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Modeling and simulation of a sliding mode observer for position sensorless control of PMSM

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Abstract— **The main objective of this paper is to provide a position sensorless control scheme for permanent magnet synchronous motor (PMSM) drive using a sliding mode observer (SMO). The rotor position and speed are estimated with only measuring stator voltages and currents. Compared with traditional SMO, the sign function is replaced by a sigmoid function in order to weaken the inherent chattering problem and increase estimation accuracy of the rotor position. The observer structure and its design method are discussed. The simulation results of the overall system are presented to demonstrate the effectiveness of the approach.**

Index Terms— **Permanent magnet synchronous motor, Sliding mode observer, Sensorless control, Sigmoid function.**

I. Introduction

Permanent magnet synchronous machine (PMSM) drive have been increasingly applied in a wide variety of industrial applications by replacing classic dc drives. The reason comes from the special advantages of PMSM such as inherent high power density, high efficiency, simple structure and absence of filed losses. To achieve high performance field-oriented control, accurate rotor position information, which is usually measured by rotary encoders is necessary. However, the cost of a sensor may exceed the cost of a small motor in some applications. Also, the presence of the mechanical sensors not only increases the cost and complexity of the total material with additional wiring but also reduces its reliability with additional sensitivity to external disturbances. In addition, it may be difficult to install and maintain a position sensor due to the limited space and rigid work environment with high vibration or high temperature. Therefore, the idea is to replace the mechanical sensor by a soft sensor which offers a number of attractive properties one of them being a low cost alternative to hardware speed measurement used in classical motor drives [1–3].

Currently, two kinds of approaches seem to be preferable, depending on the speed operating range required by the application: high-frequency soft sensors and model-based soft sensors. The first one, based on the signal injection techniques, takes advantage of the magnetic saliency of the machine to detect the rotor position. This kind method offers a best solution both for standstill and low speed operation [4–6]. However, the injected signal will bring noise to the system, causing the degradation to the system performance. At high speed, model-based soft sensors give excellent results. Several techniques inspired from control theory [7–9], such as adaptive observers [10–13], reference models [14–16], and extended Kalman filter [17].

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Among the existing sensorless approaches, sliding mode has been recognized as the prospective control methodology for electric machines. Previous studies show that sliding mode observers (SMO) have attractive advantages of robustness to disturbances, low sensitivity to parameter variations and speed of convergence. At present, a variety of sensorless control methods based on SMO have been proposed. In [18–19], the sign function is applied to the sliding mode observer allowing the estimation of the rotor position and speed from the measurements of voltages and stator currents. The simulation results show that the estimated rotor position tracks actual position. However, the chattering problem due to the discontinuous control in SMO is the major factor to make the high system oscillation. Generally, the low pass filter is used to reduce the chattering problem but it produces the delay time.

In order to reduce the chattering problem and to increase the accuracy of the rotor position estimation at low speed and stability of the high-speed system, some improvements were made by replacing the sign function with smoother features. Some researchers have used the a saturation function with a valid boundary to solve the chattering problem [20–22]. The simulation results verify that this estimation method accurately estimate the rotor position in a wide speed range and the chattering problem is greatly reduced, but the presence of a low-pass filter can not be avoided.

Another solution is to replace the sign function by the sigmoid function [23–25]. Significant reduction in chattering is noticed in the system with saturation and sigmoid function compared to the conventional sign function. The sigmoid function could even reduce chattering far better than the saturation function. Use of sigmoid function also avoids the use of low pass filter and hence the compensation algorithms.

This paper will present a sliding mode technique for position sensorless control of PMSM over wide speed range. The design of sliding mode observer is based on the machine model. Existence condition of sliding mode and proof of its stability will be given using Lyapunov method.

II. The mathematical model of PMSM

Nowadays, synchronous machines, especially PMSM spread increasingly like actuators in automated industries where they replace the DC motors. Indeed, the use of the permanent magnets synchronous machines had a very important development in several industrial sectors because of its simplicity of design, its high-speed operating ability, performance in terms of torque-to-weight ratio and low maintenance.

The PMSM considered in this study has a stator composed of a three-phase winding represented by the three axes (a, b, c) phase-shifted with respect to one another by an electrical angle of 120° and a rotor having p pole pairs. To simplify the modeling of the machine, we adopt the usual simplifying assumptions given in the majority of references [26]

- The stator windings are symmetrical and have perfect sinusoidal distribution along the air gap.
- The permanence of the magnetic paths on the rotor is independent of the rotor positions.
- Saturation and hysteresis effects are inexistent.

The PMSM model in the stationary reference frame *(α, β)* is shown below:

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \begin{bmatrix} R_s + \frac{d}{dt}\ell_\alpha & \frac{d}{dt}L_1 \sin 2\theta_e \\ \frac{d}{dt}L_1 \sin 2\theta_e & R_s + \frac{d}{dt}\ell_\beta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \omega_e \psi_{pm} \begin{bmatrix} -\sin\theta_e \\ \cos\theta_e \end{bmatrix} \quad (1)$$

$$\ell_\alpha = L_0 + L_1 \cos 2\theta_e, \ell_\beta = L_0 - L_1 \cos 2\theta_e,$$

$$L_0 = \frac{L_d + L_q}{2}, L_1 = \frac{L_d - L_q}{2}.$$

where

$i_{\alpha\beta} = [i_\alpha \, i_\beta]^T$ is the stator current vector, $u_{\alpha\beta} = [u_\alpha \, u_\beta]^T$ is the motor terminal voltage vector, R_s is the stator windings resistance, ψ_{pm} is the magnetic flux, θ_e is the electrical rotor position and ω_e is the electrical rotor speed.

Equation (1) can be given by as follow

$$u_\alpha = R_s i_\alpha + \frac{d}{dt}\left(L_0 - L_1 + L_1 \cos 2\theta_e\right) i_\alpha + \frac{d}{dt} L_1 i_\alpha + \frac{d}{dt} L_1 i_\beta \sin 2\theta_e - \omega_e \psi_{pm} \sin\theta_e \quad (2)$$

and

$$u_\beta = R_s i_\beta + \frac{d}{dt}\left(L_0 - L_1 - L_1 \cos 2\theta_e\right) i_\beta + \frac{d}{dt} L_1 i_\beta + \frac{d}{dt} L_1 i_\alpha \sin 2\theta_e + \omega_e \psi_{pm} \cos\theta_e \quad (3)$$

So

$$u_\alpha = R_s i_\alpha + \frac{d}{dt} L_q i_\alpha + \frac{d}{dt}\lambda_\alpha \quad (4)$$

$$u_\beta = R_s i_\beta + \frac{d}{dt} L_q i_\beta + \frac{d}{dt}\lambda_\beta \quad (5)$$

For a salient-pole PMSM, the extended electromotive forces (EEMF) can be given by the following equations:

$$e_\alpha = \dot{\lambda}_\alpha = -\left(2L_1 \omega_e i_d + \omega_e \psi_{pm}\right)\sin\theta_e \quad (6)$$

$$e_\beta = \dot{\lambda}_\beta = \left(2L_1 \omega_e i_d + \omega_e \psi_{pm}\right)\cos\theta_e \quad (7)$$

The motor speed changes slowly during one estimation period, i.e., $\dot{\omega}_e = 0$, then the λ_α and λ_β can be simply written as

$$\lambda_\alpha = \left(2L_1 i_d + \psi_{pm}\right)\cos\theta_e \quad (8)$$

$$\lambda_\beta = \left(2L_1 i_d + \psi_{pm}\right)\sin\theta_e \quad (9)$$

It can be seen from (8) and (9) that the EEMF signal contains the information of rotor speed and position. Therefore, after the EEMF signal is estimated by using the observer, the information of rotor speed and position can be obtained.

It should be noted that the EEMF exist if $i_d \neq \frac{\psi_{pm}}{L_q - L_d}$.

III. Sliding mode observer

In order to estimate the rotor position, the SMO is based on a stator current estimator using discontinuous control. Due to the fact that only stator currents are directly measurable in a PMSM drive, the sliding surface S(x)=0 is selected on the real stator current trajectory. In this way, when the estimated currents, reach the manifold and then the sliding mode happens and has been enforced, the current estimation error becomes zero and the estimated currents track the real ones regardless of certain disturbances and uncertainties of the drive system.

The sliding mode control design is composed of three steps.

- First, a sliding surface, given by S(x)=0, should be designed.
- Then, the convergence condition must be define.
- Finally, the control law have to be determined.

A. The conventional SMO

The electrical equations of PMSM model in the stationary reference frame *(α, β)* may be formulated as follows using the EEMF:

$$\begin{bmatrix} \lambda_\alpha \\ \lambda_\beta \end{bmatrix} = \begin{bmatrix} -L_q i_\alpha \\ -L_q i_\beta \end{bmatrix} + \int \begin{bmatrix} u_\alpha - R_s i_\alpha \\ u_\beta - R_s i_\beta \end{bmatrix} \quad (10)$$

Furthermore

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{L_q}\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} - \frac{R_s}{L_q}\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} - \frac{1}{L_q}\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} \quad (11)$$

By using the mathematical model of PMSM in the stationary reference frame, the SMO can be shown as follows:

$$\begin{bmatrix} \dot{\hat{i}}_\alpha \\ \dot{\hat{i}}_\beta \end{bmatrix} = \frac{1}{L_q}\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} - \frac{R_s}{L_q}\begin{bmatrix} \hat{i}_\alpha \\ \hat{i}_\beta \end{bmatrix} - \frac{K_{SM}}{L_q}\begin{bmatrix} sign\left(\hat{i}_\alpha - i_\alpha\right) \\ sign\left(\hat{i}_\beta - i_\beta\right) \end{bmatrix} \quad (12)$$

where K_{SM} is a constant observer gain and

$$sign\left(\hat{i}_\alpha - i_\alpha\right) = \begin{cases} 1 & if \quad \left(\hat{i}_\alpha - i_\alpha\right) > 0 \\ 0 & if \quad \left(\hat{i}_\alpha - i_\alpha\right) = 0 \\ -1 & if \quad \left(\hat{i}_\alpha - i_\alpha\right) < 0 \end{cases}$$

The current errors between estimated currents and actual ones, along the sliding surface are defined as

$$\begin{bmatrix} \dot{\tilde{i}}_\alpha \\ \dot{\tilde{i}}_\beta \end{bmatrix} = -\frac{R_s}{L_q}\begin{bmatrix} \tilde{i}_\alpha \\ \tilde{i}_\beta \end{bmatrix} + \frac{1}{L_q}\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} - \frac{K_{SM}}{L_q}\begin{bmatrix} sign\left(\tilde{i}_\alpha\right) \\ sign\left(\tilde{i}_\beta\right) \end{bmatrix} \quad (13)$$

where $\tilde{i}_\alpha$ and $\tilde{i}_\beta$ are the observation errors given by

$$\tilde{i}_\alpha = \hat{i}_\alpha - i_\alpha, \quad (14)$$

$$\tilde{i}_\beta = \hat{i}_\beta - i_\beta. \quad (15)$$

In order to verify the stability of the SMO, a Lyapunov function V is selected as

$$V = \frac{1}{2}\left(\tilde{i}_\alpha^2 + \tilde{i}_\beta^2\right) \quad (16)$$

The derivative function is given by:

$$\begin{aligned} \dot{V} &= \tilde{i}_\alpha \dot{\tilde{i}}_\alpha + \tilde{i}_\beta \dot{\tilde{i}}_\beta \\ &= -\frac{R_s}{L_q}\left(\tilde{i}_\alpha^2 + \tilde{i}_\beta^2\right) + \frac{1}{L_q}\left(e_\alpha \tilde{i}_\alpha + e_\beta \tilde{i}_\beta\right) - \frac{K_{SM}}{L_q}\left(\left|\tilde{i}_\alpha\right| + \left|\tilde{i}_\beta\right|\right) \end{aligned} \quad (17)$$

The sliding mode exists if $\dot{V} < 0$.
As

$$-\frac{R_s}{L_q}\tilde{i}_\alpha^2 \le 0$$

and

$$-\frac{R_s}{L_q}\tilde{i}_\beta^2 \le 0$$

Therefore we have to verify the following inequality

$$\frac{e_\alpha \tilde{i}_\alpha}{L_q} - \frac{K_{SM}}{L_q}\left|\tilde{i}_\alpha\right| + \frac{e_\beta \tilde{i}_\beta}{L_q} - \frac{K_{SM}}{L_q}\left|\tilde{i}_\beta\right| < 0 \quad (18)$$

Equation (18) shows that, if K_{SM} is large enough, i.e.,

$$K_{SM} > \max\left\{\left|e_\alpha\right|, \left|e_\beta\right|\right\} \quad (19)$$

then $\dot{V} < 0$ is always guaranteed until $\tilde{i}_\alpha = 0$ and $\tilde{i}_\beta = 0$.

In order to force the convergence of the observed current values to the measured ones, the desired error values between the observed and actual current values in the stationary reference frame are set to zero. Then we apply the control scheme presented in Fig. 1. Once the sliding surface is reached and the observation error tends to zero, the extended electromotive force can be given by the following equations:

$$e_\alpha = K_{SM}\, sign_{eq}\left(\tilde{i}_\alpha\right) \quad (20)$$

$$e_\beta = K_{SM}\, sign_{eq}\left(\tilde{i}_\beta\right) \quad (21)$$

where $sign_{eq}$ (.) represents the sign function on the sliding surface.

Low-pass filters are used to extract e_α and e_β. Finally, the rotor position is obtained by

$$\hat{\theta}_e = -\tan^{-1}\left(\frac{e_\alpha}{e_\beta}\right) = -\tan^{-1}\left(\frac{K_{SM}\, sign_{eq}\left(\tilde{i}_\alpha\right)}{K_{SM}\, sign_{eq}\left(\tilde{i}_\beta\right)}\right) \quad (22)$$

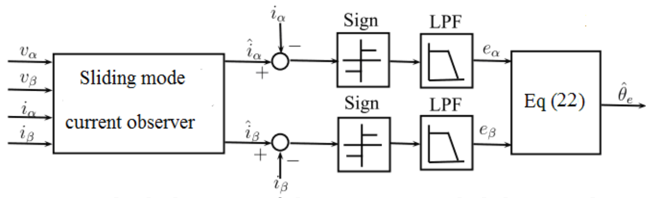

Fig. 1. Block diagram of the conventional sliding mode observer.

In the ideal case, i.e., when the system is stable, the trajectory given by the observation errors slides on the sliding surface. But using the sliding mode observer presented above and owing to the delay due to the switching time, the estimated currents fluctuate around the actual ones. This phenomenon is called chattering. It affects the control accuracy by causing oscillation or instability and degrading the system performance. Thus, the improved SMO is proposed to eliminate this tuning process.

B. The improved SMO

In order to reduce the chattering phenomenon, the sign function is replaced by a continuous function, i.e., the sigmoid function which is defined as

$$\begin{bmatrix} H\left(\tilde{i}_\alpha\right) \\ H\left(\tilde{i}_\beta\right) \end{bmatrix} = \begin{bmatrix} \left(\dfrac{2}{1+e^{-a\tilde{i}_\alpha}}\right) - 1 \\ \left(\dfrac{2}{1+e^{-a\tilde{i}_\beta}}\right) - 1 \end{bmatrix} \quad (23)$$

where *a* is positive constant used to adjust the slope of the sigmoid function. It acts on the reaching mode, i.e., by revising *a*, the time and speed of the points reaching the sliding surface can be changed.

Then, the SMO can be rewritten as

$$\begin{bmatrix} \dot{\hat{i}}_\alpha \\ \dot{\hat{i}}_\beta \end{bmatrix} = \frac{1}{L_q}\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} - \frac{R_s}{L_q}\begin{bmatrix} \hat{i}_\alpha \\ \hat{i}_\beta \end{bmatrix} - \frac{1}{L_q}\begin{bmatrix} kH\left(\hat{i}_\alpha - i_\alpha\right) \\ kH\left(\hat{i}_\beta - i_\beta\right) \end{bmatrix} \quad (24)$$

The sliding surface can be defined as follows

$$S_n = \left[s_\alpha \quad s_\beta\right]^T = \left[\tilde{i}_\alpha \quad \tilde{i}_\beta\right]^T = 0 \quad (25)$$

In order to verify the stability of the SMO, the Lyapunov function is defined as

$$V = \frac{1}{2}S_n^T S_n = \frac{1}{2}\left(\tilde{i}_\alpha^2 + \tilde{i}_\beta^2\right) \quad (26)$$

Then the stability condition of the SMO is as follows:

$$\dot{V} = S_n^T \dot{S}_n < 0 \quad (27)$$

The stability condition of SMO can be derived as:

$$\dot{V} = -\frac{R_s}{L_q}\left(\tilde{i}_\alpha^2 + \tilde{i}_\beta^2\right) + \frac{1}{L_q}\left(e_\alpha \tilde{i}_\alpha - k\tilde{i}_\alpha H\left(\tilde{i}_\alpha\right)\right) + \frac{1}{L_q}\left(e_\beta \tilde{i}_\beta - k\tilde{i}_\beta H\left(\tilde{i}_\beta\right)\right)$$

As a result, if $k > \max\left(\left|e_\alpha\right|, \left|e_\beta\right|\right)$, then we can ensure both the existence of sliding motion and the asymptotical stability of sliding motion in the global scope. The EEMF can be given by

$$\hat{e}_\alpha = k\left(H\left(\tilde{i}_\alpha\right)\right)eq \quad (28)$$

$$\hat{e}_\beta = k\left(H\left(\tilde{i}_\beta\right)\right)eq \tag{29}$$

Then the chattering problem is solved by using the proposed observer presented in Fig. 2 where the sigmoid function is used as a switching function. This function is characterized by an operating range given by $\left(-1 < H\left(\tilde{i}_\alpha\right) < 1\right)$ and $\left(-1 < H\left(\tilde{i}_\beta\right) < 1\right)$ while the sign function is either -1 or 1.

Using the estimated EEMF voltages, the position and velocity of the rotor are calculated from

$$\hat{\theta}_e = -\tan^{-1}\left(\frac{e_\alpha}{e_\beta}\right) = -\tan^{-1}\left(\frac{\left(kH\left(\tilde{i}_\alpha\right)\right)_{eq}}{\left(kH\left(\tilde{i}_\beta\right)\right)_{eq}}\right) \tag{30}$$

$$\hat{\omega}_e = \frac{d}{dt}\hat{\theta}_e \tag{31}$$

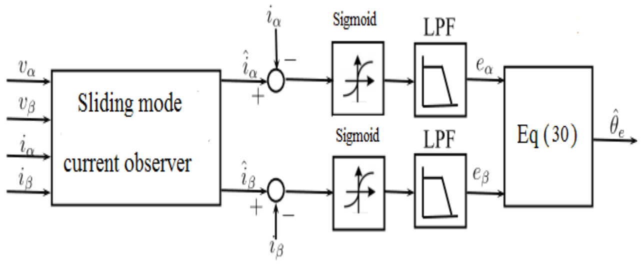

Fig. 2. Block diagram of the improved sliding mode observer.

IV. Simulation Results

In order to be validated, the sliding mode observer must provide good speed measurements for all the operating points of the motor. The synchronous motor is driven through a Field Oriented Control (FOC). The speed controller imposes the rotor speed whatever the load torque is provided by the DC motor. PI controllers are used for the control of the currents. The SMO provides the speed and position estimates which are used in Park's transformation.

A SPMSM, whose parameters are shown in Table. I, is used for simulation tests. The SMO has been implemented in the Matlab/Simulink programming environment. Several tests can be performed to investigate the observer validation.

Table I. Nominal parameters of synchronous machine

Features	**Values**
Pole pair	*3*
d-axis inductance	*0.77e-3 mH*
q-axis inductance	*0.77e-3 mH*
Stator resistance	*0.2525 Ω*
Permanent magnet flux	*0.075 Wb*

Fig.3 presents the response of the machine towards a full-load torque application at the nominal speed (628r/min). The load was applied to the machine at $t = 1s$ and was then removed at $t = 2s$. The estimated rotor position is nearly coincides with the actual one. Consequently, the sliding mode observer improves the accuracy of rotor position estimation.

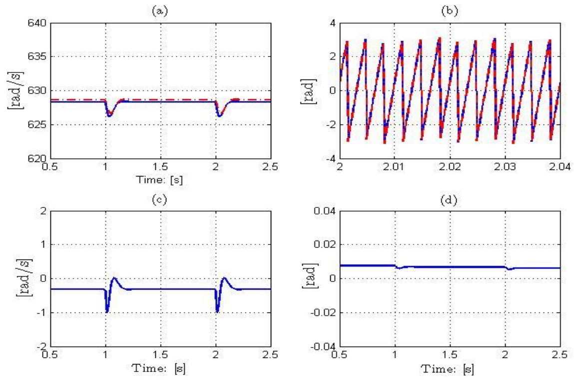

Fig. 3. Rated load-torque step at *628r/min*: (a) actual and estimated rotor speed (b) actual and estimated rotor position (c) speed estimation error (d) position estimation error.

In Fig.4, we tested the response of the motor at low speed due to nominal load-torque steps. The load was applied to the machine at $t = 1s$ and was then removed at $t = 2s$. We observe that the estimated speed and the estimated position track the actual speed and the actual position respectively with a very small error during the load dynamics. Therefore, this observer seems to be able to operate even at a low speed with full load.

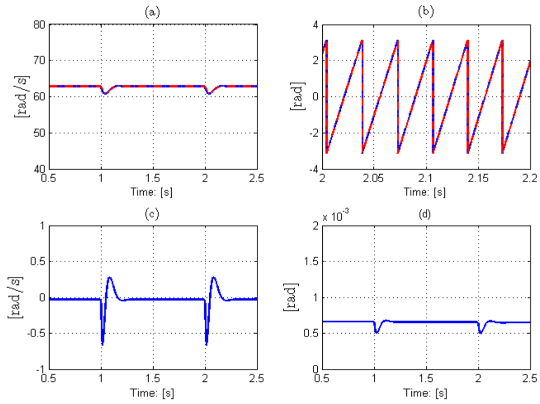

Fig. 4. Rated load-torque step at low speed: (a) actual and estimated rotor speed (b) actual and estimated rotor position (c) speed estimation error (d) position estimation error.

On Fig.5 and Fig.6 we reviewed the cases of speed step with full load. The high-speed dynamics response is shown in Fig.5. The estimated speed follows the actual speed with small error during the transition to the high speed field. We observed the same thing at low-speed in Fig.6.

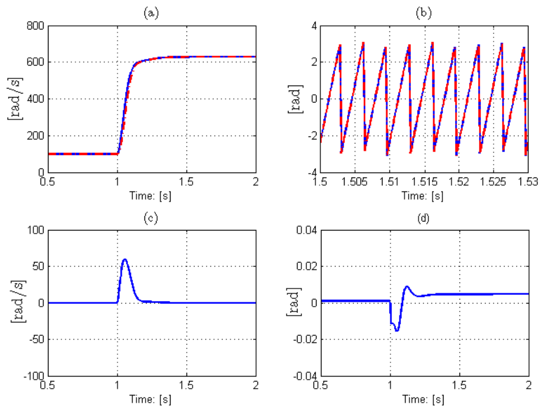

Fig. 5. High speed step at *t=1s* with full load: (a) actual and estimated rotor speed (b) actual and estimated rotor position (c) speed estimation error (d) position estimation error.

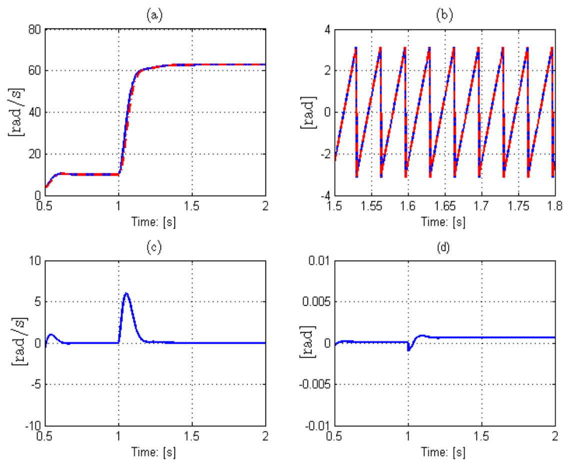

Fig. 6. Low speed step at *t=1s* with full load: (a) actual and estimated rotor speed (b) actual and estimated rotor position (c) speed estimation error (d) position estimation error.

V. CONCLUSION

In this paper, an improved sliding mode observer is presented. The sigmoid function instead of the sign function is applied to the SMO to weaken the inherent chattering problem and increase estimation accuracy of the rotor position. This observer exhibits the following advantages:

- it is based on the extended electromotive forces which can be applied to all types of synchronous machines,
- it uses only two parameters of the machine: the stator resistance R_s and the stator inductance L_q.
- it does not use the machine speed as input.

Simulation results show the robustness of the SMO and demonstrate the effectiveness of the approach.

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