The Research on Sensorless Control of Permanent Magnet Synchronous using SMC and SMO

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Abstract. This work proposes a way to achieve the sensorless control of permanent-magnet synchronous motor using sliding mode controller (SMC) and Sliding Mode Observer(SMO). In this Paper, the SMC is designed to replace the speed control loop PI controller from the original permanent magnet synchronous motor control system with the sliding mode variable structure control theory. Combined with the modified SMO, the “SMC and modified SMO” motor control system is proposed. Compared with the “PI and modified SMO” mode, the performance of the motor control is increased substantially, the interference torque speed attenuation is decreased by 87.5%, and the speed control error was also reduced by 67.7%. There is no overshoot with the reaction speed, and significant improvement in response speed, anti-interference performance, control accuracy and observation precision are achieved. Overall, both the system control and observation performance are significantly improved.

1. Introduction
The main disadvantage of the sliding mode observer is that the high frequency buffeting caused by the sliding mode variable structure control may increase the possibility of system crash, and it may also damage the system hardware. Therefore, the research on suppression of buffeting caused by sliding mode observer has become a research hotspot in recent years among researchers [1].

At present, in domestic areas, famous universities such like Harbin Institute of Technology, Hunan University are engaged in this program. Professor Li Tiecai’s team from Harbin Institute of Technology has successively put forward adaptive sliding mode observer [2] and fourth-order hybrid sliding mode observer [3] of extended equation of state. The sliding surface of the two sliding mode observers is the difference between the actual current value and the estimated value, and through this to estimate the magnetic linkage of the motor.

In the field, because the PI controller is simple in structure, easy to set parameters, and it is easier to implement than other controllers, the PI controller is always used as the speed loop controller to form...
a structure of "PI and SMO". However, there are still many serious defects existing, such as overshoot and poor robustness. In some high-precision control situations, it is very difficult for PI controllers to reach the requirements \[4,5\]. At present, the control of permanent magnet synchronous motor is developing into high precision high stability level. In order to obtain better control effect of the motor, it is necessary for us to replace the PI controller with a new type of controller. The sliding mode controller (SMC) has better robustness and speed than the PI controller, and the overshoot caused by PI control can also be avoided \[6\]. Nowadays, there are only a few literatures which have applied sliding mode observers (―SMC and SMO‖) to position sensorless control systems, thus it is very significant to study their specific effects.

2. SMC based on tan function and exponential approach law

The classic exponential approach law was proposed by Academician Gao Weibing \[7\], and its formula is as follows:

\[
\dot{s} = -\epsilon \text{sign}(s) - qs
\]  

(1)

In the middle $\epsilon$, $q$ is greater than zero constant. $-qs$ is exponential approach, The $q$ value affects the dynamic transition process of the control function. The larger the $q$ value, the faster the point from the sliding surface reaches the sliding surface. The $-\epsilon \text{sign}(s)$ is constant velocity trend, and the $\epsilon$ affects the rate at which the point reaches the sliding surface, and its rate decreases as the value of $\epsilon$ increases. By selecting an appropriate $q$ value, not only the approach speed can be improved, but also the chattering can be effectively reduced.

The theoretical basis of the sliding mode controller and the sliding mode observer are the same, and they are all designed according to the sliding mode variable structure theory \[8\]. The motor voltage equation can be expressed as equation (2):

\[
\begin{align*}
\dot{u}_d &= R_s i_d + \frac{d}{dt} \psi_d - \omega_e \psi_q \\
\dot{u}_q &= R_s i_q + \frac{d}{dt} \psi_q - \omega_e \psi_d
\end{align*}
\]  

(2)

$ud$, $uq$——Voltage component on d-axis and q-axis(V);

$id$, $iq$——Current component on d-axis and q-axis(A);

$\psi_d$, $\psi_q$——Magnetic flux component on d-axis and q-axis(Wb).

Motor stator flux equation:

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

(3)

The $Ld$ is the d-axis inductance component and $Lq$ is the q-axis inductance component(H). Rewriting the mathematical model of the motor according to Equations 2 and 3.

\[
\begin{align*}
\dot{u}_d &= R_s i_d + L_s \frac{d}{dt} i_d - p_n \omega_m L_s i_q \\
\dot{u}_q &= R_s i_q + L_s \frac{d}{dt} i_q + p_n \omega_m L_s i_d + p_n \omega_m \psi_f \\
\frac{d}{dt} \omega_m &= \frac{3}{2} p_n \psi_f i_q - T_L
\end{align*}
\]  

(4)

In the equation $\omega_m$ is the actual angular velocity of the motor(rad/s), TL is the load torque(N·m).

Relationship between actual motor speed and electrical angular velocity: $\omega_e=\omega_m p_n$.

Defining system state variables:

\[
\begin{align*}
x_1 &= \omega_{ref} - \omega_m \\
x_2 &= \dot{x}_1 = -\dot{\omega}_m
\end{align*}
\]  

(5)
In the equation $\omega_{ref}$ is the set reference speed, according to Equation 2 and Equation 36:

$$
\begin{align*}
\dot{x}_1 &= -\dot{\omega}_m = \frac{1}{J}(T_L - \frac{3}{2}p_n \Psi_f i_q) \\
\dot{x}_2 &= -\dot{\omega}_m = -\frac{3}{2}p_n \Psi_f i_q
\end{align*}
$$

(6)

Define the sliding surface as the $s=cx_1+x_2$, and deriving it

$$
d\frac{s}{dt} = c \frac{dx_1}{dt} + \frac{dx_2}{dt} = cx_2 - \frac{3p_n \Psi_f}{2J} \frac{di_q}{dt}
$$

(7)

The equation of the sliding mode controller is as follows:

$$
i_q = \frac{2J}{3p_n \Psi_f} \int_0^t [cx_2 + \varepsilon \text{sign}(s) + qs] \, dt
$$

(8)

Using the tanh function as the control function of the sliding mode controller, the improved sliding mode controller equation is as follows:

$$
i_q = \frac{2J}{3p_n \Psi_f} \int_0^t [cx_2 + \varepsilon \tanh(s) + qs] \, dt
$$

(9)

The structure block diagram of the sliding mode controller of Figure 1 can be constructed by Equation 9, and the difference between the actual speed and the set speed is taken as the input of the controller. The value is $x_1$, and $x_2$ passing through the differential module to get $x_1$. The current $i_q$ is used as the output of the sliding mode controller.

**Figure 1.** Sliding mode controller block diagram.

3. **Simulation analysis of PMSM based on SMC and SMO**

According to the mathematical model of permanent magnet synchronous motor, combined with vector control method and coordinate transformation relationship, the block diagram of the motor vector control system shown can be built and simulated by Matlab/Simulink. The speed loop and the current loop controller use the classic PI controller, and the position and speed signals are obtained by the motor position/speed detecting device. The speed loop PI controller parameters: $kp = 0.15$, $ki = 7$; the current loop PI controller parameters: $kp = 9.35$, $ki = 3162.5$. The sliding mode observer proposed by Zhang has a good observation performance [9]. This paper has established a modified SMO with reference to this document, which means removed the position/speed detection device and switched to the sliding mode observer module. Combined with the SMC mode that proposed in this paper, the PMSM control system of “SMC and SMO” is formed. The simulation structure block diagram is shown in Figure 2. Compared and analyzed with the traditional “PI and SMO” simulation results.
In order to obtain the anti-disturbance performance of the motor, the simulation is carried out under the disturbance of the speed switching and the disturbance of the load torque.

3.1 Simulation results under the influence of speed switching
The motor set has two speeds. The first speed is 300r/min, the second speed is 1000r/min, and the switching time is 0.06s.

Figure 3 shows the speed response curve of the motor speed rising from zero speed to 300r/min and then accelerating to 1000r/min. The method of using SMC to improve SMO is faster than the “PI modified SMO” control, and the stability of the former’s speed switching is much higher than the latter.

Figure 4 is the velocity observation error corresponding to Figure 3. Using the “SMC and modified SMO” method improve the accuracy of estimating the motor speed of the sliding mode observer in the starting phase and the speed switching phase.

Figure 5 shows the effect of speed switching on the torque of the motor. Under the “SMC and modified SMO” method, the torque has very good stability in both the starting phase and the speed switching phase.

3.2 Simulation results under torque interference
The reference speed set by the simulation is 1000r/min. When t=0.06s, a disturbance torque of 5N·m
is applied to obtain the results of motor speed response curve, position curve, current curve, torque curve and observation error curve experiment.

**Figure 6.** Speed response curve.  
**Figure 7.** Speed error curve.  
**Figure 8.** Torque response curve.

Figure 6 shows the speed response curve. The dotted line in the figure is the actual speed and estimated speed of the permanent magnet synchronous motor rotor under the “PI and modified SMO” method. The actual line is the actual speed and estimated speed of the permanent magnet synchronous motor rotor under the “SMC and modified SMO” method. It can be seen from the curve that under the “SMC and modified SMO” method, there is no speed overshoot and oscillation in the starting phase of the motor, and the start stability is obviously better than “PI and modified SMO”.

Figure 7 shows the speed estimation error curve. After using the sliding mode controller, it not only improves the smoothness of the motor starting but also improves the speed tracking performance of the motor starting phase.

Figure 8 shows the torque response curve of the motor. The red line is the motor torque curve under the control of “PI and modified SMO” method, and the black line is the motor torque curve under the control of “SMC and modified SMO” method. It can be seen from the torque response curve that in the starting phase, the torque oscillation amplitude of the former is extremely large, which will reduce the life of the motor. Compared with the latter, the latter has better motor starting performance.

The specific evaluation indicators are as follows:

| Table 1. System evaluation index. |
|-----------------------------------|
| Control model | $t_r$ (s) | $t_p$ (s) | $t_s$ (s) | $\sigma_p$ (%) | $\omega_{se}$ (r/min) | $N$ | $K$ | $S$ | $\Delta\omega$ (r/min) | $\Delta\theta$ (rad) |
| PI and SMO | 0.061 | 0.00 | 0.00 | 9 | 4.5 | 0.8~0.9 | 1 | 0.238 | 0.017 | 0.000075 |
| SMC and SMO | 0.053 | / | 0.00 | 8 | 0 | 0.2~0.3 | 0 | 0.238 | 0 | 0.14 | 0.000074 |

From Table 1, we can analyze the “SMC and modified SMO” method proposed in this paper. Compared with “PI and modified SMO”, the rise time and adjustment time of the speed response are significantly improved, and the time is reduced by 16.7% and 10.2% respectively. No overshoot and oscillation, the actual motor speed error decreases from 0.8~0.9r/min to 0.2~0.3r/min, the speed
control is more precise, and the stability is further improved.

4. Conclusions
In this paper, a "SMC and modified SMO" permanent magnet synchronous motor control system is established, which could enable the system possess a better capacity of resisting disturbance, significantly improves the reaction speed and the revolving speed control accuracy, eliminates the overshoot of the speed response.

5. References:
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