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# Mechanical Sensorless Control of SPMSM Based on HF Signal Injection and Kalman Filter

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**Abstract-** To reduce control system's cost and complexity of permanent magnet synchronous motors (PMSM), mechanical sensorless control is becoming a research focus. This paper presents a novel high frequency (HF) signal injection method for the mechanical sensorless control of surface mounted permanent magnet synchronous motors (SPMSM) in low speed and even zero speed regions based on the little saturation effects of stator circuit. Adaptive Kalman filter is used to deal with the signal processing instead of traditional filters to simplify the control system and improve performance. Simulation and experimental results have shown the performance of the proposed method.

**Keywords:** high frequency signal injection, PMSM, Kalman filter, mechanical sensorless control, low speed

## I. INTRODUCTION

Permanent magnet synchronous motors (PMSM) are more and more used because of their high performance, such as high efficiency, high power density, high torque to inertia ratio. In high performance closed-loop control system of PMSM, the rotor position and speed information are needed and normally measured by mechanical sensor. The mechanical sensors increase the system cost, motor volume and the complexity. In fact, the rotor position and speed can be estimated by the measured voltages and currents of the electrical motor. So the mechanical sensorless control is becoming a research focus now.

The rotor position and speed estimation methods can be classified as two kinds. The first one is the methods based on back electrical motive force (EMF), such as EMF calculation method, model reference adaptive system (MRAS), state observer and extended Kalman filter. Because the back EMF is very small in low speed region, so these methods cannot obtain satisfying performance in low speed and zero speed region. The second kinds are the methods based on salient or saturation characteristics of the motor, such as high frequency (HF) signal injection method. The HF injection method has very good performance in low speed even zero speed regions where the motor's parameters aren't needed<sup>[1-3]</sup>.

For high frequency signal injection method, the motor should have salient or saturation characters to produce the difference of the stator inductance at different rotor position. The surface mounted permanent synchronous motors (SPMSM) are

non-salient, but exists saturation effects made by rotor flux passing stator circuit, so the stator inductances are different with different rotor position. Then the high frequency signal injection method can also be applied on SPMSM. In the high frequency signal injection method, the most difficult point is how to obtain the HF components from the measured currents. Normally a band-pass filter is firstly used to pick up the HF frequency signal from the measured currents. Then a low pass filter is added to obtain the amplitude of the HF signals which is needed for the speed and position estimation. Because the measured currents contain HF components, fundamental frequency component, disturbance and noises, these filters should be carefully designed to get satisfying amplitude frequency response. Otherwise, the disturbances, noises, amplitude and phase error made by the filters will affect performance of the system<sup>[3-4]</sup>.

In this paper, a novel signal processing method is proposed and a Kalman filter is used to replace the traditional filters in the HF signal injection method. Kalman filter is an adaptive filter and considers the effects of the noise and parameter errors. So it is possible to identify the desired signal with known frequency from measured currents, and can remove the effects of noises and disturbance by this method. Also the desired signals can be separated from other ones with close frequency and the amplitude and phase of the HF signals can be obtained. With the information obtained by Kalman filter, the rotor position and speed can be estimated to realize a mechanical sensorless control system, especially at low speed and zero speed. Simulation and experimental results have been done to verify the performance of this method.

## II. HF INJECTION METHOD

First of all, the rotating coordinates oriented by actual rotor flux position and oriented by estimated rotor flux position are defined as shown in Fig. 1.

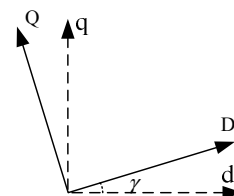


Fig. 1 Coordinates oriented by actual and estimated position

Then define the position estimation error:

$$\gamma \equiv \theta - \hat{\theta} \quad (1)$$

Where  $\theta$  is the actual rotor flux position and  $\hat{\theta}$  is the estimated position.

In the synchronous rotating coordinate oriented by actual rotor flux (DQ axes), the mathematical model of the PMSM is as follows:

$$\begin{bmatrix} u_D \\ u_Q \end{bmatrix} = \begin{bmatrix} R + L_D s & -\omega L_Q \\ \omega L_D & R + L_Q s \end{bmatrix} \cdot \begin{bmatrix} i_D \\ i_Q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega \psi_D \end{bmatrix} \quad (2)$$

Here  $u_D$ ,  $u_Q$  are stator voltages.  $i_D$  and  $i_Q$  are stator currents.  $R$  is stator resistance.  $L_D$  and  $L_Q$  are stator inductances on D and Q axes.  $\omega$  is electrical rotor angle speed.  $s$  is the calculation of differential.

For the salient PMSM, normally  $L_D < L_Q$ . For the SPMSM are non-salient, the flux passing the stator windings is different when the rotor position is different, so the saturation of the stator is different. This will make some difference between the inductance of  $L_D$  and  $L_Q$ . Based on this point, the HF injection method can also be applied to SPMSM.

In (2), the crossing-coupling between two equations are produced by rotor speed. Suppose that the frequency of injected signal is much larger than the rotor speed, then the crossing-coupling in HF circuits can be ignored<sup>[3]</sup>.

$$\begin{bmatrix} u_{Dh} \\ u_{Qh} \end{bmatrix} = \begin{bmatrix} R_{Dh} + L_{Dh} s & 0 \\ 0 & R_{Qh} + L_{Qh} s \end{bmatrix} \cdot \begin{bmatrix} i_{Dh} \\ i_{Qh} \end{bmatrix} \quad (3)$$

Here the footnote h is used to mark the HF values. If only the static state is considered, (3) can be simplified as follows:

$$\begin{bmatrix} u_{Dh} \\ u_{Qh} \end{bmatrix} = \begin{bmatrix} R_{Dh} + j\omega_h L_{Dh} & 0 \\ 0 & R_{Qh} + j\omega_h L_{Qh} \end{bmatrix} \cdot \begin{bmatrix} i_{Dh} \\ i_{Qh} \end{bmatrix} \quad (4)$$

$$= \begin{bmatrix} Z_{Dh} & 0 \\ 0 & Z_{Qh} \end{bmatrix} \cdot \begin{bmatrix} i_{Dh} \\ i_{Qh} \end{bmatrix}$$

And we can also define:

$$\begin{aligned} Z_{Dh} &= R_{Dh} + j\omega_h L_{Dh} \\ Z_{Qh} &= R_{Qh} + j\omega_h L_{Qh} \end{aligned} \quad (5)$$

Since the actual rotor flux position cannot be known, only the equations in the coordinate oriented by estimated position can be used. Taking voltage as example, the state variables transformation between these two coordinates is as follows:

$$\begin{bmatrix} u_D \\ u_Q \end{bmatrix} = \begin{bmatrix} \cos \gamma & \sin \gamma \\ -\sin \gamma & \cos \gamma \end{bmatrix} \cdot \begin{bmatrix} u_d \\ u_q \end{bmatrix} = R(\gamma) \cdot \begin{bmatrix} u_d \\ u_q \end{bmatrix} \quad (6)$$

Where

$$R(\gamma) = \begin{bmatrix} \cos \gamma & \sin \gamma \\ -\sin \gamma & \cos \gamma \end{bmatrix}. \quad (7)$$

In the coordinate oriented by estimated rotor flux position:

$$\begin{bmatrix} u_{dh} \\ u_{qh} \end{bmatrix} = R(\gamma)^{-1} \begin{bmatrix} z_{Dh} & 0 \\ 0 & z_{Qh} \end{bmatrix} R(\gamma) \cdot \begin{bmatrix} i_{dh} \\ i_{qh} \end{bmatrix}$$

$$= \begin{bmatrix} z_{avg} + \frac{z_{diff}}{2} \cos 2\gamma & \frac{z_{diff}}{2} \sin 2\gamma \\ \frac{z_{diff}}{2} \sin 2\gamma & z_{avg} - \frac{z_{diff}}{2} \cos 2\gamma \end{bmatrix} \begin{bmatrix} i_{dh} \\ i_{qh} \end{bmatrix} \quad (8)$$

$$= \begin{bmatrix} z_{dh} & z_{ch} \\ z_{ch} & z_{qh} \end{bmatrix} \cdot \begin{bmatrix} i_{dh} \\ i_{qh} \end{bmatrix}$$

Where

$$z_{avg} \equiv \frac{z_{Dh} + z_{Qh}}{2} = \frac{R_{Dh} + R_{Qh}}{2} + j\omega_h \frac{L_{Dh} + L_{Qh}}{2} \quad (9a)$$

$$z_{diff} \equiv z_{Dh} - z_{Qh} = (R_{Dh} - R_{Qh}) + j\omega_h (L_{Dh} - L_{Qh}) \quad (9b)$$

$$z_{dh} \equiv z_{avg} + \frac{z_{diff}}{2} \cos 2\gamma \quad (9d)$$

$$z_{qh} \equiv z_{avg} - \frac{z_{diff}}{2} \cos 2\gamma \quad (9d)$$

$$z_{ch} \equiv \frac{z_{diff}}{2} \sin 2\gamma \quad (9e)$$

$$R_{diff} \equiv R_{Dh} - R_{Qh} \quad (9f)$$

$$L_{diff} \equiv L_{Dh} - L_{Qh} \quad (9g)$$

So the equations of HF currents become:

$$\begin{bmatrix} i_{dh} \\ i_{qh} \end{bmatrix} = \frac{1}{z_{dh} z_{qh} - z_{ch}^2} \begin{bmatrix} z_{qh} & -z_{ch} \\ -z_{ch} & z_{dh} \end{bmatrix} \cdot \begin{bmatrix} u_{dh} \\ u_{qh} \end{bmatrix} \quad (10)$$

$$= \frac{1}{z_{Dh} z_{Qh}} \begin{bmatrix} z_{qh} & -z_{ch} \\ -z_{ch} & z_{dh} \end{bmatrix} \cdot \begin{bmatrix} u_{dh} \\ u_{qh} \end{bmatrix}$$

In order to decrease the ripples of torque, the HF signal is injected only on d-axis:

$$\begin{bmatrix} u_{dh} \\ u_{qh} \end{bmatrix} = \begin{bmatrix} u_{inj} \cos \omega_h t \\ 0 \end{bmatrix} \quad (11)$$

$\omega_h$  is the angle frequency of the injected signal.

The produced HF currents can be obtained by:

$$\begin{bmatrix} i_{dh} \\ i_{qh} \end{bmatrix} = \frac{1}{z_{Dh} z_{Qh}} \begin{bmatrix} z_{qh} & -z_{ch} \\ -z_{ch} & z_{dh} \end{bmatrix} \cdot \begin{bmatrix} u_{inj} \cos \omega_h t \\ 0 \end{bmatrix} \quad (12)$$

And the q-axis HF current is:

$$\begin{aligned} i_{qh} &= \frac{-z_{ch}}{z_{Dh} z_{Qh}} u_{inj} \cos \omega_h t \\ &= -\frac{1}{2} \frac{(R_{diff} + j\omega_h L_{diff}) u_{inj} \sin 2\gamma}{(R_{Dh} + j\omega_h L_{Dh})(R_{Qh} + j\omega_h L_{Qh})} \cos \omega_h t \end{aligned} \quad (13)$$

Considering that in HF circuit, there is  $\omega_h L \gg R_h$ , then we can get:

$$\begin{aligned} i_{qh} &\approx \frac{u_{inj}}{2} \left[ \frac{R_{diff} \cos \omega_h t}{\omega_h^2 L_{Dh} L_{Qh}} - \frac{\omega_h L_{diff} \sin \omega_h t}{\omega_h^2 L_{Dh} L_{Qh}} \right] \sin 2\gamma \\ &= \frac{u_{inj} \sin 2\gamma}{2\omega_h^2 L_{Dh} L_{Qh}} (R_{diff} \cos \omega_h t - \omega_h L_{diff} \sin \omega_h t) \end{aligned} \quad (14)$$

By (14), we can see that when the position estimation error is not zero, some crossing-coupling will appear between the d and q axis equations, and the injected HF voltage on d axis will

produce some HF currents on q-axis. When  $\gamma$  is near zero, the amplitude of the q-axis HF component is proportional to the position estimation error.

So the HF currents in the measured q-axis currents can be used as a correction of the rotor position estimation. Because  $R_{\text{diff}}$  is very small, so the sine component is selected.

Firstly a band-pass filter is adopted to pick up the HF component from the measured current. Then the HF signal is treated as follows to get the amplitude:

$$-i_{\text{qh}} \sin \omega_h t = \frac{u_{\text{inj}} \sin 2\gamma}{2\omega_h^2 L_{\text{Dh}} L_{\text{Qh}}} \left[ \frac{\omega_h L_{\text{diff}}}{2} - |z_{\text{diff}}| \sin(2\omega_h t - \phi) \right] \quad (15)$$

Here:

$$|z_{\text{diff}}| = \sqrt{R_{\text{diff}}^2 + (\omega_h L_{\text{diff}})^2} \quad (16a)$$

$$\tan \phi = \frac{\omega_h L_{\text{diff}}}{R_{\text{diff}}} \quad (16b)$$

And then a low-pass filter (LPF) is used to get the amplitude of the sine-component:

$$f(\gamma) \equiv \text{LPF}[-i_{\text{qh}} \sin \omega_h t] = \frac{u_{\text{inj}} L_{\text{diff}}}{4\omega_h L_{\text{Dh}} L_{\text{Qh}}} \sin 2\gamma \quad (17)$$

The signal processing method is shown in Fig.2.

Because the high frequency resistance cannot be known exactly, an adaptive operation like PI regulator or a band-band controller will be adopted to estimate the rotor speed and position according to the obtained amplitude in (17). In [5], a Kalman filter is also adopted to observe the rotor speed and position based on the values obtained in (17).

Because the HF components are only used for the estimation of rotor position, they are not necessary for the torque control. So the HF components should be removed before the current feedback. Two low-pass filters are adopted to remove off the HF currents whose phase lag will affect the control performance of currents. The system scheme is shown in Fig. 3.

In the traditional signal treatment method, about five filters are used and should be carefully designed. Otherwise, the disturbance, noises and other signals with similar frequency will affect the precision of control.

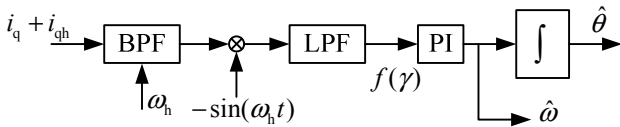


Fig.2 Signal treatment method

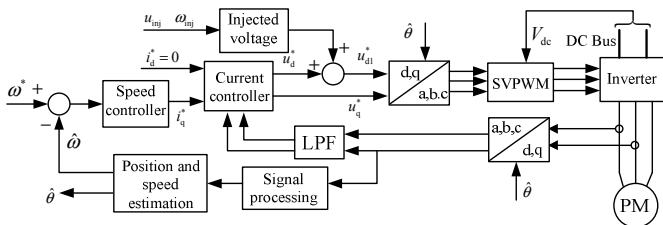


Fig.3 System scheme of traditional HF injection method

### III. SIGNAL PROCESSING BASED ON KALMAN FILTER

Kalman filter is an adaptive filter and is widely used in signal processing fields, such as communication, GPS navigation and other systems. Suppose that there is no disturbance or noises, the measured stator currents of the SPMSM are:

$$I_d = i_d + i_{\text{dh}} = i_d + a \cos \omega_h t + b \sin \omega_h t \quad (18)$$

$$I_q = i_q + i_{\text{qh}} = i_q + c \cos \omega_h t + d \sin \omega_h t$$

Here  $i_d$  and  $i_q$  are the d-q components of fundamental frequency currents (DC components) which are needed for the torque control.

In order to improve the identification precision of the Kalman filter, we try to remove the d-q DC components from the measured currents before the input of the Kalman filter. To be simple, the reference values are used instead of the actual DC d-q values and the errors can be compensated by the adaptive Kalman filter.

$$I'_d = i_d + i_{\text{dh}} - i_d^* \quad (19a)$$

$$I'_q = i_q + i_{\text{qh}} - i_q^* \quad (19b)$$

The d and q axes currents can be written as follows:

$$y = A \cos \omega_h t + B \sin \omega_h t + D \quad (20)$$

$D$  is the d-q fundamental components of currents.

Take the amplitudes of sine and cosine components, and the d-q DC components as state variables:

$$\mathbf{x} = [A \ B \ D]^T \quad (21)$$

Suppose that the amplitudes of the high frequency AC components and the DC components change very slowly, and consider the effects of noise and disturbance:

$$\mathbf{x}_{k+1} = \mathbf{x}_k + \mathbf{w}_k = \mathbf{F} \cdot \mathbf{x}_k + \mathbf{w}_k \quad (22a)$$

$$\mathbf{y}_k = \mathbf{C} \cdot \mathbf{x}_k + \mathbf{v}_k = [\cos \omega_h t \ \sin \omega_h t \ 1] \cdot \mathbf{x}_k + \mathbf{v}_k \quad (22b)$$

Here  $\mathbf{F}$  is unity matrix.  $\mathbf{w}$  and  $\mathbf{v}$  are random disturbances. In fact  $\mathbf{w}$  is the process noise which stands for the errors of the parameters;  $\mathbf{v}$  is the measurement noise which stands for the errors in the measurement and sampling.

The noise covariance matrices are defined as follows:

$$\mathbf{Q} = \text{cov}(\mathbf{w}) = E\{\mathbf{w}\mathbf{w}^T\} \quad (23a)$$

$$\mathbf{R} = \text{cov}(\mathbf{v}) = E\{\mathbf{v}\mathbf{v}^T\} \quad (23b)$$

Define matrix  $\mathbf{P}$  as the error covariance of state estimation.

$$\mathbf{P}_k = E\{\mathbf{e}_k \cdot \mathbf{e}_k^T\} = \sum_{i=1}^n E\{[\mathbf{x}_i - \hat{\mathbf{x}}_i][\mathbf{x}_i - \hat{\mathbf{x}}_i]^T\} \quad (24)$$

$E\{\cdot\}$  is the computation of expectation value.

Kalman filter can be realized by iteration as follows:

1. Compute the state 'a priori' and the error covariance 'a priori'.

$$\hat{\mathbf{x}}_{k|k-1} = \hat{\mathbf{x}}_{k-1|k-1} + \dot{\mathbf{x}} \cdot T_s \quad (25a)$$

$$\mathbf{P}_{k|k-1} = \mathbf{F}_{k-1} \mathbf{P}_{k-1|k-1} \mathbf{F}_{k-1}^T + \mathbf{Q}_{k-1} \quad (25b)$$

2. Compute the Kalman gain.

$$\mathbf{K}_k = \mathbf{P}_{k|k-1} \cdot \mathbf{C}^T \cdot (\mathbf{C} \cdot \mathbf{P}_{k|k-1} \cdot \mathbf{C}^T + \mathbf{R}_{k-1})^{-1} \quad (25c)$$

3. Update estimation with measurement.

$$\hat{\mathbf{x}}_{k|k} = \hat{\mathbf{x}}_{k|k-1} + \mathbf{K}_k (\mathbf{y}_k - \mathbf{C} \cdot \hat{\mathbf{x}}_{k|k-1}) \quad (25d)$$

4. Update the error covariance matrix.

$$\mathbf{P}_{k|k} = [\mathbf{I} - \mathbf{K}_k \cdot \mathbf{C}] \cdot \mathbf{P}_{k|k-1} \quad (25e)$$

Here  $T_s$  is the sampling time.

By the definition, matrix  $\mathbf{Q}$  and  $\mathbf{R}$  should be diagonal, matrix  $\mathbf{P}$  will be symmetric, and these characters will make some calculation repeated in the iteration of Kalman filter. So the calculation will be simplified.

The outputs of the both Kalman filters for the d and q axis currents are as follows:

$$\hat{\mathbf{x}}_d = [\hat{A}_d \quad \hat{B}_d \quad \hat{D}_d]^T \quad (26a)$$

$$\hat{\mathbf{x}}_q = [\hat{A}_q \quad \hat{B}_q \quad \hat{D}_q]^T \quad (26b)$$

And the subtracted reference values are added to get the full values of the d-q DC components of currents which will be used as the feedback of the current regulator.

$$\hat{i}_d = \hat{D}_d + i_d^* \quad (27a)$$

$$\hat{i}_q = \hat{D}_q + i_q^* \quad (27b)$$

Based on the identified HF components, the rotor speed and position can be estimated as follows:

$$\hat{\omega} = \left( K_p + \frac{K_i}{s} \right) \cdot \hat{B}_q \quad (28a)$$

$$\hat{\theta} = \int \hat{\omega} dt + \hat{\theta}_0 \quad (28b)$$

Here  $\hat{\theta}_0$  is the initial position of the rotor. System scheme is shown in Fig. 4.

Two Kalman filters are used to replace the five filters in the traditional method, because the Kalman filter is an adaptive filter and can be easily designed, only the frequency of the HF signal is needed, the system can be simplified. As the noise, disturbance and parameter errors cannot be known exactly, the  $\mathbf{Q}$  and  $\mathbf{R}$  matrix can only be obtained by practical adjustment.

In the proposed system, the rotor speed is a mechanical variable and cannot change very quickly, so another low pass filter is usually added in the speed feedback route.

The injected high frequency voltage is added in the voltage reference. The SVPWM module and the inverter will produce the desired high frequency voltage according the combined voltage reference and the additional high frequency voltage source is not necessary.

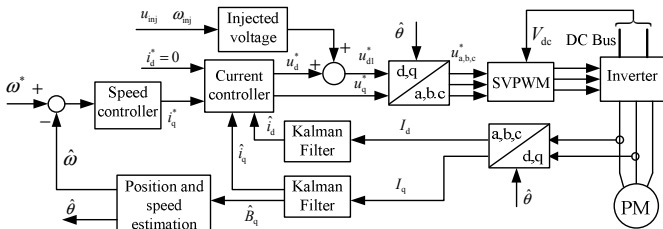


Fig.4 System scheme of the HF injection method based on Kalman filter

#### IV. SIMULATION RESULTS

In order to verify the theoretical analysis and the performance of the proposed system, some simulations have been carried out on a MATLAB platform. In the simulation, the parameters of the motor are as follows:

$L_D=1.0\text{mH}$ ,  $L_Q=1.5\text{mH}$ ,  $R=0.1555 \Omega$ , the amplitude of the injected voltage is 20V and its frequency is 500Hz. The switching frequency of the inverter is 10K Hz.

The covariance matrixes of the noises and state estimation errors are selected as follows:

$$\mathbf{P}_0 = \begin{bmatrix} 1.0 & & \\ & 1.0 & \\ & & 1.0 \end{bmatrix} \quad \mathbf{Q}_0 = \begin{bmatrix} 10 & & \\ & 10 & \\ & & 10 \end{bmatrix} \quad \mathbf{R}_0 = [1.0]$$

Both Kalman filters have the same parameters.

The simulation results of the signal treatment by Kalman filter during start-up are shown in Fig. 5 and Fig. 6.

When the load torque is changed from zero to 5Nm, the signal treatments during load torque impact are shown in Fig. 7 and Fig. 8.

From the simulation results, it is shown that Kalman filter can pick up the desired high frequency currents from measured currents in both static and dynamic states with very good precision. During the startup, a short time is needed for the convergence of the Kalman filter.

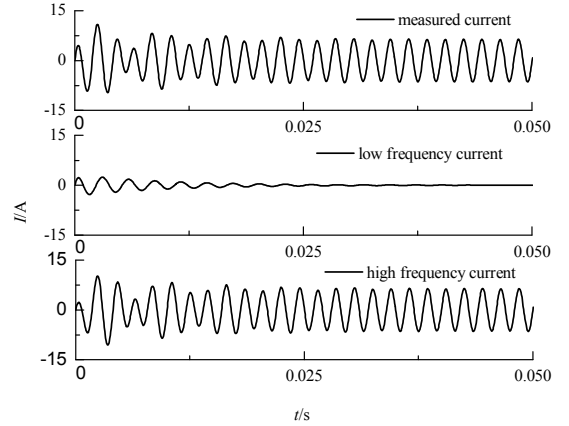


Fig. 5 d-axis currents during startup

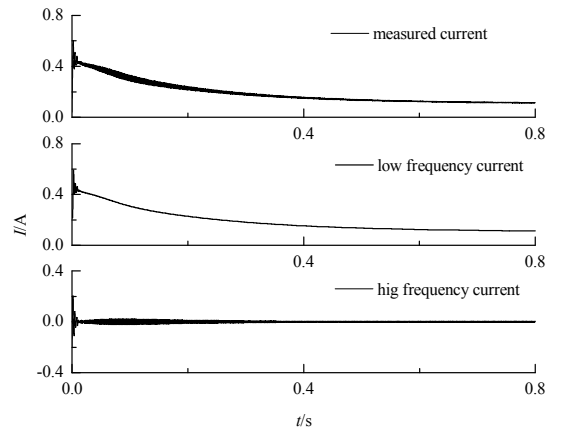


Fig.6 q-axis currents during startup

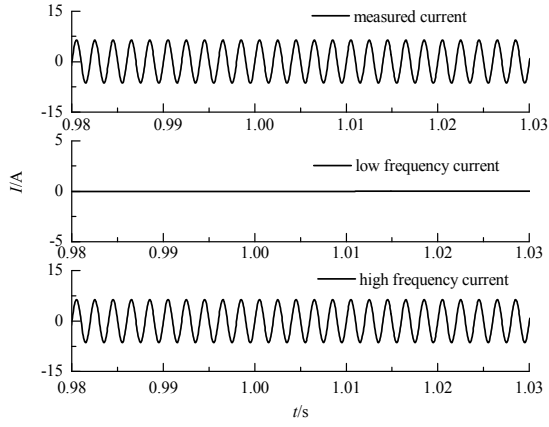


Fig. 7 d-axis currents during load torque impact

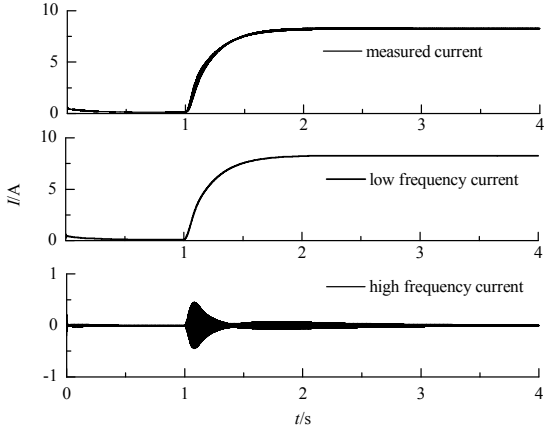


Fig. 8 q-axis currents during load torque impact

## V. EXPERIMENTAL RESULTS

Some experiments have been carried out on a motor control system. A surface mounted permanent magnet synchronous motor is used with the parameters as follows:

Stator inductance  $L=1.25\text{mH}$ , stator resistance  $R=0.1555\ \Omega$ , the amplitude of the injected voltage is  $30\text{V}$  with the frequency of  $500\text{Hz}$ . The DSP TMS320C6711 is used as the core controller. Another FPGA Altera EP1K100 is used to produce PWM and to control the AD circuit. The initial values of the covariance matrixes are as follows:

$$\mathbf{P}_0 = \begin{bmatrix} 1.0 & & & \\ & 1.0 & & \\ & & 1.0 & \\ & & & 1.0 \end{bmatrix} \quad \mathbf{Q}_0 = \begin{bmatrix} 10 & & & \\ & 10 & & \\ & & 10 & \\ & & & 10 \end{bmatrix} \quad \mathbf{R}_0 = [10.0]$$

During startup, the d and q-axes currents are shown in Fig. 9 and Fig. 10. It can be seen that the Kalman filter can get the exactly high frequency currents from the measured currents, and can converge at a very short time.

After startup, when a load torque is added and removed, the measured and estimated speeds are shown in Fig. 11, where the estimated speed is almost the same with the measured one during dynamic course.

During acceleration and deceleration, the speed estimation results and the position estimation error is shown in Fig. 12 and Fig.13.

If the speed reference is zero, and some load torque is added,

the speed estimation result is shown in Fig. 14. It can be seen that the motor has a very good low speed even zero speed control performance. The q-axis current response is shown in Fig. 15.

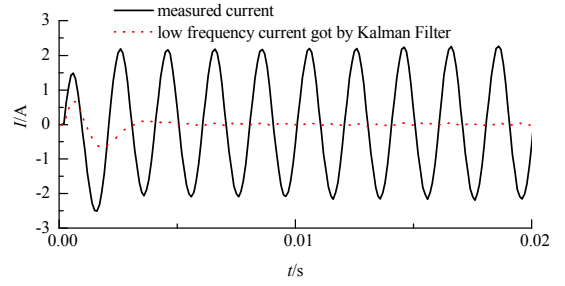


Fig. 9 d-axis currents during startup

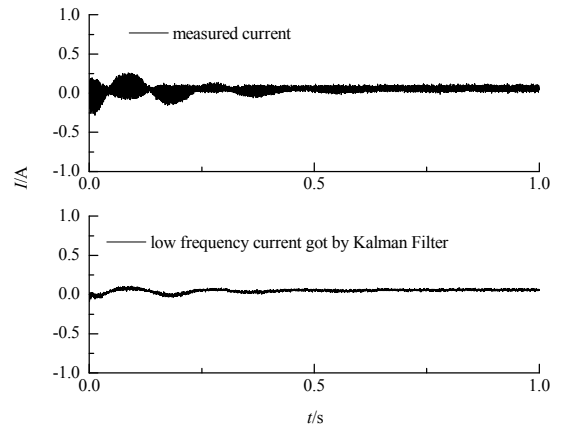


Fig.10 q-axis currents during startup

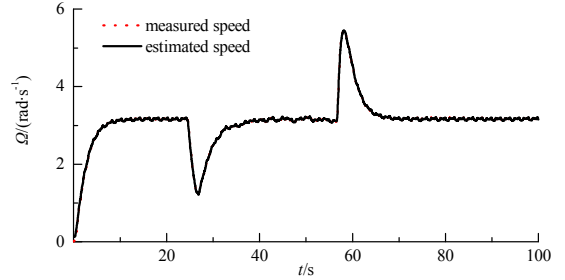


Fig. 11 Measured and estimated speed during startup and load changes.

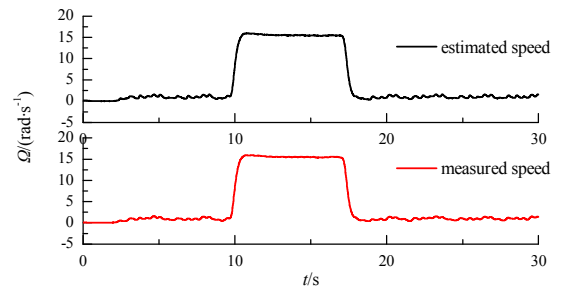


Fig.12 measured and estimated speed during acceleration and deceleration

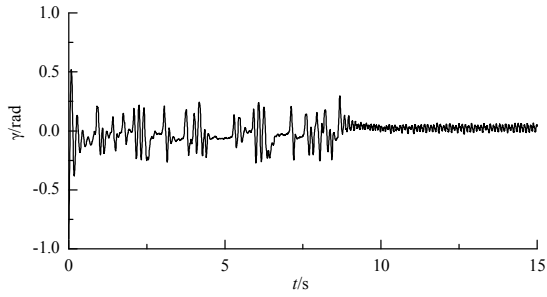


Fig. 13 Position estimation error during acceleration

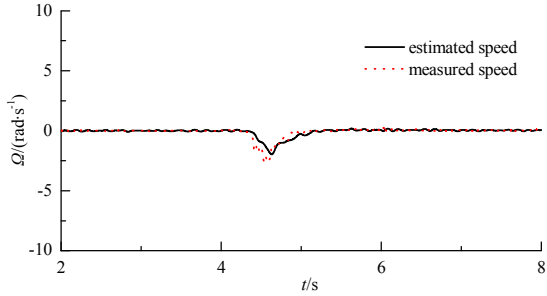


Fig. 14 Estimated and measured speed near zero speed with load torque impact

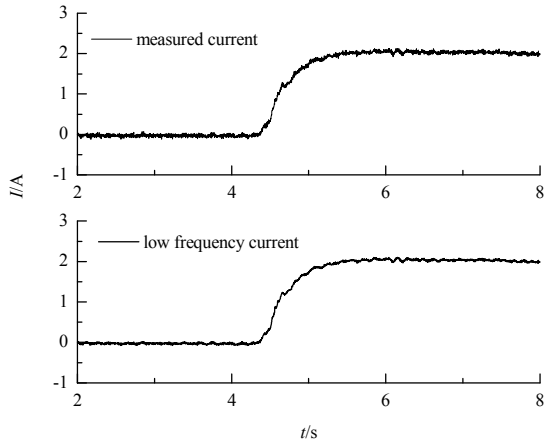


Fig. 15 q-axis currents at zero speed with load torque impact

## VI. CONCLUSION

The Kalman filter is a very good signal processing method for the HF signal injection method in mechanical sensorless control of PMSM. It can obtain the required high frequency signals from measured currents with noises and disturbance. All the filters used in the traditional HF signal processing method can be replaced by the proposed Kalman filters and the system will be simplified. Using the flux saturation of SPMSM, this method can also be applied on surface mounted motors. Simulation and experimental results show that the proposed HF signal injection method with Kalman filter is robust and the mechanical sensorless control of PMSM can be realized with good low speed and even zero speed control performance.

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## REFERENCES

- [1] M. Cuius, V. Bostan, S. Ambrosii, et al, "Luenberger, Kalman and neural network observers for sensorless induction motor control," *IPEMC 2000*, vol. 3, pp. 1256-1261, Aug. 2000.
- [2] S. Bolognani, R. Oboe, M. Zigliotto, "DSP-based extended Kalman filter estimation of speed and rotor position of a PM synchronous motor," *IECON 1994*, vol. 3, pp. 2097-2102, Sep. 1994.
- [3] J.-H. Jang, J.-I. Ha, M. Ohto, et al, "Analysis of permanent-magnet machine for sensorless control based on high-frequency signal injection," *IEEE Transactions on Industry Applications*, vol. 40, pp. 1595-1604, 2000.
- [4] M. J. Corley, R. D. Lorenz, "Rotor position and velocity estimation for a permanent magnet synchronous machine at standstill and high speeds," *IAS '96*, vol. 1, pp. 36-41, Oct. 1996.
- [5] F. Parasiliti, R. Petrella, and M. Tursini, "Sensorless speed control of salient rotor PM synchronous motor based on high frequency signal injection and Kalman filter," *ISIE 2002*, vol. 2, pp. 623-628, Dec. 2002.
- [6] D. Mingli, Z. Qingdong, and W. Qi, "The application of self-adaptive Kalman filter in NGIMU/GPS integrated navigation system," *Sixth International Conference on Intelligent Systems Design and Applications*, vol. 2, pp. 61-65, Oct. 2006.