Simulation System of PMSM Based on Space Vector Pulse Width Modulation

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Abstract. This paper analyzes the mathematical model of PMSM, vector control strategy, the principle and implementation of SVPWM technology, on this basis, the simulation model of SVPWM and current velocity double closed-loop vector control system was built in MATLAB/Simulink, then the experiment’s results verify the feasibility of the design scheme. The design scheme of this paper provides a theoretical basis for PMSM vector control system in engineering practice.

1. Introduction

In recent years, AC motor speed regulation technology has developed rapidly[1]. People gradually use SVPWM instead of SPWM to drive inverter to improve motor performance. Compared with the traditional SPWM, the algorithm of SVPWM is easy to be realized. In addition, using SVPWM technology can reduce the distortion of current waveform and torque ripple and improve the efficiency of dc voltage. In light of the working principle of AC motor, SVPWM produces approximately circular flux trajectories through different conduction modes of the inverter. This flux trajectories is close to the flux trajectories generated by the three-phase winding during the operation of the motor, thus achieving higher control performance[2].

2. PMSM vector control strategy

2.1. Mathematical model of PMSM

The mathematical model of PMSM in dq rotating coordinate system is as follows:

The stator flux equation:

\[
\begin{align*}
\psi_d &= L_d i_d + \psi_f \\
\psi_q &= L_q i_q
\end{align*}
\]  (1)

The stator voltage equation:

\[
\begin{align*}
u_d &= R_i i_d + \psi_d - p_n \omega \psi_f \\
u_q &= R_i i_q + \psi_q + p_n \omega \psi_d
\end{align*}
\]  (2)

Substituting equation (1) into equation (2), we get
\[
\begin{align*}
\dot{i}_d &= -\frac{R_s}{L_d} i_d + p_s \omega \left( \frac{L_d}{L_q} i_q + \frac{1}{L_d} u_d \right) \\
\dot{i}_q &= -p_s \omega \left( \frac{L_d}{L_q} i_d - \frac{R_s}{L_q} i_q + \frac{1}{L_q} \left( u_q - p_s \alpha \psi_f \right) \right)
\end{align*}
\]  
(3)

The electromagnetic torque equation:
\[
T_e = 1.5 p_s \left[ \psi_f i_d - (L_q - L_d) i_d i_q \right]
\]  
(4)

Equations of motion:
\[
J \frac{d\omega}{dt} = T_e - B\omega - T_L
\]  
(5)

2.2. Vector control strategy

According to the equation of motion, the control of the motor is the control of its electromagnetic torque. It is not difficult to see from the electromagnetic torque equation that the electromagnetic torque is closely related to the d-axis current and the q-axis current of the motor. In order to realize the decoupling control, respectively control d axis and q axis current (d axis and q axis current is independent and orthogonal), which is the basic principle of vector control. In this way, the control of PMSM can be realized by simulating the control method of DC motor.

It can be seen from equation (4), If \( i_d = 0 \), the electromagnetic torque equation can be reduced to
\[
T_e = 1.5 p_s \psi_f i_q
\]  
(6)

At the same time
\[
\begin{align*}
i_a &= -i_q \sin \theta \\
i_b &= -i_q \sin(\theta - 2\pi / 3) \\
i_c &= -i_q \sin(\theta + 2\pi / 3)
\end{align*}
\]  
(7)

According to equation (6), \( T_e \) and \( i_q \) present linear relationships, therefore, the motor can be controlled by controlling the amplitude of three-phase stator current. The SVPWM control system of double closed-loop PMSM is shown in figure 1.

![Figure 1. Block diagram of SVPWM control system of double closed-loop PMSM](image)

3. The principle and realization of SVPWM technology

3.1. Principle of SVPWM

When using SVPWM technology to drive the three-phase inverter, the rule is: when any stator of the PMSM is connected to the positive pole of the power supply, its state is expressed as 1; when it is connected to the negative pole, its state is expressed as 0[3]. According to this regulation, the three-phase inverter will appear eight different working states, corresponding to eight voltage vectors,
respectively. Among them, six non-zero vectors $U(000)$ to $U(111)$ have the same amplitude, and the electrical angles of each other differ by $\frac{\pi}{6}$, and they divide the vector space into six sectors.

The spatial voltage vector distribution is shown in figure 2. $U(000)$ and $U(111)$ are zero vectors.

![Figure 2. Space voltage vector distribution](image)

It is difficult to obtain ideal sinusoidal voltage for three-phase stator in motor operation, so the actual air-gap flux trajectory of PMSM is not an ideal circle. SVPWM technology can solve this problem by combining the equivalent reference vector $(u_a)$ with 6 non-zero vectors and 2 zero vectors to make the actual air-gap flux trajectory of the motor close to the ideal circle[4].

### 3.2. Realization of SVPWM

Define

\[ u_a = u_\beta \quad (8) \]
\[ u_b = \frac{1}{2} (\sqrt{3} u_\alpha - u_\beta) \quad (9) \]
\[ u_c = \frac{1}{2} (-\sqrt{3} u_\alpha - u_\beta) \quad (10) \]

According to the specific calculation results of $u_a, u_b, u_c$,

\[ A = \begin{cases} 1 & (u_a > 0) \\ 0 & (u_a \leq 0) \end{cases} \]
\[ B = \begin{cases} 1 & (u_b > 0) \\ 0 & (u_b \leq 0) \end{cases} \]
\[ C = \begin{cases} 1 & (u_c > 0) \\ 0 & (u_c \leq 0) \end{cases} \]

The formula for sector number calculation is as follows

\[ \text{Sector} = A + 2B + 4C \quad (14) \]

After determining the sector number of the reference voltage vector, the reference voltage vector can be synthesized by using the two effective vectors and the zero vector in the sector. The effective vector action time of each sector is shown in Table 1; $X, Y, Z$ in the table is the intermediate variable defined, and its expression is shown in the formula(15-17); $t_1$ and $t_2$ represents the time when two adjacent operating voltages operate.

| Sector | I   | II  | III | IV  | V   | VI  |
|--------|-----|-----|-----|-----|-----|-----|
| $t_1$  | Z   | Y   | -Z  | -X  | X   | -Y  |
| $t_2$  | Y   | -X  | X   | Z   | -Y  | -Z  |

\[ X = \sqrt{3} \frac{T}{u_d} u_\beta \quad (15) \]
\[ Y = \frac{T}{u_d} (\frac{3}{2} u_\alpha + \frac{\sqrt{3}}{2} u_\beta) \quad (16) \]
\[ Z = \frac{T}{u_d} (-\frac{3}{2} u_\alpha + \frac{\sqrt{3}}{2} u_\beta) \quad (17) \]

Define

\[ t_{\text{on}} = \frac{T - t_1 - t_2}{4} \quad (18) \]
\[ t_{\text{on}} = t_{\text{on}} + \frac{t_1}{2} \quad (19) \]
\[ t_{\text{on}} = t_{\text{on}} + \frac{t_2}{2} \quad (20) \]
The switching time of A, B and C of the three-phase inverter is shown in table 2; according to this table and combined with the main control chip comparison register, engineers can get the PWM waveform generated by using SVPWM technology modulation.

| Sector | I    | II   | III  | IV   | V    | VI   |
|--------|------|------|------|------|------|------|
| A      | $t_{boa}$ | $t_{oan}$ | $t_{oan}$ | $t_{con}$ | $t_{con}$ | $t_{boa}$ |
| B      | $t_{oan}$ | $t_{con}$ | $t_{bon}$ | $t_{bon}$ | $t_{oan}$ | $t_{con}$ |
| C      | $t_{con}$ | $t_{boa}$ | $t_{con}$ | $t_{oan}$ | $t_{bon}$ | $t_{oan}$ |

4. Simulation experiment of the system

4.1. The construction of SVPWM simulation module

According to the implementation steps of SVPWM technology, the simulation model of sector judgment, calculation of X, Y, Z variablesis, voltage action time calculation and conduction time of invert A,B,C was built in Simulink. The modeling of each functional module is shown in Figure 3 to figure 7. The SVPWM simulation model can be obtained by connecting the above sub-modules and encapsulating them.

Figure 3. Sector judgment model
Figure 4. The calculation model of X, Y and Z variables
Figure 5. Voltage action time calculation model
Figure 6. The conduction time model of inverter A, B and C
4.2. System overall simulation

According to the Figure 1, the overall simulation model of the system was built, and the model is shown in figure 8. Then set the simulation parameters as follows: (1) set the step length as variable step length ode45 algorithm; (2) max step size is set to 1e-5; (3) relative tolerance is 1e-3; (4) simulation time is 0.2s; (5) PWM modulation period is 0.001s; (6) Motor load is 5 N·m. The parameters of the PMSM are shown in table 3. The simulation waveform are shown in FIG. 9 ~ FIG. 12.

Figure 7. PWM driven waveform generation model

Figure 8. Overall simulation model of the system

| Table 3. Parameters of PMSM |
|-----------------------------|
| parameter                  | value          |
| $P$                        | 1.6 kW         |
| $R_s$                      | 1.24 Ω         |
| $L_d$                      | 7.2 mH         |
| $L_q$                      | 19 mH          |
| $J$                        | 0.00343 kg·m²  |
| $K_T (1.5p_n \psi_r)$      | 0.601 Nm/A     |
| $p_n$                      | 2              |
5. Conclusion

According to the simulation waveform, the three-phase stator current and electromagnetic torque fluctuate slightly when the motor started; subsequently, the motor speed accelerated rapidly. When the motor runs for about 0.02s, the current, electromagnetic torque and speed enter into the steady state at the same time; at 0.1s, the motor is affected by the load, so the speed fluctuated slightly due to the load, but then the speed quickly returned to the given value, at this time the stator three-phase current is very close to the standard sine wave. The experimental results show that the system has fast response, good robustness and low current and torque ripple, small ripple of current and torque. In summary, the system can be applied to engineering practice. This paper also lays a theoretical foundation for subsequent practice and further research[5].

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