Research On Sensorless Control Of Permanent Magnet Synchronous Motor

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Abstract: Aiming at the problem that there is no position sensor to observe the rotor position and speed of the built-in permanent magnet synchronous motor under the traditional method of high frequency rotating voltage signal injection, the estimation accuracy of rotor position and speed is low because of the use of a variety of filters in the signal demodulation process. The generalized second-order integrator is used to replace the traditional filters to extract the high frequency response current. In order to reduce the filtering delay problem existing in the traditional signal demodulation method, a new signal demodulation method is proposed, and the rotor position estimation is compensated with appropriate phase compensation. At the same time, appropriate phase compensation is carried out for the estimation of rotor position. By constructing IPMSM sensorless vector control simulation module in Simulink simulation, compared with the traditional high-frequency injection method, the improved algorithm can estimate the rotor magnetic pole position more accurately and faster in the process of sensorless control of the motor in the low speed range, and has better stability introduction.

1. Introduction

In this paper, a new signal extraction method is proposed to calculate the rotor position and speed in the sensorless control of permanent magnet synchronous motor running at zero low speed. And this method is used as a redundant control system of electric vehicle[1]. In order to protect the safety of electric vehicles at low speeds. When the electric vehicle runs at zero low speed, the signal containing rotor position information is relatively weak and can not be extracted efficiently, which is contrary to the situation that the signal is relatively strong and can directly extract the signal containing rotor position information at medium and high speed[3]. Therefore, high frequency signal injection method is usually used to solve this problem.

The high-frequency rotating voltage signal injection method in the high-frequency signal injection method is widely used because of its strong robustness and convenient and fast adjustment[6]. However, this method uses a large number of filters when extracting the signal containing rotor position information, which leads to the low accuracy of rotor position and speed, which seriously violates the purpose of safety as a redundant system of electric vehicle[7]. Therefore, how to improve the accuracy and fast response of rotor position has become the focus of this paper.

In this paper, through the establishment of physical model and mathematical model derivation, and the sensorless simulation model based on internal permanent magnet synchronous motor is built. When running at zero low speed, the accuracy and stability of rotor position and speed are compared and analyzed by comparing the newly proposed method with the traditional method.
2. Vector control model of IPMSM under high frequency rotating voltage injection

When IPMSM operates in redundant mode, the serious error caused by rotor position is mainly due to the use of a large number of filters, such as SFF and BPF, when extracting the signal containing rotor position information. Therefore, how to reduce the use of filter, accurately and quickly extract the signal containing rotor position information, and finally obtain accurate rotor position and speed is the focus of this paper.

2.1. The mathematical model of IPMSM in two-phase static reference system is:

\[
\begin{bmatrix}
    u_a \\
    u_b
\end{bmatrix} =
R \begin{bmatrix}
    i_a \\
    i_b
\end{bmatrix} +
\begin{bmatrix}
    L_u + L_u \cos(2\theta) & L_u \sin(2\theta) \\
    L_u \sin(2\theta) & L_u - L_u \cos(2\theta)
\end{bmatrix} \begin{bmatrix}
    L_u + L_u \cos(2\theta) & -L_u + L_u \cos(2\theta) \\
    -L_u + L_u \cos(2\theta) & L_u - L_u \cos(2\theta)
\end{bmatrix} \begin{bmatrix}
    i_a \\
    i_b
\end{bmatrix} +
\begin{bmatrix}
    -L_u \sin(2\theta) \\
    L_u \sin(2\theta)
\end{bmatrix} +
\begin{bmatrix}
    \omega \phi \\
    \omega \phi
\end{bmatrix} \begin{bmatrix}
    -\sin \theta \\
    \cos \theta
\end{bmatrix}
\]

(1)

Where: \( u_a, u_b \) with \( i_a, i_b \) are voltage component and current component under two-phase static reference system; \( R \) is stator phase resistance; \( \theta \) is the electrical angle of rotor magnetic pole position; \( L_u \) is the common mode inductance, \( L_u = \frac{L_u + L_u}{2} \), \( L_u, L_u \) is the direct axis inductance and quadrature axis inductance under the rotor reference system; \( L_1 \) is differential mode inductance, \( L_1 = \frac{L_u - L_u}{2} \); \( \omega_e \) is the electrical angular velocity of the rotor; \( \gamma_i \) is rotor permanent magnet flux linkage; \( P \) is the differential operator.

When voltage drop caused by resistance and rotor electrical angle can be ignored. The simplified mathematical model is as follows:

\[
\begin{bmatrix}
    u_{ah} \\
    u_{bh}
\end{bmatrix} =
R \begin{bmatrix}
    i_{ah} \\
    i_{bh}
\end{bmatrix} +
\begin{bmatrix}
    L_u + L_u \cos(2\theta) & L_u \sin(2\theta) \\
    L_u \sin(2\theta) & L_u - L_u \cos(2\theta)
\end{bmatrix} \begin{bmatrix}
    L_u + L_u \cos(2\theta) & -L_u + L_u \cos(2\theta) \\
    -L_u + L_u \cos(2\theta) & L_u - L_u \cos(2\theta)
\end{bmatrix} \begin{bmatrix}
    i_{ah} \\
    i_{bh}
\end{bmatrix} +
\begin{bmatrix}
    -L_u \sin(2\theta) \\
    L_u \sin(2\theta)
\end{bmatrix} +
\begin{bmatrix}
    \omega \phi \\
    \omega \phi
\end{bmatrix} \begin{bmatrix}
    -\sin \theta \\
    \cos \theta
\end{bmatrix}
\]

(2)

Inside: \( u_{ah}, u_{bh} \) and \( i_{ah}, i_{bh} \) are high-frequency voltage component and high-frequency current component in two-phase static reference system. Rewrite the above formula into the differential form of current, and you can get:

\[
n \begin{bmatrix}
    i_{ah} \\
    i_{bh}
\end{bmatrix} =
\begin{bmatrix}
    L_u - L_u \cos(2\theta) & -L_u \sin(2\theta) \\
    -L_u \sin(2\theta) & L_u + L_u \cos(2\theta)
\end{bmatrix} \begin{bmatrix}
    u_{ah} \\
    u_{bh}
\end{bmatrix}
\]

(3)

The high frequency voltage injected into the two-phase static reference system is:

\[
\begin{bmatrix}
    u_{ah} \\
    u_{bh}
\end{bmatrix} =
\begin{bmatrix}
    V_h \cos \omega_i t \\
    V_h \sin \omega_i t
\end{bmatrix} =
V_h e^{j\omega_i t}
\]

(4)

Where: \( V_h \) is the amplitude of high frequency voltage; \( \omega_i \) is the electrical angular velocity of high frequency voltage; the \( t \) is the injection time of rotating high frequency voltage signal. Substituting equation (4) into equation (3), it can be obtained that the high-frequency current response under the static reference system is:

\[
i_{ah} =
\begin{bmatrix}
    I_{ah} \cos(\omega_i t) + I_{ah} \cos(-\omega_i + 2\theta) \\
    I_{ah} \sin(\omega_i t) + I_{ah} \sin(-\omega_i + 2\theta)
\end{bmatrix} =
I_{ah} e^{j\omega_i t} + I_{ah} e^{-j\omega_i t}
\]

(5)

Where: \( I_{ph} \) with \( I_{nh} \) is the amplitude of positive sequence component and negative sequence component of high frequency current respectively, and

\[
I_{ah} = V_h L_0 / [\omega_i (L_0^2 - L_1^2)], I_{ah} = -V_h L_1 / [\omega_i (L_0^2 - L_1^2)]
\]
2.2 Traditional signal demodulation method of IPMSM

\[ i_{d\beta} = e^{j(\alpha t)} i_{a\beta} = I_{ph} + I_{nh} e^{2j(\alpha t + \theta)} \]  \hspace{1cm} (6) \\
\[ i_{n,\alpha,\beta,h} = I_{h} e^{j(-\alpha h t + 2\theta)} \]  \hspace{1cm} (7)

Then the rotor position error signal is obtained by heterodyne method:

\[ \epsilon = i_{n,\alpha,h} \cos(2(\theta_\alpha - \alpha h t)) + i_{n,\alpha,h} \sin(2(\theta_\alpha - \alpha h t)) = 2I \sin(\theta_\alpha - \theta_h) \]  \hspace{1cm} (8)

Finally, the rotor position information is obtained by lomberg observer and corrected by magnetic pole discrimination, so that the rotor position accurately converges to the actual rotor position.

3. Improved signal demodulation method of IPMSM:

3.1 A new signal demodulation method is adopted

In order to reduce the filtering delay of traditional signal demodulation methods, a new signal demodulation method is proposed: The stator three-phase sampling current \( i_{abc} \) is changed to obtain the current under the static reference system \( i_{a\beta} \). It mainly includes three parts: Fundamental frequency control current \( i_{a\beta f} \), high-frequency current \( i_{a\beta h} \), And higher harmonic currents generated by switching devices \( i_{a\beta f} \). That is, the current under the static reference system can be expressed as:

\[ i_{a\beta} = i_{a\beta f} + i_{a\beta h} + i_{a\beta f} \]  \hspace{1cm} (9)

If the coordinate change as shown in equation (6) will be carried out directly without passing through the filtering device, After coordinate change \( i_{a\beta f}, i_{a\beta f}, i_{a\beta h} \) They are:

\[ i_{a\beta} = e^{j(\alpha t)} i_{a\beta} = I_{ph} + I_{nh} e^{2j(\alpha t + \theta)} \]  \hspace{1cm} (6) \\
\[ i_{n,\alpha,\beta,h} = I_{h} e^{j(-\alpha h t + 2\theta)} \]  \hspace{1cm} (7)

Then the rotor position error signal is obtained by heterodyne method:

\[ \epsilon = i_{n,\alpha,h} \cos(2(\theta_\alpha - \alpha h t)) + i_{n,\alpha,h} \sin(2(\theta_\alpha - \alpha h t)) = 2I \sin(\theta_\alpha - \theta_h) \]  \hspace{1cm} (8)
\[ i_{qdh} = e^{j(-\omega t)} i_{dph} = i_{dph} e^{j(\alpha_n - \alpha_v)} \]  
\[ i_{shh} = e^{j(-\omega t)} i_{dph} = I_{ph} + I_{nh} e^{j(\alpha_n - \alpha_v)} \]  
\[ i_{dqq} = e^{j(-\omega t)} i_{dph} = i_{dph} e^{j(\alpha_n - \alpha_v)} \]

Where: \( \omega_r \) is the angular frequency of the higher harmonic component generated by the switching device, and its frequency is much higher than the voltage injection frequency. After coordinate transformation, the current in the static reference system can be expressed as:

\[ \dot{i}_{dq} = \dot{i}_{dph} + \dot{i}_{dhh} + \dot{i}_{dqq} \]  

It can be seen from the above formula that the rotor position information item is included, \( I_{sh} e^{j(-2\omega_t + 2\Theta_v)} \). A variety of filters are used in the extraction process, which inevitably leads to amplitude attenuation and phase lag.

### 3.2 Selection of second-order generalized integrator

In this paper, the second-order generalized integrator (SOGI) can be used as a filter, and can also adaptively change the selected frequency, which is equivalent to a BPF. Moreover, the synchronous shafting high pass filter can also replace the high pass filter, which can effectively reduce the delay and phase lag caused by the extraction of high-frequency response current.

The SOGI structure adopted in this paper is shown in the figure, and its transfer function is:

\[ D(s) = \frac{v'(s)}{v(s)} = \frac{K\omega'}{s^2 + K\omega' + \omega'^2} \]  

Where: \( v(s) \) and \( v'(s) \) are input and output signals respectively; \( \omega' \) is the center frequency of the filter; \( K \) is the damping coefficient.

![Block diagram of generalized second order integrator](image-url)

Rewrite equation (14) to obtain:

\[ D'(s) = A \cdot \frac{\omega'}{Q_D} \frac{s}{s^2 + \omega'^2 + \omega'^2} \]  

Where: \( A \) is the gain coefficient of \( D'(s) \); \( Q_D \) is the quality factor of SOGI.

Through equations (13) and (14), it can be obtained that the quality factor of the SOGI is:

\[ \frac{1}{Q_D} = \frac{1}{K} \]  

From the above formula, compared with the traditional method using a large number of filters. In this paper is simpler than the parameter tuning process of the traditional BPF. It only needs to adjust the \( K \) value, which makes it possible for the on-line debugging of system parameters.

The component containing rotor position can be extracted by SOGI:

\[ i_{qph} = e^{j2\omega_t} I_{nh} e^{j(\alpha_n + 2\Theta_v)} = I_{nh} e^{j2\Theta_v} \]  

The rotor position error signal is obtained by heterodyne method:

\[ \varepsilon = i_{qph, 0} \cos(2\Theta_v) - i_{qph, 0} \sin(2\Theta_v) = 2I_{nh} \sin(\Theta_v) \]  

The improved signal demodulation method is shown in the figure:
4. System simulation of IPMSM under high frequency rotating voltage injection

4.1 Simulation model
IPMSM sensorless control system is built in Simulink simulation platform. Set the injected high-frequency signal amplitude as 20V and frequency as 1000Hz. By comparing the proposed method with the traditional method, the accuracy of the calculated rotor position and speed is observed to identify the advantages of the proposed method. The parameters of IPMSM are shown in Table 1.

| Parameter | Value |
|-----------|-------|
| $p_n$/kw  | 1.5   |
| $U_N$/V   | 311   |
| $P_N$     | 2     |
| $n_{N}$/r/min | 3000 |
| $R$/Ω     | 0.33  |
| $\Psi_f$/Wb | 0.646|
| $J_m$/g.m² | 0.008 |
| $L_d$/mH  | 5.2   |
| $L_q$/mH  | 17.4  |

4.2 Simulation waveform and analysis
IPMSM uses the traditional high-frequency rotating voltage injection control without position sensor and the high-frequency rotating voltage injection control of improved signal demodulation method to observe the rotor position and speed. The given speed is 100r/min and the simulation time is 0.4s. Under the injection of high-frequency rotating voltage signal, the comparison diagram between the observed rotor speed and position through traditional signal demodulation and the actual rotor speed and rotor position obtained with position sensor is shown in the figure below.
Fig 8. Actual value of rotor position in system with position sensor

Fig 9. Rotor position observation based on traditional signal demodulation

Fig 10. The error between the actual value of rotor position with position sensor and the estimated value of rotor position with traditional demodulation

Under the injection of high-frequency rotating voltage signal, the comparison diagram between the observed rotor speed and position through improved signal demodulation and the actual rotor speed and rotor position obtained with position sensor is shown in the figure below:

Fig 11. Rotor speed with improved signal demodulation and rotor speed with position sensor

Fig 12. Error between rotor speed obtained by improved signal demodulation and rotor speed obtained by position sensor
Fig 13.Rotor position observation with improved signal demodulation

Fig 14.Error value between rotor observed speed and rotor actual speed under improved signal demodulation

5. Conclusion

From the above comparative analysis, the proposed SOGI can completely replace the band-pass filter (BPF) and synchronous shafting high pass filter (SFF), has little impact on the extraction of the signal containing rotor position information, and can obtain the rotor position and speed accurately and efficiently.

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