Research on Rotor Position Self-Sensing Control System of a PMSM for Electric Vehicles

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Abstract: There are many problems existing in the traditional rotor position self-Sensing control. To overcome these problems, a hybrid approach of rotor position self-sensing control based on a PMSM for Electric Vehicles is investigated in this paper. The proposed method has good robustness and position tracking performance at full speed including zero speed. Based on the proposed algorithm, a PMSM position self-Sensing control system is set up. Simulation and experiment are implemented on the platform. The results verify the feasibility and effectiveness of the proposed method.

1. Introduction
In this paper, a composite control algorithm of rotor position self-detection is proposed. Combining the new sliding mode observer with the high frequency pulse injection method, it not only has good robustness, but also has good position tracking effect in the range of full speed including zero speed[1].

2. New Sliding Mode Observer
2.1. Design of Back EMF Observer
The back EMF equation of permanent magnet synchronous motor is

\[
\begin{align*}
    e_a &= -\psi_f \omega_x \sin \theta \\
    e_b &= \psi_f \omega_x \cos \theta 
\end{align*}
\]

Assumption \( \omega_x = 0 \), derivation of equation (1) is

\[
\begin{align*}
    \frac{de_a}{dt} &= -\omega_x e_b \\
    \frac{de_b}{dt} &= \omega_x e_a 
\end{align*}
\]

According to formula (2), a back EMF observer can be constructed:
\[
\begin{align*}
\dot{e}_a &= -\omega_0 \dot{e}_a - l_1 (\dot{e}_a - e_a) \\
\dot{e}_\beta &= -\omega_0 \dot{e}_\beta - l_1 (\dot{e}_\beta - e_\beta) \\
\dot{\omega}_e &= (e_a - e_a) \dot{e}_\beta - (e_\beta - e_\beta) \dot{e}_a.
\end{align*}
\]

By making a difference between equation (3) and equation (2), the error equation of the back EMF observer is obtained as follows:
\[
\tilde{\omega}_e = \dot{\omega}_e - \omega_e
\]

Among them, \( \tilde{e}_a = \dot{e}_a - e_a, \tilde{e}_\beta = \dot{e}_\beta - e_\beta \) and \( \bar{e}_a = \dot{e}_a - e_a, \bar{e}_\beta = \dot{e}_\beta - e_\beta \).

In order to prove the stability of formula (4), by Lyapunov theorem, there are
\[
V = \frac{1}{2} \left( \dot{e}_a^2 + \dot{e}_\beta^2 + \dot{\omega}_e^2 \right)
\]

Derivatives from the Upper Form
\[
\dot{V} = \tilde{e}_a \dot{\tilde{e}}_a + \tilde{e}_\beta \dot{\tilde{e}}_\beta + \tilde{\omega}_e \dot{\tilde{\omega}}_e
\]

Substitution of formula (4) in upper form can be obtained:
\[
\dot{V} = -l_1 \left( \bar{e}_a^2 + \bar{e}_\beta^2 \right) \leq 0
\]

It can be seen from the formula (7), the back EMF observer is asymptotically stable.

### 2.2. Design of a New Sliding Mode Observer

The voltage equation of permanent magnet synchronous motor can be expressed as
\[
\begin{align*}
\frac{d}{dt} i_\alpha &= -\frac{R_\alpha}{L_\alpha} i_\alpha - \frac{1}{L_\alpha} e_\alpha + \frac{1}{L_\alpha} u_\alpha \\
\frac{d}{dt} i_\beta &= -\frac{R_\beta}{L_\beta} i_\beta - \frac{1}{L_\beta} e_\beta + \frac{1}{L_\beta} u_\beta
\end{align*}
\]

If sigmoid function is used as sliding mode variable structure function, then
\[
\begin{align*}
\frac{d}{dt} i_\alpha &= -\frac{R_\alpha}{L_\alpha} i_\alpha - \frac{1}{L_\alpha} (u_\alpha - l_2 F_\alpha - F_\alpha) \\
\frac{d}{dt} i_\beta &= -\frac{R_\beta}{L_\beta} i_\beta - \frac{1}{L_\beta} (u_\beta - l_2 F_\beta - F_\beta)
\end{align*}
\]

Define variable structure systems as follows
\[
F = \begin{bmatrix} F_\alpha \\ F_\beta \end{bmatrix} = k \times \text{sigmoid} (S) = k \left[ \frac{2}{1 + e^{-ax}} - 1 \right]
\]

In formula, \( \hat{i}_\alpha, \hat{i}_\beta \) are estimate component for stator current \( \alpha \) and \( \beta \) axis; \( F \) is sigmoid switch function; \( F_e \) is the equivalent control function. Its value is obtained by sigmoid function \( F \) through back EMF observer; \( l_2 \) is the feedback gain coefficient of \( F_e \); \( k \) is the sliding mode coefficient; \( S \) is the difference between the estimated current and the actual current.

By subtracting formula (9) from formula (8), the dynamic equation of a new sliding mode observer can be obtained:
\[
\begin{align*}
\frac{d}{dt} S_\alpha &= -\frac{R_\alpha}{L} S_\alpha + \frac{1}{L} (e_\alpha - l_2 F_\alpha - F_\alpha) \\
\frac{d}{dt} S_\beta &= -\frac{R_\beta}{L} S_\beta + \frac{1}{L} (e_\beta - l_2 F_\beta - F_\beta)
\end{align*}
\]
According to the sliding mode variable structure control theory, when the system slides on the sliding surface, then

\[
\begin{aligned}
S_{\alpha} &= \hat{i}_\alpha - i_\alpha = 0 \\
S_{\beta} &= \hat{i}_\beta - i_\beta = 0
\end{aligned}
\]  

(12)

Substitute formula (12) into formula (11), and get

\[
\begin{aligned}
e_{\alpha} &= F_{\alpha} + l_2 F_{e\alpha} \\
e_{\beta} &= F_{\beta} + l_2 F_{e\beta}
\end{aligned}
\]  

(13)

After estimating the back EMF, the estimated rotor approximate position angle is

\[
\hat{\theta} = -\tan^{-1} \left( \frac{e_{\alpha}}{e_{\beta}} \right) = -\tan^{-1} \left( \frac{F_{e\alpha}}{F_{e\beta}} \right)
\]  

(14)

From the condition of sliding mode motion, it can be concluded that the rotor position of the motor can be estimated smoothly when

\[
S_{\alpha \beta} S_{\alpha \beta} < 0, S_{\alpha} S_{\beta} < 0. \text{ Contact Formula (11) Available}
\]  

(15)

Because \(-R S_{\alpha}^2 / L_s < 0, -R S_{\beta}^2 / L_s < 0\), and combine formula (9), So the condition for satisfying formula (15) is

\[
(1 + l_2) k > \max \left( |e_{\alpha}|, |e_{\beta}| \right)
\]  

(16)

3. Pulsation High Frequency Injection Method

According to reference [2], the high frequency cosine voltage signal and high frequency current are:

\[
\begin{aligned}
\hat{u}_{dh} &= V_{inj} \cos \omega_h t \\
\hat{u}_{qh} &= 0
\end{aligned}
\]  

\[
\begin{aligned}
\hat{i}_{dh} &= \frac{V_{inj} \cos \omega_h t}{z_{dh} z_{qh}} (z_{avg} - z_{diff} \cos 2\tilde{\theta}) \\
\hat{i}_{qh} &= \frac{V_{inj} \cos \omega_h t}{z_{dh} z_{qh}} (-z_{diff} \sin 2\tilde{\theta})
\end{aligned}
\]  

(17)

(18)

Among them, \(\hat{u}_{dh} \cdot \hat{u}_{qh}\) are estimates of high frequency voltage components for d and q axes; \(\hat{i}_{dh} \cdot \hat{i}_{qh}\) are the estimates of high frequency current components of D and Q axes, \(z_{dh} \cdot z_{qh}\) are high frequency impedance for d and q axes; \(\omega_h\) is high frequency angular frequency; \(V_{inj}\) is the high frequency voltage signal of pulse vibration; \(\tilde{\theta}\) is the estimates of rotor position; Average impedance is \(z_{avg} = (z_{dh} + z_{qh}) / 2\); half difference impedance is \(z_{diff} = (z_{dh} - z_{qh}) / 2\). The high frequency impedance of the dq axis and the high frequency current of the q axis in formula (18) can be abbreviated as:

\[
\begin{aligned}
z_{dh} &= R_{dh} + j \omega_h L_{dh} \\
z_{qh} &= R_{qh} + j \omega_h L_{qh}
\end{aligned}
\]  

(19)

\[
\hat{i}_{qh} = \frac{V_{inj} \sin 2\tilde{\theta}}{\omega_h^2 L_{dh} L_{qh}} (R_{diff} \cos \omega_h t - \omega_h L_{diff} \sin \omega_h t)
\]  

(20)
Among them, $L_{dh}$, $L_{qh}$ are high frequency inductors of d-axis and q-axis. and $R_{diff} = (R_{dh} - R_{qh})/2$, $L_{diff} = (L_{dh} - L_{qh})/2$. The extraction process about the error angle of rotor position estimation in formula (20) is as follows:

$$i_{sh} \sin \omega_o t = \frac{V_m}{2\omega_o L_{dh} L_{qh}} \cdot \left[ \omega_o L_{diff} + \frac{1}{2} \left( \frac{V_{diff}}{\omega_o} \right) \sin(2\omega_o t + \varphi) \right]$$

(21)

$$i_q = LPF(i_{sh} \sin \omega_o t) = -\frac{V_m}{2\omega_o L_{dh} L_{qh}} \sin 2\tilde{\theta}$$

(22)

Among them, $|z_{diff}| = \sqrt{R_{diff}^2 + (\omega_o L_{diff})^2}$, $\tan \varphi = \frac{\omega_o L_{diff}}{R_{diff}}$

When the error angle of rotor position estimation is very small, it can be considered that $i_q$ is proportional to $\tilde{\theta}$, then equation (22) is simplified as follows:

$$i_q \approx -\frac{V_m L_{diff}}{\omega_o L_{dh} L_{qh}} \tilde{\theta} = K_{er} \tilde{\theta}$$

(23)

The Lumberg observer is used to obtain the rotor pole position [3].

The mechanical motion equation of permanent magnet synchronous motor is:

$$\begin{bmatrix} \dot{\theta} \\ \dot{\omega}_z \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \theta \\ \omega_z \end{bmatrix} + \begin{bmatrix} 0 \\ \nu \end{bmatrix} T_r - \begin{bmatrix} 0 \\ \nu \end{bmatrix} T_L$$

(24)

$$y = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \begin{bmatrix} \dot{\theta} \\ \omega_z \end{bmatrix}$$

(25)

Among them, $T_r$ is electromagnetic torque, $T_L$ is mechanical torque and $J$ is moment of inertia.

The state equation based on Romberg state observer for rotor position estimation is as follows:

$$\begin{bmatrix} \dot{\theta}_{\text{inj}} \\ \dot{\omega}_{\text{inj}} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \hat{\theta}_{\text{inj}} \\ \hat{\omega}_{\text{inj}} \end{bmatrix} + \begin{bmatrix} 0 \\ \nu \end{bmatrix} T_r + \begin{bmatrix} K_r \\ K_p \end{bmatrix} (\theta - \hat{\theta}_{\text{inj}})$$

(26)

$$\hat{y} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \begin{bmatrix} \hat{\theta}_{\text{inj}} \\ \hat{\omega}_{\text{inj}} \end{bmatrix}$$

(27)

Among them, $\hat{\theta}_{\text{inj}}$ is the estimated rotor position and $\hat{\omega}_{\text{inj}}$ is the estimated angular frequency.

4. New Compound Control Technology of Position Self-detection

A new type of composite position self-detection control system can be formed by combining the new sliding mode observer with the pulse high frequency voltage signal injection method. The structure block diagram of the new compound control system of rotor position self-detection is shown in Figure 1.
5. Simulation Research

The main parameters of the motor in the simulation are as follows: rated speed is 400 r/min, stator phase winding resistance is 2.18 $\Omega$, stator phase winding inductance is 20 mH, permanent magnet flux linkage is 0.1 Wb, rotor pole logarithm is 23, rated electromagnetic torque is 8 Nm, inertia of driving control system is 0.021658 kg m$^2$, friction coefficient is 0.025 N m s/rad. 30 r/min is selected for simulation.

Figure 2 is a simulation waveform based on the position self-detection control of high frequency voltage injection method. Figure 3 is a simulation waveform based on variable speed operation is carried out for the model shown in Figure 1.
Figure 2. Waveform under position self-detection

Figure 3. Simulation results of variable speed operation control based on pulse high frequency voltage injection method

6. Experimental study
An experimental platform is built, and the DSP TMS320F2812 is selected as the control core. The experimental results are shown in Figure 4-7.

Figure 4 is the experimental waveform with rated load under the control of position self-detection. Figure 5 shows the experimental results of the motor in steady state operation at rated speed. Figure 6 shows the experimental waveform of the actual and estimated speed of the rotor when the motor reduces from 250 rpm to 150 rpm and then rises back to 250 rpm at variable speed. Figure 7 shows the experimental waveform of the loading and unloading the motor.
7. Conclusion
In this paper, a new PMSM drive and control system based on a new composite method of rotor position self-detection is established. The simulation and experiment verify the good performance of the PMSM position self-detection control system, which meets the requirements of the electric vehicle for the drive system.

Reference
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