An Improved Performance of Sensorless PMSM Drive Control with Sliding Mode Observer in Low Speed Operation

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***Abstract*— The aim of these paper is to realize a sensorless vector control scheme for a non-salient pole PMSM using a state observer of kind "Sliding Mode" for rotor flux position and speed estimation. The proposed scheme of SMO is simulated for different switching functions and the performance is compared during low speed operation which is a non-observable region. This scheme has greater accuracy than the conventional SMO and is simpler too. The PMSM parameters variations are compensated by means of SMO and the initial rotor position is not needed. The results taken from simulations in MATLAB/Simulink, validate the effectiveness of sensorless control system for PMSM with Sliding Mode Observer.**

***Keywords*— Permanent Magnet Synchronous Motor, Sliding Mode Observer, vector control.**

I. Introduction

Drive applications with PMSM are receiving more and more interest because of their better performance in dynamic and steady state responses, from their greater power density, larger torque/ampere and torque/inertia ratio, best efficiency, lower cost, easier maintenance. However, the strong nonlinearity and time-varying nature of a PMSM drive, demands fast switching power electronic devices and a large computation capacity.

The PMSM-s are constructed with a constant rotor field established by permanent magnets mounted to rotor. In absence of mechanical comutator-brush assembly, the rotor position (the position of the magnetic rotor field) may be known by a shaft-mounted encoder or by a resolver, but their presence in a servo drive has some drawbacks from the standpoint of drive cost, reliability, noise immunity, encumbrance. The need to avoid these disadvantages, has made important a task toward the researchers: to develop and to improve sensorless strategies for PMSM control.

Modern control techniques are generally based on the elimination or the reduction of number of sensors in industrial applications. In this way, hardware sensors are replaced by software based on parameter identification, estimation, observation, signal injection.

Several methods have been proposed from different researchers. A real system with PMSM drive, suffer by some internal and external disturbances and uncertainties: load and parameters variations, non-modelled dynamics, friction forces etc. These disturbances may not rapidly limited by a linear control method like PI or PID algorithms. Therefore, nonlinear control methods are preferred from many researchers to develop and to improve the control performance for a practical implementation in systems with different kind uncertainties and disturbances.

Several efforts made in field of sensorless control of AC drives have shown that nonlinear technique of Sliding Mode Control has notable advantages on robustness to disturbances and low sensitivity to parameters varying. Peixoto at [1] have proposed a speed control for a PMSM drive system using sliding mode to estimate the induced back-EMF, rotor position and speed based on the electrical dynamic equations. The back EMF information was obtained from the filtered switching signals relative to current estimation error. It could be a hard job design the switching gain over a wide speed range based on this observer model [1].Han et al, presented a method to estimate the speed of PMSM using sliding mode observer. Lyapunov functions were chosen for determining the adaptive law for the speed and stator resistance estimator. It is that the existence condition of sliding mode cannot be easily guaranteed for the convergence by this method. Also the integration of rotor angular velocity may bring more error on the estimated rotor position angle [2]. Elbuluk et al, investigated sliding mode observer for estimating the rotor position and speed of PMSM. Instead of directly using filtered switching signals by a low-pass filter, an observer was designed to undertake the filtering task for the estimated back-EMF. It is stated that the observer has the structure of an extended Kalman filter and is expected to have high filtering properties [3]. Unfortunately, no experimental results were presented. Kang et al, proposed an iterative sliding mode observer for the estimation of back-EMF and thus the rotor position of PMSM in high-speed range. By iterating the conventional SMO recursively several times within a sample period of PI current regulators, chattering components superimposed on the estimated and back-EMF were reduced. However, this method doesn't help much for the low-speed operation [4].

This paper attempt employ motor terminal variables(stator voltages and currents), its parameters and machine model to estimate the rotor speed and position. By improving the theta correction component including the cut-off frequency to speed operation ratio, and switching surface law, it is made possible to get a better performance for very low speed operation.

II. The Methodology

The methodology used in this paper is based on mathematical model of PMSM in stationary reference frame for constructing an observer for states estimation. The observer is chosen to be of type "Sliding Mode" for having many advantages like: robustness to disturbances, low sensitivity to the system parameters vibrations compared to other methods[5],[6]. Otherwise, it has its own problem: the chattering phenomena. The structure of is simple and effective, based on a concept of back EMF detection and introduces a more complex corrector function which differ from traditional The observer contains a corrector of estimated angle of rotor position with a Low Pass Filter with variable cut-off frequency according to rotor speed for compensating the phase delay angle.

III. The PMSM Model

For high dynamic drives is very important achieving a low computation time of control algorithm in real time implementation because of fast change of operation point. Therefore, the observer's equations should be quite simple. Based on ordinary simplified assumptions, the mathematical model of PM synchronous motor can be represented in term of two-phases-equivalent stator-fixed αβ windings as follows:

$$\dot{i}_S = Ai_S + Bv_S + K_E E_S + \xi \qquad (1)$$

where : $i_s = \begin{bmatrix} i_\alpha & i_\beta \end{bmatrix}^T$: stationary α-β currents vector

$v_s = \begin{bmatrix} v_\alpha & v_\beta \end{bmatrix}^T$: stationary α-β voltages vector

$E_s = \begin{bmatrix} e_\alpha & e_\beta \end{bmatrix}^T = \begin{bmatrix} -\omega sin\theta & \omega cos\theta \end{bmatrix}^T$: back EMF vector

$A = \left(-\dfrac{R_s}{L_s}\right)I \quad , \quad B = \left(\dfrac{1}{L_s}\right)I$

R_s,L_s :stator winding resistance and inductance

I : 2×2 identity matrix, K_E : back EMF constant.

$\zeta = \begin{bmatrix} \zeta_\alpha & \zeta_\beta \end{bmatrix}^T$: Disturbance vector.

A. *Conventional Sliding Mode Observer*

The sliding mode observer is designed as:

$$\dot{\hat{i}}_s = A\hat{i}_s + Bv_s + K_{sw}\,\mathrm{sgn}(\hat{i}_s - i_s) \qquad (2)$$

where $\hat{i}_s$: is the estimated value of i_s

$K_{sw}=kI$: Observer switch gain

$\mathrm{sgn}(\hat{i}_s - i_s) = \begin{bmatrix} \mathrm{sgn}(\hat{i}_\alpha - i_\alpha) & \mathrm{sgn}(\hat{i}_\beta - i_\beta) \end{bmatrix}^T$

The sliding plane S is realized on the state variables, i.e., the stator currents, by the switching functions as:

$$S = \hat{i}_s - i_s \equiv e_s = 0 \qquad (3)$$

The estimation error dynamic is obtained by subtracting (1) from (2) as

$$\dot{e}_S = Ae_S - K_E E_S + K_{SW}\,\mathrm{sgn}(e_S) - \xi \qquad (4)$$

To satisfy the necessary conditions for the sliding mode convergence, K_{sw} must be chosen to satisfy $e_s \dot{e}_s^{\,T} < 0$. Using the equivalent control design method [7], the expression is obtained as following:

$$\dot{e}_S = e_S = 0 \tag{5}$$

Hence, the characteristics of SMO on the sliding plane might be defined as:

$$z \equiv K_{sw}\,\mathrm{sgn}(e_S) = K_E E_S + \xi \tag{6}$$

$$z = K_E \begin{bmatrix} -\omega \sin\theta \\ \omega \cos\theta \end{bmatrix} - \begin{bmatrix} \xi_\alpha \\ \xi_\beta \end{bmatrix} = \begin{bmatrix} z_\alpha \\ z_\beta \end{bmatrix}$$

where *z*, the switching signal about the current error, contain the information of the estimated back EMF.
Estimated back EMF is obtained by the low pass filter of the switching signals *z:*

$$\hat{e}_\alpha = \frac{\omega_{cutoff}}{s + \omega_{cutoff}} z_\alpha$$

$$\hat{e}_\beta = \frac{\omega_{cutoff}}{s + \omega_{cutoff}} z_\beta \tag{7}$$

The main problem to successfully apply sensorless control for PMSM is the existence of operating regimes for which the observer performance is notably deteriorated due to the difficulties in estimating correctly the motor position. For the PMSM drives, the position observable problems at zero speed ,that is an unobservable state point , are on focus of the researchers. The rotor position, when the motor operates out of the unobservable region, can be obtained from (7) as following:

$$\hat{\theta} = -\tan^{-1}\left(\frac{\hat{e}_\alpha}{\hat{e}_\beta}\right) \tag{8}$$

The overall block diagram for sensorless control of PMSM drive with SMO is shown in Fig.1

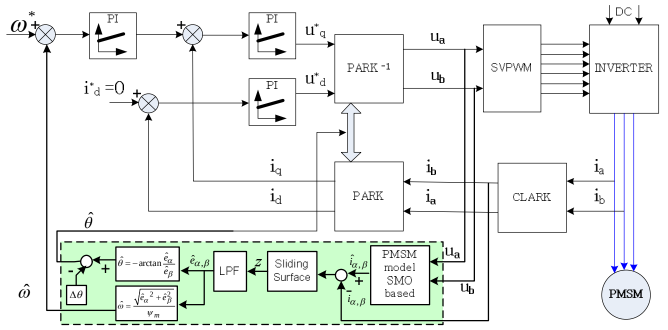

Fig.1 The overall functional scheme of speed and position control of PMSM drive with SMO

The block diagram of the conventional sliding mode observer (SMO) is shown in Fig. 2.

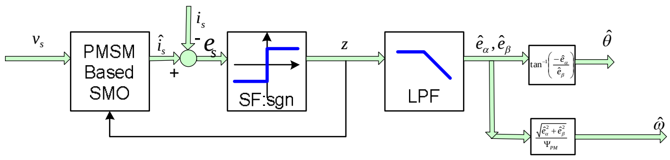

Fig.2 The conventional SMO block diagram with "sign" swiching function

Since the switching signals of the sliding mode observer contain the back EMF of the motor, it is possible to obtain the speed and position of the motor directly from the switching signals[6]. Undesirably, the chattering problem is present due to the discontinuous controls (sgn function) in sliding mode observer and make it the major factor for the high system oscillation. For overcoming a such problem, the low pass filter with cutoff frequency ω_n is used but it produces the delay time in estimating the position of the rotor. In the case of the conventional SMO, the cutoff frequency ω_n for the low-pass filter is calculated as follows:

$$\omega_n = \omega_{n-1} + \left(\frac{\omega_{c2} - \omega_{c1}}{\omega_2 - \omega_1}\right)\omega_{ref} - \left(\frac{\omega_{c2} - \omega_{c1}}{\omega_2 - \omega_1}\right)\omega_1 \tag{9}$$

where $\omega_n = 2\pi f$, ω_{ref} is the reference speed of the rotor, f is the cutoff frequency for the filter, and ω_{n-1} is the previous value of ω_n. Also, ω_{c1} and ω_{c2} are the angular frequencies at rotor speeds of ω_1 and ω_2, respectively. According to (9), it is recognized that the adjustment of the cutoff frequency is utilized to estimate the position and velocity of the rotor as precisely as possible in the conventional SMO.
So, the calculated rotor position is normally added with offset position. The improved sliding mode observer replace the discontinuous control by using the saturation or sigmoid function in order to reduced chattering problem.

B. *SMO with "Saturation" switching function*

For estimation of back EMF from switching function *z*, at the conventional SMO is used a low pass filter . For high performance applications, the bang-bang control is replaced by saturation function as shown in Fig.3.

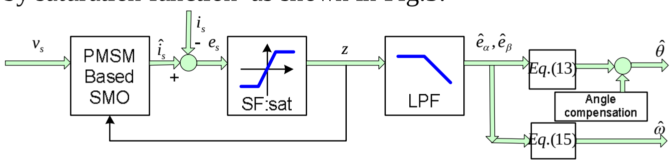

Fig.3 The SMO block diagram with "saturation" swiching function

Low pass filter is used to estimate the back EMF from the switching function z of the observer as shown in Fig.1. The rotor speed and position are calculated from this back EMF. But the phase delay of the estimated rotor position and speed is caused by the variation of the rotor speed because the low pass filter is used to acquire this back EMF from the switching function z. A large capacity of data memory such as ROM table is needed to compensate the phase delay in the conventional low pass filter as shown in Fig. 2 since the cutoff frequency of the conventional method is constant regardless of the rotor speed. To simplify the H/W system of the motor drive a new low pass filter is proposed. This filter is designed to have a variable cutoff frequency according to the rotor speed. So the cutoff frequency of the proposed low pass filter can be chosen as follows:

$$\omega_{cutoff} = \frac{\hat{\omega}}{K} \quad (10)$$

The low pass filter with variable cutoff frequency satisfies:

$$H(j\omega) = \frac{\omega_{cutoff}}{j\omega + \omega_{cutoff}} = \frac{1}{1 + jK} \quad (11)$$

and the phase delay angle is :

$$\tan^{-1}\left(\frac{\omega}{\omega_{cutoff}}\right) = \tan^{-1} K \quad (12)$$

From Eq. (12) is seen that the phase delay angle is constant K all over the rotor speed range. So the need for data memory such as ROM to compensate the phase delay angle is reduced compared to the conventional method.

The rotor position is not observable at zero speed and acceleration because back EMF are no existent in this condition and then we can't use the observer equation (8). For this reason, an Estimator/Observer swapping system proposed by [8] allows the use of the observer at high speed and swap automatically to the estimator when the speed becomes under a defined very low value. The estimated position is calculated as:

$$\hat{\theta} = \int_0^t \left|\hat{\omega}\right| dt + Cte \quad (13)$$

$$\left|\hat{\omega}\right| = \frac{\sqrt{\hat{e}^2{}_\alpha + \hat{e}^2{}_\beta}}{\Psi_{PM}} \quad (14)$$

The initial value of the estimated position is equal to the last value computed by the observer (8) before swapping to the estimator. The estimated speed is calculated as:

$$\hat{\omega} = \frac{\sqrt{\hat{e}^2{}_\alpha + \hat{e}^2{}_\beta}}{\Psi_{PM}} \operatorname{sgn}(\hat{e}_\alpha \sin\hat{\theta} - \hat{e}_\beta \cos\hat{\theta}) \quad (15)$$

C. *SMO with "Sigmoid" switching function*

Another way to improve and simplify the conventional SMO is replacing the discontinuous switching function "sign" with a continuous one, such as "sigmoid". In this case, the low pass filter is not needed anymore. The block diagram of SMO with "sigmoid" switching function is shown in figure 4.

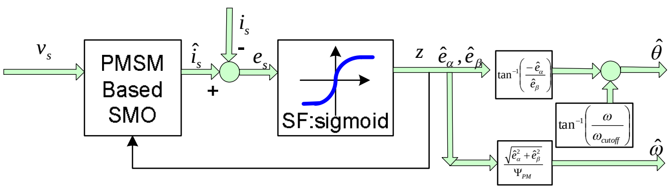

Fig.4 The SMO block diagram with "sigmoid" switching function

The state equations of the observer in this case can be represented as:

$$\dot{\hat{i}}_s = -\frac{R_s}{L_s}\hat{i}_s + \frac{1}{L_s}v_s - \frac{1}{L_s}kH(\hat{i}_s - i_s) \quad (16)$$

H represents the "sigmoid" switching function which replaces the "signum" and a low pass filter, and is formulated as:

$$H(e_s) = \left(\frac{2}{1 + \exp^{(-ae_s)}}\right) - 1 \quad (17)$$

where a>0 for the slope of sigmoid function and e_s is the currents error vector. The sliding mode surface s_n can be defined as the estimation error of the stator current. When the condition $\dot{s}_n s_n < 0$ is satisfied, the sliding mode exists, and this implies that $s_n \to 0$ for $t \to \infty$.

To set up the existence condition of the sliding mode, the Lyapunov function candidate is defined as:

$$V = \frac{1}{2}s^T{}_n s_n = \frac{1}{2}\left(s^2{}_\alpha + s^2{}_\beta\right) \quad (18)$$

From equation of PMSM dynamics and equation of observer, (1) and (16), the error equations are derived as:

$$\dot{s}_n = \dot{\hat{i}}_s - \dot{i}_s = -\frac{R_s}{L_s}(\hat{i}_s - i_s) + \frac{1}{L_s}E_s - \frac{1}{L_s}kH(\hat{i}_s - i_s) \quad (19)$$

The existence condition of the sliding mode is reached if satisfy: $\dot{V} = s^T{}_n \dot{s}_n < 0$.

With no many efforts, we can prove that the observer condition is obtained as:

$$k \geq \max(\left|e_\alpha\right|, \left|e_\beta\right|) \quad (20)$$

The observer gain k must be a constant value between $-k_{max}$ and $+k_{max}$ for satisfying the Lyapunov Stability condition. Remember that when the "signum" switching function is used at conventional SMO the value of k is either -1 or 1.

The adopted sigmoid function can reduce the chattering caused by discontinuous switching and the necessity of the integrator after the signum function has been eliminated. So, the total computational cost with this sigmoid function becomes lower than the one with both the signum function and an integrator. Its drawback is that slows the system response and the estimation errors are grown due to the small gains near the switching boundary. Therefore, for a high-speed operation, a high gain is needed for the switching function to compensate the estimation errors. The high switching gain cause the chattering in the estimation again, even though it make the response time smaller. It is not desirable to keep the switching gain high to reduce the estimation error. When the switching gain is not properly selected, the observer cannot converse because of the phase delay.

IV. SYSTEM CONFIGURATION

The block diagram of the sensorless control system for the PMSM is shown in Fig. 1. The PMSM is modeled in three-phase stationary coordinates, and it is transformed into the (*d, q)* two-phase synchronous coordinates system for the vector control. The PI control is used to reduce effectively the accumulative errors of currents and speed reference. The current is supplied to the stator of the motor through the SVPWM control in the form of a sinusoid.
Using the estimated position and velocity of the rotor, the sensorless control of the motor was implemented.

Because of the focus of my research work is on advanced techniques for sensorless PMSM drives, in order to make a comparison of performances for different algorithms, the PMSM used for simulations on MATLAB/Simulink environment has the following specifications [9]: Nominal Power P_n =1100 W, Nominal Speed ω_n =1500 rpm, Stator Resistance R_s=2.875 Ω, Inductance in d-axis L_d=8 mH, Inductance in q-axis L_q=8 mH, Magnetic Flux linkage Y_{PM} =0.175 Wb, Pole Number p= 4, Inertia J =0.001 kgm², Friction coefficient *B =0.00038 Nms*.

In traditional vector control with FOC, the reference current by direct d-axis is zero, i.e., i^*_d=0 and the control of three phase inverter is realized by Space vector PWM(SVPWM). The essential feedback signals are stator currents and stator voltages transformed on stationary reference frame.In this case, a sensorless algorithm is used. The fast control loop executes two independent current control loops. They are the direct and quadrature-axis current (i_d, i_q) PI controllers. Because of the direct-axis current (i_d) control the rotor magnetizing flux which is constant, i_d*=0.The quadrature-axis current (i_q) corresponds to the motor torque. The current PI controllers' outputs are summed with the corresponding d and q axis components of the decoupling stator voltage. Thus, the desired space vector for the stator voltage is obtained and then applied to the motor[9].

V. RESULTS FROM SIMULATIONS

The aim of this paper is performance evaluation of sensorless FOC of PMSM drive with Sliding Mode Observer at the very low speed operation region, therefore the simulations of schemes are made for these condition:
The PMSM drive is start with reference speed 30 rpm or 2% of nominal speed for 0.5Nm torque as load, and at the time instant of 0.1s the speed reference is 1500 rpm ,equal to nominal speed and the load torque is changed with a step function to 2Nm. For this regime, there are made the simulations for three different schemes of SMO described above, having these properties:

A. the first graphic of each triplet belong to results of SMO with "saturation" switching function with LPF.
B. the second graphic of each triplet belong to results of SMO with "saturation" switching function without LPF.
C. the third graphic of each triplet belong to results of SMO with "sigmoid" switching function without LPF.

The first triplet, Fig. 5,show the back EMF estimated from SMO. Because the SMO is back EMF model based, analyzing them is important. It is clearly seen that : SMO with "sat" switching function with LPF and SMO with "sigmoid" switching function without LPF have the same very good performance for back EMF estimations, without ripples.
The SMO with "sat" switching function without LPF demonstrate a poorer performance, evidently seen by presence of 10% ripple for nominal speed region. At the very low speed region , the three schemes have already the same performance , without ripples.

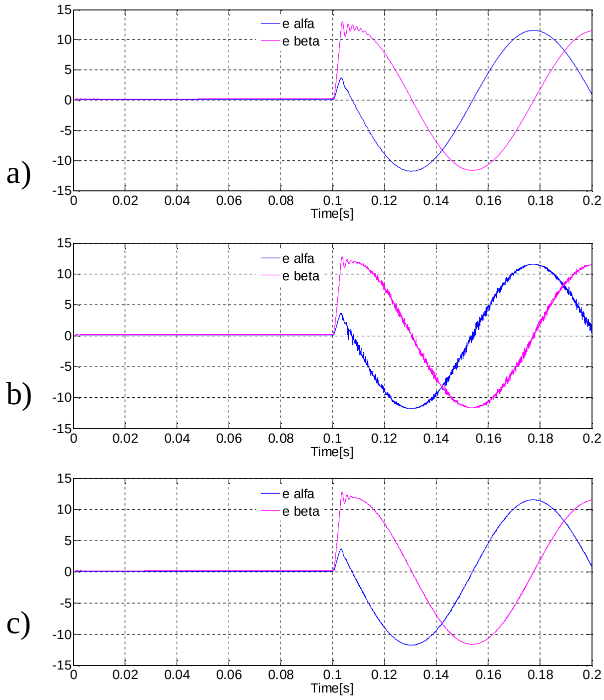

Fig.5 The back EMF estimated :
a) SMO with "sat" switching function with LPF
b) SMO with "sat" switching function without LPF
c) SMO with "sigmoid" switching function without LPF

The second triplet, Fig.6, show the rotor speed control for sensorless PMSM drive with SMO for very low speed operation and nominal speed operation. If we evaluate both static and dynamic performance for speed response, it is clearly seen that the three schemes have not evident differences on their performances. Therefore, if we would make a choice, that couldn't be for the speed estimation , but for the other parameters.
The third triplet, Fig.7, show rotor position control of PMSM drive with SMO. If we evaluate the details of these performances , is evident that they are different. The SMO with "sat" switching function without LPF has the poorer performance because of presence of greater chattering, around 0.04rad for nominal speed and 0.01 rad for very low speed, but the tracking position is good. The SMO with "sigmoid" switching function without LPF has better performance than

the first, 0.15 rad chattering, but the SMO with "sat" switching function with LPF has the best one. The absolute error for position estimation is 0.01 rad for nominal speed range and already no error but 0.005 rad ripple for 30 rev/min speed operation.

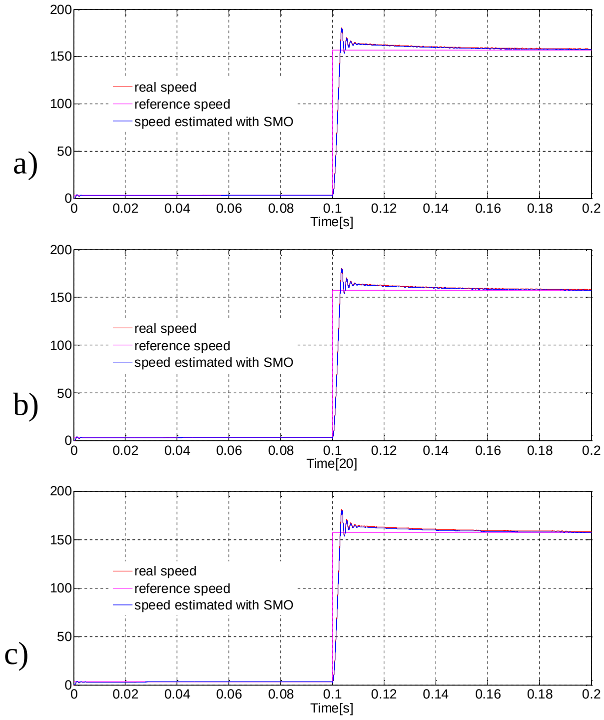

Fig.6 The rotor speed control[rad/s] :

a) SMO with "sat" switching function with LPF
b) SMO with "sat" switching function without LPF
c) SMO with "sigmoid" switching function without LPF

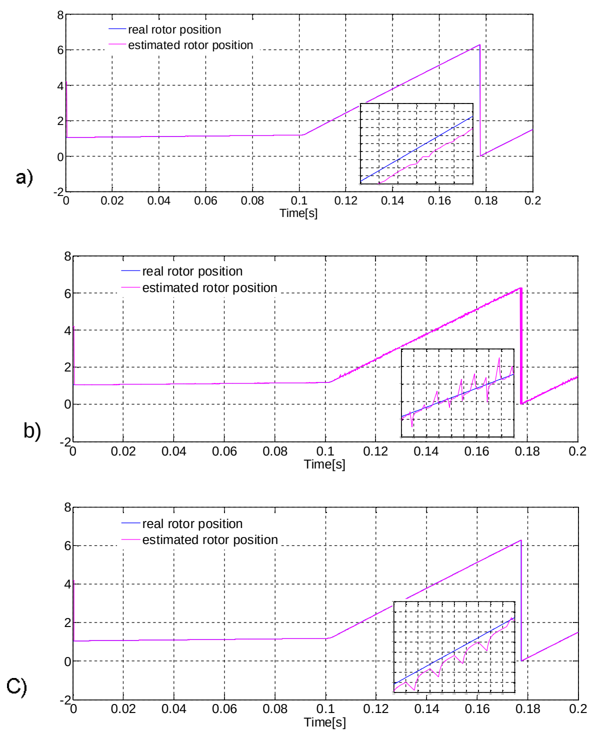

Fig.7 The position control [rad] :

a) SMO with "sat" switching function with LPF
b) SMO with "sat" switching function without LPF
c) SMO with "sigmoid" switching function without LPF

Figure 8 show Torque response for three schemes proposed. It is seen evidently that performance on steady state operation has the same properties, but the dynamic response is quite different. SMO with "sigmoid" switching function and SMO with "sat" switching function realize better performance for torque control, with smaller torque vibration and faster response than SMO with "sat" switching function without LPF.

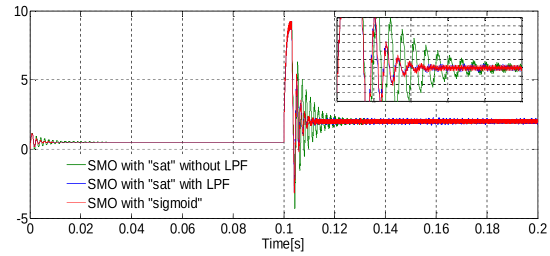

Fig.8 The Electromagnetic Torque control [Nm]

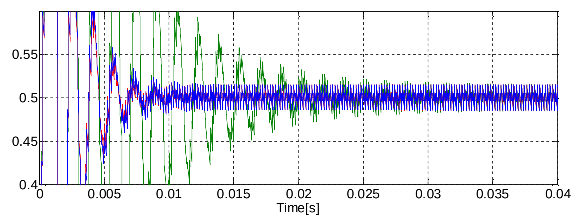

Fig.9 A detailed view of Electromagnetic Torque control for very low speed operation [Nm].

The settings and gains of Sliding Mode Observer and PI controllers are choice carefully, because they are very important and directly affect the dynamics of closed loop control and accuracy of observation. The process of synthesis is optimised by a procedure that is fast and no sensitive to the local minimum of the optimized criterion. The settings and gains used in simulation are as below:

The PI Controller for speed: k_p=1.4, k_i=45;

The PI Controller for i_d: k_p=10, k_i=1000 ;

The PI Controller for i_q: k_p=12, k_i=1000;

The SMO gain: K_{sw}=625.

VI. CONCLUSIONS

The nonlinear Sliding Mode control of PMSM drive based on Field Oriented Control technique is discussed for a non- observable point of operation such as low speed region. Different schemes of Sliding Mode Observers, are simulated at MATLAB/Simulink environment and their static and

and dynamic performances are compared. Results of simulations have shown that SMO make the sensorless PMSM drive immune against the disturbances and parameters variations. Three schemes are available for practical implementation, but the choosing will be dependent on technological requirements. From above graphics it seems clearly that according to rotor speed regulation requirements , all SMO can be used because they guarantee the same quality, but if from the PMSM drive is required a certain quality to rotor position regulation , the choose would be according to accuracy achieved by each Sliding Mode Observer.

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