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Sliding-Mode Observer for Speed and Position Sensorless Control of Linear-PMSM

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Abstract **– The paper presents a sliding-mode observer that utilizes sigmoid function for speed and position sensorless control of permanent-magnet linear synchronous motor (PMLSM). In conventional sliding mode observer method there are the chattering phenomenon and the phase lag. Thus, in order to avoid the usage of the low pass filter and the phase compensator based on back EMF, in this paper a sliding mode observer with sigmoid function for detecting the back EMF in a PMLSM is designed to estimate the speed and the position of the rotor. Most of conventional sliding mode observers use sign or saturation functions which need low pass filter in order to detect back electromotive force (back EMF). In this paper a sigmoid function is used instead of discontinuous sign function to decrease undesirable chattering phenomenon. By reducing the chattering, detecting of the back EMF can be made directly from switching signal without any low pass filter. Thus the delay time in the proposed observer is eliminated because of the low pass filter. Furthermore, there is no need to compensate phase fault in position and speed estimating of linear-PMSM. Advantages of the proposed observer have been shown by simulation with MATLAB software.**

Keywords **– Permanent magnet motors; Motor drives; Observers; Sliding mode control; Sensorless control.**

I. INTRODUCTION

Permanent magnet linear synchronous motors (PMLSMs) are used widely in systems which need linear drives. They are good alternatives for rotary motors operating with mechanical converters to produce linear movement. The main reasons of absorbing many attentions by PMLSMs are larger power density, high efficiency as well as better time response due to the magnetic field that is absent in linear induction motors [1] - [5]. Researches of vector control are divided into two major groups: 1) Field oriented control approach which is analyzed completely in [5]. This method is sensitive to variation of parameters and its equations are obtained from complex transformations. 2) Direct torque and flux control (DTC and DFC) approach which is accepted as a form of vector control methods beside vector current control. This control approach carries out a strong operation in both of transient and steady state and has a structure which responses fast and robust to the variation of parameters. It does not have complexity of first method and can be feasible [6], [7]. There are three techniques for direct torque and flux control: 1) Switching table, 2) Direct self-control, 3) Space vector modulation. From these mentioned method, switching table is widely used because it is easily feasible. Furthermore it does not need to complicate the technique of modulation. In [8], [9] DTC approach for rotary synchronous motor has been turned into a PMLSM successfully. This control method pays special attention to estimating the flux, speed and position of the motor. There are two ways for estimating the flux: 1) Estimation based on the current of motor, 2) Estimation based on voltage of motor. The drawback of the first way is that a change of rotary speed leads to a change in the values of parameters. In the second one, the linkage flux is given directly by the electromotive force with an integrator, so there is no need in speed signal. It means that the second way is better and more complete than the first one [7], [8].

Sensorless control is divided into two main types: 1) Estimation with the use of observers, 2) Signal injection method. Comparative methods, Kalman filter and sliding mode are some of estimating methods that are based on observers. In general, the first type methods depend on the precision of the motor's model, especially the comparative methods. In other words, as the model of the motor is accurate, efficacy of this method will be improved. Kalman filter method requires a large amount of calculations. In order to reduce the time of the computations, the system must be improved by the hardware, but it is not affordable. Among the mentioned methods for estimation based on observers, sliding mode with sign function has a simple algorithm and is firm against disturbances, fault of parameters and noise. In this way, the back EMF is given by sliding mode observer. But, they also have high frequency components, though they cannot be used to compute the velocity and position of the rotor. In conventional sliding mode observers, a low pass filter is used for operation of filtering, but using of the low pass filter causes a lag of phase that depends on the angular frequency of the input signal and on the cut frequency of the filter. In order to compensate the phase lag completely, the received information from the real angular velocity must be used and the information given by the estimated angular velocity is not enough for compensating [10] - [14].

In sliding mode observer, the dynamic behavior of the system is determined by the switching level and is independent of non-deterministic events and exoteric faults. Experimentally, the constraint of the switching frequency leads to the fact that the states of the system do not stay on the switching level and fluctuate around it. These fluctuations are called chattering which is an undesirable phenomenon. It increases control activities and excites the high frequency dynamics of the system, so that the low pass filter is needed for decreasing the chattering phenomenon effects.

As it is mentioned above, the conventional sliding mode observer method has the chattering phenomenon and the phase lag. Thus, in order to avoid the using of the low pass filter and the phase compensator based on back EMF, in this paper a sliding mode observer with sigmoid function for detecting the back EMF in a PMLSM is designed to estimate the speed and the position of the rotor. Overview of direct thrust force control & the mathematical model of PMLSM is given in section 2. In section 3 the proposed sliding mode observer design is presented. Section 4 presents estimation rotor position and velocity using the proposed method. The simulation result is presented in section 5. The last section 6 presents summary and conclusions.

II. Direct Thrust Force Control & Mathematical Model of PMLSM

Direct thrust force control (DTFC) method is a version of DTC for the linear motors. Its only difference compared with common DTC is that it deals with linear velocity and thrust force instead of the angular velocity and torque. The DTC/DTFC provides quick electromagnetic torque / thrust force response of the motor. The common vector control utilizes the stator current vector to alter the torque / thrust force. In contrast, the control variable of the DTC is the stator flux linkage vector. The structure of the DTFC controller is presented in Fig.1. As it is seen from this picture, the regulation of the flux linkage is finally provided by VSI by means of the optimal operation of its power switches [7], [13].

In order to obtain the PMLSM model in dq reference frame, first the stator voltage equation should be introduced [6]:

$$u_d(t) = Ri_d + \frac{d\psi_d}{dt} - \omega\psi_q\,, \tag{1}$$

$$u_q(t) = Ri_q + \frac{d\psi_q}{dt} - \omega\psi_d \quad \text{and} \tag{2}$$

$$\omega = \frac{\pi}{\tau}\upsilon_{lin}\,, \tag{3}$$

where u_d and u_q are components of voltage space vector, but i_d and i_q are the components of current space vector across the d and q axis. At the same time R is the phase resistance of armature.

The linkage fluxes ψ_d and ψ_q in the above equations are yielded from these ones:

$$\psi_d = L_d i_d + \psi_{PM} \quad \text{and} \tag{4}$$

$$\psi_q = L_q i_q\,, \tag{5}$$

where L_d and L_q are the inductance of armature and ψ_{PM} is the linkage flux of permanent magnet.

The input three phase instant power of armature p is obtained by the following:

$$P = u_A i_A + u_B i_B + u_C i_C = \frac{3}{2}\left(u_d i_d + u_q i_q\right), \tag{6}$$

where u_A, u_B and u_C are the instant phase voltages, i_A, i_B and i_C are the instant phase currents, u_d and u_q are the d and q axis voltages, i_d and i_q are the d and q axis currents.

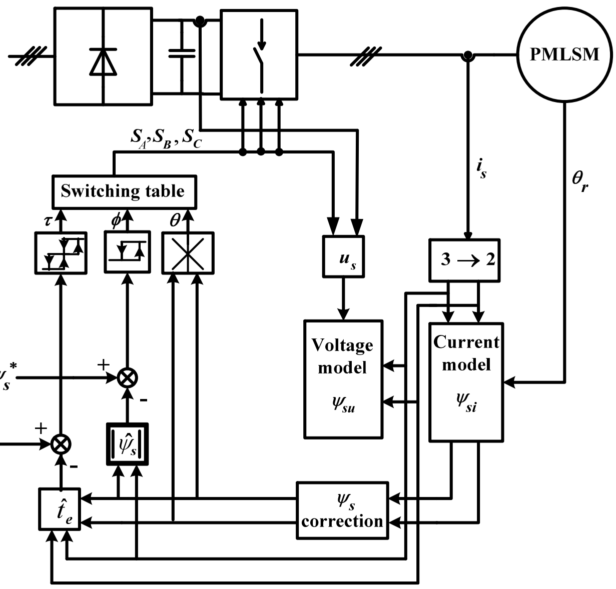


Fig. 1. DTFC block diagram.

By using the stator voltage equations, the power equation is expressed as:

$$u_d i_d + u_q i_q = Ri_d^2 + \frac{d\psi_d}{dt}i_d + Ri_q^2 + \frac{d\psi_q}{dt}i_q + \\ + \omega(\psi_d i_d - \psi_q i_q)\,, \tag{7}$$

where the last component is the electromagnetic power of two poles synchronous machine in each phase. In three phase machines, the power equation is:

$$P_{elm} = \frac{3}{2}\omega\left(\psi_d i_q - \psi_q i_d\right) = \frac{3}{2}\left(\psi_{PM} + \left(L_d - L_q\right)i_d\right)i_q\,. \tag{8}$$

The electromagnetic thrust of PMLSM F_{thrust} with p pair poles is concluded from (3) and (8) as follows:

$$F_{thrust} = \frac{3}{2}p\frac{\pi}{\tau}(\psi_d i_q - \psi_q i_d) = \\ = \frac{3}{2}p\frac{\pi}{\tau}\left(\psi_{PM} + (L_d - L_q)\,i_d\right)i_q\,. \tag{9}$$

Equations (1)-(5) and (9) is the base of PMLSM model and its equations are as follows:

$$\begin{aligned} \frac{di_\alpha}{dt} &= -\frac{R_s}{L_s}i_\alpha - \frac{1}{L_s}e_\alpha + \frac{1}{L_s}u_\alpha \\ \frac{di_\beta}{dt} &= -\frac{R_s}{L_s}i_\beta - \frac{1}{L_s}e_\beta + \frac{1}{L_s}u_\beta \\ e_\alpha &= -\psi_{PM}\,\omega\sin\theta \\ e_\beta &= -\psi_{PM}\,\omega\cos\theta \end{aligned} \quad . \tag{10}$$

In motion control application, nonlinear elements in a linear motor cause insignificant errors in tracking or increase settling time. So, they must be considered carefully to prevent their negative effects. The dynamic behaviour of the linear motor can be expressed as:

$$F_{thrust} = m_{tot} \frac{d\upsilon_{lin}}{dt} + F_{load}(t) + F_{friction}(\upsilon_{lin}) + F_{disturb}(x), \quad (11)$$

where m_{tot} is the total mass of the mover and the load, υ_{lin} is the linear velocity of the mover, $F_{friction}$ is the friction force which is caused by viscosity, coulomb and static effects, F_{load} is the extra force which is produced by the load and $F_{disturb}$ is the force which includes cogging and end effect.

III. The Proposed Sliding Mode Observer

The equations which are used in a conventional sliding mode observer are written as (10). By using mathematical model of PMLSM and defining slip level as $S=\hat{i}_s - i_s=0$ the equations are written as follows [15]-[17]

$$L_s \frac{di_\alpha}{dt} = -R_s \hat{i}_\alpha + u_\alpha - k\ \text{sign}\left(\hat{i}_\alpha - i_\alpha\right)$$
$$L_s \frac{di_\beta}{dt} = -R_s \hat{i}_\beta + u_\beta - k\ \text{sign}\left(\hat{i}_\beta - i_\beta\right) \quad . \quad (12)$$

In the above analysis due to the chattering reduction it is possible to substitute a continuous function for the sign function. The continuous function is defined as:

$$F(x) = \left[\frac{2}{\left(1+e^{-\alpha x}\right)}\right] - 1, \quad (13)$$

where α is the adjustable value. By defining the continuous function as above, the sliding mode observer equation is rewritten as:

$$L_s \frac{d\hat{i}_\alpha}{dt} = -R_s \hat{i}_\alpha + u_\alpha - kF\left(\hat{i}_\alpha - i_\alpha\right)$$
$$L_s \frac{d\hat{i}_\beta}{dt} = -R_s \hat{i}_\beta + u_\beta - kF\left(\hat{i}_\beta - i_\beta\right) \quad . \quad (14)$$

For stability analysis of the above sliding mode observer, Lyapunov function is chosen as:

$$V = \frac{1}{2} S(X)^T S(X) \quad . \quad (15)$$

Requisite condition for stability of sliding mode observer is obtained as follows:

$$\dot{V} = S(X)^T \dot{S}(X) \le 0 \quad . \quad (16)$$

By subtracting (10) from (14), the error equation is concluded:

$$L_s \left[\frac{dS_\alpha(X)}{dt}\right] = -R_s S_\alpha(X) + e_\alpha - kF\left(\hat{i}_\alpha - i_\alpha\right)$$
$$L_s \left[\frac{dS_\beta(X)}{dt}\right] = -R_s S_\beta(X) + e_\beta - kF\left(\hat{i}_\beta - i_\beta\right). \quad (17)$$

S(X) is defined as:

$$S(X) = \begin{bmatrix} S_\alpha(X) \\ S_\beta(X) \end{bmatrix} = \begin{bmatrix} \hat{i}_\alpha - i_\alpha \\ \hat{i}_\beta - i_\beta \end{bmatrix} \quad . \quad (18)$$

By derivative from the above equation, the stability condition is as follows:

$$\begin{aligned} \dot{V} &= S(X)^T \dot{S}(X) = S_\alpha \dot{S}_\alpha + S_\beta \dot{S}_\beta \\ &= \frac{1}{L_s}\left[\left(\hat{i}_\alpha - i_\alpha\right)e_\alpha - k\left(\hat{i}_\alpha - i_\alpha\right)F\left(\hat{i}_\alpha - i_\alpha\right)\right] \\ &+ \frac{1}{L_s}\left[\left(\hat{i}_\beta - i_\beta\right)e_\beta - k\left(\hat{i}_\beta - i_\beta\right)F\left(\hat{i}_\beta - i_\beta\right)\right] \\ &- \frac{R_s}{L_s}\left[\left(\hat{i}_\alpha - i_\alpha\right)^2 + \left(\hat{i}_\beta - i_\beta\right)^2\right] \le 0 \quad . \end{aligned} \quad (19)$$

Thereupon:

$$k > \max\left(|e_\alpha||e_\beta|\right). \quad (20)$$

As k is high enough, the asymptotic stability and slip movement seems certain. When the system is getting to the slip level:

$$\dot{S}(X) = S(X) = 0. \quad (21)$$

By putting above equation in (17), which is based on equivalent control way, the following are given:

$$e_\alpha = kF\left(\hat{i}_\alpha - i_\alpha\right)$$
$$e_\beta = kF\left(\hat{i}_\beta - i_\beta\right) \quad . \quad (22)$$

IV. Estimation Rotor Position and Speed with Proposed Method

Back EMF can be obtained by the described sliding mode observer, but the signals still include high frequency components. Therefore, they can not be used directly to estimate the rotor position and speed. In a conventional sliding mode observer a low pass filter is used for filtering operation causing the phase lag that depends on the cut frequency and the input signal angular one. In order to compensate the phase lag completely the acquired information from the real linear speed must be used and the information given by the estimated linear speed is not enough for the compensating. Thus, to avoid the use of the low pass filter and the phase compensator based on back EMF, a sliding mode observer for detecting the back EMF in a PMLSM is designed to estimate the speed and the position of the rotor. As the changes of the motor linear speed are less than those of the stator's current, it is assumed that $\dot{\omega}=0$. So, back EMF of PMLSM can be expressed as:

$$\frac{de_\alpha}{dt} = -\omega e_\beta$$
$$\frac{de_\beta}{dt} = -\omega e_\alpha . \quad (23)$$

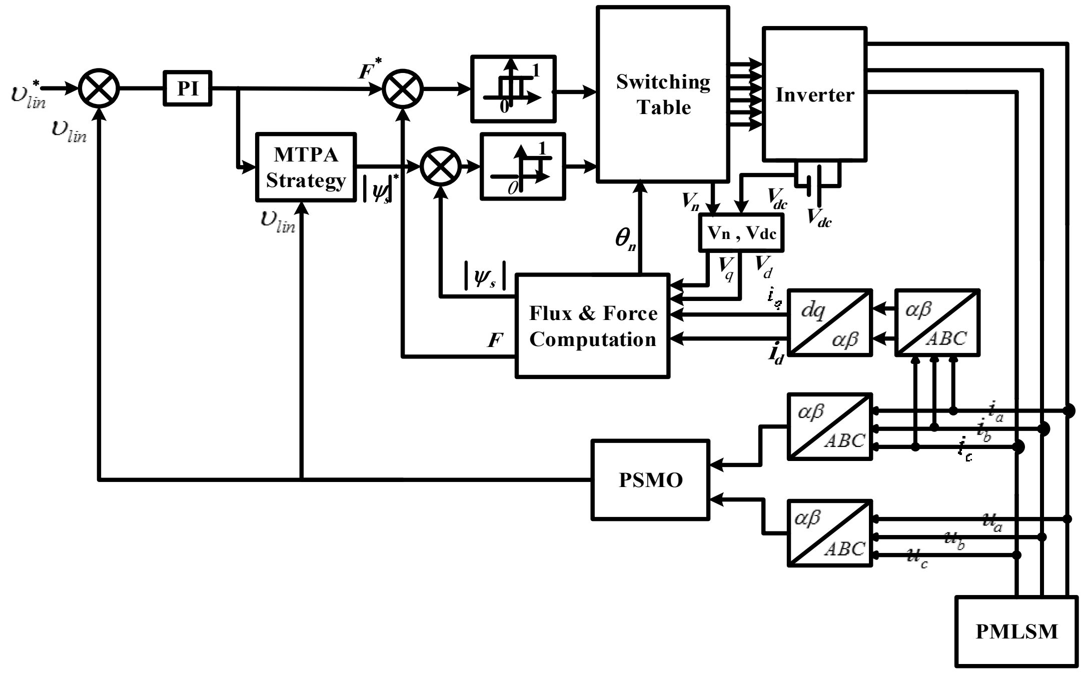


Fig. 2. Block diagram of the PMLSM sensorless control.

In consideration of above equation, the back EMF observer is designed which is based on the following:

$$\frac{d\hat{e}_\alpha}{dt} = -\hat{\omega}\hat{e}_\beta - l\left(\hat{e}_\alpha - e_\alpha\right)$$
$$\frac{d\hat{e}_\beta}{dt} = -\hat{\omega}\hat{e}_\beta - l\left(\hat{e}_\beta - e_\beta\right)$$
$$\frac{d\hat{\omega}}{dt} = \left(\hat{e}_\alpha - e_\alpha\right)\hat{e}_\beta - \left(\hat{e}_\beta - e_\beta\right)\hat{e}_\alpha , \tag{24}$$

where l is the gain of the observer (>1).

The equation of the observer error can be obtained by subtracting (23) from (24):

$$\frac{d\tilde{e}_\alpha}{dt} = -\tilde{\omega}\hat{e}_\beta - \omega\tilde{e}_\beta - l\tilde{e}_\alpha$$
$$\tilde{\omega}=\acute{\omega}-\omega \quad \frac{d\tilde{e}_\beta}{dt} = -\tilde{\omega}\hat{e}_\alpha - \omega\tilde{e}_\alpha - l\tilde{e}_\beta$$
$$\frac{d\tilde{\omega}}{dt} = \tilde{e}_\alpha\hat{e}_\beta - \tilde{e}_\beta\hat{e}_\alpha \quad , \tag{25}$$

where $\tilde{e}_\alpha=\hat{e}_\alpha-e_\alpha$, $\tilde{e}_\beta=\hat{e}_\beta-e_\beta$ and $\tilde{\omega}=\acute{\omega}-\omega$.

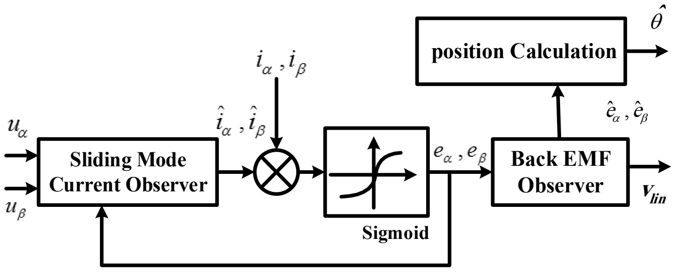


Fig. 3. Block diagram of the purposed sliding mode observer (PSMO).

Since (24) is stable, it is possible to define Lyapunov function as follows:

$$V = \frac{\left(\tilde{e}_\alpha^2 + \tilde{e}_\beta^2 + \tilde{\omega}^2\right)}{2} . \tag{26}$$

Derivative from the above equation is led to:

$$\dot{V} = \tilde{e}_\alpha\dot{\tilde{e}}_\alpha + \tilde{e}_\beta\dot{\tilde{e}}_\beta + \tilde{\omega}\dot{\tilde{\omega}} . \tag{27}$$

Inserting (25) in (27) produces:

$$\dot{V} = -l\left(\tilde{e}_\alpha^2 + \tilde{e}_\beta^2\right) \le 0 . \tag{28}$$

The mentioned equation proves the fact that the proposed back EMF observer is asymptotic stable. Therefore, the use of the back EMF obtained from the observer, as well as the use of the relationship of the back EMF and state of the rotor, allows estimating the position signal as:

$$\hat{\theta} = -\arctan\left(\frac{\hat{e}_\alpha}{\hat{e}_\beta}\right) . \tag{29}$$

The speed is obtained easily by using an integrator in the observer. The overall scheme of the PMLSM sensorless control and the block diagram of the purposed sliding mode observer (PMSO) are shown in sequence in Fig. 2 and Fig. 3. In the first one, it must be noticed that the input of the sliding mode observer comes from the motor's voltage and the output voltages of the current loop u_α^* and u_β^* are not used. Usage of

u_α and u_β reduces relatively the dead time effect in the inverter. So, the motor's voltage is obtained more precisely and thus estimates accuracy of the motor position and speed are improved.

V. Simulation Results

The parameters given by the manufacturer of the motor [18] and inverter parameters are presented in Table I.

The step function is considered as a reference signal. The speed which is estimated by a sliding mode observer has been shown in Fig. 4. Chattering phenomenon in these types of observers which use discontinuous sign function is seen obviously [19], [20].

The speed which is estimated by the proposed sliding mode observer has been shown in Fig 5. As it is seen, comparison with conventional observers, chattering phenomenon is reduced effectively. Moreover, low pass filter and phase lag compensator are not required.

Fig.6 shows acceleration of the mover in order for a conventional observer and the proposed sliding mode. Fig. 7 shows the force which has been developed by the mover considering the end effects of the cogging and friction forces. Comparison of Fig. 7 (a) [16] with Fig. 7 (b) shows that the reference and estimated forces in system which uses the proposed sliding mode observer is more accurate than others which use conventional ones, because choosing continuous function instead of discontinuous sign function leads to eliminate chattering phenomenon.

Fig. 8 shows the current of the system which uses the proposed sliding mode observer during accelerating time of the mover at the stability speed and when acceleration of the mover is reduced.

TABLE I

Parameters of the Motor Model and Inverter

Symbol	**Value**	**Parameter**
R	1.6 Ω	Phase resistance
L_d	0.013 H	d-axis inductance
L_q	0.013 H	q-axis inductance
p	1	Number of pole pairs
τ	0.012 m	PM pole pitch
ψ_{PM}	0.237 Wb	PM flux linkage
U_N	560 V	Rated voltage inverter
P_N	3.5 kW	Rated power
F_N	1800 N	Rated force
V_{max}	4.5 m/s	Peak speed

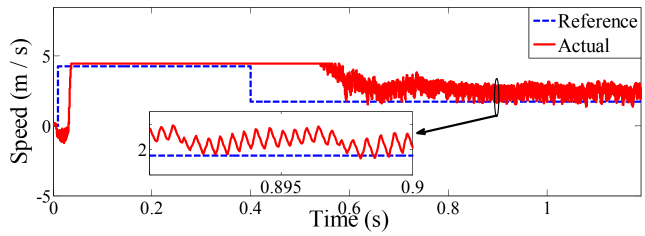


Fig. 4. Speed reference signal and actual speed of the motor by sliding mode observer.

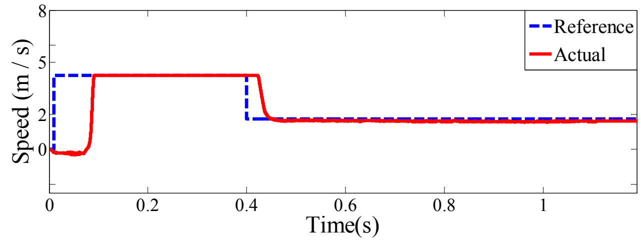
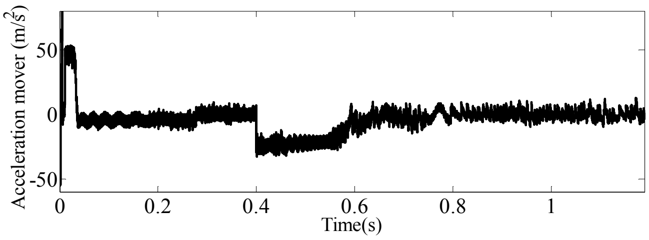
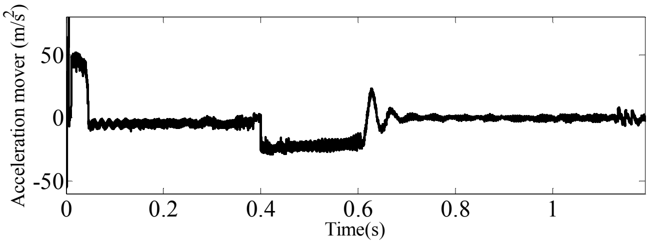


Fig. 5. Speed reference signal and speed actual of the motor by the proposed sliding mode observer.



(a)



(b)

Fig. 6. Acceleration of the mover (a) by using a conventional sliding mode observer (b) by using the proposed sliding mode observer.

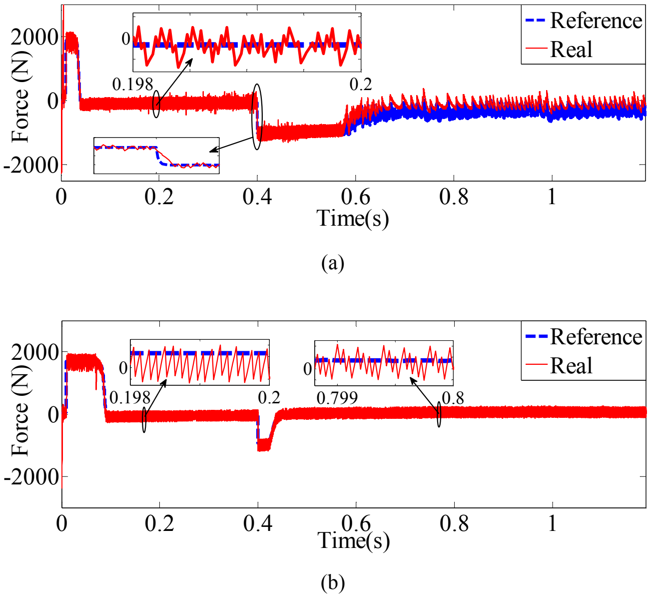


Fig. 7. The produced force of the mover (a) by using a conventional sliding mode observer (b) by using the proposed sliding mode observer.

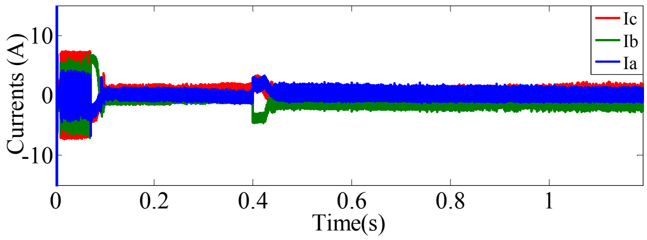


Fig. 8. The currents of PMLSM which uses the proposed sliding mode observer.

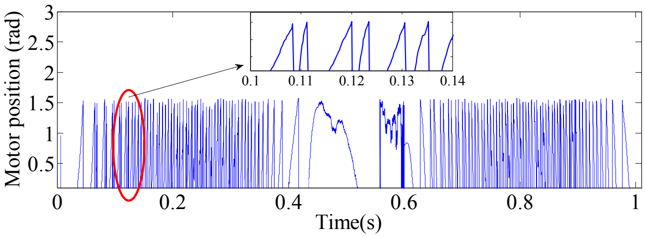


Fig. 9. Position response for the motor.

The position which is estimated by the proposed sliding mode observer has been shown in Fig. 9. It is possible to see that the phenomenon of chattering of the estimated rotor position is reduced. Moreover, low pass filter and phase lag compensator are not required.

VI. Conclusions

In this paper the improved sliding mode observer which uses sigmoid function was proposed for PMLSM sensorless control. The paper illustrates that the use of sigmoid function instead of sign function, that is usual in sliding mode observers, leads to reduce undesirable chattering phenomenon effectively. Reducing chattering phenomenon results in the fact that back EMF can be detected directly from switching signal without any need to low pass filter. So the delay time caused by the presence of low pass filter in the proposed observer is omitted. Moreover, there is no need to compensate phase fault in estimated position. Advantages of the proposed observer over conventional ones have been shown with the results obtained from simulation in MATLAB/Simulink software.

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