A Position Sensorless Control of an Axial Flux-Switching Permanent-Magnet Motor Based on High-Frequency Pulsating Voltage Vector Injection

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Abstract—Flux-switching permanent magnet (FSPM) machines are novel brushless machines having magnets in the stator and currently are under intensive research due to their novel features, such as simple and robust rotor, flux focusing effect, sinusoidal phase back-EMF, high torque/power density and high efficiency. In this paper, a sensorless high-frequency sinusoidal signal injection scheme for a novel yokeless and segmented armature axial flux-switching sandwiched permanent-magnet motor (YASA-AFFSSPM) is proposed. Firstly, pulsating voltage injection is investigated in detail. In addition, a simpler method (Direct signal process method) for position error signal processing is presented based on pulsating signal injection. The principle and the realization of this method are analyzed in depth. Through experiment, the traditional signal process method and direct signal process method with high-frequency pulsating sinusoidal signal injection are compared to verify the validity these methods.

Keywords: Permanent Magnet, Flux switching motor, Sensorless, Signal injection, Yokeless.

1) Introduction

Traditional rotor permanent magnet motors are widely used due to their simple structure, reliable operation, high efficiency and power density, etc. However, because the permanent magnets are located on the rotor, the cooling conditions are poor and the heat dissipation is difficult, which leads to irreversible demagnetization of the permanent magnets, which affects the motor operation and power density. Therefore, stator permanent magnet motors, double salient permanent magnet (DSPM) motors and flux switching permanent magnet (FSPM) motors have been extensively studied in recent years [1-4].
The FSPM motor has the advantages of sinusoidal back-EMF, simple and strong rotor structure, high power density, and strong anti-demagnetization ability, making it very suitable for brushless AC (BLAC) transmission systems. Its mathematical model is the same as the rotor permanent magnet synchronous motor, and the mature vector control and direct torque control technologies can be widely applied to FSPM motors. A high-performance transmission system needs to install a position sensor to measure the real-time rotor position, but at the same time, the speed control system has high cost, large size, and low reliability, which limits its application range. In order to overcome the defects caused by mechanical position sensors, scholars have carried out a lot of research on the position sensorless technologies of AC motors [5-16]. Sensorless technology reduces the size and cost of the motor, and improves the reliability of the system. These technologies can be divided into two categories, namely based on the back EMF [5-7] and the based on salient pole effect [8-15]. The method based on the back EMF has superior performance at medium and high speeds, but since the magnitude of the back EMF is proportional to the rotation speed, it is not suitable for zero-speed and low-speed operation. The principle of the position sensorless technology based on the salient pole effect is to inject a high-frequency signal into the motor to track the salient pole of the motor to achieve position estimation. High-frequency signal injection is divided into rotation signal injection [8-11] and pulse signal injection, which is suitable for zero-speed and low-speed operation [9, 12-14]. The traditional high-frequency sinusoidal signal injection method needs to use a low-pass filter to obtain a position error signal, and the use of a low-pass filter causes signal delay, thereby affecting the performance of the control. A high-frequency square wave injection method to achieve sensorless control of AC motors from zero speed to low speed is proposed in [15]. It eliminates the low-pass filter in the process of obtaining the position error signal, so that the control performance is improved, and the bandwidth of current loop and speed loop is increased. Although the mathematical model of the 12/10 pole permanent magnet flux switching motor and the rotor permanent magnet synchronous motor (BLAC) are the same [1-3], the rotor has a salient pole structure without permanent magnets and windings. An initial position detection and sensorless control of a 6Slotes/4Poles FSPM motor is presented in [16]. But a 6Slotes/4poles FSPM motor is equivalent to the control of a brushless DC (BLDC) motor, and its mathematical model is different from that of a BLAC motor.
in [17], Rahmani et al. proposed a novel yokeless and segmented armature axial FSPM motor (YASA-AFFSSPM) which has dual-rotor/single-stator and shows more desired performance including low cogging torque, large torque/power density, high efficiency. This paper studies the zero-speed and low-speed operation of a 12Slotes/19Poles YASA-AFFSSPM motor, and studies a position sensorless control method based on high-frequency pulsating sinusoidal signals.

The traditional signal processing method is analyzed, and then a direct signal process method for position error signal processing is studied. In the direct signal processing method, q-axis current signal of the estimated synchronous rotating reference frame processed through the band pass filter (BPF) directly multiplied by the square wave signal to get the position error signal, which can eliminate the low-pass filter to make the signal process simple. Finally, through experiment, the traditional signal process method and direct signal process method with high-frequency pulsating sinusoidal signal injection are compared to verify the validity these methods.

2) Configuration and operation principle

Fig.s 1 and 2 show the configuration and operation principle of the 12Slotes/19Poles YASA-AFFSSPM machine, respectively. The design and operation principle are proposed in detail in [17].

The 3-D FEM model of the 12S/19P YASA-AFFSSPM motor is provided in the “Ansys Maxwell 16” software. The 3D mesh of the 12S/19P YASA-AFFSSPM motor is illustrated in Fig. 3.

The open-circuit magnetic flux density distribution is shown in Fig. 4.

In the synchronous rotation d-q coordinate system, the voltage equations of the YASA-AFFSSPM are as follows

\[
\begin{align*}
    u_d &= R_i_d + \frac{d\psi_d}{dt} - \psi_q \omega_e \\
    u_q &= R_i_d + \frac{d\psi_q}{dt} + \psi_d \omega_e
\end{align*}
\]

(1)

where \( u_d \) and \( u_q \) are the \( dq \)-axes stator voltages, \( i_d \) and \( i_q \) are the \( dq \)-axes stator currents, \( \psi_d \) and \( \psi_q \) are the \( dq \)-axes stator flux, \( \omega_e \) is the electrical angular velocity and \( R \) is the armature winding resistance. Moreover, we have \( \psi_d = L_d i_d + \psi_m \) and \( \psi_q = L_q i_q \), where \( L_d \) and \( L_q \) are dq-
axes inductances and $\psi_m$ is the PM flux linkage. The electromagnetic torque in YASA – AFFSSPM motor can be expressed as:

$$T_{em} = \frac{3}{2} P_r \left( \psi_m I_m \sin\delta - \frac{1}{2} (L_d - L_q) I_m^2 \sin 2\phi \right)$$

(2)

where $\delta$ is angle torque and for 12/19 YASA-AFFSSPM motor.

Fig. 5 shows the three-phase self-inductances and mutual inductances of a 12/19 YASA-AFFSSPM motor obtained by finite element simulation. The inductance changes twice in the electric cycle but the amplitude changes are small.

Fig. 6 shows the calculated d and q axes inductances. It can be seen that the difference between $L_d$ and $L_q$ is small, and $L_q / L_d$ is about 1.13. Therefore, the 12/19 YASA-AFFSSPM motor has a salient pole effect ($L_d \neq L_q$). Furthermore, the saliency can be tracked to perform sensorless control of the high-frequency injection method.

3) **High frequency pulsating sinusoidal signal injection with sensorless control**

3.1) **The mathematical model of the motor under high frequency excitation**

The HF model of the YASA-AFFSSPM motor in the low-speed condition and at standstill can be expressed as [18]:

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} j\omega L_{dh} + R & 0 \\ 0 & j\omega L_{qh} + R \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} Z_{dh} & 0 \\ 0 & Z_{qh} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix}$$

(3)

The HF impedance model, Eq. (3), is used to derive the expression of the induced HF currents for rotor position estimation. The HF pulsating voltage vector is injected into the estimated $\hat{d}\hat{q}$ rotating reference frame. The angle between the $\hat{d}$ axis and the $\alpha$ axis, which is aligned with the direction of the phase A magnetic axis, is defined as the estimated rotor position, as shown in Fig. 7. The error between the real $\theta_{real}$ and estimated rotor positions $\theta_{est}$ is denoted as $\Delta \theta$,

$$\Delta \theta = (\theta_{real} - \theta_{est})$$

$$\begin{bmatrix} f_d \\ f_q \end{bmatrix} = \begin{bmatrix} \cos(\Delta \phi) & \sin(\Delta \phi) \\ -\sin(\Delta \phi) & \cos(\Delta \phi) \end{bmatrix} \begin{bmatrix} \hat{f}_d \\ \hat{f}_q \end{bmatrix}$$

(4)
In (4), \( f_d \) and \( f_q \) represent the voltage or current in the \( dq \) axes coordinate system. According to Eq.s (3) and (4), the mathematical model of the estimated coordinate system as follows:

\[
\begin{bmatrix}
\hat{i}_d \\
\hat{i}_q
\end{bmatrix} = \frac{1}{Z_{dh}Z_{qh}} \begin{bmatrix}
Z - \Delta Z \cos(2\Delta \theta) & -\Delta Z \sin(2\Delta \theta) \\
-\Delta Z \sin(2\Delta \theta) & Z + \Delta Z \cos(2\Delta \theta)
\end{bmatrix} \begin{bmatrix}
\hat{u}_d \\
\hat{u}_q
\end{bmatrix}
\]

(5)

where \( Z \) and \( \Delta Z \) can be expressed as:

\[
Z = \frac{Z_{dh} + Z_{qh}}{2}, \quad \Delta Z = \frac{Z_{dh} - Z_{qh}}{2}
\]

(6)

\[3.2] \text{Pulsating voltage injection method and Position error signal extraction} \]

A HF sinusoidal voltage vector, described by Eq. (7), is injected into the estimated \( \hat{dq} \) reference frame [19].

\[
\begin{bmatrix}
\hat{u}_d \\
\hat{u}_q
\end{bmatrix} = \begin{bmatrix}
U \cos \omega t \\
0
\end{bmatrix}
\]

(7)

In the conventional method, the rotor position information is extracted from the induced HF current signals in the \( \hat{dq} \) reference and from Eq.(5) \( \hat{i}_d, \hat{i}_q \) can be expressed as [20]

\[
\hat{i}_d = \frac{Z - \Delta Z \cos(2\Delta \theta)}{Z_{dh}Z_{qh}} U \cos \omega t
\]

(8)

\[
\hat{i}_q = -\frac{\Delta Z \sin(2\Delta \theta)}{Z_{dh}Z_{qh}} U \cos \omega t
\]

(9)

As shown in Eq.s (8) and (9), the rotor position estimation error, \( \Delta \theta \), is contained in \( \hat{i}_q \). However, the magnitude of \( \hat{i}_q \) depends on the rotor saliency, which is small for an 12S/19P YASA-AFFSSPM. The conventional signal processing method is shown in Fig. 6. \( \hat{i}_q \) passes through a band pass filter (BPF) and then is multiplied by the \( \sin(\omega_b t) \) and the error signal \( f(\Delta \theta) \) is obtained by passing a low pass filter.
Therefore, the general transfer function of the position estimation system can be obtained according to Fig. 8.

Equations 11 and 12 are derived from Fig. 8 as:

\[ \theta_{est} = K \Delta \theta \times \left( K_p + \frac{K_i}{s} \right) \times \frac{1}{s} \]  \hspace{1cm} (11)

and

\[ \frac{\theta_{est}}{\theta_{real}} = \frac{KK_p s + KK_i}{s^2 + KK_p s + KK_i} \]  \hspace{1cm} (12)

From (12), since \( K > 0 \) and the PI parameters are greater than zero, the poles of the transfer function are located in the left half of the s plane and the steady-state gain of the transfer function is 1. Therefore, the estimated position can track the actual position.

Through analysis, it can be seen that the principle of sensorless control based on the traditional signal processing method is simple, but the process of obtaining the position error signal includes a low-pass filter. The selection of the cut-off frequency affects the performance of sensorless control. When the cut-off frequency of the low-pass filter is selected lower, the position estimation delay of the system is larger, and if the cut-off frequency is selected higher, the ability to filter interference signals is weaker. Therefore, it is necessary to repeatedly select the cut-off frequency in the actual experiment to achieve the best control effect. Based on high-frequency pulsating sinusoidal signal injection, this paper studies a direct signal processing method that can eliminate low-pass filtering and simplify the signal processing process.

4) Direct signal processing method

In this proposed method, the estimated q-axis current, \( \hat{i}_q \), can be further simplified to obtain:

\[ \hat{i}_q = \frac{j \omega_h (L_d - L_q) \sin(2 \Delta \theta)}{2 (j \omega_h L_d + R)(j \omega_h L_q + R)} U \cos \omega_h t \]  \hspace{1cm} (13)
By ignoring the resistance, when the high frequency signal is injected, \( \hat{i}_q \) can be reduced as

\[
\dot{i}_q = \frac{(L_d - L_q) \sin \omega_h t}{2 \omega_h L_d L_q} U \sin (2\Delta \theta) = K \sin (2\Delta \theta)
\]

(14)

where

\[
K = \frac{(L_d - L_q)}{2 \omega_h L_d L_q} U \sin \omega_h t
\]

(15)

Fig. 9 shows the relationship between the sine injection signal and the coefficient K. It can be seen that K is a sine function and changes at \( \omega_h \) frequency. The traditional signal processing method is to obtain the position error signal by multiplying the sine signal of the same frequency and then low-pass filtering it, and then enter the position estimation observer.

In the direct signal processing method \( \hat{i}_q \) signal of the estimated synchronous rotating reference frame processed through the band pass filter (BPF) directly multiplied by the square wave signal to get the position error signal. Therefore, the position error signal \( g(\Delta \theta) \) is obtained as follows:

\[
g(\Delta \theta) = K \sin (2\Delta \theta) \times f = |K| \times \sin (2\Delta \theta) = \frac{(L_q - L_d)}{2 \omega_h L_d L_q U} |\sin (\omega_h t)| \sin (2\Delta \theta) \approx K_{er} \Delta \theta
\]

(16)

where \( f \) is the sign function. The signal \( g(\Delta \theta) \) is the input of the PI regulator and can write as:

\[
g(\Delta \theta) \times \left(K_p + \frac{K_i}{s}\right) \times \frac{1}{s} \approx K_{er} \Delta \theta \times \left(K_p + \frac{K_i}{s}\right) \times \frac{1}{s} = \left(K_p' + \frac{K_i'}{s}\right) \times \frac{1}{s} \times \Delta \theta
\]

(17)

As can see from (17), the estimated position depends on PI parameters. In order to investigate the stability of the position estimation system, the Nyquist criterion is used. The system transfer function is described as:

\[
\frac{\theta_{est}}{\theta_{real}} = \frac{K_p' s + K_i'}{s^2 + K_p' s + K_i'}
\]

(18)

Since the parameters \( K_p' \) and \( K_i' \) are time-varying variable, it cannot be solved directly. It is transformed into a steady state space system. Let the intermediate variable be \( x \). Thus, one can write
\[
\begin{align*}
\dot{x} &= Ax + B\theta_{\text{real}} \\
\dot{\theta}_{\text{est}} &= Cx + D\theta_{\text{real}}
\end{align*}
\] (19)

Using the knowledge of the principle of automatic control, the Eq. (19) can be written as:

\[
\begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2
\end{bmatrix} =
\begin{bmatrix}
0 & 1 \\
-K_i' & -K_p'
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2
\end{bmatrix} +
\begin{bmatrix}
K_p' \\
K_i' - (K_p')^2
\end{bmatrix}
\theta_{\text{real}}
\]

\[
\dot{\theta}_{\text{est}} = [1 \quad 0]
\begin{bmatrix}
x_1 \\
x_2
\end{bmatrix}
\] (20)

The Nyquist curves of the system are obtained using the Matlab software. As shown in Fig. 8, the \( K_p' \) and \( K_i' \) have sinusoidal changes with frequency 500 Hz. According to the Nyquist criterion, every curve vs time is stable, so the stability of the method is verified, and it is easy to know that the steady-state gain is 1. Thus, the estimated position at steady state is consistent with the actual position. Direct signal processing method is shown in Fig. 11, which eliminate the need for the low-pass filter. The overall principle of the high-frequency voltage injection method based on the direct signal processing method is shown in Fig. 12.

5) Experimental results

Using the digital control system with TMS320F2812 as the core, the high-frequency pulsating signal injection method is verified by experiments without sensorless control in a 12S/19P YASA-AFFSSPM motor. The switching frequency of the power device is 16kHz, the amplitude of the injected sine wave voltage signal is 30V, and the frequency is 500Hz. The experimental setup is shown in Fig. 13. Parameters of investigated motor are shown in Table I. The back-EMF is shown in Fig. 14.

Due to the consistency and complementarity of the windings, the back EMF is highly sinusoidal. In order to verify the sensorless control analysis based on the two signal processing methods, the verification experiment of the position error signal is first carried out.

Fig. 15(a) shows the position error signal obtained by the traditional low-pass filtering method. The cut-off frequency of the low-pass filter is 5Hz. Fig. 15(b) shows the position error signal obtained by the direct signal processing method. It can be seen that the position error signal changes as the absolute of a sine wave which is consistent with the Eq. (14).
Fig. 16(a) and 16 (b) show the low-speed and sensor-less control of two signal processing methods. The position tracking waveforms are given during deceleration from +50 to -50 rpm. Fig. 16(a) shows the traditional signal processing method and Fig. 16 (b) shows the direct signal processing method. Both methods can achieve good results without a position sensor. In order to verify the superiority of the direct signal processing method, the difference between the two positions is compared with tracking the initial position of the rotor. The tracking of the position of the two methods is not very different.

Fig. 17 shows the magnetic flux and electromagnetic torque. It can be seen that the flux and torque ripple in direct signal processing method are lower than those of the traditional signal processing method.

Fig. 18 shows the initial position tracking with two methods. The initial rotor position is 55 °. Fig. 18 (a) and (b) are related to the traditional signal processing method. The low-pass cut-off frequencies are 20Hz and 5Hz, respectively. It can be seen that the tracking times are 30ms and 250ms. Fig. 18 (c) is related to the direct signal processing method and the tracking time is 28ms. The selection of the low-pass filter frequency effects on the actual position estimation, otherwise the delay of the system is caused. The direct signal processing method eliminates the needs for low-pass filtering, which makes the signal processing simpler and more effective. For better comparison, the results are listed in Table II.

6) Conclusion

In this paper, through the finite element analysis and verification of the saliency of the 12/19 poles YASA-AFFSSPM motor, the position sensorless control based on high frequency pulsating sinusoidal signal injection is studied. Traditional signal processing methods use low-pass filters to obtain position error signals, and the selection of the cut-off frequency of the low-pass filter has higher requirements. The sensorless control using the direct signal processing method eliminates the need for a low-pass filter, so the control is simple and effective. Finally, through experiments, the zero-speed and low-speed operation performance of the motor based on
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REFERENCES


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Fig. 14. Back-EMF harmonics at 200 r/min.
Injected signal
Position error ∆𝜽
(30V/div)
t(50ms/div)
(5º/div)

(a)                                                           (b)

Fig. 15. (a) The position error signal obtained by the traditional low-pass filtering method. (b) The position error signal obtained by the direct signal processing method

Given speed
Estimated speed
Actual position 𝜽
Estimated position 𝜽_{est}
(300º/div)
t(50ms/div)
(100rpm/div)

(a)                                                           (b)

Fig. 16. (a) The traditional signal processing method (b) The direct signal processing method
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Table I. Parameters of 12S/19P YASA- AFFSSPM motor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Rated speed n / rpm</td>
<td>200</td>
</tr>
<tr>
<td>Rated Torque T_n / N.m</td>
<td>12</td>
</tr>
<tr>
<td>Rated Power P / kW</td>
<td>0.75</td>
</tr>
<tr>
<td>PM flux linkage ( \phi_m / )Wb</td>
<td>0.10</td>
</tr>
<tr>
<td>Stator resistance R / ( \Omega )</td>
<td>0.65</td>
</tr>
<tr>
<td>dq axes rated current ( I_d = I_q / A )</td>
<td>10</td>
</tr>
<tr>
<td>Sampling time T / s</td>
<td>( 10^{-4} )</td>
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Table II: Comparison of the results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Traditional signal processing method (cut-off frequency 5HZ)</th>
<th>Traditional signal processing method (cut-off frequency 20HZ)</th>
<th>Direct signal processing method</th>
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<tbody>
<tr>
<td>Flux linkage ripple</td>
<td>4.6%</td>
<td>4.5%</td>
<td>3%</td>
</tr>
<tr>
<td>Torque ripple</td>
<td>7%</td>
<td>7%</td>
<td>2.8%</td>
</tr>
<tr>
<td>Estimated speed settling time</td>
<td>40ms</td>
<td>250ms</td>
<td>39ms</td>
</tr>
<tr>
<td>The ratio of overshoot</td>
<td>30%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Posotion tracking Time</td>
<td>30ms</td>
<td>230ms</td>
<td>28ms</td>
</tr>
</tbody>
</table>

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