A New Method for Detecting Initial Position of IPMSM Rotor

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Abstract. Aiming at the speed sensorless control system of permanent magnet synchronous motor which embedded in rotor magnet steel, a new method for detecting the initial position of the rotor is proposed in this paper. This method is injecting a high-frequency rotating voltage to generate a high-frequency current in the stator windings that contains the spatial position information of the rotor. Compared with the traditional high-frequency injection method, this paper uses Discrete Fourier Transform (DFT) to demodulate high-frequency current. It avoids the signal phase delay caused by the use of a large number of filters when demodulating the traditional heterodyne method. At the same time, this method has nothing to do with the initial phase of the injected signal. Compared with the heterodyne method, the extracted rotor position angle is more accurate, and the structure is simple number system. The validity and feasibility of the method are verified by simulation and experimental platform based on dSPACE.

1. Introduction

In the sensorless control system, if the accurate initial position angle of the rotor cannot be obtained when the motor is started, it will cause incomplete decoupling of the magnetic flux and torque, which will degrade the system performance. What’s worse, it will cause a long-term starting current impact or even damage the inverter and motor. For PMSM which embedded in rotor magnetic steel, the high-frequency injection method is a practical rotor position identification method[1]. In this method, the negative sequence components in the high-frequency current response are first separated by a filter, and the error term containing the rotor spatial position information is extracted from the heterodyne method, and the rotor position angle is obtained by the Romberg observer[2,3]. This method not only needs to use a large number of filters when extracting negative sequence components, causing signal phase delay, but also the trigonometric function of heterodyne extrapolation is related to high-frequency carrier signals. In practice, due to the delay of sampling, communication, and signal processing, the phase angle of the carrier signal is superimposed on the obtained rotor position angle, causing an error in sizing up the position information. Moreover, the Romberg observer requires mechanical parameters such as the moment of inertia, which are related to the mechanical equations of the motor. In some cases, accurate parameters cannot be obtained.

For the above problems, this paper proposes a novel high-frequency injection rotor initial position detection method. This method does not need to extract the negative sequence components of the high-frequency current. The DFT is used to pick up the amplitudes of the d and q-axis components of the high-frequency current. The position information of the rotor is obtained through the relationship between the amplitudes of the two. And then use the PI regulator to pick up the rotor position angle.
from the error term. In this paper, the core saturation effect of the motor is used to judge the magnetic pole N / S polarity based on the change characteristics of the high-frequency current vector amplitude. The simulation and dSPACE experimental platform are used to verify the method proposed in this paper. The simulation and experimental results verify the effectiveness and feasibility of the method.

2. Rotor initial position detection method based on DFT demodulation

2.1. DFT demodulation method of high-frequency current signal

In order to analyze DFT demodulation principle of high-frequency current signals, a new coordinate system $dq\hat{\wedge}$ which based on the $dq$ coordinate system is introduced. This new coordinate system is rotated as per the equation $\Delta \theta = \theta - \hat{\theta}$, where $\hat{\theta}$ is the estimated rotor angle. The transformation matrix of this coordinate system can be expressed as $^{[4]}$

$$
T_{dq\hat{\wedge} \rightarrow dq} = \begin{bmatrix}
\cos \Delta \theta & \sin \Delta \theta \\
-\sin \Delta \theta & \cos \Delta \theta
\end{bmatrix}
$$

(1)

Because the angular velocity of the injected high-frequency voltage excitation signal is much greater than the angular velocity of the rotor, the permanent-magnet flux linkage $\Psi_f$ is negligible compared with the flux generated by the stator current. The flux linkage equation in the $dq$ coordinate system is transformed into the coordinate system $dq\hat{\wedge}$:

$$
\begin{bmatrix}
\dot{\psi}_d \\
\dot{\psi}_q
\end{bmatrix}
= T_{dq\hat{\wedge} \rightarrow dq} \begin{bmatrix}
L_d & 0 \\
0 & L_q
\end{bmatrix} T_{dq \rightarrow dq\hat{\wedge}} \begin{bmatrix}
i_d \\
i_q
\end{bmatrix}
$$

(2)

Eq. (2) is transformed to get the current response expression as:

$$
\begin{bmatrix}
i_d \\
i_q
\end{bmatrix}
= \frac{1}{L_d^2 - L_q^2} \begin{bmatrix}
L_d + L_s \cos(2\Delta \theta) & L_s \sin(2\Delta \theta) \\
L_s \sin(2\Delta \theta) & L_s - L_s \cos(2\Delta \theta)
\end{bmatrix} \begin{bmatrix}
\psi_d \\
\psi_q
\end{bmatrix}
$$

(3)

Inject a rotating high-frequency voltage excitation of the form:

$$
\begin{bmatrix}
\psi_d \\
\psi_q
\end{bmatrix}
= u_t \begin{bmatrix}
\sin \omega t \\
\cos \omega t
\end{bmatrix}
$$

(4)

Where $u_t$ is the amplitude of the injected signal, and $\omega$ is the frequency. Using the flux voltage equation $\Psi_{di} = \int u_{dqi} \, dt$ gives:

$$
\begin{bmatrix}
\psi_d \\
\psi_q
\end{bmatrix}
= u_t \begin{bmatrix}
-\cos \omega t \\
\sin \omega t
\end{bmatrix}
$$

(5)

Inserting Eq.(5) into Eq. (3) gives the corresponding high-frequency current:

$$
\begin{bmatrix}
i_d \\
i_q
\end{bmatrix}
= -(I_{i0} + I_{i1} \cos(2\Delta \theta)) \cos \omega t + I_{i1} \sin(2\Delta \theta) \sin \omega t \\
= -I_{i1} \sin(2\Delta \theta) \cos \omega t + (I_{i0} - I_{i1} \cos(2\Delta \theta)) \sin \omega t
$$

(6)

According to Eq.(6), the amplitude expression of the current component is:
Then, it can get:

\[ \left| \dot{i}_d \right|^2 - \left| \dot{i}_q \right|^2 = 4I_i I_\theta \cos(2\Delta \theta) \]  

(8)

It can be seen from Eq. (8) that the relationship between the \(d\) and \(q\) axis components of the high-frequency current response signal contains the position information of the rotor, and the current amplitude can be obtained by Fourier transform. Analogous to the heterodyne method, if the rotor position angle is extracted from the error term, the error term needs to be reduced to \(\sin(2\theta)\). Therefore, the coordinates \(\dot{i}_{dq}\) can be transformed into the \(\dot{i}_{d\dot{q}}\) coordinate system whose coordinate-transformation matrix is:

\[
T_{i_{d\dot{q}} \rightarrow i_{dq}} = \begin{bmatrix}
\cos\left(\Delta \theta - \frac{\pi}{4}\right) & \sin\left(\Delta \theta - \frac{\pi}{4}\right) \\
-\sin\left(\Delta \theta - \frac{\pi}{4}\right) & \cos\left(\Delta \theta - \frac{\pi}{4}\right)
\end{bmatrix}
\]  

(9)

Thus, in the \(\dot{i}_{d\dot{q}}\) coordinate system, we can get:

\[
\dot{\theta} = \frac{1\omega}{s} \sin(2\theta)
\]

(10)

Therefore, from the above analysis, the rotor angle is the angle obtained after the closed-loop regulation to zero (by using the PI regulator) of the error correction shown in Eq. (10). Figure 1 shows a schematic for extracting the rotor angle on the basis of DFT demodulation of the high-frequency current.

The rotor position information in the high-frequency signal injection method exists in the high-frequency current response in the form of \(2\Delta \theta\), and the N/S polarity of the rotor magnetic pole cannot be directly identified. A second-order Taylor series is used to expand the positive-sequence high-frequency current component, and the N/S pole is discriminated according to the quadratic term coefficient\(^5\). This method has a large amount of calculations and the signal-to-noise ratio of the quadratic term is very low. Hardware circuit requirements Very high. This paper adopts a method of judging the polarity of magnetic poles based on the change characteristics of high frequency current amplitude.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{schematic.png}
\caption{DFT demodulation of rotor position angle extraction schematic diagram.}
\end{figure}
Figure 2 shows the relationship between the d-axis stator flux and the current. It can be seen from the figure that the degree of saturation of the stator core is connected with the magnitude of the d-axis current. When the magnetic flux component generated by the d-axis current is the same as the rotor magnetic flux direction, the degree of saturation increases; When the magnetic flux direction is opposite, the degree of saturation decreases. Due to the existence of this saturation effect, when the high-frequency rotating voltage is injected to stimulate the high-frequency current response, the generated high-frequency current response will be concocted. When the high-frequency current response vector signal is transferred to the N pole of rotor, the amplitude will reach the maximum. S pole saturation decreases, inductance increases, and current amplitude decreases.

![Figure 2. d shaft stator flux and current relationships.](image)

According to the above principle, the position $\theta_N$ of the N pole of the rotor can be obtained by detecting the corresponding phase when the amplitude of the high-frequency current response signal reaches the maximum. Comparing with the actual position angle of the rotor, there is a large error, but this angle can be used to judge the polarity of the magnetic pole. Comparing with the rotor position angle which is picked up by DFT high-frequency current demodulation $\theta_N$ above. If the difference between the two is less than 90°, the extracted rotor position angle is the actual rotor position angle. If the difference is greater than 90°, the extracted rotor position angle is the S-pole position, plus 180° is the actual rotor position angle. The principle of detecting the initial position angle of the rotor by the DFT method with magnetic pole polarity identification is shown in Figure 3.

![Figure 3. Polarity identification detection of initial rotor position angle.](image)

### 3. Simulation and verification

In order to verify the validity and accuracy of the rotor initial position detection method based on the DFT high-frequency current demodulation, simulation is performed on the Matlab / Simulink software platform. It should be noted that the motor component model ignores the saturation effect, so it cannot be based on the iron core. Simulation of magnetic pole polarity identification with saturation characteristics. This paper first verifies the correctness of the rotor position angle extraction method based on DFT demodulation in the software environment, and then verifies the rotor initial position angle detection based on the method in the dSPACE hardware online platform. The parameters of the simulated motor are the same as those of the experimental motor: rated power 2kW, rated current 8A, winding resistance of each phase of the armature is 7Ω, direct axis inductance is 2.5mH, quadrature axis inductance is 8.5mH, and the number of pole pairs is 3. Injected high-frequency voltage frequency 1250Hz, amplitude 5V.
Figure 4. DFT amplitudes extraction of high frequency current waveform.

Figure 4 shows the d-axis component of the high-frequency current induced by the injection of high-frequency rotational excitation and its amplitude waveform. As it can be seen from the figure, the designed DFT demodulation method of the high-frequency current signal can extract the high-frequency current amplitude of the injected frequency, and then lay a foundation for extracting the rotor position error term from the amplitude relationship.

Figure 5. Rotor position angle extraction based on DFT demodulation waveform.

Figure 5 shows the rotor position angle extraction waveform based on the DFT high-frequency current demodulation method. Figure 5(a) shows the error term $4I_{i1}I_{i0} \sin (2\Delta \theta)$ waveform obtained according to the relationship between the d and q axis current amplitudes. Figure 5(b) shows the angle and measured angle waveforms extracted from the error term using the PI regulator. As can be seen from the figure, this method can extract the rotor position angle with high accuracy and fast response.

4. Experimental verification

In order to verify the effectiveness of the above-mentioned method for detecting the initial position of the rotor based on DFT high-frequency current demodulation, an embedded PMSM variable frequency speed regulation experiment platform as shown in Fig.6 was established. It is mainly composed of embedded permanent magnet synchronous motor, general-purpose inverter DR50A and dSPACE real-time simulation system. The dSPACE single-board processor DS1104 automatically completes the code compilation and then generates PWM pulses to drive the switching device to work. The actual position of the rotor is measured by the encoder, and a rotating high-frequency voltage with a frequency of 1250 Hz and an amplitude of 10 V is injected. The high-frequency current is demodulated by DFT to pick up the rotor position.
Figure 7 shows the trajectory waveform of the high-frequency current vector at different initial positions. It can be seen from the figure that the trajectory of the high-frequency current is an ellipse, and the angle between the long axis of the ellipse and the horizontal line is the rotor position angle.

![Figure 7](image1.png)

(a) 0°  
(b) 45°  
(c) 90°  
(d) 135°

**Figure 7.** Different initial positions and high frequency current trajectories

Figure 8 shows the experimental results of initial position detection based on DFT high-frequency current demodulation. The actual position of the rotor is measured with an encoder in advance, and then the high-frequency current is decoupled under no fundamental wave excitation to extract the rotor position, and the error of the detection result is curve fitted, as shown in Figure 8(b), the actual result is within 5° electrical angle, the accuracy is high, and it can meet the requirements of vector control.

![Figure 8](image2.png)

(a) Actual and test values  
(b) Detection error

**Figure 8.** Initial position detection experiment

5. **Conclusion**

This paper proposes a new method for detecting the initial position of the rotor of an embedded permanent magnet synchronous motor. This method uses discrete Fourier transform to demodulate high-frequency currents containing rotor spatial position information. The rotor position error term is obtained by extracting the amplitude of the high-frequency current component and the relationship between the amplitude and the square of the magnitude of the two, and then using the PI regulator to extract the rotor position angle from the error term. Compared with the traditional heterodyne method, this method is not only independent of the initial phase of the injected signal, but also does not require the use of a large number of filters. It has a simple structure and is easy to implement digitally. Simulation and experimental results prove the effectiveness of the method and provide a new idea for the extraction of rotor position angle in sensorless control based on high-frequency injection method.
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