

Postprint: Initial Position Detection Method for SPMSM Based on Pulsating High-Frequency Current Injection

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Abstract

When employing the pulsating high-frequency current injection method for initial position estimation of surface-mounted permanent magnet synchronous motors (SPMSMs), magnetic pole identification is required. To address the issues of rotor jitter and long detection time associated with conventional positive and negative pulse voltage injection methods, this paper proposes a segmented interval integration approach. This method uniformly divides one injection signal period into four intervals, integrating the d-axis high-frequency voltage response within intervals I and III, and determines the positive direction of the d-axis based on the sign of the integral value. The proposed technique eliminates the need for additional positive and negative pulse signal injection to ascertain the d-axis positive direction, thereby reducing estimation time, simplifying the estimation procedure, avoiding potential rotor jitter problems in low-inertia motors during positive and negative pulse voltage injection, and expanding the application scope. Theoretical analysis, simulation, and experimental results all validate the correctness of this method.

Full Text

Preamble

Initial Rotor Position Detection Method for SPMSM Based on Pulsating High-Frequency Current Injection

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Abstract: When using the pulsating high-frequency current injection method for initial position estimation of surface-mounted permanent magnet synchronous motors (SPMSM), magnetic polarity judgment is required. To address issues such as rotor jitter and long detection time associated with traditional positive/negative pulse voltage injection methods, this paper proposes an interval-based integration method. A single injection signal period is uniformly divided into four intervals, and the d-axis high-frequency voltage response is integrated within intervals I and III. The sign of the integral value determines the positive direction of the d-axis. This method eliminates the need for additional positive/negative pulse signals to determine the d-axis direction, shortens estimation time, simplifies the estimation process, avoids rotor jitter problems in low-inertia motors during pulse voltage injection, and broadens the application scope. Theoretical analysis, simulation, and experimental results all verify the correctness of the proposed method.

Keywords: SPMSM, high-frequency current injection, magnetic polarity detection, initial position detection

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1 Introduction

Permanent Magnet Synchronous Machines (PMSM) have been widely applied due to their high power density and high efficiency. However, their control process requires accurate rotor position information, while mechanical position sensors suffer from large volume and mass, high cost, difficult installation, and poor reliability in special applications. Consequently, numerous scholars have devoted themselves to sensorless control technology for PMSM, where position estimation in the standstill and low-speed region represents a major research focus and challenge. Most studies employ high-frequency signal injection methods to track physical or magnetic saturation saliency characteristics. For interior permanent magnet synchronous motors, the d- and q-axis inductances are unequal, exhibiting physical saliency, and thus the rotating high-frequency signal injection method is commonly used [1-5]. For Surface-Mounted Permanent Magnet Synchronous Machines (SPMSM), the d- and q-axis inductances are approximately equal, showing insignificant saliency, requiring external excitation signals to generate saturation saliency. Therefore, the pulsating high-frequency signal injection method is often adopted [6-10].

Traditional pulsating high-frequency signal injection methods mostly employ voltage injection, which is relatively simple to implement but requires two Low Pass Filters (LPF) in the dq-axis current loops, increasing system complexity. Therefore, this paper selects the pulsating high-frequency current injection

method for SPMSM initial position detection. Compared with voltage injection, this approach features a simpler structure, and the convergence of the rotor position error function is unaffected by impedance variations, which benefits system stability improvement.

The proposed interval-based integration method divides an injection signal period into four intervals and integrates the d-axis high-frequency voltage response within intervals I and III. The sign of the integral value determines the positive d-axis direction. This method eliminates the need for injecting positive/negative pulse voltages, shortens initial position estimation time, simplifies the estimation process, reduces current detection accuracy requirements, avoids rotor jitter problems in low-inertia motors during positive/negative voltage pulse injection, broadens the application scope, and features simple algorithm implementation. Both simulation and experimental results verify the correctness of the theoretical analysis.

2 Mathematical Model of PMSM

For PMSM, assuming a sinusoidal distribution of the stator magnetic field and ignoring effects such as hysteresis and eddy current losses, the voltage equations in the synchronous rotating dq coordinate system under $i_d = 0$ rotor field-oriented control are:

$$u_d = r_s i_d + L_d \frac{di_d}{dt} - \omega_r L_q i_q \quad (1)$$

$$u_q = r_s i_q + L_q \frac{di_q}{dt} + \omega_r L_d i_d + \omega_r \psi_f \quad (2)$$

where u_d, u_q are the d- and q-axis voltages; i_d, i_q are the d- and q-axis currents; L_d, L_q are the d- and q-axis inductances; r_s is the stator resistance; ψ_f is the magnetic flux linkage between the permanent magnet and stator; and ω_r is the rotor electrical angular velocity.

At zero or low speed, the cross-coupling terms and back-EMF components in equation (1) can be neglected, simplifying the voltage equations in the dq coordinate system to:

$$u_d = r_s i_d + L_d \frac{di_d}{dt} \quad (3)$$

$$u_q = r_s i_q + L_q \frac{di_q}{dt} \quad (4)$$

Initial position estimation consists of two steps: preliminary initial position estimation and magnetic polarity judgment. Existing literature partially em-

employs pulse voltage injection for polarity judgment, injecting pulse voltages of equal amplitude and width in the estimated positive and negative d-axis directions. When the magnetic polarity direction aligns with the positive pulse voltage, the forward pulse voltage creates a forward current response, saturating the magnetic circuit and reducing impedance, resulting in a larger current response amplitude. Conversely, the negative pulse voltage creates a negative current response without saturating the magnetic circuit, increasing impedance and yielding a smaller current response amplitude. Thus, the current response amplitudes under positive and negative pulse voltages can be detected to obtain polarity information. However, additional voltage injection inevitably consumes considerable time, and improper selection of pulse voltage amplitude and width affects polarity judgment accuracy. In low-inertia motors, injected d-axis pulse voltages may cause rotor micro-movement, leading to rotor position estimation errors.

In summary, if magnetic polarity direction information can be extracted solely from the high-frequency current response without additional positive/negative pulse voltage injection, the initial position estimation process will be simplified and position estimation reliability improved. This paper proposes dividing an injection signal period into four intervals and integrating the d-axis high-frequency voltage response within intervals I and III, using the integral value sign to determine the positive d-axis direction.

3 Pulsating High-Frequency Current Injection Method

3.1 Principle of Pulsating High-Frequency Current Injection

Define the actual rotor synchronous rotating coordinate system as the dq-axis system, where the d-axis angle relative to the phase-A winding axis is θ . The estimated rotor synchronous rotating coordinate system is the $\hat{d}\hat{q}$ -axis system, where the \hat{d} -axis angle relative to the phase-A winding axis is $\hat{\theta}$. The two-phase stationary coordinate system is the $\alpha\beta$ -axis system, where the α -axis coincides with the phase-A winding axis. The position estimation error is $\Delta\theta = \theta - \hat{\theta}$. The relationship among these coordinate systems is shown in Figure 1 [Figure 1: see original paper].

When only a high-frequency current signal of appropriate amplitude is injected into the \hat{d} -axis, its expression in the estimated dq-axis system is:

$$\hat{i}_{dh} = I_{mh} \sin(\omega_h t) \quad (5)$$

$$\hat{i}_{qh} = 0 \quad (6)$$

where \hat{i}_{dh} is the \hat{d} -axis current under high-frequency excitation; \hat{i}_{qh} is the \hat{q} -axis current under high-frequency excitation; I_{mh} is the amplitude of the injected

high-frequency current; and ω_h is the angular frequency of the injected high-frequency current.

Substituting into the PMSM mathematical model and ignoring stator impedance, the high-frequency voltage response expression in the $\hat{d}\hat{q}$ -axis system is:

$$\hat{u}_{qh} = \omega_h \Delta L \sin(2\Delta\theta) I_{mh} \cos(\omega_h t)$$

where \hat{u}_{qh} is the high-frequency voltage response on the \hat{q} -axis; and ΔL is the differential inductance between dq axes, with $\Delta L = (L_d - L_q)/2$.

Equation (5) shows that magnetic saturation saliency causes the \hat{q} -axis high-frequency voltage response \hat{u}_{qh} to contain position estimation error $\Delta\theta$. If $\Delta\theta$ is extracted through appropriate modulation and an estimated position closed-loop is constructed to regulate $\Delta\theta$ to zero, the estimated position will coincide with the actual position, achieving rotor position estimation.

3.2 Initial Position Detection

First, the ω_h harmonic is extracted from the q-axis voltage response, yielding the high-frequency signal form shown in equation (5). Multiplying \hat{u}_{qh} by $\cos(\omega_h t)$ for modulation gives:

$$\hat{u}_{qh} \cos(\omega_h t) = \omega_h \Delta L I_{mh} \sin(2\Delta\theta) (1 + \cos(2\omega_h t))$$

Equation (6) contains both DC and high-order harmonic components $\cos(2\omega_h t)$. Extracting the DC component through a low-pass filter yields the rotor position error function:

$$f(\Delta\theta) = \text{LPF}(\hat{u}_{qh} \cos(\omega_h t)) = \omega_h \Delta L I_{mh} \sin(2\Delta\theta)$$

A PI regulator is used to regulate $f(\Delta\theta)$ to zero, obtaining the preliminary initial position estimate $\hat{\theta}_0$. The signal processing module is shown in Figure 2 [Figure 2: see original paper].

3.3 Convergence Analysis of Initial Position

Figure 3 [Figure 3: see original paper] shows the $f(\Delta\theta)$ curve. When $f(\Delta\theta) = 0$, the closed-loop regulation may converge $\Delta\theta$ to positions of $0, \pi/2, \pi, 3\pi/2$, and 2π , though some convergence points are unstable.

When $\Delta\theta \in (\pi/4, 3\pi/4)$, the convergence point is at $\Delta\theta = \pi/2$. If a small positive disturbance makes $\Delta\theta > \pi/2$, then $f(\Delta\theta) < 0$, and after the PI regulator, $\hat{\theta}_0$ increases, causing $\Delta\theta$ to deviate from the convergence point $\Delta\theta = \pi/2$. Similarly, a small negative disturbance also causes deviation. Therefore, $\Delta\theta = \pi/2$ is

an unstable convergence point. Since $\Delta\theta = \pi/2$ is a reverse zero-crossing point of the $f(\Delta\theta)$ curve, the regulation system is unstable for reverse zero-crossing points.

When $\Delta\theta \in (3\pi/4, 5\pi/4)$, the convergence point is at $\Delta\theta = \pi$. If a small positive disturbance makes $\Delta\theta > \pi$, then $f(\Delta\theta) > 0$, and after the PI regulator, $\hat{\theta}_0$ decreases, pulling $\Delta\theta$ back to the convergence point $\Delta\theta = \pi$. Similarly, a small negative disturbance is also corrected back to $\Delta\theta = \pi$. Therefore, $\Delta\theta = \pi$ is a stable convergence point. Since $\Delta\theta = \pi$ is a forward zero-crossing point of the $f(\Delta\theta)$ curve, the regulation system is stable for forward zero-crossing points.

In summary, the stable convergence points of this estimated position closed-loop system are $\Delta\theta = 0$ or π . Therefore, after preliminary initial position estimation, magnetic polarity judgment is still required to obtain the accurate rotor initial position.

3.4 Interval-Based Magnetic Polarity Judgment Method

After preliminary initial position estimation, the rotor position estimation error is $\Delta\theta = 0$ or π . The estimated d-axis current matches the reference under the PR regulator, i.e., $\hat{i}_d = I_{mh} \sin(\omega_h t)$. The estimated d-axis voltage equation is:

$$\hat{u}_d = R_s \hat{i}_d + L_d(i_d) \frac{d\hat{i}_d}{dt}$$

The corresponding d-axis high-frequency voltage response is:

$$\hat{u}_{dh} = R_s I_{mh} \sin(\omega_h t) + \omega_h L_d(i_d) I_{mh} \cos(\omega_h t) \quad (9)$$

The relationship between \hat{u}_{dh} and $\omega_h t$ is shown in Figure 4 [Figure 4: see original paper].

Due to d-axis magnetic field saturation, the d-axis inductance satisfies:

$$L_d(i_d > 0) < L_{d0} < L_d(i_d < 0)$$

Dividing the \hat{u}_{dh} waveform into intervals and integrating separately yields:

$$\int_{\text{interval I}} \hat{u}_{dh} d(\omega_h t) = \int_{\text{interval I}} [R_s I_{mh} + \omega_h L_d(i_d) I_{mh} \cos(\omega_h t)] d(\omega_h t)$$

$$\int_{\text{interval III}} \hat{u}_{dh} d(\omega_h t) = \int_{\text{interval III}} [R_s I_{mh} + \omega_h L_d(i_d) I_{mh} \cos(\omega_h t)] d(\omega_h t)$$

If the d-axis direction is correctly identified, then:

$$\int_{\text{interval I}} \hat{u}_{dh} d(\omega_h t) = R_s I_{mh} + \omega_h L_{d0} I_{mh}$$

$$\int_{\text{interval III}} \hat{u}_{dh} d(\omega_h t) = -R_s I_{mh} - \omega_h L_{d0} I_{mh}$$

The interval integration value is:

$$k_{I,III} = \int_{\text{interval I}} \hat{u}_{dh} d(\omega_h t) + \int_{\text{interval III}} \hat{u}_{dh} d(\omega_h t)$$

Conversely, if the d-axis direction is opposite:

$$\int_{\text{interval I}} \hat{u}_{dh} d(\omega_h t) = R_s I_{mh} + \omega_h L_{d0} I_{mh}$$

$$\int_{\text{interval III}} \hat{u}_{dh} d(\omega_h t) = -R_s I_{mh} - \omega_h L_{d0} I_{mh}$$

The interval integration value becomes:

$$k_{I,III} = \int_{\text{interval I}} \hat{u}_{dh} d(\omega_h t) + \int_{\text{interval III}} \hat{u}_{dh} d(\omega_h t)$$

The above analysis shows that the sign of the integration values from intervals I and III can be used to determine the positive d-axis direction. If the integration value is less than 0, the initial estimated position has positive magnetic polarity; if greater than 0, the polarity is negative.

In summary, the pulsating high-frequency current injection method for rotor initial position estimation consists of two steps: preliminary initial position estimation and magnetic polarity judgment, as shown in Figure 5 [Figure 5: see original paper]. First, a high-frequency sinusoidal current is injected into the \hat{d} -axis, and the \hat{q} -axis current response is detected for preliminary initial position estimation to obtain $\hat{\theta}_0$. Then, the \hat{d} -axis voltage response is detected for polarity judgment to obtain compensation angle θ_c . The final estimated position is $\hat{\theta} = \hat{\theta}_0 + \theta_c$.

4 Simulation and Experimental Results

Based on the above analysis, a simulation model was built to verify the proposed initial position estimation method. OPAL-RT controller and hardware platform were also used for experimental verification. The SPMSM parameters used in simulation and experiments are listed in the table below.

Table: SPMSM Basic Parameters

Parameter	Value
Rated Voltage U_N (V)	
Rated Power P_N (W)	
Flux per Pole Φ (Wb)	
Moment of Inertia J ($\text{g} \cdot \text{m}^2$)	
Rated Speed n_N (rpm)	
Phase Resistance R_s (Ω)	
Rated Current I_N (A)	
Pole Pairs P_n	
d-axis Inductance L_d (mH)	
q-axis Inductance L_q (mH)	

4.1 Simulation Results

Figure 6 [Figure 6: see original paper] shows the simulation waveforms of initial position estimation using the proposed polarity judgment method. Preliminary initial position estimation begins at $t_1 = 0$ s, and polarity judgment is performed at $t_2 = 0.3$ s. Figure 6a corresponds to an actual rotor initial position $\theta = 1$ rad. At $t = 0$ s, the estimated position $\hat{\theta}$ begins converging to the actual position θ . At $t = 0.3$ s, the sign of $k_{I,III}$ is determined to be negative, requiring no compensation of the preliminary estimate. Figure 6b corresponds to $\theta = 3$ rad. At $t = 0$ s, the estimated position $\hat{\theta}$ converges to a position π rad away from the actual position θ . At $t = 0.3$ s, the sign of $k_{I,III}$ is positive, and π rad is added to compensate the preliminary estimate. After compensation, the estimated position $\hat{\theta}$ matches the actual position θ , and the sign of $k_{I,III}$ becomes negative.

4.2 Experimental Results

Figure 7 [Figure 7: see original paper] shows the experimental waveforms of initial position estimation using the proposed polarity judgment method. Preliminary initial position estimation begins at $t_1 = 0.05$ s, and polarity judgment is performed at $t_2 = 0.15$ s. Figure 7a corresponds to $\theta = \pi/4$ rad. At $t = 0.05$ s, the estimated position $\hat{\theta}$ begins converging to the actual position θ . At $t = 0.15$ s, the sign of $k_{I,III}$ is negative, requiring no compensation. Figure 7b corresponds to $\theta = \pi$ rad. At $t = 0.05$ s, the estimated position $\hat{\theta}$ converges to a position π rad away from the actual position θ . At $t = 0.15$ s, the sign of $k_{I,III}$

is positive, and π rad compensation is applied. After compensation, the estimated position $\hat{\theta}$ matches the actual position θ , and the sign of $k_{I,III}$ becomes negative.

5 Conclusion

This paper investigates SPMSM initial position estimation using pulsating high-frequency current injection and proposes an interval-based integration method for magnetic polarity judgment. This method eliminates the need for additional positive/negative voltage pulses and current amplitude comparison, shortens initial position estimation time, simplifies the estimation process, reduces current detection accuracy requirements, avoids rotor jitter problems in low-inertia motors during pulse voltage injection, and broadens the application scope. Both simulation and experimental results effectively verify the correctness and feasibility of the proposed method.

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