Improved sliding mode observer based sensorless control for PMSM

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Abstract: In this paper, an improved sliding mode observer (SMO) is proposed to guarantee the position detection accuracy of the permanent magnet synchronous motor (PMSM) developed for magnetic suspension molecular pumps (MSMP). Since the traditional SMO based sensorless scheme has chattering problems, and considering the existence of harmonics component, the estimated back-EMF waves should be further processed. For this reason, a novel back-EMF observer is proposed to extract the fundamental wave of the estimated back-EMF signals. Experimental results show the effectiveness of the proposed sensorless control of PMSM.

Keywords: sensorless control, sliding mode observer, back-EMF observer, position detection

Classification: Circuits and modules for electronic instrumentation

References

1 Introduction

Magnetic suspension molecular pump uses high-speed PMSM as its driver. High-performance PMSM control must obtain accurate rotor position and speed information, in order to achieve high-performance closed-loop automatic speed regulation control [1]. Because of the structure of the MSMP and the requirement of its internal cleanliness, position sensors are difficult to install and maintain. Therefore, the sensorless control method is introduced to obtain the rotor position and speed information. At present, there are many methods applied in sensorless control field, such as model reference adaptive system (MRAS) [2], extended kalman filter (EKF) [3], flux observer [4] and so on. Among them, the sliding mode observer is one of the most commonly used sensorless control methods, through the control of switching function, the estimated value rapidly approaching the true value. So, it has the advantages that algorithm is simple, free from parameter change, and better robustness [5, 6]. However, there exists inherent chattering phenomenon in SMO [7], which causes the back-EMF wave not ideal. At the same time, a large number of harmonics can be observed by analyzing the back-EMF signal. Thus, it is necessary to estimate the back-EMF signal further. This paper proposes a back-EMF observer after the traditional current observer, combining the fundamental wave extractor (FWE) and the second order generalized integrator (SOGI) to extract the fundamental wave of the back-EMF.

2 Proposed sliding mode observer

The current state equation can be expressed as [8]:

$$\frac{d}{dt} \begin{bmatrix} i_a \\ i_\beta \end{bmatrix} = \begin{bmatrix} -\frac{R_S}{L_S} & \frac{1}{L_S} \\ \frac{1}{L_S} & -\frac{1}{L_S} \end{bmatrix} \begin{bmatrix} u_a \\ u_\beta \end{bmatrix} - \frac{1}{L_S} \begin{bmatrix} e_a \\ e_\beta \end{bmatrix}$$  \hspace{1cm} (1)

where \(i_a, i_\beta\) are the stator currents component, \(u_a, u_\beta\) are the stator voltages component, \(R_S\) is the phase resistance; \(L_S\) is the phase inductance.
According to the variable structure control theory, the sliding surface is constructed by using the current estimation error:

\[
S = \begin{bmatrix} s_\alpha \\ s_\beta \end{bmatrix} = \begin{bmatrix} \hat{i}_\alpha - i_\alpha \\ \hat{i}_\beta - i_\beta \end{bmatrix}
\]  \tag{2}

where “\(^\wedge\)" represents the estimated value, “—” represents the error value.

In order to obtain smoother back-EMF waveform, a continuous sigmoid function is required to replace the signum function. The sigmoid function is proposed as follows:

\[
S_{\text{Sig}} = \frac{2}{1 + \exp[-a(\hat{i}_i - i_i)]} - 1
\]  \tag{3}

where \(\hat{i}_i = [\hat{i}_\alpha \quad \hat{i}_\beta]^T\), \(i_i = [i_\alpha \quad i_\beta]^T\) and \(a\) is a positive real number.

Based on the current state equation and the sigmoid function, the sliding mode observer is constructed as follows:

\[
\frac{d}{dt} \begin{bmatrix} i_\alpha \\ \hat{i}_\beta \end{bmatrix} = -\frac{R_s}{L_s} \begin{bmatrix} i_\alpha \\ \hat{i}_\beta \end{bmatrix} + \frac{1}{L_s} \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} - \frac{1}{L_s} k \cdot S_{\text{Sig}} \cdot \begin{bmatrix} \hat{i}_\alpha \\ \hat{i}_\beta \end{bmatrix}
\]  \tag{4}

where \(k\) is the gain of SMO. When \(k\) satisfies the stability conditions, the expression for estimated back-EMF can be approximately obtained by combining Eq. (1) and Eq. (4):

\[
\begin{bmatrix} \hat{e}_\alpha \\ \hat{e}_\beta \end{bmatrix} = \begin{bmatrix} k \cdot S_{\text{Sig}} \cdot (\hat{i}_\alpha - i_\alpha) \\ k \cdot S_{\text{Sig}} \cdot (\hat{i}_\beta - i_\beta) \end{bmatrix}
\]  \tag{5}

Although the introduction of sigmoid function eliminates the chattering of back-EMF in a certain extent, the back-EMF wave is still not a standard sine wave. Due to the nonlinearity of the inverter and the uneven distribution of the air gap magnetic field, there is a large amount of higher order harmonics in the estimated back-EMF \(\hat{e}_\alpha\) and \(\hat{e}_\beta\) \[9\].

Considering the existence of harmonics, the estimated back-EMF of \(\alpha\)-axis can be rewritten as:

\[
\hat{e}_\alpha = -A_0 \sin(\omega_0 t) - \sum_{k=1}^{n} A_{6k\pm1} \sin(\omega_{6k\pm1} t)
\]  \tag{6}

where \(A_0\) is the fundamental amplitude of back-EMF, \(\omega_0\) is the angular frequency of fundamental, \(A_{6k\pm1}\) is the \(6k\pm1\) harmonic amplitude and \(\omega_{6k\pm1}\) is the angular frequency of harmonic.

In order to obtain more ideal back-EMF, a back-EMF observer based on FWE-SOGI is proposed to optimize the estimated back-EMF signal. The block diagram of FWE-SOGI is shown in Fig. 1. The equations of FWE can be expressed as below:

\[
G(s) = \frac{\hat{e}_\alpha'}{\hat{e}_\alpha} = \frac{us}{s^2 + us + \omega^2}
\]  \tag{7}
\[ e'_a = \sin(\hat{\theta}) \cdot u \cdot \left[ e_a \cdot \sin(\hat{\theta}) \right] + \cos(\hat{\theta}) \cdot u \cdot \left[ e_a \cdot \cos(\hat{\theta}) \right] \]  

(8)

\[ e''_a = \hat{e}_a - \ddot{e}_a = -A_0 \sin(\omega_0 t) \]  

(9)

where \( u \) is an adjustable gain, which has an influence on convergence speed and steady-state error of FWE.

\[ \begin{aligned}
\text{Fig. 1.} & \quad \text{The proposed SMO structure based on FWE combining SOGI} \\
\end{aligned} \]

After the initial filtration and fundamental wave extraction by FWE, the estimated back-EMF signal is further filtered through SOGI and generated two quadrature signals \( \hat{E}_a \) and \( \hat{E}_\beta \) [10]. The closed-loop transfer function of the SOGI can be expressed as:

\[ D(s) = \frac{\hat{E}_a}{\hat{e}'_a} = \frac{k \omega_0 s}{s^2 + k \omega_0 s + \omega_0'^2} \]  

(10)

\[ Q(s) = \frac{\hat{E}_\beta}{\hat{e}'_a} = \frac{k \omega_0'^2}{s^2 + k \omega_0 s + \omega_0'^2} \]  

(11)

where \( \omega_0' \) is the speed value provided by FLL.

Therefore, as shown in Fig.1, the novel back-EMF observer replaces the low pass filter in traditional SMO and avoids the phase lag. The FWE-SOGI structure can be equivalent to two of the second order band-pass filter cascade.

With the accurate back-EMF signal, the rotor position can be calculated through the PLL structure [11]. The closed-loop transfer function of PLL after normalization is:

\[ G_{PLL} = \frac{k_p s + k_i}{s^2 + k_p s + k_i} \]  

(12)

where \( k_p \) is the proportional gain, \( k_i \) is the integral gain.

### 3 Result

In order to verify the effectiveness of the proposed method, a hardware platform is built for experimental verification as shown in Fig. 2. The experimental subject is the PMSM of the MSMP with following parameters: Number of pole \( p = 2 \), stator inductance is 0.21 mH, rated power is \( P = 1 \text{kW} \).
The experiment results are shown in Fig.3 and Fig.4. The Fig.3 (a) and Fig.3 (b) show the estimated back-EMF signals in $\alpha$-$\beta$ stationary coordinate system at given speed 8000rpm. The waves observed by conventional SMO and novel SMO are shown in Fig.3 (a) and Fig.3 (b), respectively. Compared with the signals filtered by the proposed back-EMF observer, the signals estimated through conventional method have apparent distortion. The presence of chattering causes the boundary of the waveform to become indistinct. The higher harmonic is superimposed on the fundamental wave, which leads the back-EMF to be worse. Therefore, the back-EMF observer which is proposed in the novel SMO, can achieve a good performance in the experiment.

The Fig.4 (a) and Fig.4 (b) show the position estimation results at the speed of 10000rpm. The position signal estimated by conventional method is shown in the Fig.4 (a). As can be seen from the figure, the estimated position signal contains regular waves, which is due to the influence of harmonics in the back-EMF. Fig.4 (b) shows the position signal estimated by proposed method. The estimated position signal becomes smooth and is similar to the reference position signal. From the position error signal at the bottom of each figure, it is also clear that the improved method can significantly reduce the position error.
4 Conclusion
This paper presents a new SMO to observe back-EMF. The SMO uses sigmoid function as switching function and a new back-EMF observer to replace the low pass filter. The back-EMF observer is based on FWE-SOGI structure. The FWE is used to preprocess the signals and extract the fundamental back-EMF signals. The SOGI is used to further suppress chattering and harmonics, and obtain two orthogonal signals. Because of the characteristics of SOGI, the control system requires only one initial voltage signal and one current signal for SMO, which can reduce the computation. What’s more, the FWE-SOGI structure has a satisfactory performance in detecting the back-EMF. The estimated back-EMF is very similar to the standard sine curve, which is used to calculate the rotor position. With accurate rotor position, the PMSM can perform better.

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