Research on PMSM Low-speed Sensorless Control Strategy based on Rotating High Frequency Injection Method

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Abstract. In this paper, by studying the Permanent Magnet Synchronous Motor (PMSM) position sensorless control strategy, a method for error compensation of current response by high frequency error signal is proposed. Since the high-frequency carrier current contained in the stator current causes the erroneous adjustment of the current regulator, the control system contains a high-frequency error signal, which affects the motor rotor position and speed estimation accuracy. The high-frequency error voltage signal is extracted in the stationary $\alpha-\beta$ coordinate system, and the high-frequency error response current in the stator current is estimated, and the estimation system is compensated. The PMSM position sensorless control system based on the rotating high frequency voltage injection method and the Matlab-Simulink system model of the error compensation are established. The results show that the speed and position estimation are more accurate after error compensation, and the steady-state error is smaller, which improves the smoothness of the motor at low speed.

1. Introduction
PMSM has the advantages of high efficiency and strong reliability. It is therefore widely used in various fields such as aerospace, automobiles and household appliances [1]. How to further improve the control accuracy of PMSM is of great significance.

As an emerging motor control strategy, position sensorless control technology opens up new mind for people. It avoids the use of traditional position sensors, simplifies system construction and saves space. Its core is estimating the rotor angle and speed value for closed loop control [2-3]. Estimation accuracy is a key factor which affects the system performance.

Many sensorless algorithms have been successfully applied in industry and life. But each algorithm has its advantages and disadvantages. Till now, there has been no one fully mature sensorless algorithm suitable for all kinds of conditions [4-6].

Through a large number of experiments, combined with the synovial observer algorithm, the literature [7-8] has improved the problem of unstable motor starting, chattering, and even startup failure. However, this algorithm requires the rotor to be pulled to a fixed angle before the motor starts normally. Obviously this algorithm has lost its effect on the car-use motor.

The rotating high frequency injection method is a way to get rotor position by injecting a high frequency signal on a given frequency into the stationary axis, and then analyzing the high frequency response of the signal [9-10]. However, this algorithm is very susceptible to interference in practical applications. To this end, the literature [11-12] proposed the use of Kalman filter to reduce the degree of interference of the algorithm, but it is very complicated and low feasibility.
In this paper, based on the rotating high-frequency voltage signal injection method, a response current error compensation method for position estimation is proposed. The method calculates the high-frequency current response error. By extracting the error of the voltage in the stationary $\alpha - \beta$ axis and using the mathematical model under high-frequency excitation. Finally compensates in the position estimation system. The oscillation caused by the high frequency error is reduced, and estimated results of the algorithm are more accurate. By analyzing the PMSM vector control scheme, a complete position sensorless speed control system is well established.

2. Rotating high frequency voltage injection principle

In the case of low-speed operation of the embedded PMSM, the rotary high-frequency voltage injection method is used to obtain the rotor position and rotational speed. The voltage equation under the d-q axis system is:

$$
\begin{align*}
    u_d &= R_i d + \frac{d}{dt} \psi_d - \omega L q_i, \\
    u_q &= R_i q + \frac{d}{dt} \psi_q - \omega L d_i
\end{align*}
$$

(1)

The stator flux linkage equation is:

$$
\begin{align*}
    \psi_d &= L_0 d + \psi_f, \\
    \psi_q &= L_0 q
\end{align*}
$$

(2)

Substituting equation (2) into equation (1), the voltage equation becomes:

$$
\begin{align*}
    u_d &= R_i d + L_0 d \frac{d}{dt} i_d - \omega L q_i, \\
    u_q &= R_i q + L_0 q \frac{d}{dt} i_q + \omega L d_i + \psi_f
\end{align*}
$$

(3)

In the formula, $u_d, u_q$ are the d and q axis voltage components, $i_d, i_q$ are the current components, $L_0, L_q$ are the inductances, $\omega$ is the electrical velocity, $\psi_f$ is the permanent magnet flux linkage.

Since the frequency of the injected high-frequency signal is much higher than the fundamental frequency, the voltage difference caused by the current change rate is much higher than other factors. This high frequency model can be simplified to:

$$
\begin{align*}
    u_{\text{d,in}} &\approx L_0 d \frac{d}{dt} i_{\text{d,in}}, \\
    u_{\text{q,in}} &\approx L_0 q \frac{d}{dt} i_{\text{q,in}}
\end{align*}
$$

(4)

$u_{\text{d,in}}, u_{\text{q,in}}, i_{\text{d,in}}, i_{\text{q,in}}$ are the injection voltage and current response in the d-q axis. Assuming the injection frequency is $\omega_n$, the amplitude is $V_n$, the injected signal representation can be expressed as follows:

$$
    u_{\text{d,in}} = u_{\text{af,in}} e^{-j\theta} = V_n e^{j(\omega_n t - \theta)}
$$

(5)

$\theta$ is the electrical angle of the rotor. And the solution of the high frequency excitation current equation is as follows:

$$
\begin{align*}
    i_{\text{af,in}} &= i_{\text{af,in}} e^{-j\theta} = u_{\text{af,in}} e^{-j\theta} = I_{\text{cp}} e^{j\omega_n t \frac{-\pi}{2}} + I_{\text{cn}} e^{j\omega_n t \frac{2\theta + \pi}{2}}
\end{align*}
$$

(6)

$I_{\text{cp}}, I_{\text{cn}}$ are the amplitudes of the positive and negative phase sequence components, respectively.

$$
\begin{align*}
    I_{\text{cp}} &= \frac{V_n}{\omega_n L_q L_0}, \\
    I_{\text{cn}} &= \frac{V_n}{\omega_n L_0 L_q}
\end{align*}
$$

(7)

By observing equation (6) we can see, with appropriate processing, the electrical angle $\theta$ can be easily extracted from the negative phase sequence components.
3. Error compensation algorithm

In order to improve the estimation accuracy, the high frequency error voltage signal is extracted in the stationary $\alpha-\beta$ axis. Expressed on the complex plane as:

$$ u_{\alpha\beta\text{err}} = u_{\alpha\beta\text{err}} + j u_{\beta\alpha\text{err}} \quad (8) $$

The purpose of the error compensation algorithm is, by using the extracted error voltage, calculating the high-frequency current response error, as shown in the Fig 1.

![Error calculation module](image)

**Figure 1.** Error calculation module

Transformed to the estimated rotating coordinate system:

$$ u_{dq\text{err}} = u_{\alpha\beta\text{err}} e^{-j\theta_e} = (u_{\alpha\beta\text{err}} + j u_{\beta\alpha\text{err}}) (\cos(\theta_e) + j \sin(\theta_e)) $$

$$ = (u_{d\text{err}} \cos \theta_e + u_{\alpha\beta\text{err}} \sin \theta_e) + j(u_{q\text{err}} \cos \theta_e - u_{\beta\alpha\text{err}} \sin \theta_e) \quad (9) $$

among them:

$$ \begin{bmatrix} u_{d\text{err}} = u_{\alpha\text{err}} \cos \theta_e + u_{\beta\text{err}} \sin \theta_e \\
 u_{q\text{err}} = u_{\beta\text{err}} \cos \theta_e - u_{\alpha\text{err}} \sin \theta_e \end{bmatrix} \quad (10) $$

Substituted into the high-frequency current response equation to obtain the error response:

$$ \begin{bmatrix} \begin{array}{l} i_{d\text{err}} = \frac{1}{L_d} \int (u_{\alpha\text{err}} \cos \theta_e + u_{\beta\text{err}} \sin \theta_e) \\ i_{q\text{err}} = \frac{1}{L_q} \int (u_{\beta\text{err}} \cos \theta_e - u_{\alpha\text{err}} \sin \theta_e) \end{array} \end{bmatrix} \quad (11) $$

Expressed on the complex plane as:

$$ i_{dq\text{err}} = (u_{\alpha\text{err}} \cos \theta_e + u_{\beta\text{err}} \sin \theta_e) + j(u_{\beta\text{err}} \cos \theta_e - u_{\alpha\text{err}} \sin \theta_e) \quad (12) $$

To compensate the error current response in the stationary coordinate system, it needs to be transformed into stationary $\alpha-\beta$ coordinate system:

$$ i_{\alpha\beta\text{err}} = i_{dq\text{err}} e^{j\theta_e} = (i_{d\text{err}} + j i_{q\text{err}}) (\cos \theta_e + j \sin \theta_e) $$

$$ = (i_{d\text{err}} \cos \theta_e - i_{q\text{err}} \sin \theta_e) + j(i_{q\text{err}} \cos \theta_e + i_{d\text{err}} \sin \theta_e) \quad (13) $$

From this, the high frequency error current response is obtained:

$$ \begin{bmatrix} \begin{array}{l} i_{d\text{err}} = \frac{\cos \theta_e}{L_d} \int (u_{\alpha\text{err}} \cos \theta_e + u_{\beta\text{err}} \sin \theta_e) - \frac{\sin \theta_e}{L_q} \int (u_{\beta\text{err}} \cos \theta_e - u_{\alpha\text{err}} \sin \theta_e) \\ i_{q\text{err}} = \frac{\cos \theta_e}{L_q} \int (u_{\beta\text{err}} \cos \theta_e - u_{\alpha\text{err}} \sin \theta_e) + \frac{\sin \theta_e}{L_d} \int (u_{\alpha\text{err}} \cos \theta_e + u_{\beta\text{err}} \sin \theta_e) \end{array} \end{bmatrix} \quad (14) $$

The obtained high frequency response error is substituted into the high frequency response current equation for error compensation, Fig 2. is the compensation structure:

![Error compensation module](image)

**Figure 2.** Error compensation module
\[ i_{\text{afin}} = i'_{\text{afin}} - i_{\text{efferr}} = I_{qf} e^{j(\alpha_\omega - \frac{\pi}{2})} + I_{cf} e^{j(-\alpha_\omega + 2\theta + \frac{\pi}{2})} \]  

Among them, \( i'_{\text{afin}} \) is the high-frequency component of the sampling current without error compensation.

4. Estimation of rotor position and speed

Since the rotor position signal is only included in the negative phase sequence of the high-frequency component, the positive phase sequence component is necessary to be filtered out in equation (15) in advance, which can be realized by a synchronous frame filter (SFF). After filtering out the positive phase sequence components, the remaining current response component is as follows:

\[ i_{n, afin} = I_{qf} e^{j(-\alpha_\omega + 2\theta + \frac{\pi}{2})} \]  

The rotor position tracking observation method can extract the angle signal from the negative phase sequence component. However, this method is limited by the bandwidth, and the frequency cannot be too high. Otherwise, the error of inertia J will bring greater fluctuation to the system.

This paper estimates the angle and velocity of the rotor by the mean of phase-locked loop. The structure is shown in the Fig 3.

\[ \text{Figure 3. Phase-locked loop structure} \]

At first, the tracking error is obtained by the heterodyne method, which is proportional to the vector phase error. The error is as follows:

\[ \varepsilon = i_{n, \phi n} \cos(2\hat{\theta} - \omega_n t) + i_{n, \phi n} \sin(2\hat{\theta} - \omega_n t) = 2I_{cs} \sin(\hat{\theta} - \hat{\theta}_c) \]  

The phase-locked loop has the advantages of stable structure and strong anti-interference ability, and finally realizes that the phase difference between the actual and the tracking signal is constant, and the frequencies of the two are equal.

5. PMSM vector control system

In order to verify the effectiveness of the compensation algorithm, the PMSM vector control system model was built in Matlab-Simulink for simulation experiments. The control system is mainly divided into three parts: vector control closed-loop module, sensorless control algorithm estimation module, and high-frequency interference error compensation module. Fig 4. is the PMSM vector control block diagram:
6. Simulation results
This control strategy is achieved based on a 10kW embedded PMSM model with Matlab-Simulink. The motor rotor initial angle is set to 30° and the reference speed is 50 rpm.

Fig 5. (a) - (b) are respectively the motor speed and steady-state speed error map in the case of error-free compensation algorithm.

The simulation results of Fig 5. (a) - (b) show that the position sensorless theoretical derivation and simulation model is accurate. Control system can quickly converge to 50 rpm. And the error of the estimated speed is lower than ±4 rpm.
Fig 6. (a) - (b) are respectively the motor speed and steady-state speed error map with error compensation algorithm.

Compared Fig 6. (a) with Fig 5. (a), after adding the compensation algorithm, the initial oscillation of the motor is small, and the steady-state operation is more stable. In comparison with Fig 6. (b) and Fig 5. (b), the speed error is lower than ±2rpm, reduced by 50%.

Acknowledgement
This work is supported by Six Talents Peak Project of Jiangsu Province under contract No. XNYQC-CXTD-001.

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