

Field-Oriented Control of PMSM Drive Based on SVPWM Using MATLAB

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Abstract: The space vector PWM has the character of wide linear range, little higher harmonic and easy digital realization. The FOC theory and SVPWM technique make the PMSM can achieve the performance as well as DC motor. The mathematical model of PMSM is analyzed and the system model of FOC vector control has been established. The control system has been also simulated by MATLAB/Simulink. The simulation results accord with the real motor's performance and provide the theory basis for the designing of real system.

Keywords: space vector PWM (SVPWM), permanent magnetic synchronous motor(PMSM), field-oriented control(FOC)

I. THE MATHEMATICAL MODEL OF PMSM

The following assumptions are made before establishing the mathematical model of PMSM:

- Neglects the saturation of the electric motor ferrite core.
- Neglects turbulent flow and hysteresis loss in electric motor.
- The current in electric motor is symmetrical three-phase sinusoidal current.

A. d-q reference coordinate system

There are two kinds of coordinate system in FOC. One is fixed on the stator, which is a static coordinate system relative to us; the other is fixed on the rotor, which is a revolving coordinate system. Both the three-phase stator A-B-C coordinate system based on three-phase winding of three-phase stator and the two-phase stator α - β coordinate system are the static coordinate system. The two-phase stator α - β coordinate system is composed of α axis fixed on A axis and β axis that is vertical to α axis. While d-q coordinate system with d axis fixed on the rotor spool thread is revolving^[1]. Figure 1 shows the relationship of α - β coordinate system and d-q coordinate system. is the angle between d and α axis which is also phase A. Equation (1) gives the transforms from A-B-C to d-q coordinate system. While Equation (2) gives the transforms from d-q to α - β coordinate system.

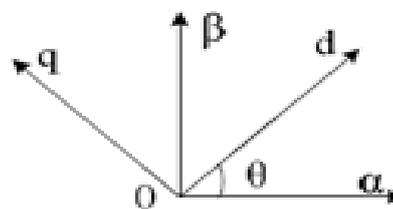


Figure 1. Relationship of the α - β and d-q coordinate system

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \quad (2)$$

B. The mathematical model of PMSM based on d-q coordinate system

The most common method in analyzing electric control PMSM is d-q axis mathematical model, which can be used in analyzing the stable state performance of PMSM as well as in studying the transient state performance. The mathematical model of PMSM is usually composed of the voltage equation, the stator flux linkage equation, the electromagnetism torque equation, the mechanical movement equation. The equations under d-q coordinate system can be expressed as follows:

The voltage equation:

$$\begin{aligned} u_d &= p\psi_d - \psi_q \omega + R_s i_d \\ u_q &= p\psi_q + \psi_d \omega + R_s i_q \end{aligned} \quad (3)$$

The stator flux linkage equation:

$$\psi_d = L_d \frac{di_d}{dt} + \psi_r \quad (4)$$

$$\psi_q = L_q \frac{di_q}{dt}$$

The electromagnetism torque equation

$$T_e = p (i_q \psi_d - i_d \psi_q) \quad (5)$$

The mechanical movement equation:

$$J \cdot p \cdot \frac{d\omega}{dt} = T_e - T_L \quad (6)$$

Where:

u_d, u_q — Applied d-q-axis control voltage i_d, i_q

— Stator d-q-axis current

ψ_q, ψ_d — d-q-axis flux linkage

L_q, L_d — d-q-axis inductance

R_s — Armature resistance

ψ_r — Permanent magnet flux linkage

T_e — Electromagnetic torque

T_L — Load torque

J — Moment of Inertia

p — Pole-pair numbers of the motor

ω — Electrical angular speed

II. THE PRINCIPLE OF ROTOR FIELD-ORIENTED VECTOR CONTROL SYSTEM

The figure 2 shows the block diagram of Rotor field-oriented vector control system [2]:

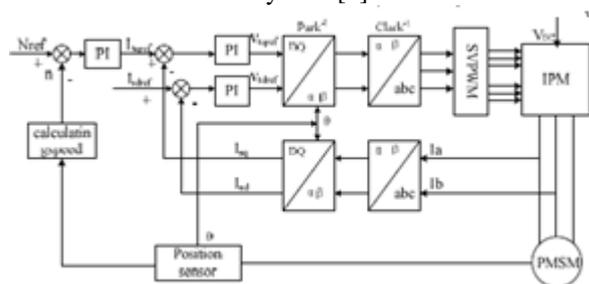


Figure 2. FOC system structure

In this control system, stator current i_A, i_B outputted by the inverter is measured using electric current sensor, and i_C is calculate with the formula $i_C = -(i_A + i_B)$. Transform the electric current i_A, i_B, i_C into the direct component i_{sq}, i_{sd} in the revolving coordinate system through the Clarke and the Park transform. Then i_{sq}, i_{sd} can be used as the negative feedback quantity of the electric current loop.

The deviation between the given speed and the feedback speed n is regulated through the speed PI regulator. The output is q axis reference component i_{sqref} to control the torque. The deviations between i_{sqref}, i_{sdref} and current feedback quantity i_{sq}, i_{sd} go through the electric current PI regulator, and the respectively output phase voltage V_{sqref} and V_{sdref} on the d-q revolving coordinate system. V_{sqref} and V_{sdref} are transformed into the stator phase voltage vector component V_{saref} and V_{sbref} under α - β coordinate system through inverse Park transform. If the stator phase voltage vector V_{sqref}, V_{sdref} and its sector number is known, we can use the voltage space vector PWM technique to produce PWM signal to control the inverter, so as to achieve closed-loop control of the PMSM.

If we take the algorithm of $i_d=0 (i_{sdref}=0)$ for a surface-mounted PMSM (SPM), the current vector trajectory as the Maximum Torque-per-Amp trajectory. On this condition, torque per current ampere becomes maximal, the copper loss decreased and the efficiency increased. That's why most SPM take the algorithm of $i_d=0$. In this paper, we also take SPM as the simulation motor model.

III. THE ESTABLISHMENT OF THE FOC SIMULATION MODEL

After analyzing the mathematical model of PMSM and the principle of Rotor field-oriented vector control system, the simulation model of field-oriented control system is established. The simulation model is under the environment of MATLAB7.0/Simulinkusing, due to its rich module libraries.

The system structure is shown as figure 3, and the main simulation modules are introduced as follows:

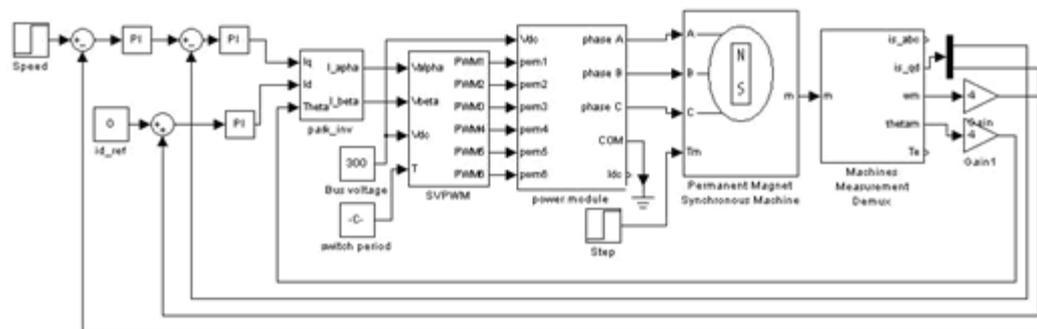


Figure 3. FOC system structure diagram of the PMSM based on SVPWM

A. The transform module from d-q to α - β coordinate system

The transform from d-q to α - β coordinate system is realized mainly according to equation (2) and the position angle of the rotor, namely the in figure 1. The specific interior simulation diagram is shown in figure 4.

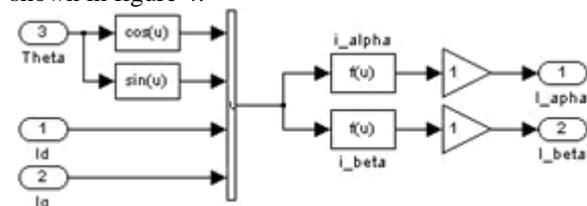


Figure 4. Block diagram of d-q to α - β transformation

B. The module of SVPWM production

The SVPWM uses two neighboring effective vectors and null vectors of the eight basis space voltage vector and their different act time to obtain the equivalent space voltage vector that the motor needs, as shown in figure 5 [3].

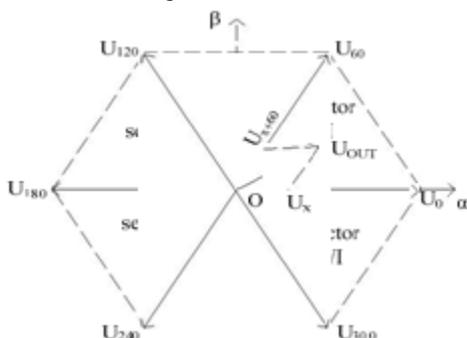


Figure 5. Basic voltage vectors and reference vector

1) The judgment of the sector

According to figure 5, when V_{out} is given in the form of the component $V_{out\alpha}$, $V_{out\beta}$ on α - β coordinate system, we can use equation (2) to calculate B_0 , B_1 , B_2 .

$$B_0 = U_\beta$$

$$B_1 = \sin 60^\circ U_\alpha - \sin 30^\circ U_\beta$$

$$B_2 = -\sin 60^\circ U_\alpha - \sin 30^\circ U_\beta$$
(7)

The value of equation P can be given by

$$P = 4\text{sign}(B_2) + 2\text{sign}(B_1) + \text{sign}(B_0)$$
(8)

where $\text{sign}(x)$ is sign function.

Then the sector number can be given by looking up table

1.

TABLE I. RELATIONSHIP OF P AND SECTOR						
P	1	2	3	4	5	6
Sector number	2	6	1	4	3	5

The sector judgment module is shown as figure 6.

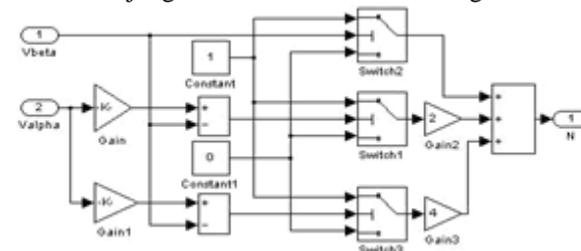


Figure 6. Simulation model of sector judgment

2) The calculation of the basic voltage vector act time

The relationship between the act time of the basic voltage vectors t^1 , t^2 and X, Y, Z, and sector N is shown as follows:

TABLE II. THE RELATIONSHIP BETWEEN t_1, t_2 AND X, Y, Z, N

Sector N	1	2	3	4	5	6
t_1	Z	Y	-Z	-X	X	-Y
t_2	Y	-X	X	Z	-Y	-Z

X, Y, Z can be given by equation (9).

$$X = \frac{VI}{U_{dc}} \sqrt{3}$$

$$Y = \frac{1(\sqrt{3}V_\beta + 3V_\alpha)I_t}{2U_{dc}}$$

$$Z = \frac{1(\sqrt{3}V_\beta - 3V_\alpha)I_t}{2U_{dc}}$$
(9)

The module diagram is shown as figure 7.

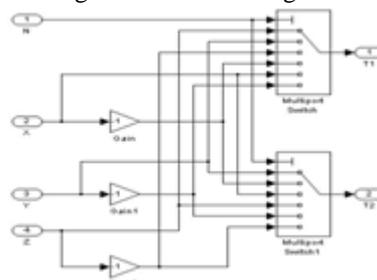


Figure 7. Simulation model of acting time of basic voltage vector

3) The calculation of switching time

Firstly, T_a , T_b , T_c can be given by

$$T_a = \frac{T_s - T_1 - T_2}{4}, T_b = T_a + 2, T_c = T_a + 2$$
(10)

The switch time is shown as the following table, where t_{aon} , t_{bon} , t_{con} means the turned-on time of the three-phase bridge arm power component respectively[4][5].

TABLE III. THE TIME SCHEDULE OF A, B, C THREE-PHASE SWITCH

Sector number	I	II	III	IV	V	VI
t_{aon}	T_b	T_a	T_a	T_c	T_c	T_b
t_{bon}	T_a	T_c	T_b	T_b	T_a	T_c
t_{con}	T_c	T_b	T_a	T_a	T_b	T_c

TABLE IV MACHINE PARAMETERS FOR SIMULATIONS

Magnet flux linkage	0.3Wb
d-axis inductance	8.5mH
q-axis inductance	8.5mH
Armature resistance	0.5Ω

The simulation diagram is shown in figure 8.

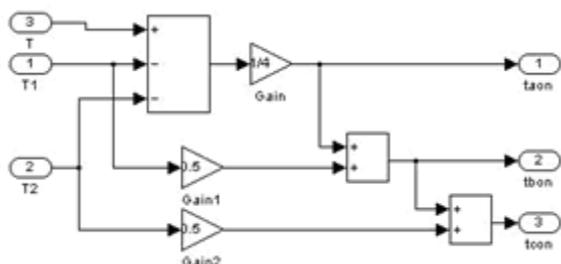


Figure 8. The simulation model of the inverter at the switch time

4) The production of PWM signal

Comparing the obtained α and β with the isosceles triangle, we can get symmetric space vector PWM signal. Making PWM1, PWM3, PWM5 reverse, we can get PWM2, PWM4 and PWM6.

The overall simulation structure diagram of SVPWM as shown in figure 9[6]:

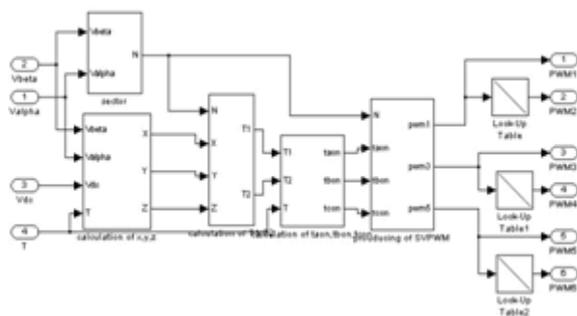


Figure 9. SVPWM simulation model

5) The model of inverter and electrical motor

Both the inverter module and the PMSM mentioned in simulation are provided by MATLAB/Simulink. The machine parameters listed in Table IV are used for the simulations. The measurement module may be used for examining the outputs physical quantity of the motor, and as feedback parameter to constitute closed-loop control system.

IV. THE RESULT OF THE SIMULATION

Set the motor speed at 500 rad/s, PWM cycle $T=0.001$ s. At time 0s, the electrical motor no-load start up, at time 0.03s, the load increases to 3 Nm. Simulation time is 0.06s, and then the simulation waveform shows as follows:

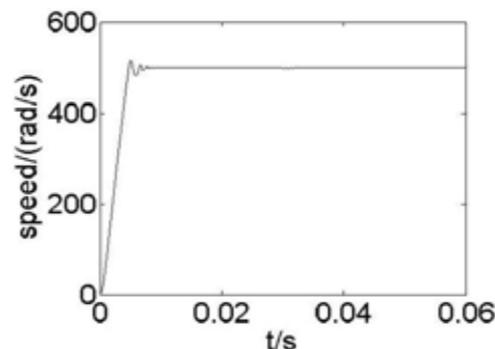
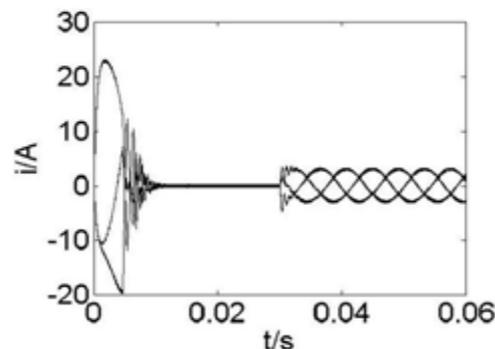


Figure 10. The current and speed response when load is increased

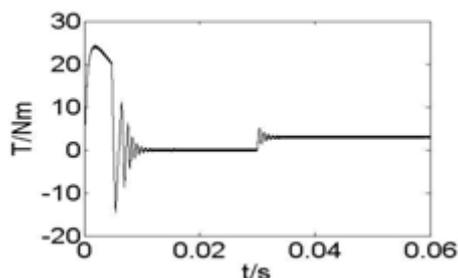


Figure 11. The torque response when load is increased

Simulation results are in accord with the performance characteristic of PMSM, which proves

the accuracy of the SVPWM algorithm and the control model, and provides theory basis for actual design of the control sy.

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