A New Model for IPMSM with Rotating High Frequency Voltage Injection

S. Damkhi[1], MS. Nait Said[2],and N.Nait Said[3]

[1]Department of Electrical Engineering, Batna University,Algeria
sihemd@ymail.com,n_naitsaid@yahoo.com
[2]Department of Electrical Engineering, Batna University,Algeria
medsnaitsaid@yahoo.fr

Abstract

Controlled synchronous machine drives without mechanical speed sensors at the motor shaft have the attractions of low cost and high reliability. The eliminating of the speed sensors requires the estimation of speed from the machine itself. At standstill and low speed only the high frequency signal injection methods (HFSIM's) able to give accurate position estimation. The HFSIM's exploit the machine saliency property which contains the information about the rotor position or flux position and track it by injecting a high frequency excitation. For applying these methods the machine drives must be presented the saliency, as the interior permanent magnet synchronous machine (IPMSM) presents an inherent saliency in its rotor, the application of HFSIM is available. This paper presented a high frequency IPMSM model adopted for sensorless control applications. This model is obtained by add the rotating high frequency signal voltage to fundamental supply. The effects of injected signal to the performance of IPMSM are studied and analyzed in this paper through the simulation test.

1. Introduction

Interior permanent magnet synchronous machine (IPMSM) is very popular in industry because of their good performance, high efficiency and power density. However for IPMSM control applications the use of position sensors to measure the rotor position angle can be increased the cost and reduces the reliability of system. Extensive research has been directed towards sensorless control of IPMSM and several approaches are reported in the literature. IPMSM position sensorless control techniques are classified in two categories: methods based on fundamental model [1,2] and methods based on spatial saliency [3,4,5].The methods based on fundamental model, estimate the rotor position from machine fundamental equations, present good performance in middle and high speed region. However at frequency near to zero, the voltage drop on the stator resistance cannot be neglected while the back emf becomes lower and lower, vanishing any possibility of having continuous low or zero speed operation and limits the application of methods based on fundamental model [6]. In order to improve the position estimation in low speed range the second type of methods are appeared. The spatial saliency based methods are often referred to as high frequency signal injection methods (HFSIM's), in which high frequency signal is superimposed on stator supply. The applied signals interact with the rotor saliency or magnetic anisotropy of the machine and the resulting current or voltage is processed to extract the rotor position information. These methods can operate over a wide speed range, including zero speed, and can achieve parameter independent position estimation [7]. The types of injected signal that have been proposed in literature can be classified into three main categories. The first one is injection high frequency carrier signal(rotating carrier injection current or voltage, pulsating carrier injection current or voltage) the second injection a transient signal(test voltage vector injection superimposed on fundamental PMW)the third standard PMW switching exploit the switching of fundamental PMW waveforms[8]. The applications of HFSIM's require the existence of saliency in the machine. Since the IPMSM has an intrinsic saliency (the direct d-axis inductance is substantially different from the quadrature q-axis inductance), so it has natural potential to be used for sensorless estimation at standstill and low speed. In this paper a new model of IPMSM based on pulsating high frequency signal injection is presented. The rotating injection is carried out by the application of a balanced set voltage. The interaction between the rotating injected signal and saliency presented in the IPMSM is detected in current response. Simulation test is applied for presenting the effects of rotating injected signal on the performance of IPMSM.

2. The model of IPMSM under fundamental voltage excitation

The equations voltage and flux linkage in the stationary reference frame (α,β) are:

$$\begin{bmatrix} V_{s\alpha} \\ V_{s\beta} \end{bmatrix} = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix} \begin{bmatrix} I_{s\alpha} \\ I_{s\beta} \end{bmatrix} + \begin{bmatrix} p & 0 \\ 0 & p \end{bmatrix} \begin{bmatrix} \Psi_\alpha \\ \Psi_\beta \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} \Psi_\alpha \\ \Psi_\beta \end{bmatrix} = \begin{bmatrix} \Sigma L - \Delta L\cos(2\theta_r) & -\Delta L\sin(2\theta_r) \\ -\Delta L\sin(2\theta_r) & \Sigma L + \Delta L\cos(2\theta_r) \end{bmatrix} \begin{bmatrix} I_{s\alpha} \\ I_{s\beta} \end{bmatrix} + \begin{bmatrix} \cos(\theta_r) \\ \sin(\theta_r) \end{bmatrix} \Psi_m \quad (2)$$

$$\Sigma L = \frac{l_d + l_q}{2}, \Delta L = \frac{l_d - l_q}{2} \quad (3)$$

Where
R_s : is stator resistance,
Ψ_m : is the amplitude of permanent magnet flux linkage.

V, I, Ψ : are voltages, current and flux linkage of the stator respectively,

L : is the average stator inductance,

ΔL : is the differential stator inductance,

l_d and l_q are the direct-axis and quadrature-axis synchronous inductances,

θ_r : is the rotor position in electrical degree,

p : is differential operator.

Substituting (2) in (1):

$$\begin{bmatrix} V_{s\alpha} \\ V_{s\beta} \end{bmatrix} = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix} \begin{bmatrix} I_{s\alpha} \\ I_{s\beta} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \Sigma L - \Delta L\cos(2\theta_r) & -\Delta L\sin(2\theta_r) \\ -\Delta L\sin(2\theta_r) & \Sigma L + \Delta L\cos(2\theta_r) \end{bmatrix} \begin{bmatrix} I_{s\alpha} \\ I_{s\beta} \end{bmatrix}$$

$$+ \frac{d}{dt} \begin{bmatrix} \cos(\theta_r) \\ \sin(\theta_r) \end{bmatrix} \Psi_m \quad (4)$$

The electromagnetic torque and system motion equation can be expressed by (5) and (6) respectively.

$$T_e = p\left(\bar{I}_s * \overline{\Psi}_s\right) \quad (5)$$

$$T_e - T_l = J\frac{d\Omega_r}{dt} \quad (6)$$

From (4), (5),(6) we can elaborate the model of IPMSM under fundamental excitation, however for sensorless control at standstill operation this model becomes not suitable therefore a new IPMSM model based on high frequency excitation will be presented.

3. The model of IPMSM under high frequency voltage excitation

In order to elaborate the model of IPMSM appropriate for sensorless control at low speed range. A persistent high frequency excitation (.5÷1khz) is used to feed the IPMSM. The persistent high frequency excitation can be rotating or pulsating; rotating if it consists a balanced set voltage, pulsating if it injected only in a phase or consists of three identical voltage[9].This paper will be concerned with rotating voltage injection. This type consists to inject a balanced polyphase voltage vector rotating at a high frequencyω . The polyphase carrier voltage can be established as in (7) and is illustrated in Fig. 1.

$$V_{s-c}^{s} = V_c e^{j\omega_c t} \quad (7)$$

Where

V_c, ω_c represent the amplitude and the frequency of the injected vector voltage, respectively.

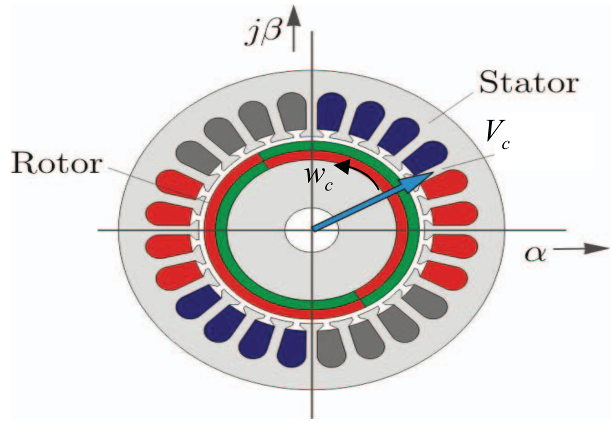

Fig.1. Rotating vector injection in the stationary reference frame [10]

As consequence of injecting of rotating voltage

-The machine responds with an elliptic current Fig .2;

-The ellipse is correlated with the anisotropies presented in the machine;

-The rotor position information is included in the high frequency current.

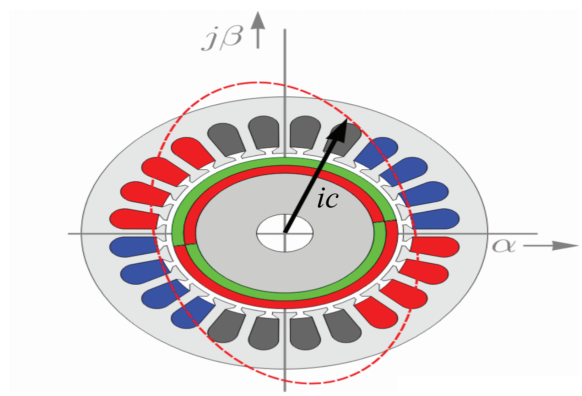

Fig.2. Elliptic current response [10]

Using (7) as injected signal, the model given by (4) can be simplified by considering the following assumptions [11, 12, 13]:

- The frequency of the injected signal ω is high to the ω

-The stator resistance R_S can be neglected compared to the high frequency reactance

-At low speeds the back-emf is negligible.

So the mathematical model of IPMSM in HF voltage excitation can be written as:

$$\begin{bmatrix} V^s{}_{s\alpha-c} \\ V^s{}_{s\beta-c} \end{bmatrix} = j\omega_c \begin{bmatrix} \Sigma L - \Delta L\cos(2\theta_r) & -\Delta L\sin(2\theta_r) \\ -\Delta L\sin(2\theta_r) & \Sigma L + \Delta L\cos(2\theta_r) \end{bmatrix} \begin{bmatrix} I^s{}_{s\alpha-c} \\ I^s{}_{s\beta-c} \end{bmatrix} \quad (8)$$

The HF current response for rotating HF voltage injection can be deduced from (8) as:

$$I^{s}_{s-c} = \frac{(L^{s}{}_{\sigma s})^{-1}}{j\omega_{c}} V^{s}_{s-c} \qquad (9)$$

Where

$L^{s}{}_{\sigma s}$ is the stator transient inductance matrix in stationary frame

The calculation of $(L^{s}{}_{\sigma s})^{-1}$ allows writing (9) as:

$$\begin{bmatrix} I^{s}{}_{s\alpha\text{-}c} \\ I^{s}{}_{s\beta\text{-}c} \end{bmatrix} = \frac{1}{j\omega_{c}\Delta} \begin{bmatrix} \Sigma L + \Delta L\cos(2\theta_{r}) & \Delta L\sin(2\theta_{r}) \\ \Delta L\sin(2\theta_{r}) & \Sigma L - \Delta L\cos(2\theta_{r}) \end{bmatrix} \begin{bmatrix} V^{s}{}_{s\alpha\text{-}c} \\ V^{s}{}_{s\beta\text{-}c} \end{bmatrix} \qquad (10)$$

Where

$$\Delta = (\Sigma L)^{2} - (\Delta L)^{2} = l_{q} l_{d} \qquad (11)$$

Substituting (7) in (10) the total expression of resulting HF current is

$$\bar{I}^{s}_{s-c} = i_{cp} e^{j(\omega_{c} t)} + i_{cn} e^{j(2\theta_{r} - \omega_{c} t)} \qquad (12)$$

Where

$$i_{cp} = \frac{V_{c}\,\Sigma L}{j\omega_{c} l_{sd} l_{sq}}, \quad i_{cn} = \frac{V_{c}\Delta L}{j\omega_{c} l_{sd} l_{sq}}$$

It can be noticed from (12) that the resulting HF current contains both positive and negative sequences components. The first component called the positive-sequence component i_{cp} proportional to the average stator transient inductance and contains no information on position θ_{r}. The second component called negative-sequence component i_{cn} proportional to the differential stator transient inductance and it contains information on the position θ_{r}. We can remark also if the machine is no salient ($l_{sd} = l_{sq}$) so $\Delta L = 0$, the negative sequence component is zero so no information about rotor position. As consequence the HFSIM's require the presence of saliency in the machine. The demodulation of negative component allows extracting the rotor position which can be used in sensorless control of IPMSM.As described previously the injected HF signal voltage induced the HF current characterized by two components. To illustrate the effects of the presence of induced HF current on IPMSM a simulation test will be applied.

4. Simulation results

For evaluating the performance of IPMSM with and without injection of high frequency signal the modelling simulation test is accomplished. The IPMSM parameters are given in Table 1.

Table 1. Machine parameters

Machine parameter	value	machine parameter	Value
Maximum speed	1800(rpm)	l_d	42.44(mH)
Number of pole pairs	2	l_q	79.57(mH)
R_s	1.93(Ω)	f	0
Ψ_f	0.314(Wb)	J	0.003(kgm^2)

4.1. IPMSM without high frequency signal injection

In the first time the simulation test correspond to simulate IPMSM without HF signal injection, the IPMSM is fed by 27, 5 (V_{rms}) balanced set stator voltage pulsate at 5 (Hz) .It runs at no-load condition. Fig.3 and Fig.4 show the speed and electromagnetic torque responses, it is evident from these figures that the speed and electromagnetic torque responses reach the main value at steady state without any oscillation.

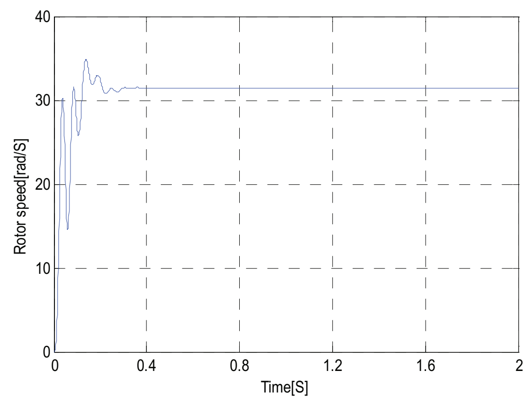

Fig.3. Rotor speed response without HF injection

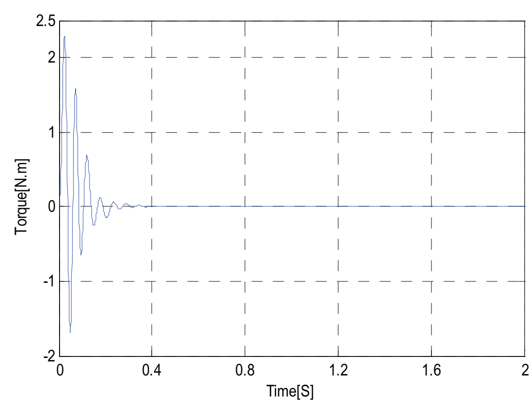

Fig.4. Electromagnetic torque response without HF injection

Due to the presence of saliency ($ld \neq l_q$) in IPMSM the stator transient inductance becomes not constant. It depends on the rotor position its trajectory presents an elliptical shape as shown in Fig.5.

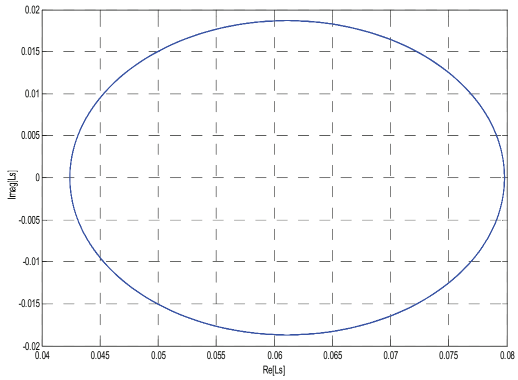

Fig.5. Stator Inductance Trajectory

From Fig.5 it can be observed that the IPMSM presents an intrinsically saliency which can be exploited for estimating the rotor position, this saliency can be tracked by high frequency signal injection. This presents the aim of next test of simulation.

4.2. IPMSM with high frequency signal injection

In this section the IPMSM is supplied by high frequency voltage superimposed to the stator voltage supply. The IPMSM is operated at no load with, $20\,(V_{rms})$, $500\,(Hz)$ as high frequency rotating voltage superimposed to $27{,}5\,(V_{rms})$,$5\,(Hz)$ normal supply stator voltage. Fig.6 shows the supply stator voltages in stationary reference frame.

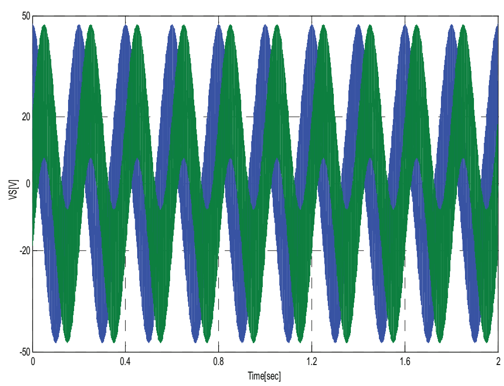

Fig.6. Supply Voltage

The injection of high frequency voltage signal creates the harmonics which appear in both current and flux responses. Generally the harmonics presented in response current are using to extract the position of rotor speed in sensorless control. In our case the harmonics present in the current are sufficient to clear the affect of high frequency signal injection.

The Fig.7 shows the stator current spectrum with HF signal injection. It can be seen from Fig.7 that a three harmonics appeared the first one corresponds to the main frequency of stator supply $f_e = 5(Hz)$. The two second harmonics are due to the injected HF signal voltage; the first one presents the positive sequence component it pulsates at $f_c = 500(HZ)$ it has high amplitude compared to the second component (negative sequence), which is the result of the interaction between the HF

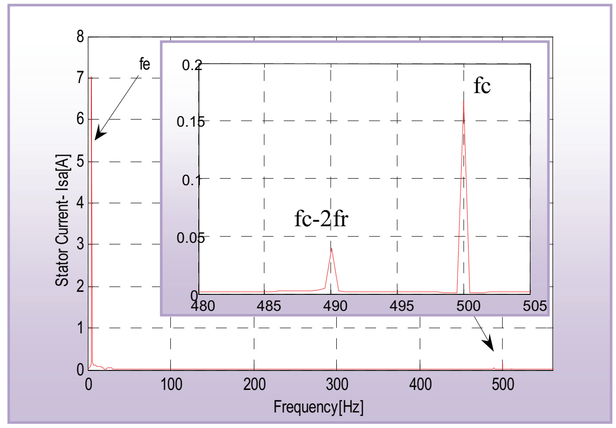

Fig.7. Spectrum of stator current I_{s-a} with HF signal injection

and the saliencies presented in the machine it pulsate at $f_c - 2f_r(Hz)$ .It contains the information on rotor position it is used for extracting the rotor position, rather the others harmonics which can be eliminated by filtering. The Fig.8 shows the effects of additional HF signal that creates a HF ripple in the electromagnetic torque but has almost no effect on the motor speed.

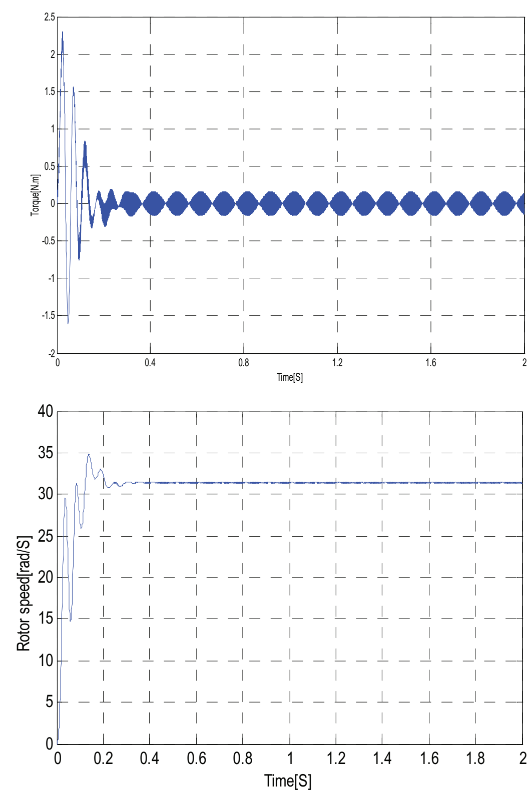

Fig.8. Electromagnetic Torque and rotor speed with HF signal injection

As describe previously the consequence of injected HF signal voltage the new stator courant is induced, presented as the negative component and positive component. The effect of HF signal voltage appeared clearly in electromagnetic torque and stator current rather than in speed response.

5. Conclusion

Recently new sensorless methods are appeared, this methods called high frequency signal injection methods (HFSIM's). It relies on the use of superimposed signal to normal supply this signal can be voltage or current, as known at low frequency the methods based model failed. The (HFSIM's) is able to provide the information about the rotor position at zero frequency and standstill. These methods require the presence of saliency in the machine. As the IPMSM presents an intrinsically saliency the application of these methods is easy. In this paper a new approach of modelling of IPMSM is presented, this approach relied on the injected of HF signal rotating voltage. When we inject a signal voltage to the normal supply an induced current is produced in stator. Simulation test using an additional HF rotating voltage has been performed. Apart from the resulting current contained two components one of these components called negative sequence included the information about a rotor position which has no parameter dependant and can be used in sensorless control. The HF injected signal has no effect on rotor speed.

6. References

[1] S. Morimoto, K. Kawamoto, M. Sanada, and Y. Takeda," Sensorless control strategy for salient-pole PMSM based on extended EMF in rotating reference frame", *IEEE Industry Applications Conference, 36th IAS Ann. Meet.,* 2001, pp. 2637-2644.

[2] B. Nahid-Mobarakeh, F, Meibody-Tabar, F. M. Sargos," Back EMF estimation-based sensorless control of PMSM: Robustness with respect to measurement errors and inverter Irregularities", *IEEE Trans. Industrial Electronics*, Vol. 43, No. 2, pp. 485-494, 2007.

[3] H. Kim, and R. D. Lorenz, " Carrier signal injection based sensorless Control methods for IPM synchronous machine drives", *IEEE Industry Applications Conference*, the *39th* IAS Ann. Meet., 2004, Vol. 2, pp. 977-984.

[4] S. Kim, Y.-C. Kwon, S.-K. Sul, J. Park, and S.-M. Kim," Position sensorless operation of IPMSM with near PWM switching frequency signal injection", *8th ICPE –ECCE Proceedings*, *Asia,* May-June 2011, pp. 1660–1665.

[5] J.-H. Jang, S.-K. Sul, J.-I. Ha, M. Ohto, and K. Ide, " Analysis of permanent magnet machine for sensorless control based on high frequency signal injection", *IEEE Trans*. *Industry Applications*,Vol. 40, Issue 6,pp. 1595-1604, 2004.

[6] A.Consoli ,G.Scarcella,G.Scelba,S.Royak,M.M.Harbaugh, "Saturation Modulation in Voltage Zero Sequence-Based EncoderlessTechniques. Part II: Implementation issues",*IEEE IEMDC Proceeding*, San Antonio, TX,MAY 15-18,2005,pp.2017-2023.

[7] Wang Jianmin, Tian Shixia, "Analysis of Stator Resistance Effects in Carrier Signal Injection Based Sensorless Control of Permanent Magnet Synchronous Machine", *Conference ICEEAC2010 Proceeding,* November 2010, pp. 305-309.

[8] C. Caruana*, Sensorless control of AC Machines*, University of Malta, Nottingham Summer School: 2008.

[9] G.Bottiglieri,A.Consoli,T.Lipo,"Modeling of Saturated Induction Machines With Injected High-Frequency Signals", IEEE Trans. *on Energy conversion*,Vol. 43, No. 2, pp. 485-494, 2007.

[10] Ralph M. Kennel, *Sensorless Motor Drives, Electrical Machines and Drives Wuppertal University.*

[11] S.Taniguchi, S.Wakao, T.Yoneyama, " Position sensorless control of Permanent Magnet synchronous Motor at low speed range using harmonic voltage injection", *Conference Power electronics and applications European Proceeding,*2007,pp.1-7.

[12] M.P .Chaudhary ,V.Patel, J.G.Jamnani, "Sensorless vector control of PMSM drive using heterodyne technique", *International Conference IEEE optimization of Electrical and Electronic Equipment Proceeding*, 2008, pp.93-99.

[13] P.Balazovic, R.Filka, "Sensorless PMSM control for H-axis washing machine drive", *Conference IEEE Power Electronics Specialists Proceeding* ,2008 pp. 4237-4242.