Space Vector Flux Weakening Control of PMSM Drivers

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Abstract. Permanent Magnet Synchronous Motor is widely used in industry, medicine and other fields. Based on the mathematical model of permanent magnet synchronous motor (PMSM), a system of modeling and simulation of PMSM was constructed by MATLAB/Simulink, and two PI controllers were used in the speed loop and current loop. This paper presents the principle of pulse width modulation based on voltage space vector, and the simulation model of PMSM control system based on SVPWM is built in MATLAB/Simulink. In the end, some experiments are carried out to the whole system, and it proves that the system is of good performance both in steady and dynamic state.

1. Introduction

Permanent magnet synchronous motor (PMSM) has a wide range of applications thanks to its simple structure, high power factor and high efficiency. Due to the permanent magnet excitation, the excitation magnetic field cannot be adjusted by the excitation winding. The permanent magnet synchronous motor must adopt the flux weakening control technology to meet the speed regulation requirement of the wide speed range. According to the operating principle of the motor, the back electromotive force will gradually increase as the rotor speed increases. The permanent magnet synchronous motor drive control is realized by the inverter, so the inverter output voltage also increases with the increase of the rotational speed. Since the maximum output voltage of the inverter is limited by the DC side bus voltage value, when the motor speed is higher than the maximum speed corresponding to the maximum voltage, the inverter will not be able to continue to provide a higher voltage to achieve an increase in the motor speed. If it is necessary to further increase the rotational speed, it can be achieved by reducing the excitation magnetic field and reducing the back electromotive force without changing the hardware. Since the excitation field of the permanent magnet synchronous motor is generated by the permanent magnet and cannot be directly changed, it is necessary to control the stator direct-axis current, and the weakening of the air gap magnetic field by the direct-axis armature reaction is equivalent to weakening the excitation magnetic field [1]-[2]. Therefore, the implementation of flux weakening control is based on this principle.

Since the mid-1980s, the mechanism of flux weakening operation has been deeply studied by scholars. In 1985, Brigette et al. analyzed the variation of motor power and torque during the field weakening process, and discussed the influence of the cross-coincidence term on the flux weakening control performance in the AC motor model. Thomas et al. obtained the maximum torque-to-current ratio (Maximum Torque Per Ampere, MTPA) curve. A method based on the direct-axis current tracking error to adjust the target value of the AC current is proposed. This achieves a smooth switching from the constant torque speed regulation phase to the constant power flux weakening speed regulation phase [3]. In the early 1990s, Japanese scholar Morimoto divided the motor operation into three areas. The research results cover both surface-mount and in-line motors and take into account the demagnetization that may be caused by flux weakening currents, which promotes the in-depth development of flux weakening speed regulation research [4].

With the in-depth development of modern motor design and control technology, scholars and engineers have proposed effective solutions from the body design and control algorithms of the motor, which greatly improved the dynamic response performance and steady state accuracy of the permanent magnet synchronous motor in the high-speed region [5]. In summary, the flux weakening control is a key problem that hinders the wide application of high-speed permanent magnet synchronous motors.

This paper introduces the basic principles of SVPWM and flux weakening, and details in the MATLAB/Simulink environment. The implementation method of SVPWM is finally combined with the permanent magnet synchronous motor control system to give the simulation experiment results.

2. Mathematical model of permanent magnet synchronous motor

The vector control is a control method based on the coordinate transformation theory. After the coordinate transformation, the permanent magnet synchronous motor has the same speed regulation performance as the DC motor. The literatures 6 and 7 first derive the vector equation of the ABC axis system, and then pass the vector transformation transform these equations into any coordinate system [6], [7]. Here, only the mathematical model of the permanent magnet synchronous motor in the d、q coordinate system is given. The circuit and torque equation are expressed as:

$$\frac{di_d}{dx} = \frac{1}{L_d} v_d - \frac{R}{L_d} i_d + \frac{L_q}{L_d} \omega_r i_q \quad (1)$$

$$\frac{di_q}{dx} = \frac{1}{L_q} v_q - \frac{R}{L_q} i_q + \frac{L_d}{L_q} \omega_r i_d - \frac{\lambda \omega_d}{L_q} \quad (2)$$

$$T_e = 1.5p[\lambda i_q + (L_d - L_q) i_d i_q] \quad (3)$$

Where L_q, L_d are the inductance of the q-axis and d-axis; ω_r is the angular velocity of the rotor; R is stator internal resistance; i_q, i_d are the current components of q-axis and d-axis; v_q, v_d are the voltage components of q-axis and d-axis; λ is electromagnetic torque coefficient; p is the stator pole pair; T_e is the electromagnetic torque.

Based on the above mathematical model of d q axis, the flux weakening control chart of permanent magnet synchronous motor is given, as shown in Figure 1. PMSM flux weakening control simulation system adopts double closed loop control scheme. The speed loop is the control outer loop, which keeps the actual speed of the motor consistent with the given speed value, and eliminates the influence of load torque disturbance and other factors on the motor speed in time. The current loop is the control inner loop. Its function is to control the inverter to generate accurate current on the stator winding.

3. SVPWM

3.1 Basic principle of SVPWM

For the three-phase voltage inverter shown in Figure 2, the phase voltage of the motor depends on its corresponding state of inverter arm. The three-phase bridge voltage inverter has eight operating states. V1 to V6 are six power switching tubes, and the switching functions (Sa, Sb, Sc) represent the switching states of the three bridge arms. There are 8 basic working states, namely: 100, 110, 010, 011, 001, 101, 111, 000. The first six working states are valid, called non-zero vectors; the latter two working states are called zero vectors. If these eight spatial states are represented by vectors, the space voltage vector of the permanent magnet synchronous motor (PMSM) is obtained as shown in Figure 3. In order to make the voltage vector of the inverter output close to a circle and finally obtain a circular rotating magnetic flux, it is necessary to use the inverter to combine the output voltages of the devices forms a polygonal voltage vector trajectory that is closer to a circle [8]. This is the basic starting point of the SVPWM principle.

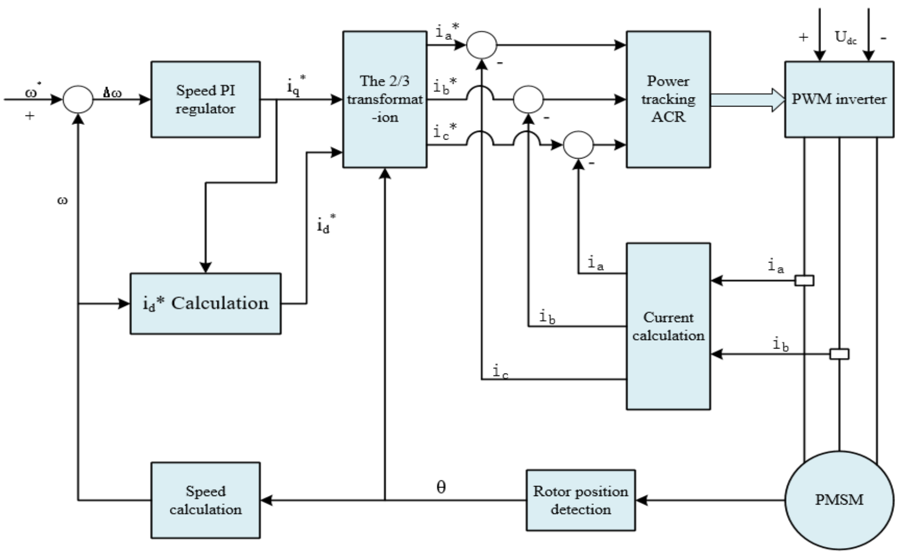
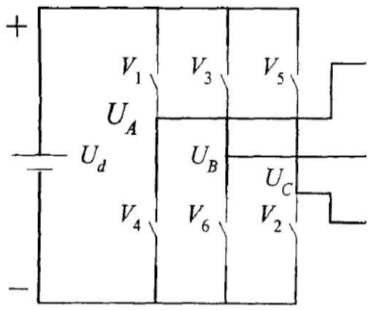


Figure 1. PMSM flux-weakening control Chart



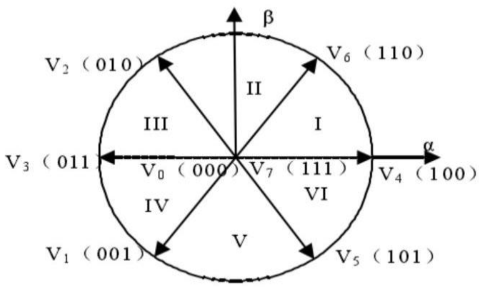


Figure 2. Inverter & Figure 3. Basic voltage space vector

3.2 Implementation of SVPWM Control Algorithm

The control scheme of SVPWM is divided into three parts, namely the interval allocation of three-phase voltage and the optimal sequence selection of vector synthesis selection and control algorithm. So the basic steps of the SVPWM algorithm are as follows:

(l) determining the sector in which the reference voltage vector U is located

For the case where U is given in the form of $[u_\alpha、 u_\beta]^T$, set 3 auxiliary variables u_{ref1}、 u_{ref2}、 u_{ref3} , The sector in which it is located can be obtained by the following algorithm.

$$u_{ref1} = u_\beta \tag{4}$$

$$u_{ref2} = \sin 60^\circ u_\alpha - \sin 30^\circ u_\beta \tag{5}$$

$$u_{ref3} = -\sin 60^\circ u_\alpha - \sin 30^\circ u_\beta \tag{6}$$

$$N = sign(u_{ref1}) + 2sign(u_{ref2}) + 4sign(u_{ref3}) \tag{7}$$

Then look at Figure 4 according to the value of N to get the sector, Figure 5 shows the simulation graph for judging the sector.

N	Sector
1	II
2	VI
3	I
4	IV
5	III
6	V

Figure 4. Relationship of N and the sectors

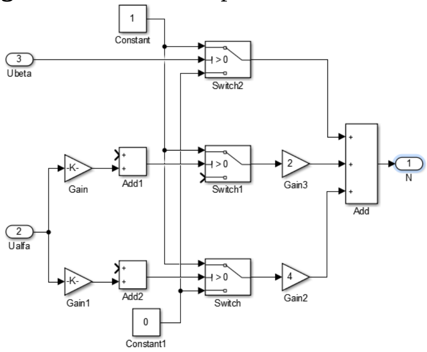


Figure 5. Judge the sectors

(2) Calculate the time of the action of the adjacent two switching voltage vectors
It should calculate the time of the switching voltage vector, and then determine if the sum of the two action times is greater than the PWM period. If it is larger than the PWM period, it will be corrected [9]. Literature 9 gives a detailed derivation and calculation of the vector action time. Figure 6 and Figure 7 below show the simulation of this step.

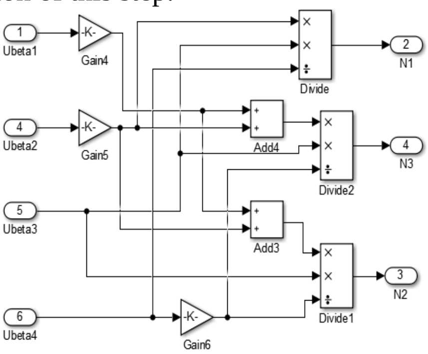


Figure 6. Neighboring motion vectors’acting time

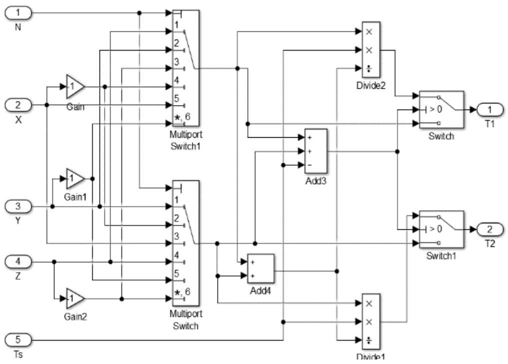


Figure 7. Neighboring motion vectors’ acting time

(3) Synthesized into three-phase PWM signals according to the switching voltage vector action time
The simulation graph for this step is shown in Figures 8, 9 and 10.

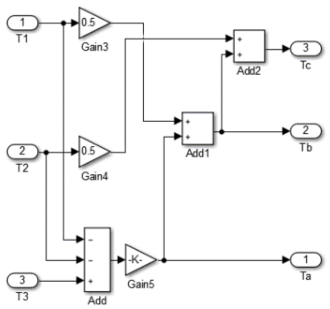


Figure 8. SVPWM wave form

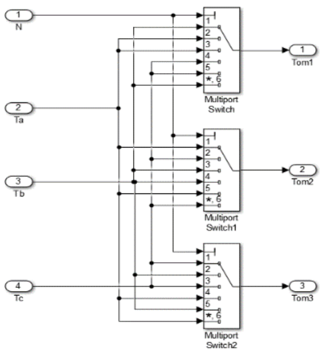


Figure 9. SVPWM wave form

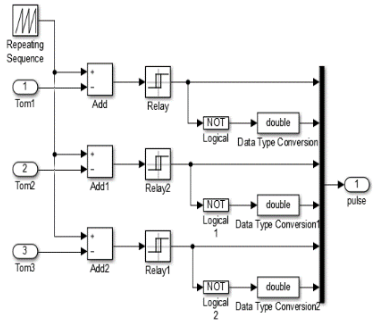


Figure 10. SVPWM wave form

4. Flux-weakening control

In a permanent magnet synchronous motor, the induced potential increases with the increase of the rotational speed. When the terminal voltage of the motor reaches the DC side voltage of the controller, the PWM controller loses the ability to track the current. Therefore, the stator terminal voltage U_s and the phase current I_s are limited by the inverter output voltage and the output current limit ($U_{s\max}$ and $I_{s\max}$) [10], [11]. Current limit circle and voltage limit circle is expressed as:

$$I_d^2 + I_q^2 \le I_{s\max}^2 \tag{8}$$

$$(E_0 + I_d x_d)^2 + (I_q x_q)^2 \le U_{s\max}^2 \tag{9}$$

Because $E_0 = \omega\psi_f, x_d = \omega L_d, x_q = \omega L_q$, so the voltage limit elliptic equation can be rewritten as：

$$(\psi_f + I_d L_d)^2 + (I_q L_q)^2 \le (U_{s\max} / \omega)^2 \tag{10}$$

The operating range of a permanent magnet synchronous motor is limited by the conditions of the current limit circle and the voltage limit ellipse. The motor's current vector I_s should be within the area enclosed by the two curves, as shown in Figure 11[12]. It can be seen from Figure 11 that the motor speed ω increases, the I_d component tends to increase, and the corresponding I_q component must decrease. Therefore, the electromagnetic torque of the motor also decreases with the increase of the rotational speed, showing the characteristic of constant power.

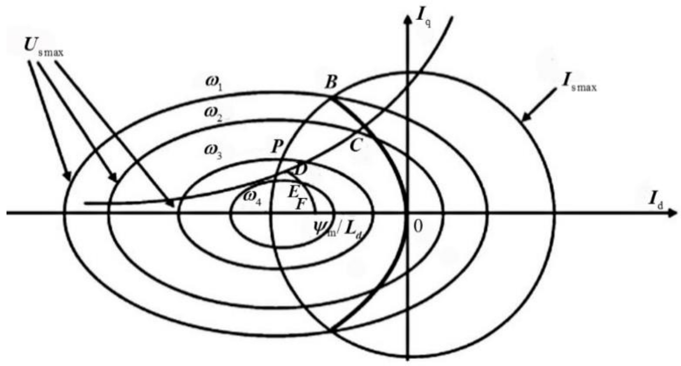


Figure 11. MAX circle

For the plug-in permanent magnet synchronous motor, the permanent magnet synchronous motor has two parts of torque due to the unequal parallel shaft inductance. They are permanent magnet torque and reluctance torque. In order to find the best match between current and torque, and use the minimum current to generate the maximum torque. Using the Lagrangian extreme value theorem in mathematics, The derivative of the current of the quadrature axis and the straight axis is obtained for the torque equation to find the optimal current and torque matching. The maximum torque/current ratio control speed trajectory of the built-in permanent magnet synchronous motor is directly given, as shown in Figure 11 above. When the motor speed exceeds the rated speed or the DC bus voltage of the voltage source inverter decreases, the voltage constraint curve retracts. The system cannot continue to run at point B. The motor torque is reduced and the current vector runs along the BP curve. The current at this time is constrained by both voltage and current constraints, and the current vector remains at the maximum effective value $I_{s\max}$. To continue to increase the speed, it is only by adjusting I_d and I_q . This is the weak magnetic speed regulation of permanent magnet synchronous motor.

If the motor initially runs at point C with a constant torque and the speed reference is increased to ω_3 , the current regulator can be guaranteed to run from point C to point D with constant torque. In this case, the current increases as the speed is given increasing. The current does not reach the maximum constraint value, and the air gap flux linkage of the motor decreases as the direct axis component of the current increases. As the given speed increases further, the motor torque is limited by the maximum voltage value. To achieve the maximum torque/current ratio, the current vector will travel along curve D-E-F. If the motor speed is given as ω_3 , the motor will travel along the field weakening curve BP to ω_3 after running to the point B at the maximum torque/current ratio.

5. SIMULINK simulation

5.1 Simulated motor parameters and waveform

The phase winding resistance R is 2.87 Ω, the limit voltage value $U_{s\max}$ is 240 V, and the d-axis inductance component L_d is 388.5 mH. The current value $L_{s\max}$ is 1.6 A, the q-axis inductance component L_q is 475.5 mH, permanent magnet flux linkage ψ_{m} is 0.3 Wb and the initial mechanical torque Ti is 4 Nm. the mechanical torque change time t is 0.015 s, the pole log p is 4, and the final mechanical torque T is 2 Nm. The simulated waveform is shown below.

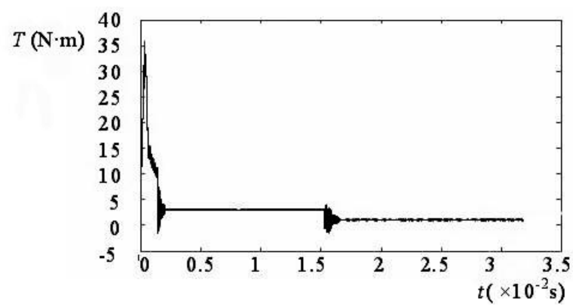


Figure 12. Torque curve

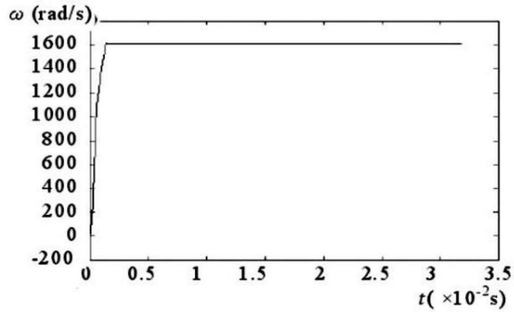


Figure 13. Speed curve

5.2 Simulation results

In the simulation, the minimum speed of the motor is set to 400 rad/s. After the flux weakening speed regulation based on SVPWM, the speed ratio of the constant power running area reaches 4:1. It can be seen from the simulation waveform that the system torque response is fast and stable at a speed of 1600 rad/s. The waveform is ideal, and there is no static difference in steady state operation. The simulation results demonstrate the effectiveness of the SVPWM-based flux weakening method used in this paper.

6. Conclusions

According to the principle of SVPWM, MATLAB/Simulink is used as the simulation software to build a SVPWM-based simulation model of flux weakening control of permanent magnet synchronous motor, the simulation results show that the designed simulation model is correct, the system has good robustness and rapidity, and effectively improves the control effect of the system. At the same time, in the simulation different control strategies can be tried to optimize the design, which provides an effective way for the analysis and design of the permanent magnet synchronous motor control system.

7. Acknowledgements

This work was supported by Postgraduate Research & Practice Innovation Program of Jiangsu Province , Project KYCX18_1223 ， KYCX18_1225 and by National Natural Science Foundation of China, Project 51607094.

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