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Study on Position Polarity Compensation for Permanent Magnet Synchronous Motor Based on High Frequency Signal Injection

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***Abstract*—**The application of a high frequency signal injection method as speed and position observer in PMSM drives has been a research focus. At present, the precision of this method is nearly good as that of ten-bit encoder. But there are some questions for estimating position polarity. Based on high frequency signal injection, this paper presents a method to compensate position polarity for permanent magnet synchronous motor (PMSM). Experiments were performed to test the effectiveness of the proposed algorithm and results present the good performance.

***Keywords*—**permanent magnet synchronous motor, sensorless, high-frequency signal injection, magnetic pole position.

I. INTRODUCTION

PERMANENT magnet synchronous motor (PMSM) has good performances such as high-inertia moment ratio, high energy density, fast dynamic response and good overload capacity. It is widely used in astronautics, electric vehicle and other industrial control fields. In order to achieve high precision and fast dynamic control performance of PMSM, rotor position and speed detections are necessary. The detections are commonly based on mechanical sensor, which will lead to increased cost and limited application in some special situations. Therefore, there have been many researches on eliminating the position sensors mounted on the rotor of the PMSM machines to obtain the rotor position information indirectly.

Generally, sensorless position estimation schemes can be classified in two categories. One is based on the fundamental model methods [1]-[4]. Such an approach is very simple and show good performance in the medium-to-high-speed range, but fails at low and zero speed. The other is based on the saliency phenomena of PMSM [5]-[8]. A high-frequency voltage (current) signal is injected into machines in order to detect the saliency phenomena. The rotor saliency affects the phase position of the high-frequency stator current which contains the rotor position information. So this approach is insensitive to parameter variation.

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This paper is organized as follows: firstly, the mathematic model of PMSM under high-frequency voltage excitation has been established. The corresponding high-frequency current can be extracted and processed, then negative sequence component which contain rotor position information has been separated from high-frequency components. According to the theoretical analysis, a rotor position observer is established and the process of rotor position signal information is described in detail. Secondly, a new method has been proposed based on the analysis of the defaults of traditional high frequency injection. This method can distinguish the magnetic pole position from second order positive high frequency component. This part has elaborated signal extraction process and produced a rotor error signal. Finally, an interior PMSM is selected to make experiment which includes rotor position estimation, the magnetic pole position distinguishing and rotor position polarity compensation. Experimental results show the effectiveness of the proposed approach.

II. PRINCIPLES OF ROTOR POSITION TRACKING

A. *Mathematic Model of the PMSM under High Frequency Voltage Excitation*

The voltage and flux equations [1] of PMSM stator in the rotor synchronously rotating reference frame can be express as:

$$\begin{bmatrix} v_q \\ v_d \end{bmatrix} = \begin{bmatrix} r_s & 0 \\ 0 & r_s \end{bmatrix} \begin{bmatrix} i_q \\ i_d \end{bmatrix} + \begin{bmatrix} p & w_r \\ -w_r & p \end{bmatrix} \begin{bmatrix} \lambda_q \\ \lambda_d \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} \lambda_q \\ \lambda_d \end{bmatrix} = \begin{bmatrix} L_q & 0 \\ 0 & L_d \end{bmatrix} \begin{bmatrix} i_q \\ i_d \end{bmatrix} + \begin{bmatrix} 0 \\ \lambda_m \end{bmatrix} \tag{2}$$

Transformed into the stationary reference frame, the above equation can be rewritten as:

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \begin{bmatrix} r_s & 0 \\ 0 & r_s \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \begin{bmatrix} p & 0 \\ 0 & p \end{bmatrix} \begin{bmatrix} \lambda_\alpha \\ \lambda_\beta \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} \lambda_\alpha \\ \lambda_\beta \end{bmatrix} = \begin{bmatrix} L - \Delta L\cos(2\theta_r) & -\Delta L\sin(2\theta_r) \\ -\Delta L\sin(2\theta_r) & L + \Delta L\cos(2\theta_r) \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \begin{bmatrix} \lambda_m \cos\theta_r \\ \lambda_m \sin\theta_r \end{bmatrix} \tag{4}$$

Where

v --Stator voltage,

i --Stator current,

λ -- Stator flux linkage,

λ_m --d-axis component of permanent magnet caused flux linkage which goes through the stator winding magnet,

p --Differential operator,

$L = (L_d + L_q)/2$ --Average inductance,

$\Delta L = (L_q - L_d)/2$ --Half-difference inductance,

L_d and L_d are the inductance components in the rotor synchronously rotating reference frame of $d-q$,

θ_r --The angle between ∂ axis and d axis.

The 3-phase balanced high-frequency voltage signal can be superposed on the fundamental component [11] to excite the motor with voltage source PWM inverter supplied. As illustrated in Fig.1.

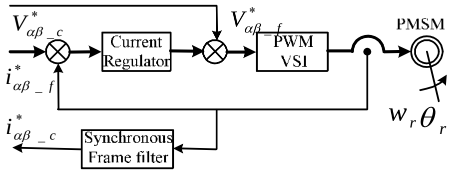

Fig. 1 The principle of a high frequency voltage signal injection

Assume that the angular frequency of the high frequency signal w_c is much greater than fundamental component w_e, and its amplitude is V_c, then the injected high frequency voltage signal in the stationary reference frame can be expressed as:

$$V_{in} = V_c \begin{bmatrix} \cos(w_c t) \\ -\sin(w_c t) \end{bmatrix} = V_c e^{-jw_c t} \quad (5)$$

The total voltage added on the motor terminal can be expressed as:

$$V_{\alpha\beta} = V_f \begin{bmatrix} \cos(w_e t) \\ -\sin(w_e t) \end{bmatrix} + V_c \begin{bmatrix} \cos(w_c t) \\ -\sin(w_c t) \end{bmatrix}$$

$$= V_f e^{-jw_e t} + V_c e^{-jw_c t} \quad (6)$$

Where, V_f is the amplitude of fundamental voltage component, w_e is the angular frequency of the fundamental component.

The frequency (500Hz) of injected high frequency must be much higher than the fundamental frequency. Under this excitation condition, the resistive drop can be neglected and the impedance of the motor is dominated by the self-inductance. So the effective motor model with high frequency injection signal can be simplified as:

$$V_{\alpha\beta c} = \bar{L}\frac{di_{\alpha\beta c}}{dt} \quad (7)$$

Where the inductance matrix is

$$\bar{L} = \begin{bmatrix} L - \Delta L\cos(2\theta_r) & -\Delta L\sin(2\theta_r) \\ -\Delta L\sin(2\theta_r) & L + \Delta L\cos(2\theta_r) \end{bmatrix} \quad (8)$$

Refer to (7) and (8), the corresponding high frequency current can be deducted as:

$$i_{\alpha\beta c} = i_{1p} e^{j(\theta_i(t) - \pi/2)} + i_{1n} e^{j(2\theta_r - \theta_i(t) + \pi/2)} \quad (9)$$

Where, the amplitudes of positive and negative sequential current components can be expressed as.

$$i_{1p} = \frac{V_{\alpha\beta c}}{w_c}\frac{L}{L^2 - \Delta L^2}, \quad i_{1n} = \frac{V_{\alpha\beta c}}{w_c}\frac{\Delta L}{L^2 - \Delta L^2}$$

From above equations, it is easily found that only the negative sequence component contains the position information of θ_r.

B. The Principal of Rotor Position Estimation by Spatial Saliency tracking Scheme

In order to extract the rotor saliency information from the negative sequence component of the current, these signals must be filtered out which include the fundamental component, PWM switching harmonics component and the positive sequence high-frequency component [12]-[14]. Among three components, the fundamental and switching harmonics component are easily removed. Because the frequency of the fundamental is extremely lower than that of the injecting voltage and the switching harmonics component frequency is extremely higher than that of the injection. So it can be easily eliminated by an ordinary band pass filter (BPF). In addition, due to the positive sequence component rotates in the opposite direction against the negative sequence component, then synchronous frame filter can be designed. It can transform the positive sequence component into a DC component. Therefore, the positive sequence can be easily filtered off by a high pass filter (HPF). In the end, only the negative sequence component is left. Figure 2 shows the signal procession of the high frequency current.

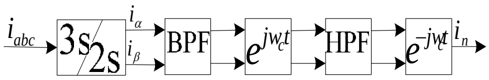

Fig. 2 Signal extraction procession of the negative sequence high frequency current

A PLL states observer extracts the rotor position from the negative part using the error ε obtained from the vector-product imaginary component. The PLL state observer is shown in Fig.3.

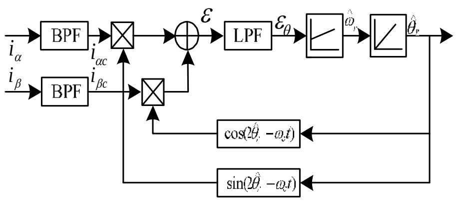

Fig.3 PLL state observer

$$\varepsilon = i_{\beta c}\cos(2\hat{\theta}_r - \omega_c t) - i_{\alpha c}\sin(2\hat{\theta}_r - \omega_c t)$$

$$= I_{c0}\sin[2(\omega_c t - \hat{\theta}_r)] + I_{c1}\sin[2(\theta_r - \hat{\theta}_r)] \quad (10)$$

Refer to (10), it is clear that the first part does not include the position information and can be removed by LPF. So the position information can be obtained from the second part.

$$\varepsilon_\theta = I_{c1}\sin[2(\theta_r - \hat{\theta}_r)] \quad (11)$$

Refer to (11), it is easily found that the estimated rotor position $\hat{\theta}_r$ is equal to actual rotor position θ_r when the error ε_θ is close to zero. Consequently, the rotor speed is equal to the time derivative of the rotor position $\hat{\theta}_r$.

C. Rotor Position Detection Scheme

The injected high frequency method using magnetic saliency still has one problem in the estimation of magnetic pole position. There are two stable points, north and south magnetic pole positions. Traditional high frequency injection method cannot distinguish the north magnetic pole position from the two magnetic pole position. If estimated angle is aligned at the south magnetic pole position, the sign of output torque will be changed and the system will be unstable. Hence, it is essential to distinguish the north magnetic pole position for PMSM sensorless control system.

High frequency current components, which produced by both of saliencies and the injected rotating carrier frequency voltage, are described as follows [11],

$$i_{\alpha\beta c} \approx i_{1p} e^{j(w_c - \pi/2)} + i_{1n} e^{j(-w_c t + 2\theta_r + \pi/2)} + i_{2p} e^{j(2w_c t - \theta_r + \varphi_{2p})} + i_{2n} e^{j(-2w_c t + 3\theta_r + \varphi_{2n})} \qquad (12)$$

Where $\varphi_{2p,2n} = \tan^{-1}\left(\dfrac{d(1/L_q)/d\lambda_q}{1/L_d - 3\lambda_f d(1/L_d)/d\lambda_d}\right)$

Only first and second order harmonic current components of high frequency, consisting of positive and negative sequence components, are considered in (12). The negative sequences and second harmonic of the positive sequence components have spatial rotor position information. Therefore, there are several method can be selected to extract rotor position information. Due to traditional high frequency injection method cannot distinguish the north magnetic pole position, so second order positive sequence component should be considered to extract rotor position polarity information. Refer to (12), it will be found that the second order positive sequence component contains rotor position information θ_r , while rotor position information 3 θ_r is contained in the second order negative sequence component. It is obvious that the former is better for the rotor position pole information extraction than the last. In order to get the second order positive component, other components must be removed. Signal procession is similar to traditional method (Fig.2).

The error signal with rotor position can be obtained after signal procession. It can be expressed as:

$$\xi = i_{2p} e^{i(\hat{\theta}_r - \theta_r + \varphi_{2p})} \qquad (13)$$

The real part is $\xi_r = \cos(\hat{\theta}_r - \theta_r + \varphi_{2p})$

If $-\frac{\pi}{2} < (\hat{\theta}_r - \theta + \varphi_{2p}) < \frac{\pi}{2}$ or ξ_r >0, then the stable point is the north magnetic pole position and rotor position do not need to be compensated. If $(\hat{\theta}_r - \theta + \varphi_{2p}) < -\frac{\pi}{2}$ or $(\hat{\theta}_r - \theta + \varphi_{2p}) > \frac{\pi}{2}$ or ξ_r <0, then the stable point is the south magnetic pole position and rotor position needs to be compensated.

III. EXPERIMENT RESULTS

The effectiveness of the proposed sensorless PMSM control system was tested experimentally. A dSPACE 1103 platform was used to carry out the proposed algorithm. The experimental device is show in Fig.4. The performance waveforms are illustrated by Fig 5/Fig.6/Fig.7 and Fig.8. The experimental device is fed by pulse width modulation (PWM) voltage-source inverter. The parameters of the motor are shown in table 1. Other parameters are signal injection voltage u_c = 20 V and angle speed ω_c = $1000 \times \pi$ rad/s, etc.

TABLE 1
IPMSM PARAMETERS

Quantities	Value	Unit
Rated power	1.5	KW
Rated speed	1500	RPM
Rated voltage	190	V
Rated torque	4.77	Nm
Rated current	6.1	A
Pole pairs	2	
Phase resistance	1.64	Ω
Ld	15.48	mH
Lq	25.8	mH
PM Flux linkage	0.42	Wb

KW = kilowatt, RPM = revolutions per minute, V = volt, Nm=Newton meter, A = ampere, Ω= ohm, mH=millihenry, Wb = Weber.

Fig. 4 Experiment setup

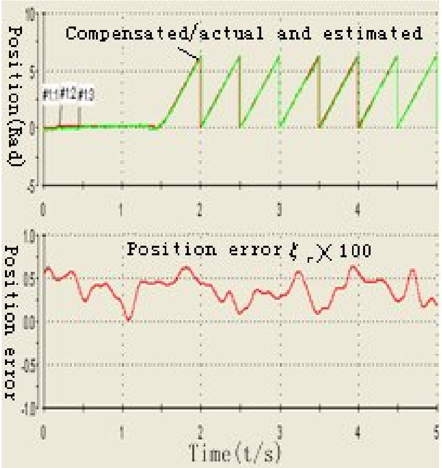

Fig. 5 Relation between the rotor position and position error signal

Fig.5 illustrates the relation between the rotor position and error signal ξ_j .The estimated rotor position, actual rotor position and compensated rotor position signals are shown in red, green and blue respectively. It is easily found that error signal ξ_j>0 when actual rotor position is aligned at the north magnetic pole position. Three curves are the same, so rotor positions do not need to be compensated.

When error signal ξ_j<0, actual rotor position is aligned at the south magnetic pole position. The green curve is different from another two curves in fig 6. The phase error is π between the green curve and other two curves. So the estimated rotor position needs to be compensated (Fig.6 the red curve).

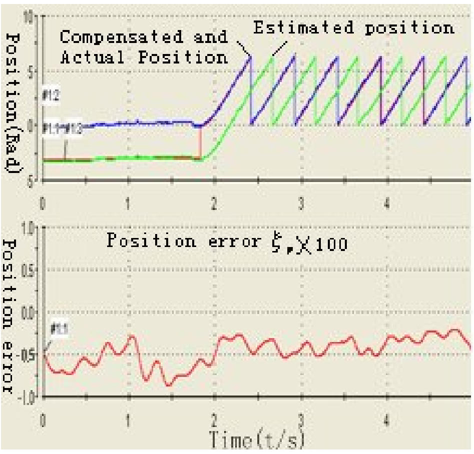

Fig. 6 Relation between the rotor position and position error signal

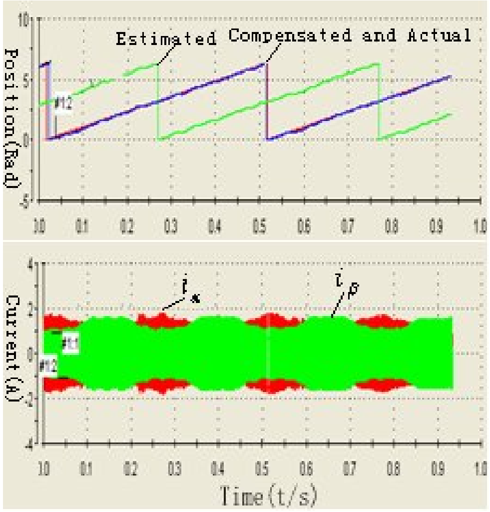

Fig. 7 Relation between the position and high frequency currents

Fig.7 demonstrates the relation between rotor position θ_r and high frequency current i_α, i_β. And the expanded chart division of current i_α, i_β are illustrated by Fig 8.

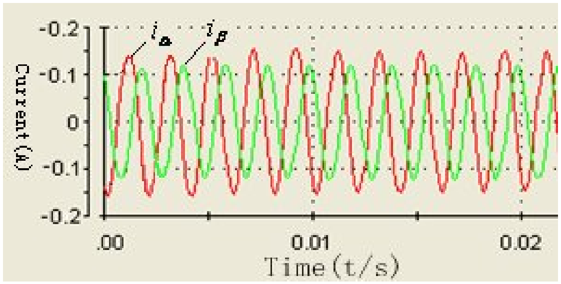

Fig. 8 high frequency currents

IV. Conclusion

This paper presents a novel method for compensating the rotor position based on high frequency injection. This method gets rotor position error information from second order positive sequence component and can distinguish the magnetic pole position. Therefore, this method combines with traditional high frequency injection to compensate the rotor position. Experimental results of the position estimation show good performance at low speed under any load condition.

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