Research on MTPA Control Strategy of Permanent Magnet Synchronous Motor Based on Fast SVPWM Algorithm

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Abstract: In recent years, the poor endurance of electric vehicles has been one of the main problems that have limited the development of new energy vehicles. Improving system efficiency and reducing system losses are currently one of the main methods to improve endurance. A fast SVPWM (Space Vector Pulse Width Modulation Technology) algorithm is used to improve the traditional SVPWM judgment, simplifying the complicated coordinate transformation and trigonometric function calculation of the traditional SVPWM technology judgment. Then it is applied to MTPA (Maximum Torque Per Ampere) control for Simulink model simulation to verify the effect. The experiment proves that the MTPA control under the improved SVPWM algorithm has higher response speed and stability than the traditional $i_d=0$ control. The size of the stator current is about 1-2A smaller than $i_d=0$ control, which achieves better MTPA control.

1.Introduction
As the power “heart” of current new energy vehicles (NEVs), electric motor is a key affecting the performance of NEVs such as battery life and stability. Therefore, research on motor control is important. Permanent magnet synchronous motors are gradually being favored by the NEV market because of their high efficiency and high starting torque. At present, the mainstream motor control such as $i_d=0$ control is simple to implement, but does not exert the maximum effect of the motor system. The list method of MTPA control requires a lot of experimentation and storage space. Although direct torque control is convenient, it is prone to produce larger torque ripples. In this paper, a fast SVPWM algorithm is applied to MTPA control to improve the efficiency of the system compared with $i_d=0$ control.

2.Model analysis of the motor
Since the stator and rotor of the permanent magnet synchronous motor (PMSM) are coupled through the air gap magnetic field, there is relative rotation between the stator and the rotor. Therefore, the original model of the PMSM is a time-varying, nonlinear, strongly coupled and multi-phase static coordinate system. For a complex system of variables, it is quite difficult to analyze and solve its differential equations. Therefore, the method of coordinate transformation based on the equivalence of magnetomotive force is usually adopted to simplify the model and reduce coupling [2]. The ABC three-
phase static coordinates of the motor was converted into the two-phase static coordinate system $\alpha \beta$ by Clarke, and the two-phase static coordinate system $\alpha \beta$ was converted into the two-phase rotating coordinate system $dq$ by Park transformation, so that the AC control of the motor was converted into the DC control, which was convenient for the realization of mathematical control.

First introduce the Clark transform: By transforming the voltage vector in the A-B-C coordinate system to the $\alpha \beta$ coordinate system, the voltage equation was obtained from Figure 1.

$$\begin{align*}
U_\alpha &= U_a - \cos \frac{\pi}{3} U_b - \cos \frac{\pi}{3} U_c \\
U_\beta &= \sin \frac{\pi}{3} U_b - \sin \frac{\pi}{3} U_c
\end{align*}$$

(1)

Figure 1 A-B-C coordinate system and $\alpha \beta$ coordinate system transformation diagram

Then introduce the Park transform: The voltage vector in the $\alpha \beta$ coordinate system was transformed into the d-q coordinate system, and the voltage relationship between the two coordinate systems was shown in Figure 2

$$\begin{align*}
u_d &= U_\alpha \cos (\theta) + U_\beta \sin (\theta) \\
u_q &= -U_\alpha \sin (\theta) = U_\beta \cos (\theta)
\end{align*}$$

(2)

In the formula, $\theta$ is the angle between the d axis and the $\alpha$ axis.

Figure 2 $\alpha \beta$ coordinate system transformation diagram and Park transformation diagram

The transformation of current and flux linkage is equivalent to that of voltage vector. The two-phase coordinate system based on the dq axis has been widely used in the model analysis of permanent magnet synchronous motors.

3. Motor control strategy

3.1. Space vector pulse width modulation technology

As the coordinate transformation and complex trigonometric function calculations of traditional Space Vector Pulse Width Modulation (SVPWM) requires relatively long calculation time, many scholars have studied and improved the SVPWM technology. For example, Dong Yan et al. proposed a new three-phase four-switch SVPWM strategy [3] and Sun Hexu et al. put forward a 120°-based non-orthogonal SVPWM algorithm [4]. Scholars generally improved the division of SVPWM sectors, which can not only save the running time of the algorithm, but also further enhance the utilization rate of the inverter bus voltage.

The fast SVPWM algorithm simplifies the six partitions of the traditional SVPWM algorithm into three partitions, using only 0°, 120°, and 240° vectors for partitioning, thus forming three large sectors.
The particularity of the basic vectors in these three directions is that they are consistent with the direction of the three-phase reference modulation voltage. The components of the space voltage vector in these three directions are the instantaneous values of the three-phase modulation voltage at this time. Thus, the reference voltage space vector on the basic vector can be obtained directly by using the given reference three-phase modulation voltage and the sector where the space voltage vector is located can be quickly determined [5]. On this basis, the three sectors (I, II, and III) are divided into six small sectors.

Let the vectors of the motor model at 0°, 120°, and 240° are \( V_A \), \( V_B \), and \( V_C \), respectively in the first, second, and third largest sectors. From the sum of vectors, we can see in Figure 6 \( V_f = V_A + V_B + V_C \). From the figure, the vector components of \( V_A \) on \( V_B \) and \( V_C \) are \( V_0 \) and \( V_1 \). It can be judged that if \( V_{C-V_0} \geq 0 \), \( V_{B-V_1} > 0 \), that is, \( V_{C-V_A} \geq 0 \), \( V_{B-V_A} > 0 \), then \( V_f \) is in the second sector. The small sector of \( V_f \) can be judged by vector analysis, that is, when \( V_B > V_A \), \( V_B + V_C - V_A > 0 \), \( V_f \) is in the third small sector.

The judgment of other sectors is similar to that of the second sector, without any more examples. Suppose the sector position as \( N, T_1 = V_A - V_B, T_2 = V_B - V_C, T_3 = V_A - V_C, T_4 = V_A + V_B - V_C, T_5 = V_B + V_C - V_A, T_6 = V_A + V_C - V_B, T_7 = V_B - V_C - V_A, T_8 = V_A - V_B - V_C, T_9 = V_B - V_A - V_C \). Using this method to judge the sector can avoid complicated coordinate system transformation and trigonometric function calculation, thereby improving the operating efficiency and resource efficiency of the system to a certain extent. The judgment of the sector is shown in Table 1:

| \( T_1 \) | \( T_2 \) | \( T_3 \) | \( T_4 \) | \( T_5 \) | \( T_6 \) | \( T_7 \) | \( T_8 \) | \( T_9 \) | \( N (\text{big}) \) | \( N (\text{small}) \) |
|---|---|---|---|---|---|---|---|---|---|---|
| > 0 | ≥0 | > 0 | | | | | | | I | 1 |
| ≥0 | ≥0 | | | | | | | | I | 2 |
| ≤0 | < 0 | > 0 | | | | | | > 0 | II | 3 |
| ≤0 | < 0 | | > 0 | | | | | | II | 4 |
| > 0 | > 0 | | > 0 | | | | | | III | 5 |
| > 0 | ≤0 | | | | | > 0 | | | III | 6 |
3.2. Motor MTPA control strategy

According to the vector analysis of the motor model, the torque equation of the permanent magnet synchronous motor under the d-q axis is (3):

$$T_e = 1.5P_n[i_q\phi_f + (L_d - L_q)i_d i_q]$$  \hspace{1cm} (3)

The internal asymmetry of the built-in permanent magnet synchronous motor (IPMSM) can generate reluctance torque $T_m$ (Equation (4)). Compared with the control strategy of $i_d=0$, making full use of the reluctance torque can improve the utilization efficiency of the system.

$$T_m = 1.5P_n(L_d - L_q)i_d i_q$$  \hspace{1cm} (4)

the flux linkage generated by the permanent magnets of the permanent magnet synchronous motor and the inductances $L_d$ and $L_q$ of the vertical and horizontal axis, the torque $T_e$ of the motor depends on the stator vertical axis current $i_d$ and $i_q$. In the $i_d-i_q$ plane, the same torque $T_e$ is generated, and there can be multiple combinations of $i_d$ and $i_q$. For each $T_e$, a group $(i_d, i_q)$ closest to the origin will always be found [6]. MTPA control can be described as an optimal solution to the stator current under certain torque constraints [7], and the Lagrangian method can be used to solve the extreme value:

$$i_s = \sqrt{i_d^2 + i_q^2}$$

$$T_e = 1.5P_n[i_q\phi_f + (L_d - L_q)i_d i_q]$$  \hspace{1cm} (5)

The Lagrangian method can be employed to solve the extreme value:

$$i_d = \frac{-\phi_f+\sqrt{\phi_f^2+4(L_d-L_q)^2i_q^2}}{2(L_d-L_q)}$$  \hspace{1cm} (6)

According to this control principle, a control model can be built in simulink. The control block diagram is shown in Figure 5:

![Figure 5 MTPA control block diagram based on fast SVPWM algorithm](image)

4. Simulink simulation results

The MTPA control strategy integrated with fast SVPWM algorithm is simulated in Matlab software to verify the control effect of this strategy on the stator current. In the simulation, the external load speed command is set to 1500r/min, d-axis inductance $L_d$ is 0.51m H, q-axis inductance $L_q$ is 1.626, and the permanent magnet flux $\phi_f$ is 0.1968Wb. The result is shown in Figure 6.

From the torque formula of the permanent magnet synchronous motor, it can be seen that when the $\phi_f$, $L_d$, $L_q$, and $P_n$ of the motor are constant, the torque is only related to the direct axis of the motor. When the control mode of $i_d=0$ is adopted, the torque equation at this time is $T_e=1.5P_n i_q \phi_f$. It can
be seen from the formula that the torque at this time is proportional to $i_q$, and the required torque can be obtained by adjusting $i_q$. The advantage of this control method is that it is relatively simple. At the same time, because there is no d-axis current, there will be no demagnetization of permanent magnet in the operation, which is beneficial to improving the life of the motor [8]. However, ignoring the effects of reluctance torque and direct-axis current, the stator current generated by the control mode of $i_d=0$ is prone to errors and fluctuations.

![Figure 6 Stator current under MTPA](image1)

![Figure 7 Stator current under id=0](image2)

Under the experimental parameters, the MTPA control with the fast SVPWM algorithm is compared with the control mode of $i_d=0$. Although the initial current is larger, the response speed of the MTPA control jitter is very fast. When the torque and speed increase gradually, it is obvious that the MTPA control is more stable, and the control mode of $i_d=0$ increases with the parameters. As the torque and speed increase, there will be a period of jitter. In a relatively stable state, the electronic current required for MTPA control is roughly 1-2A smaller than the stator current required for $i_d=0$. Obviously, when the torque and speed are the same, the maximum torque current is smaller than the stator current required for control, and the internal loss of the motor is smaller.

5. Conclusion

Through the experimental simulation, this paper draws the following conclusions: firstly, the improved fast SVPWM algorithm can be applied to MTPA control, and its operating effect is better than that of the traditional motor control; Secondly, the improved MTPA control has a good response speed and stability when the required electronic current is small, which is conducive to improving the running ability of the vehicle in various road conditions. Finally, the stator current required by this control method is smaller, which will improve the endurance of new energy vehicles and increase the economic efficiency of new energy vehicles.

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