Research on Zero Vector DTC System of Permanent Magnet Synchronous Motor Based on Super-Twisting Sliding Mode Controller

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Abstract. Permanent magnet synchronous motor (PMSM) is a nonlinear system. When the control system operates with external interference, it will obviously affect the operating characteristics of the system, and will also make the torque ripple of the system larger. To solve these problems, the zero voltage vector is introduced to suppress the torque ripple in the traditional control mode. In order to further reduce the torque ripple and speed ripple control process, improve the adaptability and stability of the system, the traditional PI controller is replaced with a Super-twisting sliding mode controller and the function sigmoid(s) in a quasi-sliding mode is used to replace the symbol function sign(s). The torque ripple of the PMSM is studied with MATLAB/Simulink simulation software. The simulation results show that in the traditional direct torque control, the super-twisting sliding mode controller has smaller torque ripple than the PI controller and improves the system robustness.

Introduction

Permanent magnet synchronous motor(PMSM) have the advantages of high output power and good working performance, and have been applied to more and more high-performance applications. Direct torque control (DTC) has some obvious advantages over vector control. The DTC coordinate transformation is simple and can directly control the torque. The control method is simple and easy to implement. It can be seen from the literature [1-2] that there is a large torque ripple in the traditional DTC.

In order to make up for system deficiencies, the literature [3-4] introduces zero vectors into traditional DTC. Using MATLAB for simulation analysis. The simulation results show that the zero voltage vector has very little effect on the torque when the PMSM is running at low speed and can be used to maintain the torque value, but when the speed is high, the zero voltage vector will reduce the torque. In [5-6], the Super-twisting sliding mode control is mainly applied to the flux linkage observer and controller, which improves the system response speed and significantly reduces the torque ripple.

In this paper, the zero-voltage vector is introduced into the traditional DTC with hysteresis comparator to reduce the torque ripple. In order to further optimize the control system and improve the robustness of the system, the only PI speed controller in the hysteresis control block diagram is replaced by the Super-twisting sliding mode controller.

The Mathematical Model of PMSM

The PMSM mathematical model in the $\alpha - \beta$ coordinate system is
\[
\begin{align*}
    u_\alpha &= R_i \alpha + \frac{d\psi_\alpha}{dt} \\
    u_\beta &= R_i \beta + \frac{d\psi_\beta}{dt} \\
    \psi_\alpha &= L_i \alpha + \psi_f \cos \theta_e \\
    \psi_\beta &= L_i \beta + \psi_f \sin \theta_e \\
    T_e &= \frac{3}{2} p_n (\psi_\alpha i_\beta - \psi_\beta i_\alpha) \\
    T_e - T_L - Bw_e &= J \frac{d\theta_e}{dt}
\end{align*}
\]

(1)

\(u_{\alpha, \beta}\) and \(i_{\alpha, \beta}\) represent the alpha and beta orthogonal components of stator voltage and current space phasors. \(\psi_{\alpha, \beta}\) are the alpha and beta orthogonal components of the stator flux space phasor, \(R_s\) denotes the stator resistance, \(L_s\) represents the stator inductance, \(\psi_f\) is the Permanent magnet flux, \(T_e\) represents the Electromagnetic torque. \(T_L\) is the load torque, \(\theta_e\) is the Rotor position angle, \(p_n\) represents the number of pole pairs, \(w_e\) represents the mechanical speed.

**The Working Principle of DTC Based on Zero Vector**

When the zero vector is introduced in the DTC, the variation of torque is:

\[
\Delta T_e = -\frac{3}{2} p_n \psi_f |\psi_e| w_e T_s \cos \delta
\]

(2)

\(T_s\) is the Control period, \(\psi_f\) is the Stator flux, \(\delta\) is the torque angle. \(\Delta T_e\) is the Zero vector working range.

From the above equation, it can be seen that under the action of zero vector, the torque change is negative, that is, the torque is actually reduced. When the motor is running at a low speed, because the control cycle is very short, usually only a few tens of microseconds, then the product of \(w_e\) and \(T_s\) is also a very small amount, then the change amount of the motor torque is also approximately 0, and the zero vector keeps the current torque constant. When the motor is running at a high speed, the product of \(w_e\) and \(T_s\) cannot be ignored. At this time, the zero vector actually acts to reduce the torque. The higher the speed, the more obvious the effect of the zero vector reducing torque.

After introducing the zero-voltage vector into the DTC, the mathematical model of the hysteresis comparator for the flux linkage and the torque is

\[
\phi = \begin{cases} 
1, & |\psi_e^+ - |\psi_e^-| > 0 \\
0, & |\psi_e^+ - |\psi_e^-| < 0
\end{cases}
\]

(3)

\[
\tau = \begin{cases} 
1, & T_e < T_e^- - \Delta T_e \\
0, & |T_e - T_e^-| \leq \Delta T_e \\
-1, & T_e > T_e^- + \Delta T_e
\end{cases}
\]

(4)

**Design of Super-Twisting Sliding Mode Controller**

**The Principle of Super-Twisting Control**

Most second-order sliding modes can be seen as controllers in the same form as equation (5). Since
equation (5) does not “memorize” the initial system, this controller is very robust to any disturbances.

\[
\dot{\sigma}(t,x) \in [-C, C] + [K_m, K_M] \dot{u}
\]

\(\sigma(t,x)\) is an output function, which is called a sliding mode variable, \(u \in R\) is an input variable of the control system, and \(C, K_M, K_m\) is a bounded positive number.

In the design of the two order sliding mode control law, the Super-twisting algorithm only needs to know the information of the sliding mode variable \(\sigma\), but does not need the information of the \(\dot{\sigma}\). Therefore, the Super-twisting algorithm can eliminate the chattering problem in the first order sliding mode control system and enhance the robustness of the system.

The control law of the Super-twisting algorithm is designed as shown in equation (6):

\[
\begin{cases}
    u = -K_p \left| \sigma \right|^\frac{1}{2} \text{sgn}(\sigma) + u_i , \\
    \frac{du_i}{dt} = -K_i \text{sgn}(\sigma),
\end{cases}
\]

\(K_p\) and \(K_i\) are positive gains.

**Design of Super-Twisting Controller**

In order to make the control effect better, the sigmoid(s) function in the quasi-sliding mode is used instead of the sign function \(\text{sgn}(s)\) to achieve the effect of optimizing the Super-twisting sliding mode control controller. Sigmoid(s)'s expression is

\[
sigmoid(s) = \frac{2}{1 + \exp(-a_s s)} - 1
\]

\(a_s\) is an adjustable parameter.

The optimized Super-twisting speed controller is

\[
\begin{align*}
    T_e^* &= K_p \left| s_w \right|^\frac{1}{2} \text{sigmoid}(s_w) + T_e \\
    \dot{T}_e &= K_i \text{sigmoid}(s_w)
\end{align*}
\]

Speed error \(s_w = w^* - w\), \(K_p\) and \(K_i\) are positive gains.

Apply the Super-twisting sliding mode controller and zero vector to the DTC of the PMSM to get the control block diagram shown in Figure 1.

![Figure 1. Zero vector DTC block diagram based on super-twisting controller.](image)

**Simulation and Result Analysis**

This article uses MATLAB to simulate. In simulation, the resistance of the PMSM stator is 1.2 Ω,
the inductance of the stator is 8.5 mH, the rotor flux is 0.175 Wb, the moment of inertia is 0.0008 kg·m², and the polar logarithm is 4. PMSM's rated speed is set to 600 r/min and stator flux reference is 0.177 Wb. The load torque at the start is 0 N·m, and the load torque changes from 0 N·m to 1.5 N·m at 0.2 s. The simulation time is 0.4s.

The simulation waveforms are shown in Figure 2-4, and the simulation analysis is shown in Table 1. It can be seen that after the introduction of the zero vector in the traditional DTC, the overshoot of its rotation speed is reduced, the dynamic response speed becomes faster, and the torque ripple is significantly reduced. To further optimize the control effect, a super-twisting sliding mode controller is introduced in the zero-vector-based DTC. Compared with the zero-vector-based DTC, the speed overshoot is significantly reduced, the dynamic response speed is significantly increased, and the torque ripple is further reduced.

![Speed response waveform](image1.png)
![Torque response waveform](image2.png)

**Figure 2.** Speed and torque waveform of traditional PI control.

![Speed response waveform](image3.png)
![Torque response waveform](image4.png)

**Figure 3.** Rotational speed and torque waveform based on zero vector.

![Speed response waveform](image5.png)
![Torque response waveform](image6.png)

**Figure 4.** Rotational speed and torque waveform with zero vector DTC based on Super-twisting sliding mode controller.
Table 1. Three control modes output response analysis.

<table>
<thead>
<tr>
<th>Control method</th>
<th>Maximum speed overshoot [r/min]</th>
<th>Time required to reach steady state [s]</th>
<th>Torque ripple [ N \cdot m ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional DTC</td>
<td>45</td>
<td>0.1</td>
<td>1.3-1.72, 0.43</td>
</tr>
<tr>
<td>Zero Vector DTC</td>
<td>12.5</td>
<td>0.06</td>
<td>1.37-1.64, 0.27</td>
</tr>
<tr>
<td>Super-twisting controller and zero vector DTC</td>
<td>2</td>
<td>0.005</td>
<td>1.4-1.6, 0.2</td>
</tr>
</tbody>
</table>

Summary

In this paper, a zero-vector DTC of PMSM based on Super-twisting sliding mode controller is designed. Through the use of Super-twisting sliding mode control and the rational use of the zero-voltage vector, the effect of PMSM on DTC output is significantly improved. Speed overshoot is significantly reduced, response speed is significantly increased, torque ripple is significantly reduced, and the robustness of the system is improved.

References


