and after applying the suggested technique in Ref. [31] are shown in Fig. 11. As shown in Fig. 11, in comparison with the presented result in Figs. 4 and 7, the proposed method in this paper is superior to the method proposed in Ref. [31]. The advantage of the proposed method in this paper is lower torque and current ripples without using a compensation element (active filter in Ref. [31]). According to the method, PCC in comparison to hysteresis current controller leads to lower current ripple.

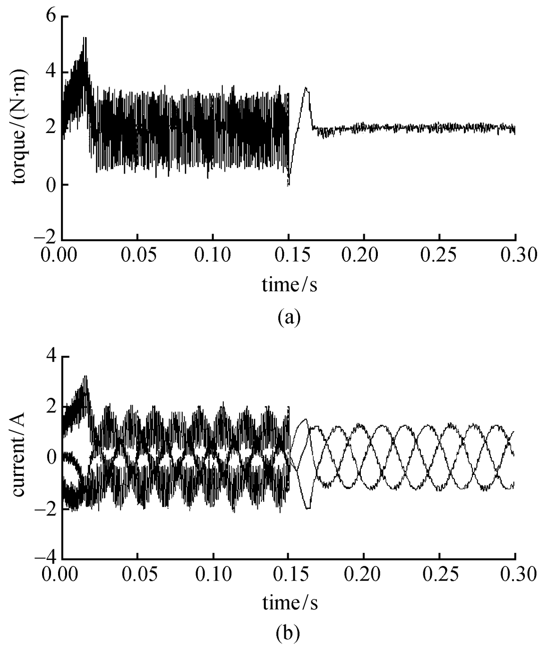

Fig. 11 Motor performances before and after applying the suggested technique in Ref. [31]. (a) Motor torque; (b) motor lines current

6 Conclusion

This paper proposes a new method for PMSM drive based on FOC and SVM. The present work has been incorporated with the PCC technique. The proposed predictive method estimates the stator current at the next sample using the motor equations. Also, on the basis of the field-oriented control, the reference currents of PMSM are calculated in terms of minimum torque ripples and fixed speed operation. Thereupon, the difference between estimated and calculated reference currents is applied to choose a proper switching vector based on SVM. Several numerical simulations using MATLAB-Simulink have been carried out in steady-state and transient-state. According to the results, the proposed technique is able to reduce torque ripple, speed error, and transient-states at abrupt mechanical load changes. As a symptom, the torque ripples is limited to 2% and 1.25% at 5 N·m and 8 N·m of the mechanical load torque, respectively. In addition, some other advantages can be enumerated, for instance, constant switching frequency, fast transient response, low current ripple, and tunable output torque and speed with lower error.

References

1. Mademlis C, Xypteras J, Margaris N. Loss minimization in surface permanent-magnet synchronous motordrives. IEEE Transactions on Industrial Electronics, 2000, 47(1): 115–122
2. Skvarenina T L. The Power Electronics Handbook. New York: CRC Press, 2002, 12-1–12-10
3. Fodorean D, Djerdir A, Miraoui A, Viorel I A. FOC and DTC techniques for controlling a double excited synchronous machine. In: Proceedings of IEEE International Electric Machines and Drives Conference. 2007, 2: 1258–1263
4. Farid N, Sebti B, Mebarka K, Tayeb B. Performance analysis of field-oriented control and direct torque control for sensorless induction drives. In: Proceedings of Mediterranean Conference on Control and Automation. 2007, 1–6
5. Hoang L H. Comparison of field-oriented control and direct torque control for induction motor drives. In: Proceedings of IEEE Industry Applications Conference. 1999, 2: 1245–1252
6. Rodriguez J, Pontt J, Silva C, Huerta R, Miranda H. Simple direct torque control of induction machine using space vector modulation. Electronics Letters, 2004, 40(7): 412–413
7. French C, Acarnley P. Direct torque control of permanent magnet drives. IEEE Transactions on Industry Applications, 1996, 32(5): 1080–1088
8. Zhong L, Rahman M F, Hu W Y, Lim K W. Analysis of direct torque control in permanent magnet synchronous motor drives. IEEE Transactions on Power Electronics, 1997, 12(3): 528–536
9. Vyncke T J, Boel R K, Melkebeek J A A. Direct torque control of permanent magnet synchronous motors—an overview. In: Proceedings of the 3rd IEEE Benelux Young Researchers Symposium in Electrical Power Engineering. 2006, 1–5
10. Pillay P, Krishnan R. Modeling, simulation, and analysis of permanent-magnet motor drives. II. The brushless DC motor drive. IEEE Transactions on Industry applications, 1989, 25(2): 274–279
11. Qian J, Rahman M A. Analysis and microprocessor implementation of field oriented control for permanent magnet hysteresis synchronous motor. In: Proceedings of IEEE Industry Applications Society Annual Meeting. 1991, 1: 198–203
12. Takahashi I, Noguchi T. Take a look back upon the past decade of direct torque control. In: Proceedings of 23rd International Conference on Industrial Electronics, Control and Instrumentation. 1997, 2: 546–551
13. Casadei D, Serra G, Tani A. Implementation of a direct torque control algorithm for induction motors based on discrete space vector modulation. IEEE Transactions on Power Electronics, 2000, 15(4): 769–777
14. Mei C G, Panda S K, Xu J X, Lim K W. Direct torque control of induction motor-variable switching sectors. In: Proceedings of IEEE International Conference on Power Electronics and Drive Systems. 1999, 1: 80–85
15. Tripathi A, Khambadkone A M, Panda S K. Space-vector based, constant frequency, direct torque control and dead beat stator flux control of AC machines. In: Proceedings of IEEE Annual Conference on Industrial Electronics Society. 2001, 2: 1219–1224
16. Lascu C, Boldea I, Blaabjerg F. A modified direct torque control for induction motor sensorless drive. IEEE Transactions on Industry Applications, 2000, 36(1): 122–130
17. Swierczynski D, Kazmierkowski M, Blaabjerg F. DSP based direct torque control of permanent magnet synchronous motor (PMSM) using space vector modulation (DTC-SVM). In: Proceedings of IEEE International Symposium on Industrial Electronics. 2002, 3: 723–727
18. Sun D, He Y K, Zhu J G. Fuzzy logic direct torque control for permanent magnet synchronous motors. In: Proceedings of the 5th World Congress on Intelligent Control and Automation. 2004, 5: 4401–4405
19. Sun D, Zhu J G, He Y K. A space vector modulation direct torque control for permanent magnet synchronous motor drive system. In: Proceedings of the 5th International Conference on Power Electronics and Drive Systems. 2003, 1: 692–697
20. Buja G S, Kazmierkowski M P. Direct torque control of PWM inverter-fed AC motors—a survey. IEEE Transactions on Industrial Electronics, 2004, 51(4): 744–757
21. Oh I H, Jung Y S, Youn M J. A source voltage-clamped resonant link inverter for a PMSM using a predictive current control technique. IEEE Transactions on Power Electronics, 1999, 14(6): 1122–1132
22. Moon H T, Kim H S, Young M J. A discrete-time predictive current control for PMSM. IEEE Transactions on Power Electronics, 2003, 18(1): 464–472
23. Wipasuramonton P, Zhu Z Q, Howe D. Predictive current control with current-error correction for PM brushless AC drives. IEEE Transactions on Industry Applications, 2006, 42(4): 1071–1079
24. Wang H, Lu J, Yang Q, Zhou J. PWM predictive current control strategy based on self-adaptive intelligent fuzzy PID controller. In: Proceedings of the 5th World Congress on Intelligent Control and Automation. 2004, 3: 2575–2578
25. Rodriguez J, Pontt J, Silva C A, Correa P, Lezana P, Cortes P, Ammann U. Predictive current control of a voltage source inverter. IEEE Transactions on Industrial Electronics, 2007, 54(1): 495–503

26. Rodriguez J, Pontt J, Silva C, Cortes P, Amman U, Rees S. Predictive current control of a voltage source inverter. In: Proceedings of IEEE 35th Annual Power Electronics Specialists Conference. 2004, 3: 2192–2196
27. Abu-Rub H, Guzinski J, Krzeminski Z, Toliyat H A. Predictive current control of voltage-source inverters. IEEE Transactions on Industrial Electronics, 2004, 51(3): 585–593
28. Handley P G, Boys J T. Space vector modulation: an engineering review. In: Proceedings of the Fourth International Conference on Power Electronics and Variable-Speed Drives. 1990, 87–91
29. Toliyat H A, Niazi P, Godbole K. Overcoming vector control challenges. Motion System Design, 2005, 20–24
30. Muthuramalingam A, Himavathi S. Performance evaluation of a neural network based general purpose space vector modulator. International Journal of Electrical, Computer, and Systems Engineering, 2007, 1(1): 19–26
31. Gulez K, Adam A A, Pastaci H. Torque ripple and EMI noise minimization in PMSM using active filter topology and field-oriented control. IEEE Transactions on Industrial Electronics, 2008, 55(1): 251–257