Sliding Mode Observer for Speed Sensorless Linear Induction Motor Drives

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ABSTRACT In this paper, a sliding mode observer (SMO) for the speed-sensorless direct torque vector control of linear induction motor (LIM) is proposed, considering the influence of dynamic end effects. The proposed SMO estimate the motor speed, the rotor flux, the angular position of the rotor flux, and the speed dependent parameter \( w \), only by using the measured stator voltages and stator currents. The nonlinear sliding mode technique guarantees very good performance for different situations of motor speed. The proposed SMO does not use complicated observer gains and robust to the parameter variation over the full-speed range. Moreover, the convergence of SMO is proven by using the Lyapunov theory. Furthermore, LIM Drive state observability is presented with detailed analysis. The performance of the proposed SMO is verified by hardware-in-the-loop test (HIL) system. Furthermore, a comparative study with and Luenberger observer (LO) and model reference adaptive system (MRAS) is presented.

INDEX TERMS Linear induction motor, dynamic end effects, sliding mode observer, nonlinear system, observability analysis.

I. INTRODUCTION

Linear induction motor is a kind of transmission device, which can convert electrical energy directly into linear motion of mechanical power. Due to the advantages of high power density, high precision and high efficiency [1], [2], LIMs have a wide range of applications in the field of transportation, such as civil and industrial areas, laser cutting, aircraft, aerospace etc [3].

The most fundamental difference between LIM and rotary induction motor (RIM) is that LIM has dynamic end effect phenomenon, which means the motor design, performance calculation and control methods become more complex than RIM [4]. The edge-end effects of LIMs are divided into transverse edge-end effects, the first type of longitudinal edge-end effects and the second type of longitudinal edge-end effects [2]. The second kind of longitudinal side effect is the electromagnetic transient phenomenon, which caused by the relative motion of primary and secondary linear motor, also known as dynamic end effect. The primary inlet and outlet of the LIM will induce eddy currents equal to and opposite to the primary end-winding current on the secondary conductive layer [1], [5]. Lenz’s law shows that the magnetic field generated by this eddy current will weaken the effective magnetic field of the air gap at the inlet and strengthen the outlet. Based on Maxwell’s field equation, the paper deduces the thrust characteristics of the motor under the influence of dynamic side effect in detail, and concludes that dynamic longitudinal end effect will cause the motor to produce reverse traveling waves during the operation, that is, with additional braking force, and then cause the thrust to drop [6], [7]. The influence of this kind of effect will increase with the increase of motor speed. For high-speed LIM, dynamic end effect is not negligible [8].

To reflect this situation, Ducan [9] introduced the space-vector equivalent T-model of LIM and presented the voltage equation and flux equation. Then, the state space equation of LIM was given in [8] with Pucci. Considering the influence of dynamic end effects, Zhang et al. [10] proposed a modified model of LIM and proposed second order sliding...
mode observer (SOSMO) method for speed estimation and flux estimation. It can be seen that the dynamic end effect model of LIM is a nonlinear dynamic system. The best way to understand sensorless control behavior is based on the nonlinear dynamic system theory [11], [12]. For LIM’s model, the problem of global observability is very critical [13], [14]. To design the nonlinear observer for a nonlinear system, we should first proof the observability of this model [15].

In addition, to improve the robustness and reliability of the drive system, extended Luenberger estimator and extended Kalman filter were proposed for electrical machines [16], [17]. The main disadvantage of such observers is the complex calculations of the system that cannot be provided by all the microprocessors. The model reference adaptive observer (MRAO) is widely used for the speed estimation purpose [18]. However, MRAO is sensitive to parameter variation particularly at low frequencies which needs the precise determination of electrical machine models at operation conditions. MRAS (Model Reference Adaptive System) techniques are also applied to estimate the speed for induction motor [19], while this method show speed errors in the low-speed range and cause an incorrect steady-state value.

To achieve high precision control purpose, we should obtain the information of rotor flux and speed. Unfortunately, the related sensors (such as flux sensor and speed sensor) will increase the overall cost for LIM system and decrease the reliability of the nonlinear system [20]. Due to these reasons, the sensorless technique attracted the industrial applications and related research, such as sliding mode observer [21], [22], fuzzy observer [23], [24] and total least squares (TLS) EXIN neuron [25]. Besides, diverse structures of output feedback and estimation using sliding mode methods have been applied for nonlinear systems [26], [27]. A cascaded sliding-mode observer based output feedback controller for multi-input multi-output (MIMO) system is proposed [28], [29], which can provide the accurate estimates of states and can be used for output tracking control purpose.

Nevertheless, all the above designed observers did not consider the influence of dynamic end effects. It should be remarked that if the LIM’s model is very close to the actual system, the designed observer will be very efficient. On this basis, Ducan [9] introduced end effect factor Q to describe equivalent T-model of LIM, and the state space equation of LIM is proposed by Pucci [8]. While few attempts have been proposed to estimate the rotor flux and motor speed simultaneously due to its highly complex model. A Model Reference Adaptive System (MRAS) method for LIM is proposed in [30], [31]. In [32], a Luenberger Observer (LO) with fuzzy tuning law has been considered to estimate the flux and the motor speed. A least square method based on LO has been studied by [33]. Second-order sliding-mode MRAS observer-based sensorless vector control of linear induction motor drives was proposed by [34], [35]. However, all of these methods are based on linearized models and are sensitive to perturbations and modeling errors.

In this article, we present a unified approach to LIM observability based on the weak local observability concept. It can be shown that both state estimation and machine parameters (speed and speed-dependent parameter) identification possibility can be evaluated by the proposed tool. Then, a modified sliding mode observer is presented for speed-sensorless linear induction motor drive systems, considering the influence of dynamic end effects. The proposed modified SMO can estimate the rotor flux, motor speed and the speed-dependent parameter w simultaneously in a robust and effective manner. Moreover, only one observer gain is needed in SMO design.

The main contributions of this paper are shown as follows

1) A method based on the nonlinear dynamical system state observability theory is applied to LIM drive state observability analysis, together with conditions allowing reliable motor speed estimation.

2) The proposed SMO estimate the motor speed, the rotor flux, the angular position of the rotor flux, and the speed-dependent parameter w, only by using the measured stator voltages and stator currents of LIM, does not use complicated observer gains and robust to the parameter variation over the full-speed range. Furthermore, the proposed can guarantee finite time convergence and robustness for state estimation of LIM.

3) The feasibility and effectiveness of the proposed SMO based controller technique for LIM system has been validated with Hardware-in-the-loop (HIL) test.

The rest of the paper is organized as follows. In Section II, the model of LIM including dynamic end effects is given and the state space equation of LIM is presented. In Section III, we present a unified approach to LIM observability based on the weak local observability concept. In Section IV, the SMO is proposed and implemented into LIM model, and its convergence performance is presented with Lyapunov analysis. In Section V, the proposed SMO scheme is validated in the environment of HIL and a comparative study with MRAS and LO was presented. Finally, some conclusions are made in Section VI.

II. LIM’S MODEL

This section consists of three parts. First, the dynamic end effect is introduced and the equivalent T-model of LIM is presented. Second, with Ducan’s T-model, the state space equation of LIM is presented in the well-known (α, β) stationary reference frame. Third, with some reasonable assumption, a novel simplified model of LIM is given.

A. T-MODEL OF LIM

Differing from RIM, the whole structure of LIM is asymmetric and its secondary part consists of a sheet of aluminum with a back core of iron. In LIM, the relative motion between the primary part and secondary part can cause the so-called the dynamic end effects. When the primary part moves, new
continuous eddy currents appear at the entry of the primary part and would disappear at the exit part. The eddy currents in the entry vary rapidly corresponds to magnetising currents, as shown in Fig. 1.

![Diagram of eddy-current generation at the entry and exit of the airgap when the primary moves with speed $v$.](image)

**FIGURE 1.** Eddy-current generation at the entry and exit of the airgap when the primary moves with speed $v$.

To reflect this phenomenon, Ducan [9] introduced an end effect factor $Q$, is defined as

$$Q = \frac{\tau_m R_r}{(L_m + L_{\sigma r})v}$$  

where $\tau_m$ is the inductor length, $R_r$ is the induced-part resistance, $L_m$ and $L_{\sigma r}$ are three-phase magnetizing inductance and three-phase magnetizing leakage inductance, respectively. It can be seen that, the higher the motor speed, the lower of the factor $Q$.

The three-phase magnetizing inductance varies with $Q$ is defined as

$$\hat{L}_m = L_m[1 - f(Q)]$$  

where

$$f(Q) = \frac{1 - e^{-Q}}{Q}$$  

The equivalent inductor inductances and induced part inductances are given as follows

$$\hat{L}_s = L_{\sigma s} + \hat{L}_m, \hat{L}_r = L_{\sigma r} + \hat{L}_m$$

Considering the eddy current losses, there is a resistance appears in the transversal branch, the resistance $\hat{R}_r$ is

$$\hat{R}_r = R_r f(Q)$$  

The space-vector equivalent circuit of the LIM is shown in Fig. 2, it can be seen that both magnetizing inductance and eddy current resistance present in the transversal branch.

![Space-vector equivalent circuit of the LIM.](image)

**FIGURE 2.** Space-vector equivalent circuit of the LIM.

With the space-vector equivalent circuit in the inductor reference frame, using the Kirchhoff law, the voltage equation of LIM can be rewritten in the inductor reference frame as follows

$$\begin{align*}
\dot{u}_s &= R_s i_s + R_r f(Q)(i_s + i_r) + \frac{d\psi_s}{dt} \\
0 &= R_r i_r + R_r f(Q)(i_s + i_r) + \frac{d\psi_r}{dt} - j\omega_r \psi_r
\end{align*}$$

The secondary flux equation are given as follows

$$\begin{align*}
\psi_s &= (L_{\sigma s} + L_m[1 - f(Q)]) i_s + L_m[1 - f(Q)] i_r \\
\psi_r &= L_m[1 - f(Q)] i_s + [L_{\sigma r} + L_m(1 - f(Q))] i_r
\end{align*}$$

where $\omega_r$ is the electrical rotating speed of the inductor; $j$ is the imaginary unit; and $u_s, i_s, i_r, \psi_s, \psi_r$ are the inductor voltage and current, the induced-part current, and the inductor and induced-part flux linkage space vectors written in the inductor reference frame, respectively.

**B. LIM’s STATE SPACE EQUATION**

From the voltage equation (6-7) and flux equation (8-9) above, the state space equation of LIM can be obtained as follows [8]

$$\begin{align*}
\frac{d}{dt} i_s &= \frac{1}{\hat{L}_s} \left\{ u_s - R_s i_s + \hat{R}_r (1 - \frac{\hat{L}_m}{\hat{L}_r}) + \frac{\hat{L}_m}{\hat{L}_r} (\frac{\hat{L}_m}{\hat{T}_r} - \hat{R}_r) \right\} i_s - \frac{\hat{L}_m}{\hat{T}_r} \left[ \frac{n_p \pi}{h} - \frac{1}{\hat{R}_r} \right] \psi_s \\
\frac{d}{dt} \psi_s &= \left[ \hat{L}_m - \hat{R}_r \right] i_s + \left[ \frac{n_p \pi}{h} - \frac{1}{\hat{T}_r} \right] \psi_r
\end{align*}$$

where $n_p$ is the number of pole pairs; $h$ is pole pitch; and $\hat{T}_r, \hat{R}_r$ are

$$\hat{T}_r = \frac{\hat{L}_r}{R_r + \hat{R}_r}, \hat{R}_r = 1 - \frac{\hat{L}_m^2}{\hat{L}_s \hat{L}_r}$$
The dynamic equation of LIM is expressed as

\[ F_e = M \ddot{v} + Dv + T_L \]  

(12)

where electromagnetic thrust \( F_e \) is defined as [8]

\[ F_e = \frac{3n_p \pi L_m}{2h L_r} (i_{\beta} \psi_{r \alpha} - i_{\alpha} \psi_{r \beta}) \]  

(13)

\section*{C. SIMPLIFIED MODEL OF LIM}

To simplify the online calculations the designed SMO-STC scheme, some reasonable assumptions are applied to the state space model of LIM. First, the secondary leakage inductance is assumed as \( L_{sr} = 0 \), for the reason of the skin effect is almost zero for the LIM with a thin secondary sheet at rated frequency [33]. Second, the derivative of linear motor speed is almost zero (\( dv/dt \approx 0 \)). With these assumptions above, we reformulate the equations in the inductor part flux reference frame (\( \alpha, \beta \)) as follows [10]

\[
\begin{align*}
\dot{i}_{\alpha} &= -c_1 i_{\alpha} + c_2 w \psi_{r \alpha} + c_3 \frac{n_p \pi}{h} \psi_{r \beta} + \frac{u_{sa}}{c_4} \\
\dot{i}_{\beta} &= -c_1 i_{\beta} + c_2 w \psi_{r \beta} - c_3 \frac{n_p \pi}{h} \psi_{r \alpha} + \frac{u_{sb}}{c_4} \\
\dot{\psi}_{r \alpha} &= c_5 i_{\alpha} - c_6 (2w - 1) \psi_{r \alpha} - \frac{n_p \pi}{h} \psi_{r \beta} \\
\dot{\psi}_{r \beta} &= c_5 i_{\beta} - c_6 (2w - 1) \psi_{r \beta} + \frac{n_p \pi}{h} \psi_{r \alpha}
\end{align*}
\]

(14-17)

where \( v \) is the motor speed; \( u_{sa} \) and \( u_{sb} \) are the stator voltages; \( i_{\alpha} \) and \( i_{\beta} \) are the stator currents; \( \psi_{r \alpha} \) and \( \psi_{r \beta} \) are the rotor fluxes; \( w \) is the speed-dependent parameter; \( D \) is viscous friction; \( M \) is the motor mass; \( T_L \) is the load torque. The related parameters are given as follows

\[
\begin{align*}
c_1 &= \frac{1}{L_{ds}} (R_s + R_r) \\
c_2 &= \frac{R_r}{L_m L_{ds}} \\
c_3 &= \frac{1}{L_{sr}} \\
c_4 &= L_{ds} \\
c_5 &= R_r \\
c_6 &= \frac{R_r}{L_m}, c_7 = \frac{3n_p \pi}{2Mh} \\
w &= \frac{1}{1-f(Q)} = e^{-(k/v)} - 1 + (k/v), k = \frac{\tau_m R_r}{L_m}
\end{align*}
\]

\section*{III. LIM MODEL OBSERVABILITY}

In this section, the observability of states of the proposed LIM mode equation (14-17) will be analyzed. The stator voltages \( u_{sa} \) and \( u_{sb} \) and stator currents \( i_{\alpha} \) and \( i_{\beta} \) are assumed can be measured. It is necessary to judge if it is possible to obtain the estimated results of modified rotor magnetic flux \( \psi_{r \alpha} \) and \( \psi_{r \beta} \) and motor speed \( v \), as well as the speed-dependent parameter \( w \), only form the measured stator quantities. Universally speaking, there is no information about the LIM load torque [11]. We can be assumed that the motor speed is only slowly varying, which is

\[ \dot{v} = 0 \]  

(18)

Now, the observability theorem will be applied to the LIM system given by the equations can be rewritten into the components

\[
\begin{align*}
\dot{i}_{\alpha} &= -c_1 i_{\alpha} + c_2 w \psi_{r \alpha} + c_3 \frac{n_p \pi}{h} \psi_{r \beta} + \frac{u_{sa}}{c_4} \\
\dot{i}_{\beta} &= -c_1 i_{\beta} + c_2 w \psi_{r \beta} - c_3 \frac{n_p \pi}{h} \psi_{r \alpha} + \frac{u_{sb}}{c_4} \\
\dot{\psi}_{r \alpha} &= c_5 i_{\alpha} - c_6 (2w - 1) \psi_{r \alpha} - \frac{n_p \pi}{h} \psi_{r \beta} \\
\dot{\psi}_{r \beta} &= c_5 i_{\beta} - c_6 (2w - 1) \psi_{r \beta} + \frac{n_p \pi}{h} \psi_{r \alpha} \\
\dot{v} &= 0
\end{align*}
\]

(19-23)

The equations can be rewritten as follows

\[ \dot{x} = f(x, u) \quad y = h(x) \]  

(24)

where \( x, f(x, u), h(x) \) are

\[ \begin{bmatrix} i_{\alpha} \\ i_{\beta} \\ \psi_{r \alpha} \\ \psi_{r \beta} \\ v \end{bmatrix}, \quad \begin{bmatrix} u_{sa} \\ u_{sb} \end{bmatrix}, \quad \begin{bmatrix} i_{\alpha} \\ i_{\beta} \end{bmatrix} \]

and the state space dimension \( n = 5 \). In our case, the result of the Lie derivative will be a vector with two components

\[ L^f h = \begin{bmatrix} L^f h_1 \\ L^f h_2 \end{bmatrix} \]  

(25)

\[ L^j h = h = \begin{bmatrix} i_{\alpha} \\ i_{\beta} \end{bmatrix} \]  

(26)

\[ L_f h = \begin{bmatrix} L^f h_1 \\ L^f h_2 \end{bmatrix} = \begin{bmatrix} -c_1 i_{\alpha} + c_2 w \psi_{r \alpha} + c_3 \frac{n_p \pi}{h} \psi_{r \beta} + \frac{u_{sa}}{c_4} \\ -c_1 i_{\beta} + c_2 w \psi_{r \beta} - c_3 \frac{n_p \pi}{h} \psi_{r \alpha} + \frac{u_{sb}}{c_4} \\ c_5 i_{\alpha} - c_6 (2w - 1) \psi_{r \alpha} - \frac{n_p \pi}{h} \psi_{r \beta} \\ c_5 i_{\beta} - c_6 (2w - 1) \psi_{r \beta} + \frac{n_p \pi}{h} \psi_{r \alpha} \end{bmatrix} \]  

(27)

As the system order is \( n = 5 \), it is necessary to evaluate Lie derivative up to the order \( k = 4 \). The resulting criterion matrix
has dimension $10 \times 5$, and it is a Jacobian

$$
O = \begin{bmatrix}
\frac{\partial L_0^0}{\partial i_{sa}} & \frac{\partial L_0^0}{\partial i_{sb}} & \frac{\partial L_0^0}{\partial \psi_{sa}} & \frac{\partial L_0^0}{\partial \psi_{sb}} & \frac{\partial L_0^0}{\partial \psi_{st}} & \frac{\partial L_0^0}{\partial \psi_{sr}} & \frac{\partial L_0^0}{\partial v} \\
\frac{\partial L_2^0}{\partial i_{sa}} & \frac{\partial L_2^0}{\partial i_{sb}} & \frac{\partial L_2^0}{\partial \psi_{sa}} & \frac{\partial L_2^0}{\partial \psi_{sb}} & \frac{\partial L_2^0}{\partial \psi_{st}} & \frac{\partial L_2^0}{\partial \psi_{sr}} & \frac{\partial L_2^0}{\partial v} \\
\frac{\partial L_2^2}{\partial i_{sa}} & \frac{\partial L_2^2}{\partial i_{sb}} & \frac{\partial L_2^2}{\partial \psi_{sa}} & \frac{\partial L_2^2}{\partial \psi_{sb}} & \frac{\partial L_2^2}{\partial \psi_{st}} & \frac{\partial L_2^2}{\partial \psi_{sr}} & \frac{\partial L_2^2}{\partial v}
\end{bmatrix}
$$

(28)

According to the observability theorem mentioned earlier, the matrix $O$ has to be a full rank matrix to guarantee that the system will be weakly locally observable [37], [38]

$$
\text{rank} \{ O \} = 5
$$

(29)

The first one contains the first five rows of $O$

$$
O_1 = \begin{bmatrix}
\frac{\partial L_0^0}{\partial i_{sa}} & \frac{\partial L_0^0}{\partial i_{sb}} & \frac{\partial L_0^0}{\partial \psi_{sa}} & \frac{\partial L_0^0}{\partial \psi_{sb}} & \frac{\partial L_0^0}{\partial \psi_{st}} & \frac{\partial L_0^0}{\partial \psi_{sr}} & \frac{\partial L_0^0}{\partial v} \\
\frac{\partial L_2^0}{\partial i_{sa}} & \frac{\partial L_2^0}{\partial i_{sb}} & \frac{\partial L_2^0}{\partial \psi_{sa}} & \frac{\partial L_2^0}{\partial \psi_{sb}} & \frac{\partial L_2^0}{\partial \psi_{st}} & \frac{\partial L_2^0}{\partial \psi_{sr}} & \frac{\partial L_2^0}{\partial v} \\
\frac{\partial L_2^2}{\partial i_{sa}} & \frac{\partial L_2^2}{\partial i_{sb}} & \frac{\partial L_2^2}{\partial \psi_{sa}} & \frac{\partial L_2^2}{\partial \psi_{sb}} & \frac{\partial L_2^2}{\partial \psi_{st}} & \frac{\partial L_2^2}{\partial \psi_{sr}} & \frac{\partial L_2^2}{\partial v}
\end{bmatrix}
$$

(30)

The matrix $L_1$ can be calculated as follows

$$
L_1 = \begin{bmatrix}
L_0^0 h_1 \\
L_2^0 h_2 \\
L_2^2 h_1
\end{bmatrix}
= \begin{bmatrix}
i_{sa} & i_{sb} & i_{st} & i_{sr} & \psi_{sa} & \psi_{sb} & \psi_{st} & \psi_{sr} & v \\
-c_1 i_{sa} + c_2 w \psi_{ra} + c_3 n \frac{np}{h} \psi_{r\beta} + u_{sa} & -c_1 i_{sa} + c_2 w \psi_{r\beta} - c_3 n \frac{np}{h} \psi_{ra} + u_{sa} & -c_1 i_{sb} + c_2 w \psi_{ra} + c_3 n \frac{np}{h} \psi_{r\beta} + u_{sb} & -c_1 i_{sb} + c_2 w \psi_{r\beta} - c_3 n \frac{np}{h} \psi_{ra} + u_{sb} & i_{st} & i_{sr} & \frac{np}{h} \psi_{sa} & \frac{np}{h} \psi_{sb} & \frac{np}{h} \psi_{st} & \frac{np}{h} \psi_{sr} & \frac{np}{h} \psi_{ra} f s
\end{bmatrix}
$$

(31)

The matrix $O_1$ can be calculated as follows

$$
O_1 = \frac{\partial L_1}{\partial x}
$$

(32)

where coefficients $a_{s1}, a_{s2}, a_{s3}, a_{s4}, a_{s5}$ are

$$
a_{s1} = c_1^2 + c_2 c_5 w
$$

(33)

$$
a_{s2} = c_3 c_5 n \frac{np}{h} \psi_{r\beta}
$$

(34)

$$
a_{s3} = -c_1 c_2 w + c_2 c_6 w (2w - 1) + c_3 n \frac{np}{h} \psi_{r\beta}^2
$$

(35)

$$
a_{s4} = -[c_1 c_3 + c_2 w + c_3 c_6 (2w - 1)] n \frac{np}{h} \psi_{r\beta}
$$

(36)

$$
a_{s5} = n \frac{np}{h} \left(-c_1 c_2 \psi_{r\beta} - c_2 w \psi_{r\beta} + c_3 \psi_{r\beta} + c_3 n \frac{np}{h} \psi_{r\alpha}
\right)
$$

(37)

The determinant of the matrix $O_1$ can be computed as

$$
O_1 = \frac{\partial L_1}{\partial x}
$$

(38)

Another possible selection is similar to the $O_1$ matrix except the last row

$$
O_2 = \begin{bmatrix}
\frac{\partial L_0^0}{\partial i_{sa}} & \frac{\partial L_0^0}{\partial i_{sb}} & \frac{\partial L_0^0}{\partial \psi_{sa}} & \frac{\partial L_0^0}{\partial \psi_{sb}} & \frac{\partial L_0^0}{\partial \psi_{st}} & \frac{\partial L_0^0}{\partial \psi_{sr}} & \frac{\partial L_0^0}{\partial v} \\
\frac{\partial L_2^0}{\partial i_{sa}} & \frac{\partial L_2^0}{\partial i_{sb}} & \frac{\partial L_2^0}{\partial \psi_{sa}} & \frac{\partial L_2^0}{\partial \psi_{sb}} & \frac{\partial L_2^0}{\partial \psi_{st}} & \frac{\partial L_2^0}{\partial \psi_{sr}} & \frac{\partial L_2^0}{\partial v} \\
\frac{\partial L_2^2}{\partial i_{sa}} & \frac{\partial L_2^2}{\partial i_{sb}} & \frac{\partial L_2^2}{\partial \psi_{sa}} & \frac{\partial L_2^2}{\partial \psi_{sb}} & \frac{\partial L_2^2}{\partial \psi_{st}} & \frac{\partial L_2^2}{\partial \psi_{sr}} & \frac{\partial L_2^2}{\partial v}
\end{bmatrix}
$$

(39)

Similarly, the determinant of this matrix is

$$
D_2 = \text{det} (O_2)
$$

(40)

Again, the matrix $O_2$ is regular if its determinant is nonzero. Equation leads to conclusion

$$
D_2 \neq 0 \iff \frac{d \psi_{ra}}{dt} \neq 0
$$

(41)

The regularity of at least one of the matrices $O_1, O_2$ is a sufficient condition for $O$ to be a full-rank matrix. Thus

$$
D_1 \neq 0 \lor D_2 \neq 0 \Rightarrow \text{rank} \{ O \} = 5
$$

(42)

and considering

$$
\frac{d \psi_{ra}}{dt} \neq 0 \lor \frac{d \psi_{r\beta}}{dt} \neq 0 \Rightarrow \text{rank} \{ O \} = 5
$$

(43)
Conditions can be rewritten as
\[
d\psi_r \neq 0 \Rightarrow \text{rank} \{\mathbf{O}\} = 5 \tag{44}
\]
where \(\dot{\psi}_r = \psi_{ra} + j\dot{\psi}_{r\beta}\). According to the observability theorem, it is possible to say that, if the modified rotor flux space vector is not constant, the state of the system described by is weakly locally observable.

The observability analysis came from nonlinear system observability theory and this method of analysis can be extend to similar Multi-input multi-output nonlinear system. For this dynamic end effect model of LIM, we carried out this method of analysis and establish the foundation for ensuring LIM speed estimation [37]. Furthermore, it is a useful and effective way can be extended to other models such as induction motors (IM), permanent magnet synchronous machines (PMSMs) etc [37].

IV. SMO DESIGN AND STABILITY ANALYSIS

For sensorless control purpose it is indispensable to make a simultaneously observation of the motor flux and motor speed [36]. The proposed SMO belongs to the classification of closed loop systems and its design structure is shown as follows:

\[
\frac{d\hat{i}_{sa}}{dt} = -c_1\hat{i}_{sa} + c_2\hat{w}\hat{\psi}_{ra} + c_3\frac{n_p\pi}{h}\hat{v}\hat{\psi}_{r\beta} + \frac{u_{sa}}{c_4} \tag{45}
\]

\[
\frac{d\hat{i}_{sb}}{dt} = -c_1\hat{i}_{sb} + c_2\hat{w}\hat{\psi}_{r\beta} - c_3\frac{n_p\pi}{h}\hat{v}\hat{\psi}_{ra} + \frac{u_{sb}}{c_4} \tag{46}
\]

\[
\psi_{ra} = c_5\hat{i}_{sa} - c_6(2\hat{w} - 1)\psi_{ra} - \frac{n_p\pi}{h}\hat{v}\hat{\psi}_{r\beta} - c_3\frac{n_p\pi}{h}\hat{v}\hat{\psi}_{ra} \tag{47}
\]

\[
\psi_{r\beta} = c_5\hat{i}_{sb} - c_6(2\hat{w} - 1)\psi_{r\beta} + \frac{n_p\pi}{h}\hat{v}\hat{\psi}_{ra} \tag{48}
\]

\[
\dot{\hat{v}} = K\text{sgn}\left(\hat{s}_n\right) \tag{49}
\]

\[
\ddot{\hat{v}} = \frac{\left(k/\dot{\hat{v}}\right)}{e^{-(k/\dot{\hat{v}})} + 1} \tag{50}
\]

where \(\hat{\dot{i}}_{sa}\) and \(\hat{\dot{i}}_{sb}\) are the estimated stator current components, \(\hat{\psi}_{ra}\) and \(\hat{\psi}_{r\beta}\) are the estimated rotor flux components and \(\hat{\psi}\) is the estimated value of the LIM speed, \(\hat{\dot{\hat{w}}}\) is estimated value of the LIM speed-dependent parameter. Using the following definition:

\[
\begin{align*}
\hat{\dot{i}}_{sa} &= \hat{i}_{sa} - \hat{i}_{sa}, \hat{\dot{i}}_{sb} = \hat{i}_{sb} - \hat{i}_{sb} \\
\hat{\psi}_{sa} &= \hat{\psi}_{ra} - \psi_{ra}, \hat{\psi}_{sb} = \hat{\psi}_{r\beta} - \psi_{r\beta} \\
\hat{\dot{v}} &= \dot{v} - \dot{\hat{v}}, \hat{\dot{\hat{w}}} = \hat{\dot{\hat{w}}} - \dot{w}
\end{align*}
\]

Then, the mismatch between estimated and real values, a new system can be obtained as follows:

\[
\begin{align*}
\hat{\dot{i}}_{sa} &= -c_1\hat{\dot{i}}_{sa} + c_2\left(\hat{\dot{\hat{w}}}\hat{\psi}_{ra} - \hat{w}\psi_{ra}\right) + c_3\frac{n_p\pi}{h}\left(\hat{\dot{\hat{w}}}\hat{\psi}_{r\beta} - \hat{w}\psi_{r\beta}\right) \\
\hat{\dot{i}}_{sb} &= -c_1\hat{\dot{i}}_{sb} + c_2\left(\hat{\dot{\hat{w}}}\hat{\psi}_{ra} - \hat{w}\psi_{ra}\right) + c_3\frac{n_p\pi}{h}\left(\hat{\dot{\hat{w}}}\hat{\psi}_{r\beta} - \hat{w}\psi_{r\beta}\right)
\end{align*}
\]

The stability analysis of the designed SMO is given below.

**Proof:** The candidate Lyapunov function is given as follows

\[
V = \frac{1}{2}\left(i_{sa}^2 + i_{sb}^2\right) \tag{55}
\]

Then the first derivative of \(V\) is

\[
\dot{V} = \hat{\dot{i}}_{sa}\hat{i}_{sa} + \hat{\dot{i}}_{sb}\hat{i}_{sb} \tag{56}
\]

where \(\hat{\dot{i}}_{sa}\) and \(\hat{\dot{i}}_{sb}\) are

\[
\begin{align*}
\hat{\dot{i}}_{sa} &= -c_1\hat{i}_{sa} + c_2\left(\hat{\dot{\hat{w}}}\hat{\psi}_{ra} - \hat{w}\psi_{ra}\right) + c_3\frac{n_p\pi}{h}\left(\hat{\dot{\hat{w}}}\hat{\psi}_{r\beta} - \hat{w}\psi_{r\beta}\right) \tag{57} \\
\hat{\dot{i}}_{sb} &= -c_1\hat{i}_{sb} + c_2\left(\hat{\dot{\hat{w}}}\hat{\psi}_{ra} - \hat{w}\psi_{ra}\right) - c_3\frac{n_p\pi}{h}\left(\hat{\dot{\hat{w}}}\hat{\psi}_{r\beta} - \hat{w}\psi_{r\beta}\right) \tag{58}
\end{align*}
\]

It can be rewritten as follows

\[
\dot{V} = -2c_1\dot{V} + c_3\frac{n_p\pi}{h}\left(\hat{s}_n - s_n\right) - c_3\frac{n_p\pi}{h}\hat{v}_{sa} + c_2\left(\hat{\dot{\hat{w}}}\hat{\psi}_{ra} - \hat{w}\psi_{ra}\right)\hat{\dot{i}}_{sa} + c_2\left(\hat{\dot{\hat{w}}}\hat{\psi}_{r\beta} - \hat{w}\psi_{r\beta}\right)\hat{\dot{i}}_{sb} \tag{59}
\]

where

\[
\hat{s}_n = \hat{i}_{sb}\hat{\psi}_{ra} - \hat{i}_{sa}\hat{\psi}_{r\beta} \tag{60}
\]

\[
s_n = \hat{i}_{sb}\psi_{ra} - \hat{i}_{sa}\psi_{r\beta} \tag{61}
\]

\[
s_c = \left(\hat{\dot{\hat{w}}}\psi_{ra} - \hat{w}\psi_{ra}\right)i_{sa} + \left(\hat{\dot{\hat{w}}}\psi_{r\beta} - \hat{w}\psi_{r\beta}\right)i_{sb} \tag{62}
\]

The current mismatch dynamics are stable if the conditions are true. The sufficient conditions dotVle0 can be rewritten as follows

\[
v \left(\hat{s}_n - s_n\right) + \hat{v}_{sa} > -\frac{2c_1}{c_3}\frac{n_p\pi}{h}V + \frac{c_2}{c_3}\frac{n_p\pi}{h}s_c \tag{63}
\]

If the following equations is selected

\[
\dot{v} = K\text{sgn}\left(\hat{s}_n\right) \tag{64}
\]

with

\[
\text{sgn}\left(\ast\right) = \begin{cases} 1, & \ast > 0 \\ 0, & \ast = 0 \\ -1, & \ast < 0 \end{cases} \tag{65}
\]

then is sufficient to state

\[
-K\left|\hat{s}_n\right| > v\left|s_n\right| + \delta \tag{66}
\]

where

\[
\delta = -\frac{2c_1}{c_3}\frac{n_p\pi}{h}V + \frac{c_2}{c_3}\frac{n_p\pi}{h}s_c \tag{67}
\]

If \(K\) is big enough, the estimated current values will converge to the real ones.
TABLE 2. Parameters of linear induction motor.

| Parameter                        | Value |
|----------------------------------|-------|
| Inductor resistance Rs [Ω]       | 11    |
| Induced-part resistance Rs [Ω]   | 32.57 |
| Inductor inductances Ls [H]      | 0.6376|
| 3-phase magnetizing inductance Lm [H] | 0.5175|
| Primary mass M [Kg]              | 20    |
| Viscous friction D [m/s]         | 20    |
| Pole-pairs n_p                   | 3     |
| Inductor length τ_m [m]          | 1.5   |
| Pole pitch h [m]                 | 0.1   |

The nominal parameters of LIM are given in Table 2, the LIM dynamic end effect model of this paper came from experiment data and has been validated as an effective model. [10]. The overall structure of STC-SMO scheme for LIM system is shown in Fig. 3. In this paper, we mainly focus on the design procedure and observer performance analysis of proposed SMO technique, and the detailed design procedure of STC can be founded in [41].

In Matlab/Simulink, the measured phase currents and the input voltages are transformed into the stationary reference frame with the relation as follows

\[
\begin{bmatrix}
  i_{sa} \\
i_{sb}
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
  1 & -\frac{1}{2} & -\frac{1}{2} \\
  0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}
\end{bmatrix} \begin{bmatrix}
  i_a \\
i_b \\
i_c
\end{bmatrix}
\]

(67)

\[
\begin{bmatrix}
  u_{sa} \\
u_{sb}
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
  1 & -\frac{1}{2} & -\frac{1}{2} \\
  0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}
\end{bmatrix} \begin{bmatrix}
  U_a \\
U_b \\
U_c
\end{bmatrix}
\]

(68)

where \(i_{sa}, i_{sb}\) and \(u_{sa}, u_{sb}\) are the currents and voltages in the (α, β) axis frame, \(i_a, i_b, i_c\) and \(U_a, U_b, U_c\) are the original three currents and voltages quantities.

In practical simulation, the \(sgn\) function can be replaced by tangent function \(\hat{v} = \text{Karctan}(\hat{s}_n)\), and the final designed SMO for LIM can be presented as follows

\[
\begin{align*}
\dot{i}_a &= -c_1 \dot{i}_{sa} + c_2 \dot{\hat{v}} \dot{\psi}_{ra} + c_3 \frac{n_p}{h} \dot{\hat{v}} \dot{\hat{v}} \dot{\hat{v}}_{ra} + \frac{u_{sa}}{c_4} \\
\dot{i}_b &= -c_1 \dot{i}_{sb} + c_2 \dot{\hat{v}} \dot{\psi}_{rb} - c_3 \frac{n_p}{h} \dot{\hat{v}} \dot{\hat{v}} \dot{\hat{v}}_{rb} + \frac{u_{sb}}{c_4} \\
\dot{\psi}_{ra} &= c_5 \dot{i}_{sa} - c_6 (2\hat{v} - 1) \psi_{ra} - \frac{n_p}{h} \dot{\hat{v}} \dot{\hat{v}} \dot{\hat{v}}_{ra} \\
\dot{\psi}_{rb} &= c_5 \dot{i}_{sb} - c_6 (2\hat{v} - 1) \psi_{rb} + \frac{n_p}{h} \dot{\hat{v}} \dot{\hat{v}} \dot{\hat{v}}_{rb} \\
\dot{\hat{v}} &= \text{Karctan}(\hat{s}_n) \\
\dot{\hat{v}} &= e^{-\left(\frac{k}{\hat{v}}\right)} - 1 + \left(\frac{k}{\hat{v}}\right)
\end{align*}
\]
A. SMO PERFORMANCE IN DIFFERENT SPEED REFERENCE SIGNALS

1) SOSMO WITH CONSTANT SPEED REFERENCE SIGNAL

In the HIL test, the initial value of state states of LIM are set as \(x_1(0) = \dot{i}_{sa}(0) = 0.1A, x_2(0) = i_{sb}(0) = 0.1A, x_3(0) = \psi_{ra}(0) = 0.1Wb, x_4(0) = \psi_{rb}(0) = 0.1Wb\). To reflect the performance of proposed SMO, the initial values of estimated currents and fluxes are chosen different from initial state variables. The estimated initial values are
chosen as: \( \hat{x}_1(0) = \hat{i}_{sa}(0) = 0.4A, \hat{x}_2(0) = \hat{i}_{sb}(0) = 0.3A, \hat{x}_3(0) = \hat{\psi}_{ra}(0) = 0.4Wb, \hat{x}_4(0) = \hat{\psi}_{rb}(0) = 0.3Wb \), the parameters of proposed SMO gains \( K \) is chosen as \( K = 200 \).

Fig. 4 (a)-(b) show the transient response of the proposed SMO during forward to reverse operation. As can be seen from these two figures one can see that the estimated stator...
are set as \( \hat{\psi} \) for the sine function as \( \sin(\cdot) \). The initial values of the states of LIM are set as

\[
\begin{align*}
\hat{x}_1(0) &= i_{sa}(0) = 0.1A, \\
\hat{x}_2(0) &= i_{sb}(0) = 0.1A, \\
\hat{x}_3(0) &= \psi_{ra}(0) = 0.1Wb, \\
\hat{x}_4(0) &= \psi_{rb}(0) = 0.1Wb.
\end{align*}
\]

Correspondingly, all the initial values of the estimated variables are set as \( \hat{x}_1(0) = \tilde{i}_{sa}(0) = 0.3A, \hat{x}_2(0) = \tilde{i}_{sb}(0) = 0.2A, \hat{x}_3(0) = \tilde{\psi}_{ra}(0) = 0.3Wb, \hat{x}_4(0) = \tilde{\psi}_{rb}(0) = 0.2Wb. \)

The HIL test result of the speed observer performance for the sine function \( f(t) = 0.3 \sin(4t), 0 \leq t \leq 2s \) is shown in Fig. 5 (a) (blue dot line). The HIL test result of the speed observer performance for the exponential function \( f(t) = 1 - e^{-t}, 0 \leq t \leq 2s \) is shown in Fig. 5 (b) (blue dot line). HIL test results for the rotor fluxes estimations are not appeared for the reason that the performances of them are similar to the previous case. It can be seen that estimated speed converges to the real speed with a rapid ratio and the estimated errors are very small, in regardless of with various speed signals in HIL test.

In order to better reflect the advantages of the modified sliding mode algorithm, the original sliding mode algorithm with sign(\( x \)) function was tested under the same initial conditions. As shown in Fig. 5 (a)-(b), the modified sliding mode algorithm (\( \arctan(\cdot) \) function) show better robustness and higher observer accuracy than original sliding mode algorithm (\( \text{sign}(\cdot) \)) function under this circumstance.

Comparatively speaking, the proposed modified SMO technique and SOSMO method in [10] both can guarantee finite time convergence for rotor flux and speed estimation over the full-speed range, only by using the measured stator voltages and stator currents. In this paper, there is no comparison between these two methods. However, SOSMO have many parameters and need complicated calculations, while the proposed SMO with simple structure can achieve the same observation performance only by tuning one parameter gain \( K \) in this paper.

2) SOSMO WITH VARIOUS SPEED REFERENCE SIGNALS

In this subsection, two typical types of speed signals are tested (see Fig. 4). The initial values of the states of LIM are set as \( x_1(0) = i_{sa}(0) = 0.1A, x_2(0) = i_{sb}(0) = 0.1A, x_3(0) = \psi_{ra}(0) = 0.1Wb, x_4(0) = \psi_{rb}(0) = 0.1Wb. \)

As shown in Fig. 4 (c)-(d) show the estimated initial values of the states of LIM are set as \( \hat{x}_1(0) = \tilde{i}_{sa}(0) = 0.3A, \hat{x}_2(0) = \tilde{i}_{sb}(0) = 0.2A, \hat{x}_3(0) = \tilde{\psi}_{ra}(0) = 0.3Wb, \hat{x}_4(0) = \tilde{\psi}_{rb}(0) = 0.2Wb. \)

Correspondingly, the estimated initial values of the states of LIM are set as

\[
\begin{align*}
\hat{x}_1(0) &= i_{sa}(0) = 0.1A, \\
\hat{x}_2(0) &= i_{sb}(0) = 0.1A, \\
\hat{x}_3(0) &= \psi_{ra}(0) = 0.1Wb, \\
\hat{x}_4(0) &= \psi_{rb}(0) = 0.1Wb.
\end{align*}
\]

In the nominal system with accurate measurement, the estimation performances with three different observers in the

B. COMPARATIVE STUDIES WITH LO AND MRAS

In this subsection, the estimated performances of the proposed SMO, LO and MRAS were tested in HIL. Considering the end effects, only LO and MRAS can be applied with the assumption that \( dv/dt \equiv 0 \), that is, \( dv/dt \equiv 0 \). In this case, low-speed signal (0.5 m/s) and high-speed signal (1.2 m/s) are chosen to better reflect the performances of these three different observers.

To fairly reflect the comparative effect of three different observers, all of the initial states and the estimated initial states are set with the same values. In the HIL test, the initial value of state states of LIM are set as \( x_1(0) = i_{sa}(0) = 0.1A, x_2(0) = i_{sb}(0) = 0.1A, x_3(0) = \psi_{ra}(0) = 0.1Wb, x_4(0) = \psi_{rb}(0) = 0.1Wb. \) To reflect the performance of proposed SMO, the initial values of estimated currents and fluxes are chosen different from initial state variables. The estimated initial values are chosen as: \( \hat{x}_1(0) = \tilde{i}_{sa}(0) = 0.4A, \hat{x}_2(0) = \tilde{i}_{sb}(0) = 0.5A, \hat{x}_3(0) = \tilde{\psi}_{ra}(0) = 0.45Wb, \hat{x}_4(0) = \tilde{\psi}_{rb}(0) = 0.55Wb. \) The parameters of proposed SMO gains \( K \) is chosen as \( K = 200. \)

In the nominal system with accurate measurement, the estimation performances with three different observers in the

FIGURE 5. SMO with various speed reference signals (a) Speed estimate performance with signal \( f(t) = 0.3 \sin(4t) \), \( 0 \leq t \leq 2s. \) (b) Speed estimate performance with signal \( f(t) = 1 - e^{-t} \), \( 0 \leq t \leq 2s. \)
HIL test are presented in Fig. 6 (a)-(b), and corresponding steady-state error index can be seen in Table 2. As can be seen from these two subfigures, exact estimation performances are obtained with three different observers (the tiny stable estimate errors can be ignored).

In the perturbed system with measurement noise, the dc offset effect is considered in these three observers, specific measured errors with $+0.2\,\text{V}$ dc offset were added on both stator voltage components $u_{s\alpha}$ and $u_{s\beta}$. As expected, the estimated speed errors were appeared with these three observers, as shown in Fig. 6 (c)-(d). However, SMO has greater estimation accuracy than LO and MRAS especial there exist noise measurement, which means SMO has better robust observer performance than LO and MRAS.

**VI. CONCLUSION**

In this article, we propose a novel SMO scheme for the linear induction motor, considering the dynamic end effects. A method based on the nonlinear dynamical system state observability theory is applied to LIM drive state observability analysis, together with conditions allowing reliable motor speed estimation. For the observer design, the proposed SMO can reconstruct stator currents, rotor fluxes, speed and speed-depended parameter $w$ simultaneously. The feasibility and effectiveness of the proposed SMO technique for LIM system has been validated with Hardware-in-the-loop (HIL) test. Results show that the estimated stator currents, rotor fluxes and speed converges to the actual value with great tracking performance. Great speed estimation performances are obtained in different speed signals (constant speed signal and various speed signals). Furthermore, the designed SMO show better robustness property than LO and MRAS both in nominal case and perturbed case. In summary, Mathematical and HIL test results are justified enough that the proposed SMO scheme is a promising route to be taken.

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