Simulation of Vector Control System of Permanent Magnet Synchronous Motor

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Abstract. The article analysed and studied the structure performance and mathematical model of the permanent magnet synchronous motor, and it further researched the principle of vector control technology and the SVPWM algorithm on this basis. A closed-loop simulation model of permanent magnet synchronous motor speed/current was built. The waveform of the simulation result is consistent with the theoretical analysis, which verifies the effectiveness of the simulation experiment platform and mathematical model. It also verifies the superiority of the id=0 control algorithm and vector control. A theory for the research and design of the permanent magnet synchronous motor vector control system basis is provided.

1. Introduction
Permanent magnet synchronous motors have the advantages of terse structure, high torque-to-inertia ratio, high power density and power factor, and good dynamic characteristics. They are widely used in industry, transportation, aviation, military and other fields [1]. Vector control and direct torque control are the two main control methods of permanent magnet synchronous motors. Direct torque control adopts discrete two-position mode to control the torque for the stator flux linkage, which speeds up the dynamic response of the torque. No coordinate transformation is required, and the precise decoupling of exciting current and torque current is not pursued. The algorithm is simple but the torque is pulsating [2] [3]. Vector control is more dependent on motor parameters, it is difficult to accurately calculate the rotor flux linkage value, and a large number of complex calculations such as coordinate transformation are required, which increases the control time and it is difficult to achieve the ideal control state [4].

Therefore, in order to more accurately analyze the vector control strategy of high-performance permanent magnet synchronous motors, it is necessary to develop modeling and simulation research for the vector control system of permanent magnet synchronous motor. It provides important practical value and theoretical research significance for the vector control technology to be better applied to the control of permanent magnet synchronous motors.

2. Mathematical model of permanent magnet synchronous motor
The physical structure of a permanent magnet synchronous motor determines that its mathematical model is multivariable, nonlinear, and strong coupling. Its electromagnetic torque is a complex function of stator and rotor current, stator and rotor flux linkages, and stator and rotor electromagnetic parameters. Therefore, methods such as coordinate transformation and field oriented control are used to reduce the order of the mathematical model of the AC motor to obtain an equivalent model.
2.1 Coordinate transformation

Based on the principle of generating the same rotating magnetomotive force as the three-phase alternating current, the mathematical model of three-phase PMSM is transformed into a two-phase coordinate system through 3s/2s coordinate transformation, which is equivalent to α β two-phase stationary coordinate system. It is equivalent to a synchronous rotating coordinate system d q by 2s/2r coordinate transformation, and its stator current is also transformed into a direct current vector accordingly. The three-phase stationary-two-phase stationary coordinate transformation (3s/2s) equation is as follows:

\[
\begin{bmatrix}
    i_d \\
    i_q
\end{bmatrix} = \begin{bmatrix}
    \frac{1}{2} & -\frac{1}{2} & \frac{1}{\sqrt{3}} \\
    \frac{1}{\sqrt{3}} & \frac{1}{2} & -\frac{1}{2}
\end{bmatrix} \begin{bmatrix}
    i_A \\
    i_B \\
    i_C
\end{bmatrix}
\]

\[
\begin{bmatrix}
    l_A \\
    l_B \\
    l_C
\end{bmatrix} = \begin{bmatrix}
    \cos \phi & -\sin \phi \\
    \sin \phi & \cos \phi
\end{bmatrix} \begin{bmatrix}
    l_d \\
    l_q
\end{bmatrix}
\]

\(\phi\) is the angle between the d axis of the d-q coordinate system and the axis of the coordinate system.

2.2 The mathematical model of PMSM

In order to facilitate analysis and modeling, the following assumptions are established on the basis of permanent magnet synchronous motors [5]:

1) Regardless of the saturation of the stator core, the eddy current loss and hysteresis loss are ignored;
2) The spatial magnetic potential distribution generated by the three-phase sinusoidal alternating current is in the shape of a sine wave, ignoring the higher harmonics of the magnetic field;
3) The salient pole effect of the rotor magnetic field is not considered;
4) The conductivity of the permanent magnet material is zero, and the magnetic field of the permanent magnet is constant.

From the above coordinate transformation theory and the assumptions of permanent magnet synchronous motors, the mathematical model is derived:

The stator voltage equation:

\[
\begin{align*}
    u_d &= R_s i_d + p \psi_d - \omega_r \psi_q \\
    u_q &= R_s i_q + p \psi_q + \omega_r \psi_d
\end{align*}
\]

(2)

Stator flux equation:

\[
\begin{align*}
    \psi_d &= \psi_f + L_d i_d \\
    \psi_q &= L_q i_q \\
    |\psi_d| &= \sqrt{\psi_d^2 + \psi_q^2}
\end{align*}
\]

(3)

Among them: \(u_d, u_q\) —— is the stator voltage d-q axis component (V); \(\psi_d, \psi_q\) —— is the stator flux d-q axis component (Wb);

\(L_d, L_q\) —— is the equivalent inductance of the stator winding d-q axis (H);

\(i_d, i_q\) —— is the d-q axis component of the stator current (A).

Electromagnetic torque equation and motion equation:

\[
T_e = \frac{3}{2} n_p (\psi_d i_q - \psi_q i_d) \quad T_e - T_m = J \frac{d\omega_r}{dt}
\]

(4)

Among them: \(T_e\) —— is the electromagnetic torque (N*m); \(T_m\) —— is the motor load torque (N*m);

\(J\) —— is the moment of inertia of the motor (kg*m^2).

3. Permanent magnet synchronous motor vector control system

3.1 Principle of vector control

The basic idea of vector control is to convert two AC components orthogonal in time phase into two DC components orthogonal in space according to the coordinate transformation theory, thereby decomposing the stator current of the AC motor into excitation and torque components. Two independent DC quantities reduce the degree of coupling of the order of the control system, thereby realizing the control of the motor flux and torque. Under vector control, a control strategy based on
3.2 Principle and realization method of SVPWM
The SVPWM method is based on the idea of flux linkage tracking. It treats the inverter and the permanent magnet synchronous motor as a whole, and uses the different combinations of the six bridge arms of the IGBT to generate 8 basic voltage space vectors to synthesize the desired actual voltage space vector. The rotation path of the composite vector is as close to the circle as possible, and the basic flux linkage circle is formed [6].

3.3 Sector judgment of reference voltage vector
The control system needs to output the vector voltage signal \( U_{\text{ref}} \), which contrarotate in space at an angular frequency \( \omega \). When it rotates to a certain sector of the vector diagram, the system calculates the basic voltage space vector required for the sector and calculates it by this vector. The corresponding state drives the power switching element to act.

1) Judgment of the sector \( N \) where the composite vector \( U_{\text{ref}} \) is located

\[
\begin{align*}
    u_1 &= u_\theta \\
    u_2 &= \sqrt{3}u_a - u_\theta \\
    u_3 &= -\sqrt{3}u_a - u_\theta \\
    N &= A + 2B + 4C
\end{align*}
\]  

Further define, if \( u_1 > 0 \), then \( A=1 \), otherwise \( A=0 \); if \( u_2 > 0 \), then \( B=1 \), otherwise \( B=0 \); If \( u_3 > 0 \), then \( C=1 \), otherwise \( C=0 \).

| Sector number | II | III | IV | V | VI |
|---------------|----|-----|----|---|----|
| N             | 1  | 5   | 4  | 6 | 2  |

2) Calculation of non-zero vector and zero vector action time

\[
\begin{align*}
    \begin{bmatrix}
        U_a \\
        U_b
    \end{bmatrix}
    Ts &= u_{\text{ref}} \begin{bmatrix}
        \cos \theta \\
        \sin \theta
    \end{bmatrix} \\
    Ts &= \frac{2}{3} U_d \begin{bmatrix}
        1 \\
        0
    \end{bmatrix} T_4 + \frac{2}{3} U_d \begin{bmatrix}
        \cos \frac{\pi}{3} \\
        \sin \frac{\pi}{3}
    \end{bmatrix} T_6

    T_4 &= \frac{\sqrt{3}T_s}{U_d} \left( \frac{\sqrt{3}}{2} u_a - \frac{u_\theta}{2} \right) \\
    T_6 &= \frac{\sqrt{3}T_s}{U_d} u_\theta
\end{align*}
\]  

In the same way, the action time of each vector in other sectors can be obtained.

Finally, the triangular carrier signal of a certain frequency is compared with the vector switching points of each sector, so that the PWM pulse signal required by the converter can be generated.

4. PMSM modeling simulation and result analysis
Use its module library in MATLAB/SIMULINK environment to build a PMSM simulation model based on the analysis of the PMSM mathematical model. The system adopts speed and current double closed loop PI control scheme.
Figure 1. Vector control simulation model of permanent magnet synchronous motor

Figure 2. View of stator current

Figure 3. 0.1s sudden load and 0.15s given speed change
The stator current waveform is consistent with the theoretical analysis. It is a sine-like waveform synthesized by the PWM wave, which verifies the principle of vector control and is also the basis for the successful simulation. Zoom in to see the "sawtooth" formed by the waves. After the speed is stable, the motor speed no longer has an acceleration constant.

![Figure 4. Waveform of electromagnetic torque after loading in 0.1s](image1)

![Figure 5. Waveform of q-axis current after loading in 0.1s](image2)

5. Simulation result analysis
The system speed setting is set to 2000 n/min, the system quickly stabilizes, and the overshoot is small. From the current waveform when the system is running, it can be seen that when the system is running stably, the motor stator current is a three-phase sinusoidal current, and its amplitude changes with the change of the motor's output electromagnetic torque. The greater the output electromagnetic torque, the greater the current amplitude, it conforms to the theoretical analysis. Realize the purpose of controlling the torque by controlling the d-axis current, thereby controlling the AC motor.

The given speed of the system changes suddenly, the system responds quickly and smoothly, and the motor speed overshoot is very small. It shows that the speed control characteristics of this control strategy can achieve control effects comparable to DC motors.

When the motor load changes suddenly, the stator current of the motor will also go through an adjustment process, and a new balance will be formed quickly. The electromagnetic torque responds quickly and can quickly keep up with the load torque; the stator current also responds quickly with
load changes, and the dynamic response performance of the system is good; the motor speed basically does not fluctuate, indicating that the simulation system has strong anti-interference ability.

6. Conclusions
The full text introduces the development of permanent magnet synchronous motors, mathematical models, and finally uses vector control strategies to establish a synchronous motor simulation model using classic speed and current double closed-loop control methods. And the simulation results are analyzed. The vector control system realizes the purpose of controlling the motor by controlling the d-axis component of the motor stator current. And the system runs smoothly, which is consistent with the theoretical analysis, and has good dynamic performance and speed control characteristics close to the speed control performance of a DC motor. The biggest advantage of \( i_d = 0 \) control strategy is that the motor torque is proportional to the amplitude of the stator current component, similar to a DC motor, so it has been widely used. The research in this paper verifies the effectiveness and superiority of MATLAB simulation, and also provides a theoretical reference for the actual control of permanent magnet synchronous motors. One thing to note is that since many models are idealized, the vector control of permanent magnet synchronous motors in practice still needs to consider many factors.

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