Research on PMSM Vector Control System Based on MTPA

Yiheng Li *
School of North China Electric Power University, Baoding, China
*Corresponding author e-mail: 201804000514@ncepu.edu.cn

Abstract. Built-in permanent magnet synchronous motors (PMSM) are widely used in social life due to their strong load capacity and high-performance speed regulation ability. This paper derives the equation conversion of PMSM from abc coordinate system to dq coordinate system, introduces the basic principle of the Maximum Torque Per Ampere (MTPA), and builds a simulation model based on the MTPA vector control system using MATLAB/SIMULINK, analyzes the changing law of the simulated waveform.

Keywords: Permanent Magnet Synchronous Motor (PMSM); Maximum Torque Per Ampere (MTPA); Vector Control System.

1. Introduction
PMSM uses permanent magnets on the rotor side to replace the excitation system. Compared with ordinary synchronous motors, the working efficiency and reliability are improved [1]. The PMSM located inside the rotor is built-in, which has a salient pole effect, and the inductance of the right-angle shaft is different. Also, the electromagnetic torque and the load capacity of the motor is greatly increased.

When studying electromagnetic torque control, the electromagnetic torque of surface PMSM does not contain reluctance torque, so the control method of $I_d=0$ can be used. However, the built-in PMSM is no longer applicable to the control method of $I_d=0$ due to the influence of the reluctance torque. With the wide application of built-in PMSM, the control method of MTPA has been studied a lot. MTPA obtains the maximum output torque by constraining the stator current. Jianguo Song[2] pointed out that the maximum torque-to-current ratio control method is used when the speed is low; when a sufficiently large torque is required, the maximum current output control method is used; when the speed exceeds the rated speed, the maximum power output control method is used. Guanghui Shi et al. used MATLAB/SIMULINK simulation to establish the MTPA control system and the $I_d=0$ control system [3]. By comparing the simulation results, the analysis shows that the MTPA has better dynamic performance than the control scheme, smaller stator current, higher power factor, and is suitable for high torque and large capacity occasions.

Based on the MTPA, this paper uses MATLAB/Simulink to build a PMSM vector control system simulation model, and observe and analyze the simulation waveform.
2. Mathematical model of PMSM in dq coordinate system

Compared with AC motors, DC motors have simple electromagnetic relationships, convenient solutions, and is easy to control. Therefore, when studying AC motors, vector coordinate conversion methods are usually used to convert the AC motor control mode into a DC motor control mode equivalently. When studying the mathematical model of permanent magnet synchronous motors, the equations in the abc coordinate system are often converted to the equations in the dq coordinate system. In the conversion process, a two-phase stationary αβ coordinate system needs to be introduced as a conversion medium. The abc coordinate equation is converted to the αβ coordinate equation through Clarke transformation, and the αβ coordinate equation is converted into the dq coordinate system equation through Park transformation. At this time, the corresponding electrical signals in the motor mathematical model are converted into time-independent variables [4].

From the positional relationship between the abc coordinate system and the αβ coordinate system, the transformation matrix between them can be obtained as:

\[
T_{Clarke} = \frac{2}{3} \begin{bmatrix} 1 & \frac{1}{2} & -\frac{1}{2} \\ 0 & \sqrt{3} & \sqrt{3} \\ 1 & \frac{1}{2} & \frac{1}{2} \end{bmatrix}
\]  

(1)

In the same way, the transformation matrix between the αβ coordinate system and the dq coordinate system is:

\[
T_{park} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix}
\]  

(2)

Using the above two matrices to transform the flux linkage equation in the abc coordinate of the permanent magnet synchronous motor, the flux linkage equation of the permanent magnet synchronous motor in the dq coordinate system can be obtained as:

\[
\begin{bmatrix} \psi_d \\ \psi_q \end{bmatrix} = \begin{bmatrix} L_d i_d + \Psi_m \\ L_q i_q \end{bmatrix}
\]  

(3)

In the formula, \( \psi_d \), \( \psi_q \) are the equivalent flux linkage of d-axis and q-axis; \( L_d \), \( L_q \) are the equivalent inductance of d-axis and q-axis; and \( i_d \), \( i_q \) are the equivalent current of d-axis and q-axis.

The electromagnetic torque of a three-phase permanent magnet synchronous motor in the dq coordinate system can be expressed as:

\[
T_e = \frac{3}{2} p \left[ \psi_m i_q + (L_d - L_q) i_d i_q \right] = \frac{3}{2} p \psi_m i_q + \frac{3}{2} p (L_d - L_q) i_d i_q
\]  

(4)

In the formula, \( T_e \) is the output torque of the motor, and \( p \) is the number of pole pairs of the motor. It can be seen that the electromagnetic torque is divided into two parts. The first part is the permanent magnet torque produced by the permanent magnets; the latter part is the reluctance torque produced by the salient pole effect on the rotor side.

3. Maximum Torque Per Ampere (MTPA)

The built-in PMSM has the salient pole effect, so the MTPA current control strategy is adopted. This method makes the motor output the maximum torque by constraining the current and improves the motor operating efficiency [5]. The current constraint equation of the motor is:

\[
I_s = \sqrt{I_d^2 + I_q^2} \leq I_{max}
\]  

(5)

In the formula, \( I_{max} \) is the constraint value of the three-phase phase current of the motor stator, that is, the maximum value that is allowed to reach. When using MTPA, the motor d-axis current equation is expressed as follows:
The expression of the motor q-axis current equation is as follows:

\[ I_q = \text{sign}(T_e) \sqrt{I_{\text{max}}^2 - I_d^2} \]  

(7)

In the formula, \( T_e \) is the given torque, and \( \text{sign} \) means the symbol in brackets. For the MTPA control system, the motor d-axis current is given according to the calculation result of formula (6), and the motor q-axis current is given according to the calculation result of formula (7).

4. Simulation process

Use MATLAB/SIMULINK to build a PMSM vector control system simulation model based on MTPA as follows:

\[ I_d = \frac{\psi_{pm}}{4(I_{q_d} - I_d)} - \sqrt{\frac{\psi_{pm}^2}{16(I_{q_d} - I_d)^2} + \frac{I_{d_{\text{max}}}^2}{2}} \]  

(6)

Start the system at no-load rated speed, increase the rated torque at 0.15s at the beginning of operation: 5r/min as interference, increase the speed from 1500r/min to 2000r/min at 0.2s after operation, observe the synchronous motor speed, d-axis and q-axis current, motor output torque, and the waveform change law of the motor stator three-phase current. Analyze the change law of the above simulation waveform: the speed control system also has good dynamic and static characteristics.

Figure 1. A simulation model of a PMSM vector control system based on MTPA

It can be seen from the figure 2 that after 0.05s of operation, the motor speed tends to stabilize, reaching 1000r/min, and its overshoot is 0.1r/min. When running to 0.15s, the system suddenly increases 5r/min load, the system is disturbed, the speed drops to 995.575r/min, and the overshoot is
0.075r/min. When running to 0.2s, set the motor speed to increase to 2000r/min, the motor speed starts to increase, and at 0.24s, the speed reaches 1995.6r/min, and the overshoot is 0.01r/min. The overshoot during the above speed change process is far less than the requirements of the general control system, that is, less than 15% of the given speed, and the fluctuation of the steady-state speed is less than 0.5r/min.

Because the simulation process uses the MTPA control method to obtain the d-axis and q-axis currents, they change synchronously with changes in motor speed and load conditions.

![Figure 3. Waveform change of d-axis and q-axis current](image)

![Figure 4. Motor output torque change waveform](image)

Figure 4 shows the waveform change of motor output torque. Since the motor starts at the no-load rated speed, the output torque of the motor drops to 0 after the system runs for 0.025s, and the overshoot is 0.1N*m. When running to 0.15s, the system suddenly increases the load of 5N*m, and the system is at 0.154s, the motor output torque rises to 5N*m, and the overshoot is 0.05N*m. When it runs to 0.2s, the motor speed increases to 2000 rpm, the motor output torque increases suddenly, and then drops to 5N*m in 0.24s, with an overshoot of 0.1N*m. The above torque fluctuations are all less than 2N*m, so it can prove that the system has good steady-state characteristics.

In the same way, since the no-load rated speed is started, the phase current drops to zero after the system runs for 0.025s. After 0.15s and 0.2s, the phase current waveform changes. Finally, after the system is stabilized at 0.24s, the phase current also tends to be stable and not zero. At this time, it is load operation.
The analysis of the simulation results is consistent with the theoretical knowledge. Therefore, the results of the simulation prove the correctness of the simulation model and further verify the correctness of the theoretical knowledge.

5. Conclusion
In this paper, the AC motor is transformed into a DC motor by coordinate transformation. Based on the MTPA, the simulation model of the PMSM vector control system is built using MATLAB/SIMULINK, and the simulation waveform is observed and analyzed. The simulation results are more consistent with theoretical knowledge, verifying the rationality of the model.

References
[1] Du Chuan. Vector control strategy of permanent magnet synchronous motor based on current predictive control[J]. Journal of Shenyang University of Technology, 2019, 41(6): 616-620. DOI:10.7688/j.issn.1000-1646.2019.06.04.
[2] Song Jianguo, Lin Qiangqiang, Mou Pengtao, et al. Built-in permanent magnet synchronous motor MTPA and field weakening control [J]. Power Electronics, 2017, 51(5): 84-86.
[3] Shi Guanghui, Yu Jia, Zhang Liang. Permanent magnet synchronous motor maximum torque current ratio control[J]. Electric Machine Technology, 2009, (5): 28-31. DOI:10.3969/j.issn.1006-2807.2009.05.009.
[4] Liu Shiming, Wang Weigu, Yin Xianggen, Chen Deshu. Synchronous motor inductance matrix analysis method[J]. Proceedings of the Chinese Society of Electrical Engineering, 2002(06): 90-96.
[5] Wei Liang. Finite element analysis of built-in permanent magnet synchronous motor and its speed control [D]. North China Electric Power University; North China Electric Power University (Baoding), 2009. DOI:10.7666/d.y1785639.