Direct Thrust Force and Flux Control of a PM-Linear Synchronous Motor Using Fuzzy Sliding-Mode Observer

Saeed MASOUMI KAZRAJI, Mohammad Bagher BANNAE SHARIFIAN

Electrical Power Department, Faculty of Electrical and Computer Engineering, University of Tabriz, 29 Bahman Blvd, 5166616471 Tabriz, Iran

masoumikazraji@tabrizu.ac.ir, sharifian@tabrizu.ac.ir

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Abstract. *In this paper, a fuzzy sliding-mode observer, which uses sigmoid function for speed sensorless control of permanent-magnet linear synchronous motor (PMLSM) is proposed. Most of the observers use sign or saturation functions that need low pass filter in order to detecting back electromotive force. In this paper, the sigmoid function is used instead of discontinuous sign function to decrease undesirable chattering phenomenon. By reducing the chattering, detecting back EMF can be done directly from switching signal without any low pass filter. So the delay time because of low pass filter, in the proposed observer is eliminated. Furthermore, there is no need to compensate phase fault in position estimating. The simulation results show advantages of proposed observer over conventional ones.*

Keywords

Direct Thrust Force and Flux Control (DTFC), Fuzzy Logic Control (FLC), Permanent Magnet Linear Synchronous Motor (PMLSM), Sliding Mode Observer (SMO).

1. Introduction

Permanent-magnet linear synchronous motors (PMLSMs) are used widely in systems that need linear drives. They are good alternatives for rotary motors that work with mechanical converters to producing linear movement. The main reasons of absorbing many attentions by PMLSMs are larger power density, high efficiency and faster response due to the presence of the magnetic field that linear induction motors do not have [1], [2], [3], [4] and [5].

Direct thrust force and flux control (DTFC) approach that is accepted as a form of vector control methods beside vector current control. This control approach carries out a strong operation in both of the transient and steady state and has a structure that responses fast and robust to variation of parameters. It does not have the complexity of field oriented control and can be feasible [6], [7]. In [8] and [9] DTFC approach for rotary synchronous motor has been turned into a PMLSM successfully. In this control method, the estimation of the flux, the position and the speed of the motor are paid much attention. Sensorless control is divided into two main types:

- Estimate with use of observers.
- 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, whatever the model of the motor is accurate; efficacy of this method will be improved. Kalman filter method requires a large amount of computing. In order to reducing the time of the computations, the system must be improved by the hardware, but it is not affordable. Between mentioned methods for estimating based on observers, sliding mode with sign function has a simple algorithm and is firm against disturbances, fault of parameters and noise. In conventional sliding mode observers, a low-pass filter is used to operation of filtering, but using the low-pass filter causes a lag of phase that depends on the cut frequency and the angular frequency of the input signal. In order to compensating the phase lag completely, the received information from the real angular velocity must be used, and the information, which is given by the estimated angular velocity, is not enough for compensating [10], [11], [12]. As it mentioned above, in conventional sliding mode observer method there are the chattering phenomenon and the phase lag. Thus, in order to avoid of using the low pass filter and the phase compensator based on back EMF, in this paper a fuzzy 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 the mathematical model of PMLSM is given in Section 2. In Section 3, the proposed fuzzy sliding mode observer design is presented. Section 4 presents estimation rotor position and velocity by using proposed method. The simulation result is presented in Section 5. Finally, section 6 presents summary and conclusions.

2. Mathematical Model of PMLSM

In order to obtain the PMLSM model in d-q reference frame, first the stator voltage equation should be introduced [13]:

$$u_d(t) = R_s i_d + \frac{\mathrm{d}\psi_d}{\mathrm{d}t} - \omega\psi_q, \tag{1}$$

$$u_q(t) = R_s i_q + \frac{\mathrm{d}\psi_q}{\mathrm{d}t} - \omega\psi_d, \tag{2}$$

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

where u_d and u_q are the d and q axis components of voltage space vector, i_d and i_q are the d and q axis components of current space vector and R_s is the phase resistance of the armature.

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

$$\psi_d = L_d i_d + \psi_{PM}, \tag{4}$$

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

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 follows:

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

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.

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

$$\begin{aligned} u_d i_d + u_q i_q = R_s i_d^2 + \tfrac{\mathrm{d}\psi_d}{\mathrm{d}t} i_d + R_s i_q^2 + \tfrac{\mathrm{d}\psi_q}{\mathrm{d}t} i_q + \\ + \omega\left(\psi_d i_d - \psi_q i_q\right), \end{aligned} \tag{7}$$

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

$$\begin{aligned} P_{elm} &= \tfrac{3}{2}\omega\left(\psi_d i_q - \psi_q i_d\right) = \\ &= \tfrac{3}{2}\left(\psi_{PM} + \left(L_d - L_q\right) i_d\right) i_q. \end{aligned} \tag{8}$$

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

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

The Eq. (1), Eq. (2), Eq. (3), Eq. (4), Eq. (5) and Eq. (9) equations are the bases of PMLSM model. using transformation $d\,q$ reference frame to $\alpha\,\beta$, its equations are as follows:

$$\frac{\mathrm{d}i_\alpha}{\mathrm{d}t} = -\frac{R_s}{L_s} i_\alpha - \frac{1}{L_s} e_\alpha + \frac{1}{L_s} u_\alpha, \tag{10}$$

$$\frac{\mathrm{d}i_\beta}{\mathrm{d}t} = -\frac{R_s}{L_s} i_\beta - \frac{1}{L_s} e_\beta + \frac{1}{L_s} u_\beta, \tag{11}$$

$$e_\alpha = -\psi_{PM}\omega\sin\theta, \tag{12}$$

$$e_\beta = -\psi_{PM}\omega\cos\theta. \tag{13}$$

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 behavior of the linear motor can be expressed as:

$$\begin{aligned} F_{thrust} = m_{tot}\tfrac{\mathrm{d}v_{lin}}{\mathrm{d}t} + F_{load}(t) + \\ + F_{friction}\left(v_{lin}\right) + F_{disturb}(x), \end{aligned} \tag{14}$$

where m_{tot} is the total mass of the mover and the load, v_{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.

3. The Proposed Fuzzy Sliding Mode Observer Design

3.1. The Proposed Sliding Mode Observer

The equations, which are used in a conventional sliding mode observer, are written as Eq. 10. By using a mathematical model of PMLSM and defining slip level as $S = \hat{i}_s - i_s = 0$ the equations are written as follows [14], [15]:

$$L_s \frac{\mathrm{d}i_\alpha}{\mathrm{d}t} = -R_s \hat{i}_\alpha + u_\alpha - k \cdot \mathrm{sign}\left(\hat{i}_\alpha - i_\alpha\right), \qquad (15)$$

$$L_s \frac{\mathrm{d}i_\beta}{\mathrm{d}t} = -R_s \hat{i}_\beta + u_\beta - k \cdot \mathrm{sign}\left(\hat{i}_\beta - i_\beta\right). \qquad (16)$$

Due to reducing the chattering phenomenon, the sign function must be exchanged for a continuous function which is defined as:

$$F(x) = \left[\frac{2}{(1+e^{-\alpha x})}\right] - 1, \qquad (17)$$

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

$$L_s \frac{\mathrm{d}\hat{i}_\alpha}{\mathrm{d}t} = -R_s \hat{i}_\alpha + u_\alpha - k \cdot F\left(\hat{i}_\alpha - i_\alpha\right), \qquad (18)$$

$$L_s \frac{\mathrm{d}\hat{i}_\beta}{\mathrm{d}t} = -R_s \hat{i}_\beta + u_\beta - k \cdot F\left(\hat{i}_\beta - i_\beta\right). \qquad (19)$$

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

$$V = \frac{1}{2}\mathbf{S}(X)^T \mathbf{S}(X). \qquad (20)$$

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

$$\dot{V} = \frac{1}{2}\mathbf{S}(X)^T \dot{\mathbf{S}}(X) \le 0. \qquad (21)$$

By subtracting Eq. (10), Eq. (11), Eq. (12) and Eq. (13) from Eq. (18) and Eq. (19), the error equation is concluded:

$$L_s \left[\frac{\mathrm{d}S_\alpha(X)}{\mathrm{d}t}\right] = \\ = -R_s S_\alpha(X) + e_\alpha - k \cdot F\left(\hat{i}_\alpha - i_\alpha\right), \qquad (22)$$

$$L_s \left[\frac{\mathrm{d}S_\beta(X)}{\mathrm{d}t}\right] = \\ = -R_s S_\beta(X) + e_\beta - k \cdot F\left(\hat{i}_\beta - i_\beta\right). \qquad (23)$$

$\mathbf{S}(X)$ is defined as:

$$\mathbf{S}(X) = \begin{bmatrix} S_\alpha(X) \\ S_\beta(X) \end{bmatrix} = \begin{bmatrix} \hat{i}_\alpha - i_\alpha \\ \hat{i}_\beta - i_\beta \end{bmatrix}. \qquad (24)$$

By derivative from the above equation, the stability condition becomes as Eq. (29), thereupon:

$$k > \max\left(|e_\alpha|\,|e_\beta|\right), \qquad (25)$$

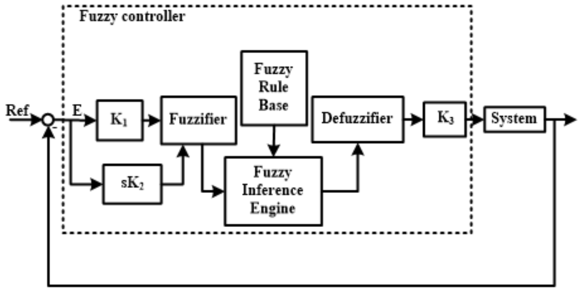


Fig. 1: The structure of the fuzzy controller.

because k is enough big, the asymptotic stability and slip movement seems certain. When the system gets to the slip level:

$$\dot{\mathbf{S}}(X) = \mathbf{S}(X) = 0. \qquad (26)$$

By putting above equation in Eq. (22) and Eq. (23), which is based on equivalent control way, follows are given:

$$e_\alpha = k \cdot F\left(\hat{i}_\alpha - i_\alpha\right), \qquad (27)$$

$$e_\beta = k \cdot F\left(\hat{i}_\beta - i_\beta\right). \qquad (28)$$

1) Fuzzy Logic Control (FLC)

Fuzzy logic controller is suitable in controller designing for complex or nonlinear systems [16]. Fig. 1 shows the structure of the fuzzy controller which is used in this paper.

As it is obvious in Fig. 1, the inputs of the fuzzy controller are the error signal and its derivative, the output is the reference value which is applied to the system. In this fuzzy controller, the input and output membership functions are normalized values. The gains K_1, K_2, and K_3 are scaling factor to adapt the variables to the normalized scales. So, determining correct values for K_1, K_2, and K_3 is very important.

Table 1 shows fuzzy roles collection, where e and ce denote error signal and its derivative respectively. The other abbreviated forms which are used in this table are: NB (Negative Big), NM (Negative Medium), NS (Negative Small), Z (Zero), PS (Positive Small), PM (Positive Medium), PB (Positive Big).

Figure 2(a) and Fig. 2(b) are the inputs and output normalized membership functions and three dimensions input-output diagram respectively. In this paper, triangular membership function is used due to simply and good control work.

In practice, the fuzzy rule sets usually have several antecedents that are combined using fuzzy operators, such as AND, OR, and NOT, though again the definitions tend to vary: AND, in one popular definition,

$$\dot{V} = \frac{1}{2}\mathbf{S}(X)^T \dot{\mathbf{S}}(X) = S_\alpha \dot{S}_\alpha + S_\beta \dot{S}_\beta = \frac{1}{L_S}\left[\left(\hat{i}_\alpha - i_\alpha\right) e_\alpha - k\left(\hat{i}_\alpha - i_\alpha\right) F\left(\hat{i}_\alpha - i_\alpha\right)\right] + \\ + \frac{1}{L_S}\left[\left(\hat{i}_\beta - i_\beta\right) e_\beta - k\left(\hat{i}_\beta - i_\beta\right) F\left(\hat{i}_\beta - i_\beta\right)\right] - \frac{R_s}{L_s}\left[\left(\hat{i}_\alpha - i_\alpha\right)^2 + \left(\hat{i}_\beta - i_\beta\right)^2\right] \leq 0. \tag{29}$$

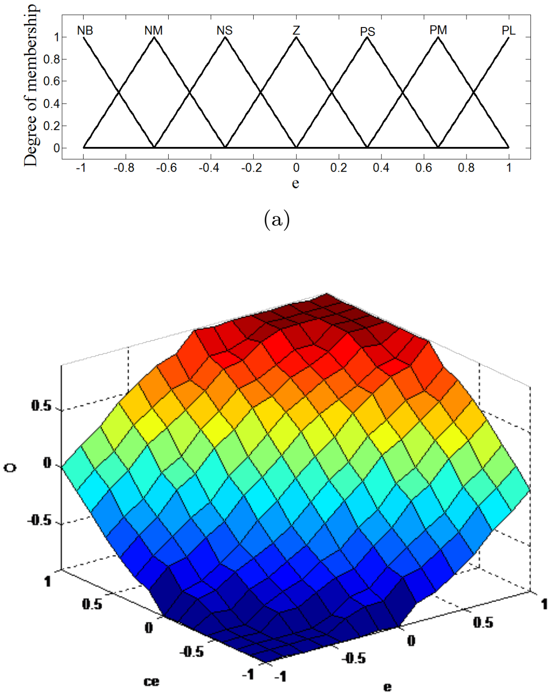
Tab. 1: Fuzzy roles.

ce	e						
	NB	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

simply uses the minimum weight of all the antecedents, while OR uses the maximum value. There is also a NOT operator that subtracts a membership function from 1 to give the "complementary" function. There are several ways to define the result of a rule, but one of the most common and simplest is the "max-min" inference method, in which the output membership function is given the truth value generated by the premise. Rules can be solved in parallel in hardware, or sequentially in software. The results of all the rules that have fired are "defuzzified" to a crisp value by one of the several methods. There are dozens, in theory, each with various advantages or drawbacks. The "centroid" method is very popular, in which the "center of mass" of the result provides the crisp value. Another approach is the "height" method, which takes the value of the biggest contributor. The centroid method favors the rule with the output of the greatest area, while the height method obviously favors the rule with the greatest output value [16] and [17].

4. Estimation Rotor Position and Speed by Using Proposed Method

Back EMF can be obtained by described sliding mode observer, but the signals still include high-frequency components. Therefore, they cannot be used directly for an estimate the rotor position and speed. In a conventional sliding mode observer, a low pass filter is used for filtering operation, which causes the phase lag that depends on the cut frequency and the input signal angular one. In order to compensating the phase lag completely, the acquired information from the real linear speed must be used, and the information, which is given by the estimated linear speed, is not enough for compensating. Thus, due to avoid of using the low pass filter and the phase compensator based on back



(a)

(b)

Fig. 2: (a) Inputs and output membership functions, (b) Three dimensions input-output diagram.

EMF, in this paper a fuzzy sliding mode observer for detecting the back EMF in a PMLSM is designed to estimate the speed and the position of the rotor. Because the changes of the motor linear speed are smaller than the changes of the stator's current, it is assumed that $\acute{\omega} = 0$. So, back EMF of PMLSM can be expressed as:

$$\frac{\mathrm{d}e_\alpha}{\mathrm{d}t} = -\omega e_\beta, \tag{30}$$

$$\frac{\mathrm{d}e_\beta}{\mathrm{d}t} = -\omega e_\alpha. \tag{31}$$

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

$$\frac{\mathrm{d}\hat{e}_\alpha}{\mathrm{d}t} = -\hat{\omega}\hat{e}_\beta - l\left(\hat{e}_\alpha - \hat{e}_\beta\right), \tag{32}$$

$$\frac{\mathrm{d}\hat{e}_\beta}{\mathrm{d}t} = -\hat{\omega}\hat{e}_\beta - l\left(\hat{e}_\beta - \hat{e}_\alpha\right), \tag{33}$$

$$\frac{\mathrm{d}\hat{\omega}}{\mathrm{d}t} = \left(\hat{e}_\alpha - e_\alpha\right)\hat{e}_\beta - \left(\hat{e}_\beta - e_\beta\right)\hat{e}_\alpha, \tag{34}$$

where l is the gain of observer which is more than 1.

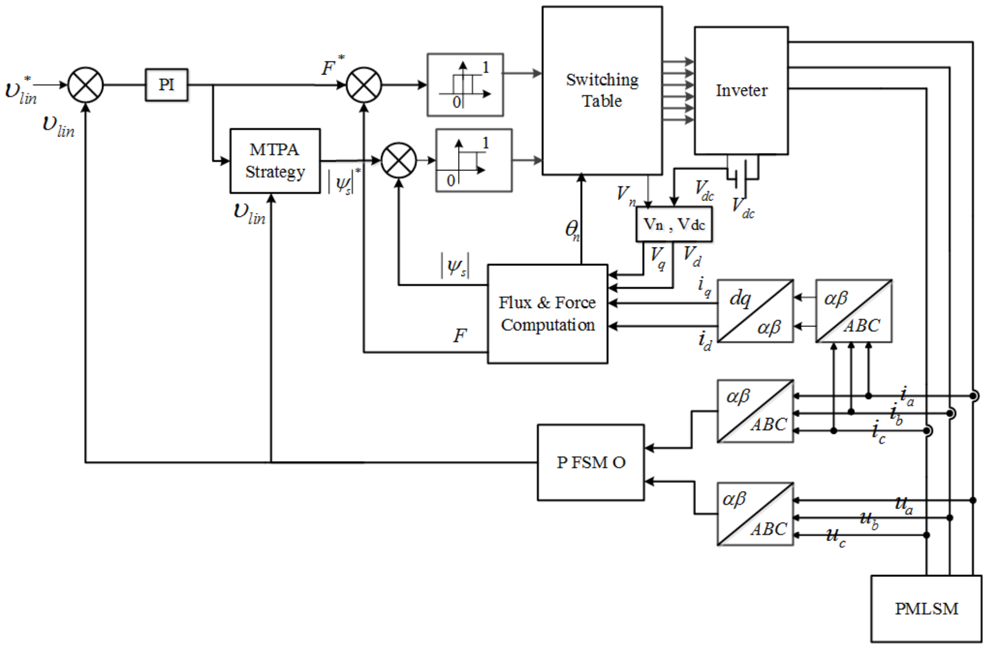


Fig. 3: Block diagram of the PMLSM sensorless control.

By subtracting Eq. (30), Eq. (31) from Eq. (32), Eq. (33) and Eq. (34), the error equation of the observer is obtained from:

$$\frac{\mathrm{d}\hat{e}_\alpha}{\mathrm{d}t} = -\tilde{\omega}\hat{e}_\beta - \omega\tilde{e}_\beta - l\tilde{e}_\alpha, \tag{35}$$

$$\frac{\mathrm{d}\hat{e}_\beta}{\mathrm{d}t} = -\tilde{\omega}\hat{e}_\alpha - \omega\tilde{e}_\alpha - l\tilde{e}_\beta, \tag{36}$$

$$\frac{\mathrm{d}\tilde{\omega}}{\mathrm{d}t} = \tilde{e}_\alpha\hat{e}_\beta - \tilde{e}_\beta\hat{e}_\alpha, \tag{37}$$

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

Due to show that Eq. (32), Eq. (33) and Eq. (34) is stable, Lyapunov function is defined as follows:

$$V = \frac{\left(\tilde{e}_\alpha^2 + \tilde{e}_\beta^2 + \tilde{\omega}^2\right)}{2}, \tag{38}$$

derivative from the above equation is led to:

$$\dot{V} = \tilde{e}_\alpha\dot{\tilde{e}}_\alpha + \tilde{e}_\beta\dot{\tilde{e}}_\beta + \tilde{\omega}\dot{\tilde{\omega}}. \tag{39}$$

By putting Eq. (35), Eq. (36) and Eq. (37) in Eq. (39), it is given that:

$$\dot{V} = -l\left(\tilde{e}_\alpha^2 + \tilde{e}_\beta^2\right) \leq 0. \tag{40}$$

From mentioned equation, it results that the proposed back EMF observer is asymptotically stable. Thus by use of back EMF that is obtained from the observer and the relationship between back EMF and the situation of the rotor, the position signal is estimated from follows:

$$\hat{\theta} = -\arctan\left(\frac{\hat{e}_\alpha}{\hat{e}_\beta}\right). \tag{41}$$

The speed is obtained easily there to by using an integrator in the observer. The overall scheme of the PMLSM sensorless control and the block diagram of the proposed fuzzy sliding mode observer are shown in sequence in Fig. 3 and Fig. 4. In 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 precise and thus estimates accuracy of the motor position and speed are improved.

5. Experiment

The parameters given by the manufacturer of the motor and the inverter parameters are presented in the Tab. 2, [18]. The voltage source inverter (VSI) drives are most widely used. There are mainly two types of VSI drives available:

- two level devices,
- three level devices.

The typical structure of the two-level VSI drive is used in this paper. The step function is considered as a reference signal. The speed, which is estimated by a sliding mode observer, has been shown in Fig. 5. Chattering phenomenon in these types of observers which use discontinuous sign function is seen obviously.

The speed, which is estimated by the proposed fuzzy sliding mode observer, has been shown in Fig 6. As it is

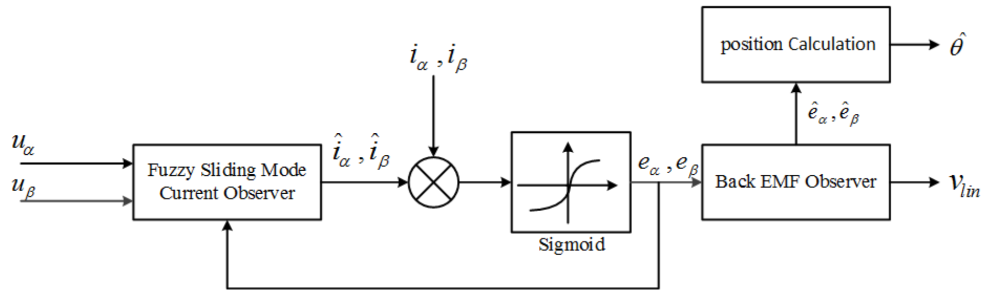


Fig. 4: Block diagram of the proposed fuzzy sliding mode observer.

Tab. 2: Parameters of the motor and inverter model.

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}	$4.5\ m{\cdot}s^{-1}$	Peak speed

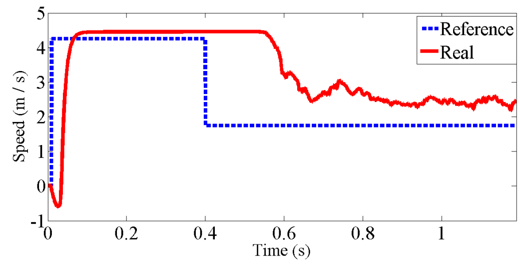


Fig. 5: Speed reference signal and real speed of the motor by sliding mode observer.

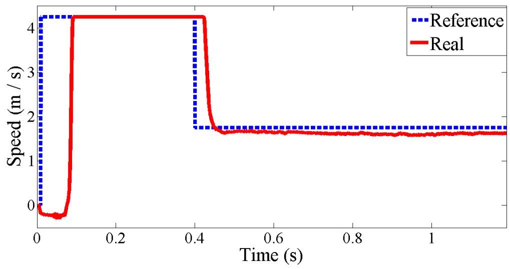


Fig. 6: Speed reference signal and speed actual of the motor by the proposed sliding mode observer.

seen, comparison with conventional observers, chattering phenomenon is reduced effectively. Moreover, low pass filter and phase lag compensator are not required.

Figure 7(a) and Fig. 7(b) show acceleration of the mover in order for a conventional observer and the proposed fuzzy sliding mode. Figure 8(b) and Fig. 8(b) show the estimated force and Fig. 9(a) and Fig. 9(b) show the force which has been made by the mover by considering end effects cogging and friction forces. Comparison Fig. 8(a) with Fig. 8(a) shows that the reference and estimated forces in system that uses the proposed fuzzy sliding mode observer is more accurate than others that use conventional ones, because choosing continuous function instead of discontinuous sign function leads to eliminate chattering phenomenon. The mentioned explanations are also true for Fig. 7.

Figure 10 show the current of the system that uses the proposed sliding mode observer during accelerating time of the mover at the stability speed and when acceleration of the mover is reduced.

6. Conclusion

In this paper for PMLSM sensorless control, the improved fuzzy sliding mode observer, which uses sigmoid function, was proposed. It was illustrated that using a sigmoid function instead of sign function that is usual in sliding mode observers leads to reducing undesirable chattering phenomenon effectively. Reducing chattering phenomenon results that back EMF can be detected directly from switching signal without any need to low pass filter. So the delay time which is caused by 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 by results, which are obtained from simulation by MATLAB/Simulink software.

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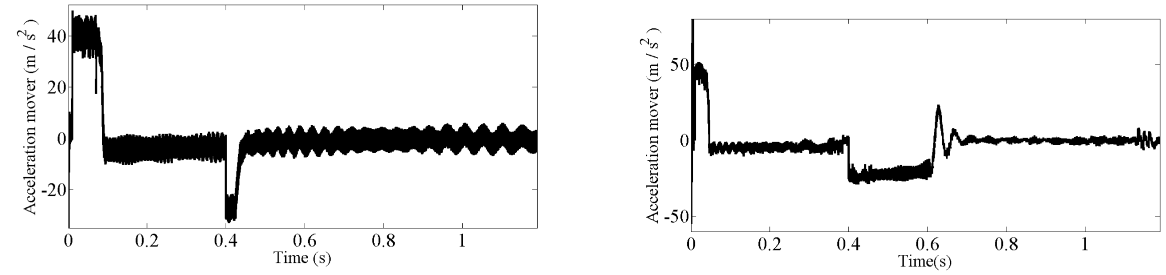
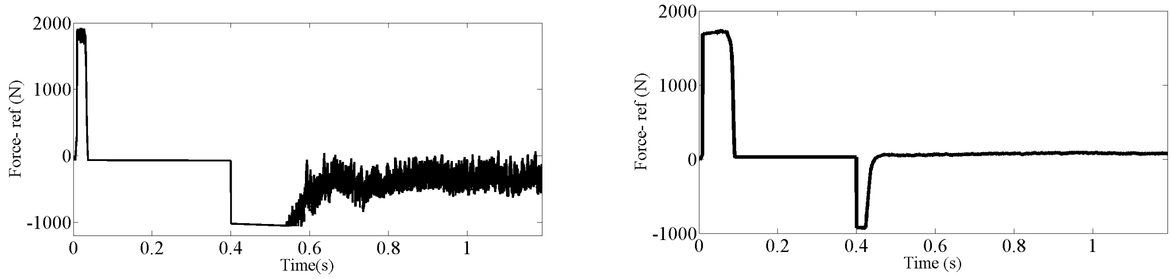


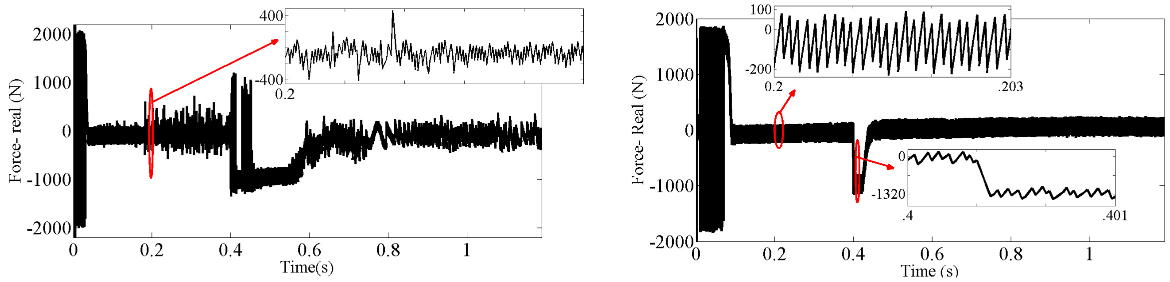
(a) (b)

Fig. 7: Acceleration of the mover (a) by using a conventional sliding mode observer (b) by using the proposed fuzzy sliding mode observer.



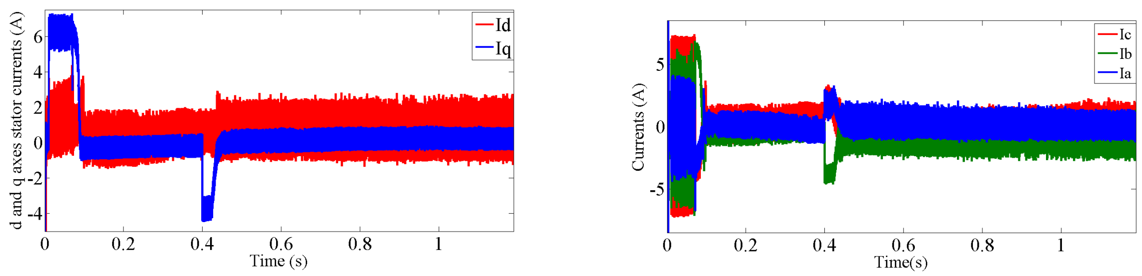
(a) (b)

Fig. 8: Force reference (a) by using a conventional sliding mode observer (b) by using the proposed sliding mode observer.



(a) (b)

Fig. 9: The produced force of the mover (a) by using a conventional sliding mode observer (b) by using the proposed sliding mode observer.



(a) (b)

Fig. 10: The currents of PMLSM, which uses the proposed sliding mode observer in d and q axes.

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About Authors

Saeed MASOUMI KAZRAJI was born in Tehran, Iran in 1989. He received the B.Sc. degree from the Sbzevar University of Tarbiat Moallem, Mashhad, Iran in 2011 and the M.Sc. degree from University of Tabriz, Tabriz, Iran in 2013 both in Electrical Power Engineering. He is currently pursuing the Ph.D. degree in electrical engineering (machine and electric drives) University of Tabriz. His research interests include drive and motion control of electric machines, machine design, linear actuator and power electronic converters.

Mohammad Bagher BANNAE SHARIFIAN studied Electrical Power Engineering at the University of Tabriz, Tabriz, Iran. He received the B.Sc. and M.Sc. degrees in 1989 and 1992 respectively from University of Tabriz. In 1992 he joined the Electrical Engineering Department of the University of Tabriz as a lecturer. He received the Ph.D. degree in Electrical Engineering from the same University in 2000. In 2000 he rejoined the Electrical Power Department of Faculty of Electrical and Computer Engineering of the same university as Assistant Professor. He is currently Professor of the mentioned Department. His research interests are in the areas of design, modeling and analysis of electrical machines, transformers, linear electric motors, and electric and hybrid electric vehicle drives.