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Vector Control for PMSM

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Abstract: This article describes the implementation of the CLARK transformation, the PARK transformation, the inverse PARK transformation and the SVPWM in the MATLAB / SIMULINK environment. The control system is then implemented with tri-cyclic nested loops, i.e., the current loop, the speed loop and the position loop. Simulation results show that the system has fast response, with small overshoot and high accuracy. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: PMSM, Vector control, Simulink, Current loop, Velocity loop, Position loop.

1. Introduction

In recent years, with the development of high-performance permanent magnet materials, microelectronics and power devices, AC servo systems with a permanent magnet synchronous motor (PMSM) [1] as the core component has been developing rapidly. The PMSM has the characteristics of superior speed, simple structure, small size, high efficiency, small inertia, and high power factor, which has been broadly applied in high-performance, high-precision servo-driven fields.

The Vector control is also known as field oriented control, the basic idea of which is to decompose the stator current vector to a magnetizing current and a torque current. The system controls the amplitudes and phases of the two currents respectively to achieve a high performance of motor control. Its characteristic is to control the AC motor's excitation and torque separately, which makes it similar to a DC motor's control feature.

2. d-q Mathematical Model of PMSM

The stator of a PMSM is composed of three armature windings and an armature rotor. The windings are generally star-connected, and the rotor of the PMSM is constituted by permanent magnet. When the stator is fed with three phase symmetrical sine wave currents, it produces a rotating magnetic field inside. The interaction with the magnetic field of the permanent magnet rotor makes the rotor rotates [2]. Fig. 1 shows the PMSM d-q model of transformation.

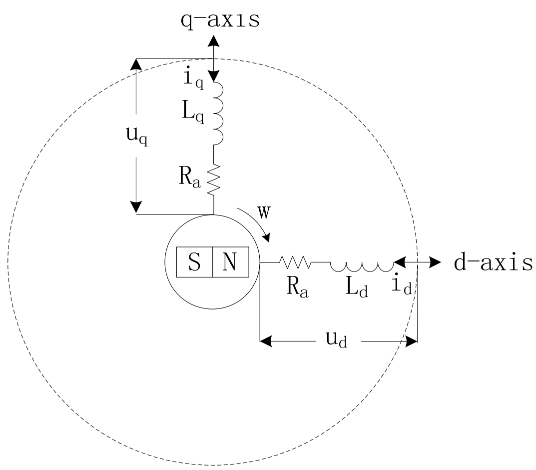

Fig. 1. PMSM d-q model of transformation.

The significance of the parameters in Fig. 1: R_a is the equivalent resistance of a single winding; u_d, u_q is equivalent voltages in the d-axis and the q-axis; i_d, i_q is equivalent current in the d-axis and the q-axis; L_d, L_q is equivalent inductances in the d-axis and the q-axis;

In the d-q coordinate system, the voltages obey the Voltage equation:

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} R_a + PL_d & -\omega L_q \\ \omega L_d & R_a + PL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega \psi_{fm} \end{bmatrix}, \quad (1)$$

where ω is the rotor angular velocity; P is the differential operator, $P = d/dt$; ψ_{fm} is the magnitude of the flux permanent magnet in stator.

In the d-q coordinate system, the inductances obey the inductance equation:

$$\begin{cases} L_d = \frac{3}{2}(L_{a0} - L_{a2}) \\ L_q = \frac{3}{2}(L_{a0} + L_{a2}) \end{cases}, \quad (2)$$

where L_{a0} is the stator inductance mean; L_{a2} is the amplitude of the second harmonic in stator inductance.

The Electromagnetic torque T_e of the motor can be expressed with the permanent magnet flux multiplied by its current, which can be expressed as

$$\begin{aligned} T_e &= p_n \psi_{fm}[-i_u \sin\theta - i_v \sin(\theta - 2\pi/3) \\ &\quad - i_w \sin(\theta + 2\pi/3)] \\ &= p_n\left[\sqrt{3/2}\psi_{fm} i_q + (L_d - L_q) i_d i_q\right] \\ &= \sqrt{3/2}\, p_n \psi_{fm} i_q + p_n (L_d - L_q) i_d i_q \end{aligned}, \quad (3)$$

where p_n is the number of pole pairs in motor. For most PMSMs, the installation of permanent magnets is in a surface manner. So

$$L_d = L_q, \quad (4)$$

So Equation 3 can be simplified as

$$T_e = \sqrt{3/2}\, p_n \psi_{fm} i_q, \quad (5)$$

From formula 5, we know that the electromagnetic torque is only associated with the number of motor poles, the amplitude of the permanent magnet flux and the q-axis stator current for surface-installed permanent magnet synchronous motors. The number of motor poles and the amplitude of the permanent magnet flux are motor-specific parameters, so we can accurately control the electromagnetic torque of the motor by controlling the q-axis current accurately.

3. The Principle of Vector Control

The methods for Vector control of a PMSM mainly includes the id = 0 control, the maximum torque control, the weakening control, the cosΦ = 1 control and the maximum efficiency control [3]. The id=0 control with the d-axis current being kept to be 0 is the most commonly used control method for PMSMs. The simulation below is based on this method. Fig. 2 is the block diagram of the vector control system with id = 0, which includes three feedback loops, a position loop, a speed loop and a current loop. The three loops are connected in series. The current loop is the inner loop, which directly controls the PMSM's torque and excitation. We can get the actual motor's torque component and excitation component according to the two-phase currents, which are detected by two current sensors, after CLARK transformation [4] and PARK transformation [5] of them. With the help of two PI controllers, we can adjust the torque component and the excitation component to desired values, i.e., the excitation component is adjusted to 0, and the torque component is adjusted to the value of the speed loop output. Outputs of the two PI controllers go through an inverse PARK (IPARK) [6] transform module and a SVPWM generation module first, and then are fed to a three-phase inverter bridge. The entire control system completes a process of decoupling followed by a coupling process.

The CLARK transformation transforms the currents in the ABC coordinate system to the stationary αβ coordinate system. It makes the three-phase windings of the motor equivalent to a two-phase quadrature winding. The formula of the CLARK transformation is:

$$\begin{cases} i_\alpha = \frac{3}{2} ia \\ i_\beta = \frac{\sqrt{3}}{2}(2ib + ia) \end{cases}, \quad (6)$$

The PARK transformation is a process of transforming the αβ coordinate system to the rotating d-q coordinate system. There is an important parameter in this transformation - the electrical angle θ which is the angle between the α-axis and the d-axis. The transform formula is:

$$\begin{cases} Ds = \cos\theta \times i_\alpha + \sin\theta \times i_\beta \\ Qs = \cos\theta \times i_\beta - \sin\theta \times i_\alpha \end{cases}, \quad (7)$$

The IPARK transformation couples the d-q components back into the αβ coordinates, it also needs the electrical angle θ, and the transform formula is:

$$\begin{cases} u_\alpha = \cos\theta \times Ds - \sin\theta \times Qs \\ u_\beta = \cos\theta \times Qs + \sin\theta \times Ds \end{cases}, \quad (8)$$

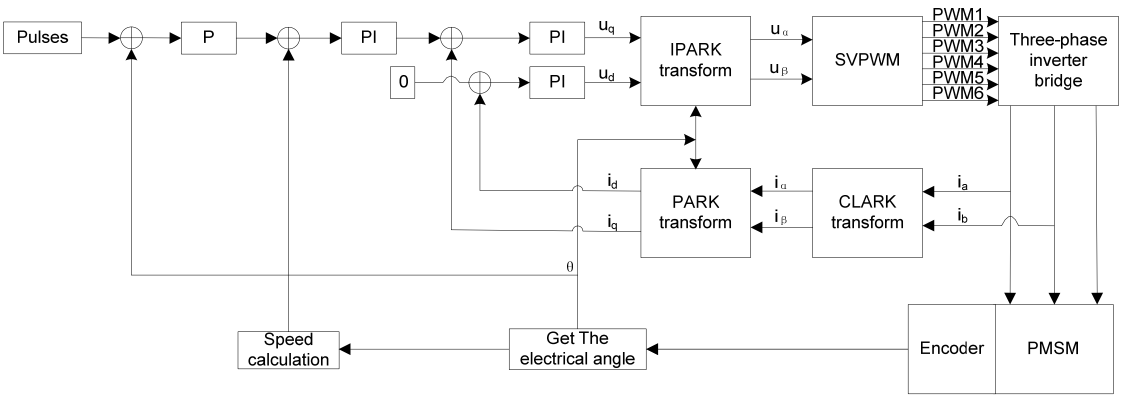

Fig. 2. The block diagram of the vector control system.

The main idea of the SVPWM is to generate and track an ideal round flux from the perspective of the motor, and then the whole system uses regular pattern to switch and form PWM waves [7]. The SVPWM has six basic vectors. With different action time, two adjacent base vectors can be composed for any vector [8]. The calculated duty cycles of two adjacent base vectors are shown in Table 1.

Table 1. Duty ratio in six sectors.

Sector	U_0,U_{60}	U_{60},U_{120}	U_{120},U_{180}
t1	$\frac{\sqrt{3}u_\alpha - u_\beta}{2}$	$\frac{u_\beta - \sqrt{3}u_\alpha}{2}$	u_β
t2	u_β	$\frac{\sqrt{3}u_\alpha + u_\beta}{2}$	$\frac{-\sqrt{3}u_\alpha - u_\beta}{2}$
Sector	U_{180},U_{240}	U_{240},U_{300}	U_{300},U_{360}
t1	$-u_\beta$	$\frac{-\sqrt{3}u_\alpha - u_\beta}{2}$	$\frac{\sqrt{3}u_\alpha + u_\beta}{2}$
t2	$\frac{u_\beta - \sqrt{3}u_\alpha}{2}$	$\frac{\sqrt{3}u_\alpha - u_\beta}{2}$	$-u_\beta$

In order to determine which sector the vector is in, we need to transform the target voltage vector into a balanced three-phase voltage vector first, using the equation:

$$\begin{cases} V_{ref1} = u_\beta \\ V_{ref2} = \frac{\sqrt{3}u_\alpha - u_\beta}{2} \\ V_{ref3} = \frac{-\sqrt{3}u_\alpha - u_\beta}{2} \end{cases}, \quad (9)$$

We then define a variable parameter to express the sector:

$$sector = 4 \times c + 2 \times b + a, \quad (10)$$

In formula 10, a = 1 when Vref1 is greater than 0, and a = 0 otherwise. b and c can be determined in a similar way according to Vref2 and Vref3 respectively. We can then judge which sectors u_α and u_β are located in, and t1 and t2 can be calculated according to the current operation sectors.

After the two basic vectors' duty cycle are calculated, three PWM timer compare register values, Ta, Tb, and Tc are then defined as follows:

$$\begin{cases} Ta = \frac{PWMPRD - t_1 - t_2}{2} \\ Tb = Ta + t_1 \\ Tc = Tb + t_2 \end{cases}, \quad (11)$$

The final generated SVPWM waveforms are shown in Fig. 3.

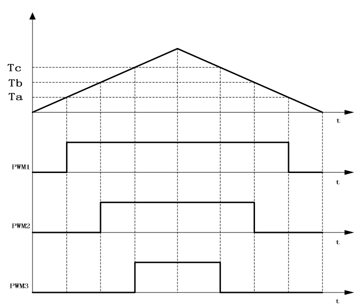

Fig. 3. The waveforms of SVPWM.

4. Establishment of MATLAB/ SIMULINK Simulation

A MATLAB / SIMULINK simulation model is built to verify the vector control method [9]. The PMSM motor model and the IGBT model come from the SimPowerSystems library of SIMULINK. The whole simulation system is divided into two parts. The first part is the power driver and feedback section. The simulation diagram is shown in Fig. 4.

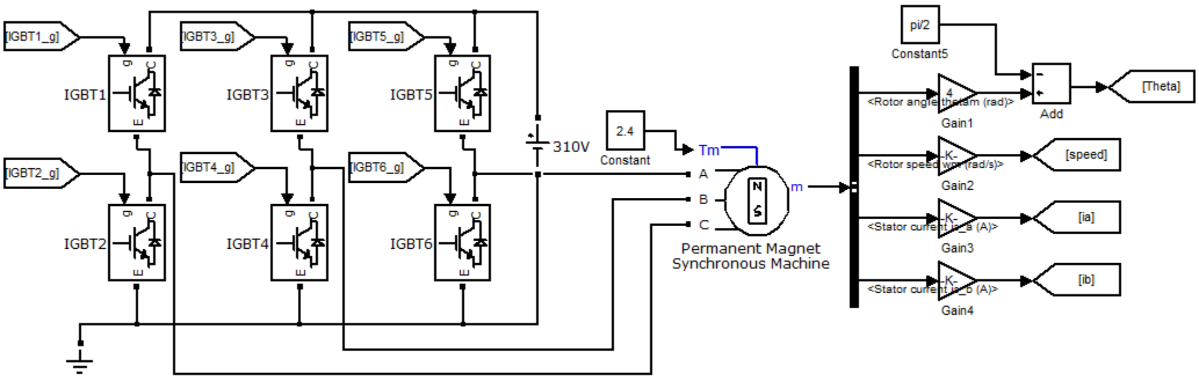

Fig. 4. Diagram of power driver and feedback section.

In this part of simulation, six separate IGBTs with free-wheeling diode are used as switches. The bus voltage is 310 V. A three-phase AC permanent magnet synchronous motor is used, which is made by MiGE Motor Co., Ltd. in Hangzhou. The nominal power of the servo motor is 750 W, with a nominal current of 3 A, a nominal speed of 3000 r/min, and a nominal torque of 2.4 Nm. All simulations are carried on at the nominal torque.

The four gain modules in Fig. 4 are defined in Table 2.

Table 2. Gain module parameters and function.

Modules	Parameter	Function
Gain1	4	Convertes the mechanical angle into electric angle
Gain2	1/100/pi	Convertes rad/s into r/min in per unit
Gain3	1/13	The system allows a maximum current of 13A, and Convertes in per unit
Gain4	1/13	The system allows a maximum current of 13A, and Convertes in per unit

The definitions of the signals in Fig. 4 are shown in Table 3.

The second part of simulation is the vector control system. The diagram of the structure is shown in Fig. 5.

This is the core part of the whole vector control system. There are four feedback parameters, the two stator currents i_a and i_b, the electrical angle and the speed. After the CLARK transformation, the PARK transformation, two PI current loops, the IPARK transformation and the SVPWM module, we can get the duty cycles of the PWM waves, and finally generates the six PWM signals through the PWM module [10]. The frequencies of the PWM signals are all 10 kHz.

Table 3. Signal definitions.

Sigal names	Define	Unit
Theta	The rotor electrical angle	rad
speed	Rotor rotational speed	Per unit, r/min
ia	The phase current of A	Per unit, A
ib	The phase current of B	Per unit, A
IGBT1_g - IGBT6_g	The gate signals of IGBT	None

5. Simulation Results and Analysis

Test 1: The external position loop Ref increases uniformly, the motor accelerates from a still state directly to 1500 r/min.

There are 10000 pulses generated when motor rotates a circle, we use the numbers 0-10000 to express the 0º-360ºmechanical angles and the initial angle is set to be 7500. The waveform of the set angle and the waveform of the feedback angle are shown in Fig. 6. The actual angle delays the set angle about 3 ms.

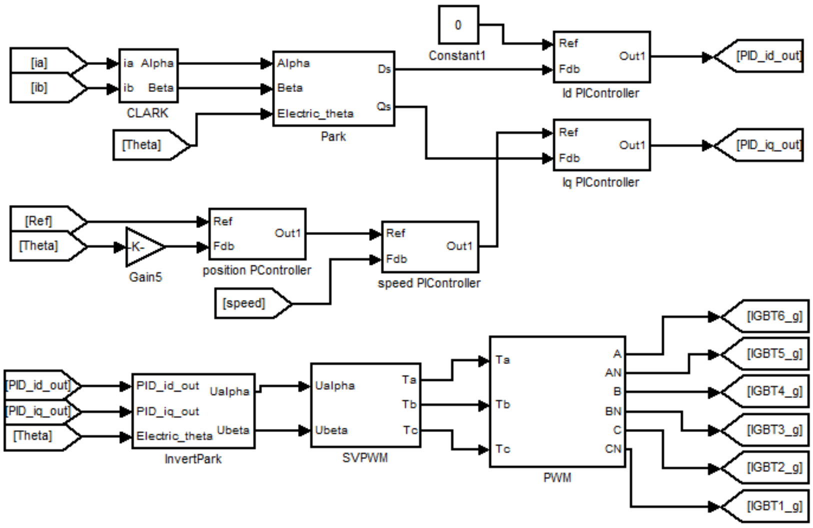

Fig. 5. The diagram of vector control algorithm system.

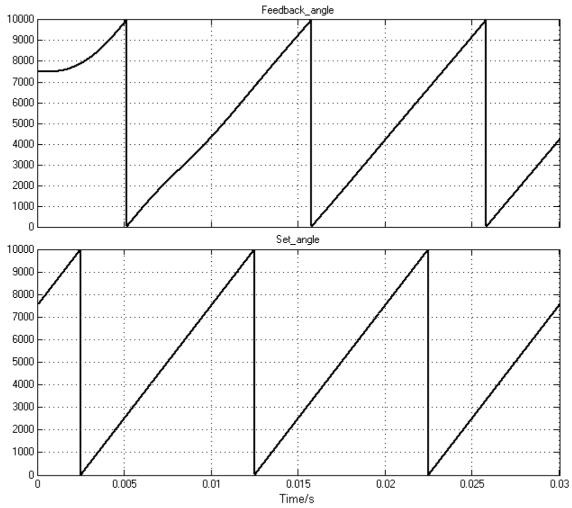

Fig. 6. Set angle and feedback angle curve in test 1.

Fig. 7 shows the set speed and feedback speed curve in test 1. The set speed is given by the output of the position loop. From Fig. 7, we can see that the motor eventually reaches -0.5 per unit, i.e., 1500 r/min. The feedback speed curve is also stable at -0.5 per unit. It takes 20 ms for the motor to adjust and stabilize at 1500 r/min.

Fig. 8 shows the three-phase current waveforms of the motor when the motor accelerates from 0 to 1500 r/min. Since the motor starts from stationary, and accelerates in a short time with full load, the currents distort a bit. When the motor stays stable, the phase currents have the shape of sine wave, and the phase difference of any two is 120°.

Fig. 9 shows the i_q and the i_d waveforms on the stator in test 1. These two waveforms are output directly by the PMSM model, which indicate the real information inside the motor when it runs. Since the maximum set current is 13 A, during the startup process, the system outputs a 13 A i_q current to keep a maximum torque, thereafter it reduces torque gradually and adjusts the motor speed to 1,500 r/min. The excitation current of the motor remains around the value of 0 A.

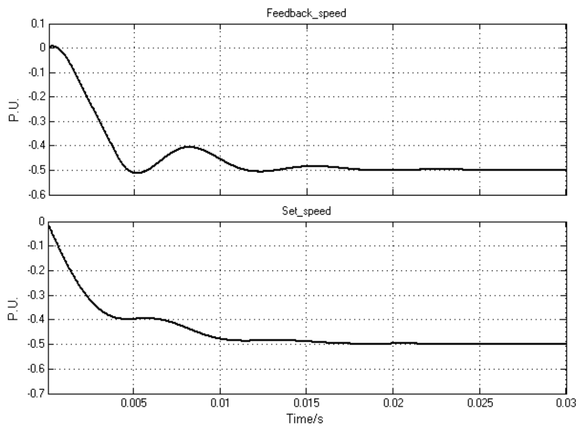

Fig. 7. Set speed and feedback speed curve in test 1.

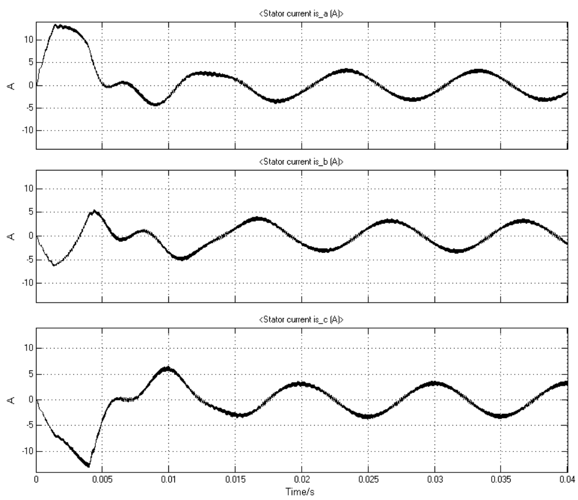

Fig. 8. ABC three-phase currents in test1.

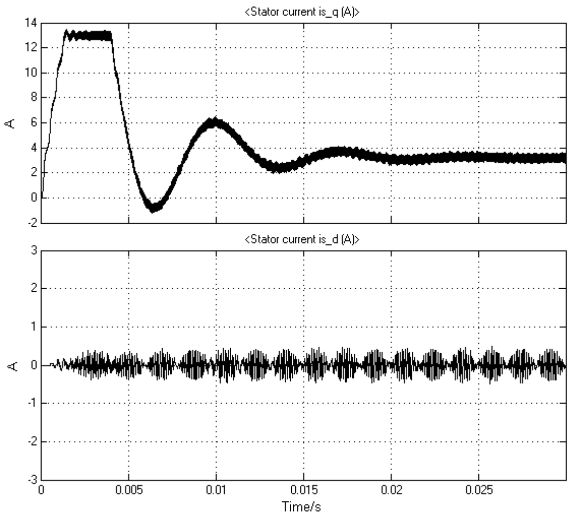

Fig. 9. I_q and id waveform in stator in test 1.

Test 2: A step signal is input to the position loop inputs at the time of 30 ms.

Fig. 10 shows the step signal at the position loop in test 2. In the beginning, the position loop is set to 7500 and the motor stays stationary, 30 ms later, the position reference changes to 8000 suddenly, so that the motor rotates 1/20 lap. We can know from Fig. 10, the time for the adjustment is 20 ms, and the feedback angle finally stabilizes in 8000. What's more, there is no overshoot in the process. So the position loop responds quickly and accurately.

Fig. 11 shows the output currents of phase A and phase B in test 2. At the time of 30 ms, the phase current increases or decreases sharply, so that it can provide a large instantaneous torque.

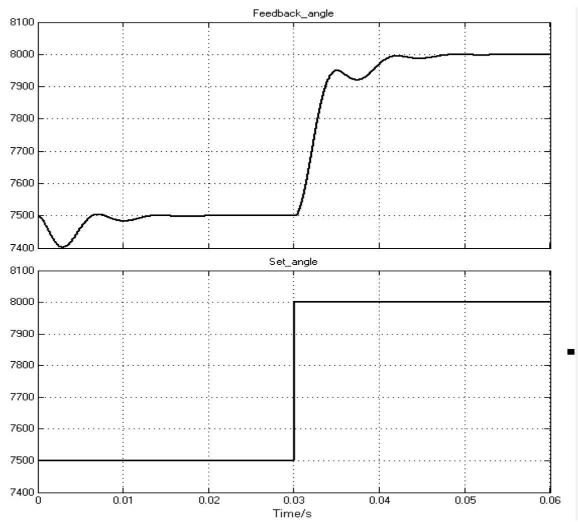

Fig. 10. Step position response in test 2.

Test 3: position loop is set to be a sine wave signal.

Fig. 12 shows the curve of the set angle and the feedback angle in test 3. The frequency of sine wave is set to 30 Hz, and the amplitude of the sine wave signal is set to 7500. From Fig. 12, the actual angle can follow the sinusoidal signal, but there is a phase difference between them, and there is also amplitude attenuation.

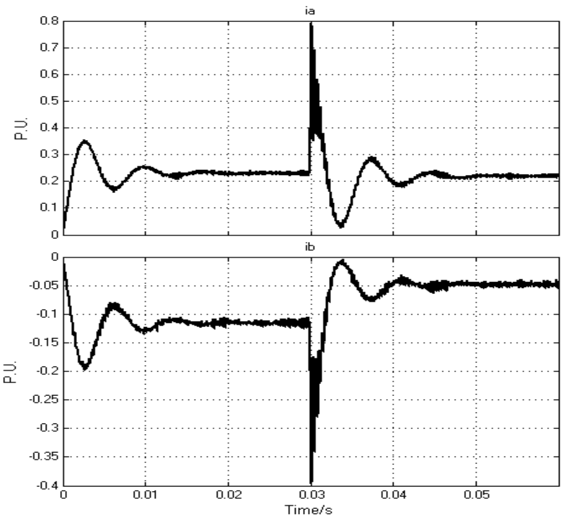

Fig. 11. Output currents in test 2.

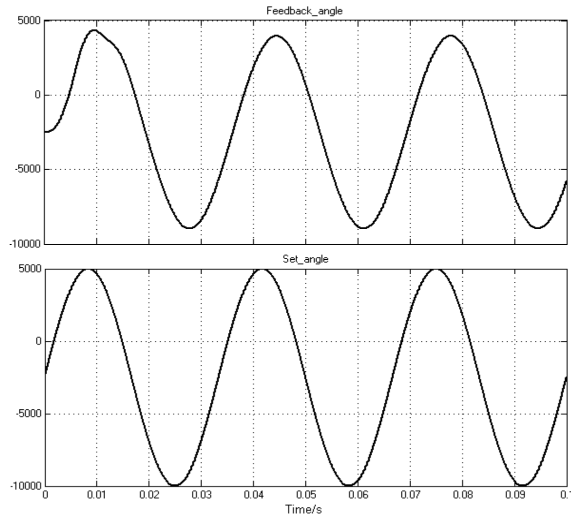

Fig. 12. Set angle and feedback angle in test 3.

Fig. 13 shows the set speed and the feedback speed in test 3. The response of the speed signal is more quickly than the response of the position signal. There is no amplitude attenuation in the speed curve, and the feedback speed can follow the set speed better.

6. Conclusion

In this paper, using discrete modules, we construct a vector control system for PMSM in MATLAB/SIMULINK environment with the id=0 control method and the simulation results are obtained to verify the system. In test 1, the experimental results show that the system has fast response and has the ability to stabilize the motor in the situation of instantaneous acceleration. It has good effect in control the torque component and the excitation component. In test 2, the experimental results show that system responses rapidly with step signal in the position loop, and it has no overshoot. In test 3, the results show that the system responses to the AC signal in position is good.

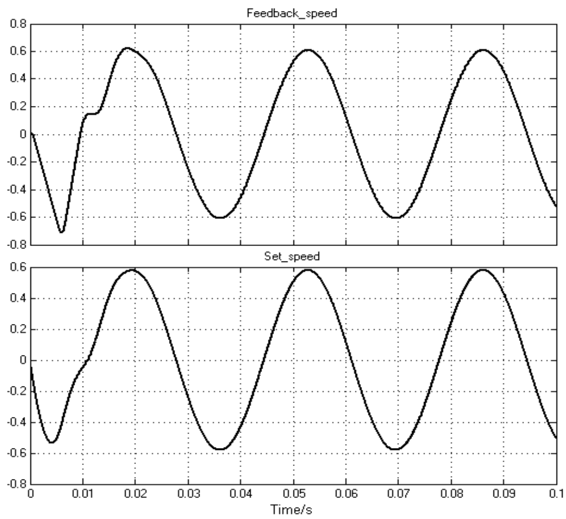

Fig. 13. Set speed and feedback speed in test 3.

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