

# A Simplified High Frequency Injection Method For PMSM Sensorless Control

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**Abstract:** This paper presents a simplified HF injection method for permanent magnet synchronous motor (PMSM) sensorless control. The discussed HF injection scheme utilizes motor magnetic saliency property which contains the information of the rotor position due to magnet saturation. A high frequency voltage signal is injected into the  $d$ -axis winding in order to detect the magnetic saliency and estimate the rotor position. Then filters are used to analyze motor  $d$ -axis current and to extract rotor position information. In the proposed method, a band pass filter used in signal processing loop is omitted in order to avoid its phase shift and magnitude decrease. Thus fewer filters are used than those conventional HF injection schemes. The simulation and experimental results are presented based on the analysis of the proposed control strategy.

**Index Terms:** high frequency signal injection, PMSM, sensorless control

## I. INTRODUCTION

Permanent magnet synchronous motors have found wide applications due to their high power density, high efficiency, easy of control, high torque-to-inertia ratio and high reliability. In the past decade, vector control of permanent magnet synchronous motor has emerged as a mature technology. A rotor shaft attached position sensor (resolvers, encoders or Hall Effect sensors) is needed in order to achieve precise rotor position control. Because of economical and reliability reasons, the elimination of the position sensors is of high interest. The advantages of sensorless control are reduced hardware complexity and lower cost, reduced size of the drives, elimination of the sensor cable, better noise immunity, increased reliability, and less maintenance requirements.

In the past different schemes have been proposed for PMSM sensorless control. Among them one group is methods based on motor fundamental equations. Rotor flux is considered as sinusoidal distributed, which neglects motor space harmonics and other secondary effects. Then motor back-EMF can be used to estimate rotor position from motor fundamental equations. These methods are either open loop structure (such as direct calculating, back-EMF integration, etc.) [1][2] or closed loop observers (MRAS, Extended Kalman Filter, Sliding Mode Observer, etc.)[3][4][5]. Open loop methods have a straightforward structure which is easy for calculating. But the estimation is greatly influenced by motor parameters variation

and current measurement noise. In order to increase the robustness and to improve the dynamics of the estimation, it is necessary to use the error signals between the measured and estimated quantities as a feedback, thus composing a closed loop observer.

When motor is at low speed, motor back-EMF is relatively small, and can not be used to precisely identify motor position information. This is the biggest problem for those methods based on motor fundamental model. Further researches have found that motor anisotropic properties provide additional information on the field angle or the position of the rotor. This inherent property makes it possible to use transient excitations by injected signals having other frequencies than the fundamental (HF injection)[6][7][8][9], or transients caused by inverter switching, to reliably identify and track rotor position even when the rotor is at standstill. Relative researches have been mentioned in many articles.

HF injection PMSM sensorless control shows good rotor position estimation result at low range. It is insensitive to parameter inaccuracy. Another advantage is that, for a PM motor whose saliency is not very prominent, flux saturation effect can be utilized by using  $d$ -axis signal injection like that does in [7]. Yet in this method many filters are used for signal processing, which will inevitably introduce phase delay and magnitude decrease. In this paper a simplified HF injection method is proposed aiming at reduce number filters that are used. Simulation and experimental results are given to verify the correctness of the proposed method.

## II. HIGH FREQUENCY INJECTION METHOD

HF injection PMSM sensorless control is based on motor magnetic saliency phenomenon. In this method a high frequency voltage or current vector signal is superimposed on motor fundamental excitation. The corresponding high frequency current (or voltage) signal contains rotor position information, and is analyzed to track spatial saliencies and to estimate the rotor or flux position.

Suppose that a high frequency signal is injected into the PM synchronous motor. When analyzing motor high frequency components based on its voltage equations, the back electromotive force (back EMF) voltage can be neglected because it does not have any high frequency component. Then the high frequency components of the voltage equations of a

PMSM contain only high frequency voltage, current and motor high frequency inductances which indicate rotor position variation. The motor voltage equations in the synchronous reference frame can be simplified into

$$\begin{cases} v_{dsh}^r = (r_{dh} + j\omega_h L_{dh}) i_{dsh}^r = z_{dsh}^r i_{dsh}^r \\ v_{qsh}^r = (r_{qh} + j\omega_h L_{qh}) i_{qsh}^r = z_{qsh}^r i_{qsh}^r \end{cases} \quad (1)$$

$$\tilde{\theta}_r = \theta_r - \hat{\theta}_r \quad (2)$$

where  $\hat{\theta}_r$  is the estimated rotor position.

In (1),  $v_{dsh}^r, v_{qsh}^r, i_{dsh}^r, i_{qsh}^r$  are  $d$ - and  $q$ -axes high frequency components in the actual synchronous reference frame, respectively. If the error between the real and estimated rotor position is defined as (2), then the relationship between the high frequency voltages and currents in the estimated synchronous reference frame can be expressed as

$$\begin{bmatrix} \hat{i}_{dsh}^r \\ \hat{i}_{qsh}^r \end{bmatrix} = \begin{bmatrix} \cos \tilde{\theta}_r & -\sin \tilde{\theta}_r \\ \sin \tilde{\theta}_r & \cos \tilde{\theta}_r \end{bmatrix} \begin{bmatrix} 1/z_{dsh}^r & 0 \\ 0 & 1/z_{qsh}^r \end{bmatrix} \cdot \begin{bmatrix} \cos \tilde{\theta}_r & \sin \tilde{\theta}_r \\ -\sin \tilde{\theta}_r & \cos \tilde{\theta}_r \end{bmatrix} \begin{bmatrix} \hat{v}_{dsh}^r \\ \hat{v}_{qsh}^r \end{bmatrix} \quad (3)$$

$$\begin{cases} \hat{v}_{dsh}^r = V_{inj} \sin \omega_h t \\ \hat{v}_{qsh}^r = 0 \end{cases} \quad (4)$$

If a high frequency AC voltage signal is injected only on the  $d$ -axis in the estimated synchronous reference frame (as is shown in (4)), the resultant high-frequency currents become

$$\begin{cases} \hat{i}_{dsh}^r = \frac{V_{inj} \sin \omega_h t}{z_{dsh}^r z_{qsh}^r} (z_{avg} - z_{diff} \cos 2\tilde{\theta}_r) \\ \hat{i}_{qsh}^r = \frac{V_{inj} \sin \omega_h t}{z_{dsh}^r z_{qsh}^r} (-z_{diff} \sin 2\tilde{\theta}_r) \end{cases} \quad (5)$$

where  $z_{avg} = \frac{z_{dh}^r + z_{qh}^r}{2}, z_{diff} = \frac{z_{dh}^r - z_{qh}^r}{2}$

In (5), the  $d$ - and  $q$ - axes high frequency current components in the estimated synchronous reference frame have rotor position information if the difference between the  $d$ - and  $q$ - axes high frequency impedances is not zero. The  $q$ -axis high frequency current is proportional to  $\sin 2\tilde{\theta}_r$ , and it becomes zero when the rotor position estimation error is zero. This component can be used for rotor position estimation. Using the  $q$ -axis current as an input, a rotor position estimator is constructed. Then the estimated rotor position is fed back for motor position control. Fig.1 shows the complete procedure of HF injection PMSM sensorless control scheme. In it two control loops, say speed loop and torque loop control motor  $d$ - and  $q$ - axis reference voltages respectively.

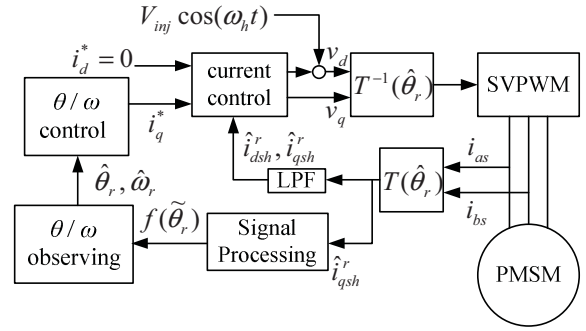


Fig.1 – Block diagram of HF injection PMSM sensorless control.

It can be seen that, due to the magnetic saliency property at high frequency, the injected  $d$ -axis high frequency voltage (Fig.1) will invoke high frequency current variation in the estimated  $q$ -axis if the estimated rotor position is not correct. This error signal is extracted using signal processing scheme, and its value is proportional to the error between the estimated and the real rotor position.

$$f(\tilde{\theta}_r) \approx \frac{V_{inj} L_{diff}}{\omega_h L_{dh}^r L_{qh}^r} \tilde{\theta}_r = K_{err} \tilde{\theta}_r \quad (6)$$

Forcing this error signal to zero by using a PI controller, motor exact position can be acquired. Fig.2 shows the block diagram of the whole signal processing procedure.

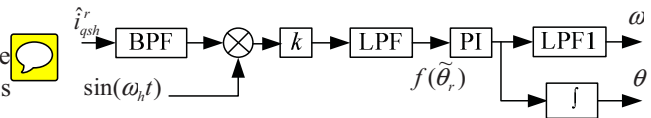


Fig.2 – Block diagram of signal processing procedure for rotor position estimation

### III. SIMPLIFIED HF INJECTION METHOD

In Fig.2, the specified current signal whose frequency is corresponding to that of the injected HF voltage will inevitably contain harmonics

$$\begin{aligned} \hat{i}_{qsh}^r &= I_{\omega_h} \sin(\omega_h + \varphi_{\omega_h}) + \sum I_n \sin(\omega_n + \varphi_n) \\ &= i_{\omega_h} + \sum i_n \\ \varphi_{\omega_h} &= 0 \text{ and } n = 0, 1, 2, \dots \infty \end{aligned} \quad (7)$$

Conventional HF injection scheme use a band pass filter (BPF) to extract the useful  $q$ -axis high frequency current  $i_{\omega_h}$ . Then it comes to

$$f(\tilde{\theta}_r) = LPF[k \cdot \sin(\omega_h t) \cdot i_{\omega_h}] \quad (8)$$

In order to filter out those useless signals as much as possible, it is preferred to design a band pass filter with a narrow passband. The usage of this band pass filter will introduce phase delay and magnitude decrease to  $i_{\omega_h}$ . This will increase the complexity of

calculation.

After this step, the signal is multiplied with  $\sin(\omega_h t)$ , and then a low pass filter is used to extract the useful signal proportional to  $\tilde{\theta}_r$ . If the band pass filter is taken away, and  $\hat{i}_{qsh}^r$  multiplies  $\sin(\omega_h t)$  directly, then the result becomes

$$\hat{i}_{qsh}^r \cdot \sin(\omega_h t) = i_{\omega_h} \cdot \sin(\omega_h t) + \sum i_n \cdot \sin(\omega_h t) \quad (9)$$

The latter part of equation (9) is a non-DC component. Choosing a properly designed low pass filter this part can be eliminated directly and the remaining signals becomes

$$\begin{aligned} f(\tilde{\theta}_r)' &= LPF[k \cdot \sin(\omega_h t) \cdot \hat{i}_{qsh}^r] \\ &= LPF[k \cdot \sin(\omega_h t) \cdot (i_{\omega_h} + \sum i_n)] \\ &= k / 2 \cdot I_{\omega_h}^2 \end{aligned} \quad (10)$$

Fig.3 shows the block diagram of the revised signal processing procedure of HF injection PMSM sensorless control scheme. In equation (10) the result is the same as that in (9), but fewer filters are needed, thus avoiding phase shift and magnitude decrease caused by the band pass filter.

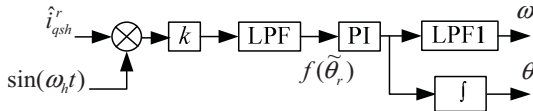


Fig.3 – Revised signal processing procedure diagram for rotor position estimation.

#### IV. SIMULAITON AND EXPERIMENTAL RESULT

In order to verify the proposed scheme, MATLAB Simulation model is built. First, motor position is observed using conventional HF injection method. A 500Hz AC voltage is injected in the  $d$ -axis of the estimated synchronous reference frame. Fig.4 shows the calculated error signal after a band pass filter and a low pass filter. Fig.5 show shows its FFT analysis result with a fundamental frequency of 50Hz. From Fig.6 it can be seen clearly that the DC component is quite small, then the PI controllers in Fig.2 should choose big proportional and integral constant values in order to achieve correct rotor position estimation result.

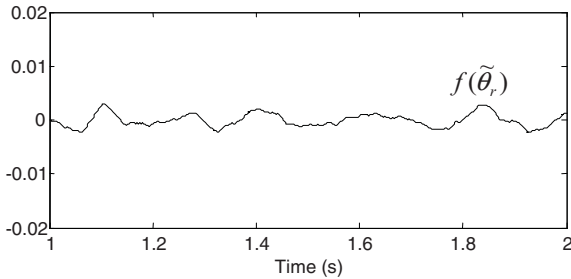


Fig.4 – Error signal extracted from LPF.

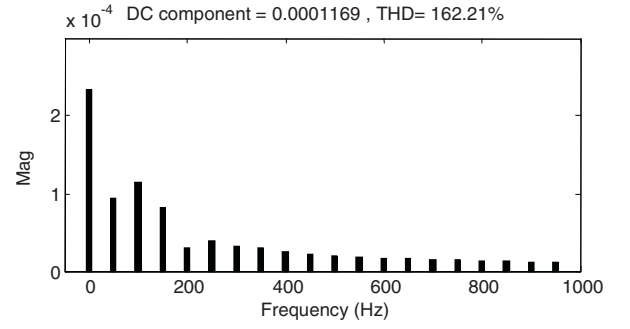


Fig.5 – FFT analysis of the signal in Fig.4.

Fig.6 shows the simulation results when the band pass filter is omitted. Compared to Fig.4, the value of the extracted error signal after the low pass filter (Fig.3) is much obvious than that when using the band pass filter(Fig.2). The DC component in Fig.7 is much higher than that in Fig.5, which means a more obvious angle error observation result. In experiment this is very important because if the measurement noise and calculation error is comparable to the value of the calculated error signal  $f(\tilde{\theta}_r)$ , motor rotor observation result will be greatly influenced. In the most serious condition the overserver may turn to wrong result.

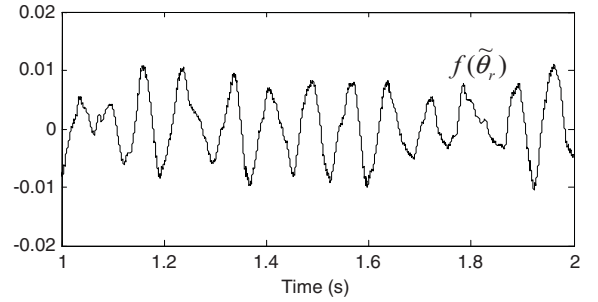


Fig.6 – Error signal extracted from LPF when BPF is omitted.

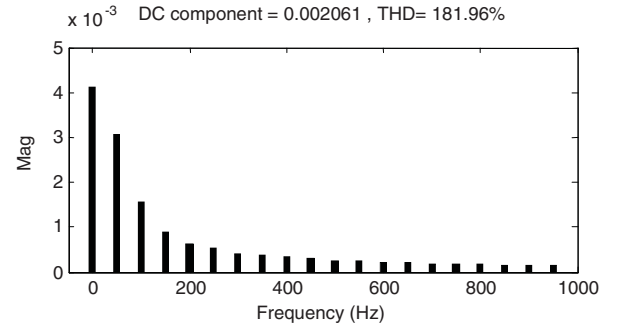


Fig.7 –FFT analysis of the signal in Fig.6

Fig.8 shows the simulation result of HF injection PMSM rotor position estimation. Motor reference speed is set as 1rad/s (electrical speed). When  $t = 0s$  motor starts. From the result it can be seen that the estimated rotor position catches the real position quickly. At steady state there is no angle deviation. The simulation result proves the correctness of the proposed method.

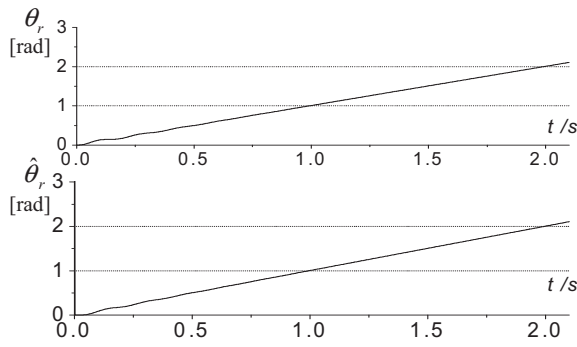


Fig.8 – Simulation of real and estimated rotor position.

In order to verify the proposed scheme in a real application environment, a prototype of 2kW PMSM control system is established using TMS320LF2812 DSP. A 400W permanent magnet synchronous motor is used (see detailed parameters in Table.1), together with a 2500 line rotor position encoder attached to motor shaft. The estimated result is compared to motor real position acquired from encoder pulse.

Parameter	Value
Rated speed $n_N$	3000 rpm
Rated torque $T_N$	1.3 Nm
Rated current $I_N$	2.497 A
Rated voltage $V_N$	114.7 V
Stator resistance $R_s$	6.06 $\Omega$
Stator inductance $L_d, L_q$	13.51 mH
Rotor inertia $J$	$0.261 \cdot 10^{-4}$ Kg $m^2$
back-EMF constant	0.411 Vs/rad
Number of pole pairs	4

In experiment, a 50V 500Hz AC voltage is injected into the estimated  $d$ -axis frame of PM motor. First, the high frequency voltage is injected at a know position referring to motor exact  $d$ -axis. Theoretically the result should remain constant, and is proportional to  $\sin(2\tilde{\theta}_r)$  (equation (5)). In the experiment, seven different voltage injection direction are chosen, each has a 45 degrees interval, differs from 0,  $\pm 22.5$ ,  $\pm 45$  and  $\pm 67.5$  electrical degrees. Fig.9 shows the experimental results. From the figure it can be seen that the results are sinusoidally distributed, which is in accordance to theoretically analysis. Then the resultant values are relatively prominent, suitable for rotor position estimation using HF injection scheme.

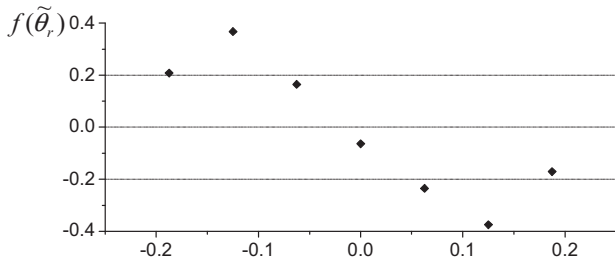


Fig.9 – Error signal from LPF when the band pass filter is omitted. At each test point the HF voltage is injected at fixed position interval equaling to 22.5 electrical degrees.

Fig.10 is the experimental result when the high frequency voltage is injected at the estimated  $d$ -axis position  $\hat{\theta}_r$ , whose value changes instantaneous according to the calculation result. Motor is controlled based on position information from encoder, and the reference electrical speed is set to 1.5 rounds per second.

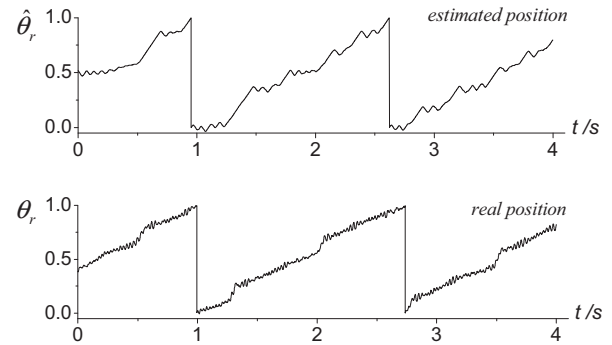


Fig.10 – Estimated and real rotor position(1/2πrad).

In the experiment the band pass filter is taken away as is mentioned in section III (Fig.3). The vertical-axis in Fig10 is nominal position angle, with a value of 1.0 refer to  $2\pi$  rad electrical angle. From the result we can see that the estimated rotor position is correct comparing to real value, and the estimated result remain stable. This proves the effectiveness of the sensorless scheme where no band pass filter is used.

## V. CONCLUSION

In this paper, high frequency signal injection PMSM sensorless control is researched. A high frequency voltage is injected into motor, and the corresponding high frequency current which contains rotor position information is analyzed. In order to reduce the influence that comes from signal processing filters, which are used to extract the error signal between the estimated and real rotor position, the band pass filter in the signal processing procedure is taken away. Thus eliminated phase delay and magnitude decrease which is introduced by this band pass filter, and the signal processing calculation is easier compared to conventional HF injection sensorless schemes. In order to verify the proposed control scheme, simulation and experiment are carried out. And the results show that use the proposed sensorless control algorithm based on motor magnetic saliency, motor position is properly estimated in the low speed region without any speed or position sensor.

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