FUZZY-SLIDING MODE CONTROLLER FOR LINEAR INDUCTION MOTOR CONTROL

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In this paper, the position control of linear induction motor using fuzzy sliding mode integral controller design is proposed. First, the indirect field oriented control LIM is derived. Then, a designed sliding mode integral control (SMIC) system with an integral-operation switching surface is investigated, in which a simple adaptive algorithm is utilized for generalized soft-switching parameter. Finally, a fuzzy sliding mode controller is derived to compensate the uncertainties which occur in the control, in which the fuzzy logic system is used to dynamically control parameter settings of the SMIC control law. The effectiveness of the proposed control scheme is verified by numerical simulation. The numerical validation results of the proposed scheme have presented good performances compared to the conventional sliding mode controller.

1. **INTRODUCTION**

Nowadays, LIM's are now widely used, in many industrial applications including transportation, conveyor systems, actuators, material handling, pumping of liquid metal, and sliding door closers, etc. with satisfactory performance [1, 2]. The most obvious advantage of linear motor is that it has no gears and requires no mechanical rotary-to-linear converters. The linear electric motors can be classified into the following: D.C. motors, induction motors, synchronous motors and stepping motors, etc. Among these, the LIM has many advantages such as high-starting thrust force, alleviation of gear between motor and the motion devices, reduction of mechanical losses and the size of motion devices, high-speed operation, silence, and so on [1, 2]. The driving principles of the LIM are similar to the traditional rotary induction motor (RIM), but its control characteristics are more

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complicated than the RIM, and the motor parameters are time varying due to the change of operating conditions, such as speed of mover, temperature, and configuration of rail.

Sliding mode control theory, due to its order reduction, disturbance rejection, strong robustness and simple implementation by means of power converter, is one of the prospective control methodologies for electrical machines [3–8]. The feature of sliding mode control (SMC) system is that the controller is switched between tow distinct control structures. In general, the design of variable structure controller generally consists of two steps, which are hitting and sliding phases [6–8]. First, the system is directed towards a switching surface by a feedback control law, the sliding mode occurs. When the system states enter the sliding mode, the dynamic of the system are determined by the choice of sliding surface. The mentioned situations are independent of parametric uncertainties and load disturbances. Hence, SMC has been employed to the position and speed control of AC machines. But because of the non-continuous switch feature of SMC, the chattering can occur in the control system [3, 6–8]. In order to reduce or overcome the system chattering, researches have proposed the fuzzy control design methods based on the sliding-mode control scheme [5, 9–12]. Recently, fuzzy sliding-mode controllers have been researched and applied to different systems; however, there are not many applications to an induction motor. Lin *et al.* [5] utilized an adaptive FSMC system for a PM synchronous motor drive, but there still existed chattering control efforts. On the other hand, introducing SMC into fuzzy neural network is one another research field. Wong *et al.* [11] combined a fuzzy controller with SMC and state feedback control or proportional-integral control to remedy the chattering phenomena and to achieve zero steady-state error.

In this paper, a fuzzy sliding mode controller which combines the merits of the sliding mode control and the fuzzy inference mechanism is proposed. In this scheme, a fuzzy sliding mode controller is investigated, in which the fuzzy logic system is used to dynamically control parameter settings of the classical SMC. The reminder of this paper is organized as follows. Section II reviews the principle of the indirect field-oriented control (FOC) of linear induction motor. Section III shows the development of sliding mode controllers design for LIM control. The proposed fuzzy sliding mode control scheme is presented in Section 4. Section 5 gives some simulation results. Finally, some conclusions are drawn in Section 6.

2. **INDIRECT FIELD-ORIENTED CONTROL OF THE LIM**

The dynamic model of the LIM is modified from traditional model of a three-phase Y-connected induction motor and can be expressed in the *d-q* synchronously rotating frame as [1, 2, 4]:

$$\frac{\mathrm{d}i_{ds}}{\mathrm{d}t}=\frac{1}{\sigma L_s}\left(-\left(R_s+\left(\frac{L_m}{L_r}\right)^2 R_r\right)\cdot i_{ds}+\sigma\cdot L_s\cdot\frac{\pi}{h}\cdot v_e\cdot i_{qs}+\frac{L_m\cdot R_r}{L_r^2}\cdot\phi_{dr}+\frac{P\cdot L_m\cdot\pi}{L_r\cdot h}\cdot\phi_{qr}\cdot v_r+v_{ds}\right); \tag{1}$$

$$\frac{\mathrm{d}i_{qs}}{\mathrm{d}t}=\frac{1}{\sigma L_s}\left(-\sigma\cdot L_s\cdot\frac{\pi}{h}\cdot v_e\cdot i_{ds}-\left(R_s+\left(\frac{L_m}{L_r}\right)^2\cdot R_r\right)\cdot i_{qs}-\frac{P\cdot L_m\cdot\pi}{L_r\cdot h}\phi_{dr}\cdot v_r+\frac{L_m\cdot R_r}{L_r^2}\cdot\phi_{qr}+v_{qs}\right); \tag{2}$$

$$\frac{\mathrm{d}\phi_{dr}}{\mathrm{d}t}=\frac{L_m\cdot R_r}{L_r}i_{ds}-\frac{R_r}{L_r}\cdot\phi_{dr}+\left(\frac{\pi}{h}\cdot v_e-P\cdot\frac{\pi}{h}\cdot v_r\right)\cdot\phi_{qr}; \tag{3}$$

$$\frac{\mathrm{d}\phi_{qr}}{\mathrm{d}t}=\frac{L_m\cdot R_r}{L_r}\cdot i_{qs}-\left(\frac{\pi}{h}\cdot v_e-P\cdot\frac{\pi}{h}\cdot v_r\right)\cdot\phi_{dr}-\frac{R_r}{L_r}\cdot\phi_{qr}; \tag{4}$$

$$F_e=K_f\left(\phi_{dr}\cdot i_{qs}-\phi_{qr}\cdot i_{ds}\right)=M\cdot\dot{v}_r+D\cdot v_r+F_L, \tag{5}$$

where R_s is the winding resistance per phase, R_r is the secondary resistance per phase referred primary, L_m is the magnetizing inductance per phase, L_r is the secondary inductance per phase, L_s is the primary inductance per phase, v_r is the mover linear velocity, *h* is the pole pitch, *P* is the number of pole pairs, ϕ_{dr} and ϕ_{qr} are *d*-axis and *q*-axis secondary flux, respectively, i_{ds} and i_{qs} are *d*-axis and *q*-axis primary current, respectively, v_{ds} and v_{qs} are *d*-axis and *q*-axis primary voltage, respectively, $\tau_r=L_r/R_r$ is the secondary time-constant, $\sigma=1-\left(L_m^2/(L_sL_r)\right)$ is the leakage coefficient, $K_f=3P\pi\cdot L_m/(2hL_r)$ is the force constant, F_e is the electromagnetic force, F_L is the external force disturbance, *M* is total mass of the moving element and *D* is the viscous friction and iron-loss coefficient.

The main objective of the vector control of linear induction motors is, as in DC machines, to independently control the electromagnetic force and the flux; this is done by using a *d-q* rotating reference frame synchronously with the rotor flux space vector [2, 4, 5]. In ideally field-oriented control, the secondary flux linkage axis is forced to align with the *d*-axis, and it follows that [1, 3, 5]:

$$\phi_{qr}\quad\frac{\mathrm{d}\phi_{qr}}{\mathrm{d}t}\quad 0 \tag{6}$$

$$\phi_{dr}\quad\phi_r\quad\text{constant.} \tag{7}$$

By use of the indirect field-oriented control technique and with the fact that the electrical time constant is much smaller than the mechanical time constant, the electromagnetic force shown in (5) can be reasonably represented by the following equations:

$$F_e = K_f \cdot i_{qs}; \tag{8}$$

$$K_f = \frac{3}{2} P \frac{\pi \cdot L_m^2}{h \cdot L_r} i_{ds}. \tag{9}$$

Moreover, using (4) the feedforward slip velocity signal can be estimated using ϕ_{rd} and i_{qs} as follows:

$$v_{sl} = \frac{h \cdot L_m}{\pi \cdot \tau_r} \frac{i_{qs}^*}{\phi_{rd}}. \tag{10}$$

3. SLIDING MODE INTEGRAL CONTROL OF LIM

A Sliding Mode Controller is a Variable Structure Controller (VSC). Basically, a VSC includes several different continuous functions that map the plant state to a control surface, and the switching among the functions is determined by the plant state and is represented by a switching function [3, 5–8]. VSS control is developed that all trajectories in the state space are directed toward some switching surface, i.e. repeatedly crosses and immediately recrosses the surface. The proposed sliding-mode position controller is shown in Fig. 1. The state variables are defined as follows:

$$x_1 = d_r^* - d_r; \tag{11}$$

$$\dot{x}_1 = -\dot{d}_r = -v_r = -x_2. \tag{12}$$

Then, the linear induction motor can be represented in the following state-space form:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & -1 \\ 0 & -D/M \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ K_f \end{bmatrix} \cdot i_{qs} + \begin{bmatrix} 0 \\ -1/M \end{bmatrix} F_L. \tag{13}$$

The trajectory, which the SLMIC forces the system to slide along [12, 13], is a straight line described in (14)

$$S = c \cdot x_1 + \dot{x}_1. \tag{14}$$

The dynamics described in (14) is a first-order response with a defined speed response time constant. Various control laws can be used to force the system response.

In case of the above system, the discontinuous control signal has the form

$$u = \begin{cases} u^{+} & \text{for} \quad S > 0, \\ u^{-} & \text{for} \quad S < 0. \end{cases} \tag{15}$$

For the linear induction motor control system, the equivalent control signal is:

$$i_{eq} = -\frac{(c+a)x_2 + f(x)}{\beta}, \tag{16}$$

where: $a = -\dfrac{D}{M}$, $\beta = \dfrac{K_f}{M}$, $f(x) = -\dfrac{F_L}{M}$.

We used the same sliding-mode speed controller, as in [12], which is a variation of that presented in [13] that is a position controller

$$i_{qs} = \varphi_1 \cdot x_1 + \varphi_2 \cdot x_2 + k \cdot \operatorname{sgn}(S), \tag{17}$$

where φ_1 and φ_2 are nonlinear functions defined in this form

$$\begin{aligned} \varphi_1 &= \begin{cases} \alpha_1 & \text{if} \quad S \cdot x_1 > 0 \\ \beta_1 & \text{if} \quad S \cdot x_1 < 0, \end{cases} \\ \varphi_2 &= \begin{cases} \alpha_2 & \text{if} \quad S \cdot \dot{x}_1 > 0 \\ \beta_2 & \text{if} \quad S \cdot \dot{x}_1 < 0, \end{cases} \end{aligned} \tag{18}$$

where α_1, β_1, α_2, β_2 and k are constants.

Using a "sign" function often causes chattering in practice. One solution is to introduce a boundary layer around the switching surface [5, 7, 8]:

$$i_{qs}^{*} = i_s + i_{eq}, \tag{19}$$

where:

$$i_s = k \cdot \operatorname{sat}\left(S/\xi \right), \tag{20}$$

where the constant factor ξ defines the thickness of the boundary layer and "$\operatorname{sat}(\cdot)$" is the saturation function.

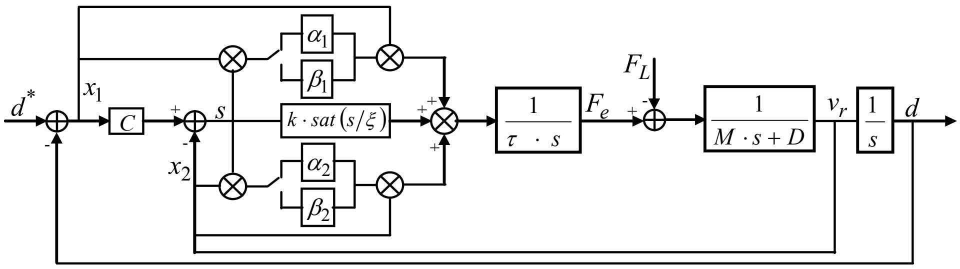

Fig. 1 – Block diagram of the conventional sliding mode integral controller of LIM.

4. FUZZY-SLIDING MODE INTEGRAL CONTROLLER FOR LIM CONTROL

The disadvantage of sliding mode controllers is that the discontinuous control signal produces chattering dynamics; chatter is aggravated by small time delays in the system. In order to eliminate the chattering phenomenon, different schemes have been proposed in the literature [5, 9–12]. In this section, a fuzzy-sliding mode controller is developed, in which a fuzzy inference mechanism is used to generate the equivalent control law parameters in (16). The proposed fuzzy-sliding mode integral controller scheme for LIM position control is shown in Fig. 4. The fuzzy logic controllers replace the inequalities given in (18) which determine the parameters of the equivalent control action. In the proposed fuzzy-SMC scheme, the sliding surface *S*, the variable x_1 and its time derivative $\dot{x}_1$ form the input space of the fuzzy implications of the major switching rule.

Because the data manipulated in the fuzzy inference mechanism is based on fuzzy set theory, the associated fuzzy sets involved in the fuzzy control rules are BN, MN, ZE, MP, BP, N and P. The membership functions of the variable x_1, $\dot{x}_1$ and S, corresponding to the fuzzy sets, BN, MN, ZE, MP and BP, are the same as shown in Fig. 2. The two membership functions of φ_1 and φ_2, corresponding to the fuzzy sets, N and P, are shown in Fig. 3. In this work, triangular Membership functions are chosen for BN, MN, ZE, MP, BP, and singleton membership functions for N and P fuzzy sets.

With fuzzy implications, φ_1 and φ_2 are switched parameters and hence the fuzzy inference mechanism can replace the soft-switching law generated by the "if" statement in the classical SMC. The fuzzy soft-switching works in such way that when S and x_1 are in the positive side, φ_1 has a positive value (bold-gray sub-tables), when S *and* x_1 are in the negative side, φ_1 is adjusted to the negative value (normal-white sub-tables). For the constant φ_2, the same logic is used to generate its parameters using S *and* $\dot{x}_1$ as inputs of the second fuzzy logic controller. The resulting fuzzy inference rules for the tow outputs variables (φ_1 and φ_2) are shown on Table 1 and Table 2:

Table 1

Fuzzy rules of φ_1

S \ x_1	BN	MN	ZE	MP	BP
BN	P	P	N	N	N
MN	P	P	N	N	N
ZE	N	N	P	P	P
MP	N	N	P	P	P
BP	N	N	P	P	P

Table 2

Fuzzy rules of φ_2

S \ $\dot{x}_1$	NB	MN	ZE	MP	BP
BN	P	P	N	N	N
MN	P	P	N	N	N
ZE	N	N	P	P	P
MP	N	N	P	P	P
BP	N	N	P	P	P

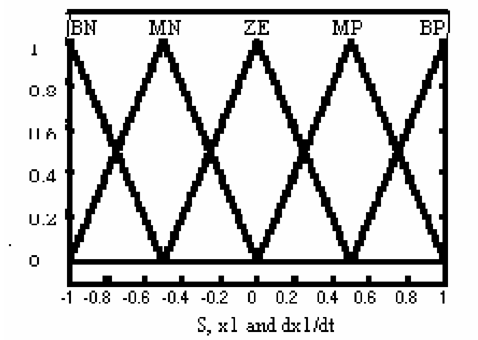

Fig. 2 – Membership functions of the surface S, x_1 and $\dot{x}_1$.

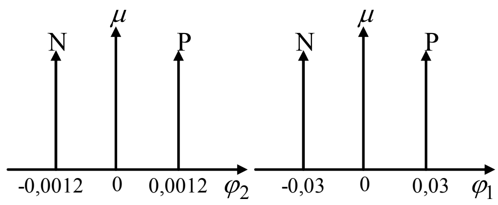

Fig. 3 – Outputs membership functions of the FSMC: φ_1 and φ_2 .

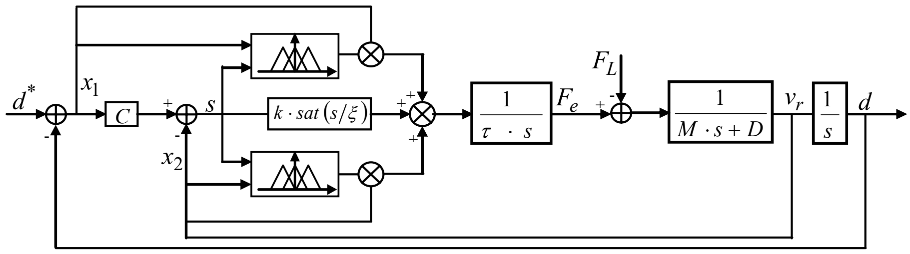

Fig. 4 – Block diagram of the Fuzzy-sliding mode controller of LIM.

5. SIMULATION RESULTS

We demonstrate the effectiveness of the proposed control scheme for position control of the linear induction motor. First, we present the simulated results of the fuzzy-sliding mode integral control system for periodic sinusoidal and triangular inputs. The parameter used in simulation are chosen as: $\phi_{2s} = 0.978$ Wb, $R_s = 0.34\ \Omega$, $R_r = 0.195\ \Omega$, $L_s = 0.1077$ H, $L_r = 0.1077$ H, $L_r = 0.1042$ H, $M = 5.47$ kg, $D = 2.36$ Nm$\cdot$s/rd, $P = 2$, $\alpha_1 = -0.03$, $\alpha_2 = 0.03$, $k = 5.5$, $\beta_1 = -0.0012$, $\beta_2 = 0.0012$ and $\xi = 0.15$.

The simulated results of the fuzzy-sliding mode integral control system for periodic step, sinusoidal and triangular inputs with load force disturbances (constant load force) are shown in Figs. 5 and 6. From simulated results, the tracking responses of the proposed controller are insensitive to load force application. A comparison between the proposed controller (fuzzy-integral sliding mode controller) and the sliding mode with integral action is shown in Fig. 7 for step and triangular reference signal (error position). In Fig. 7, it can be observed that the position response of the fuzzy sliding mode with integral action controller present better tracking characteristics and is more robust than the conventional controller.

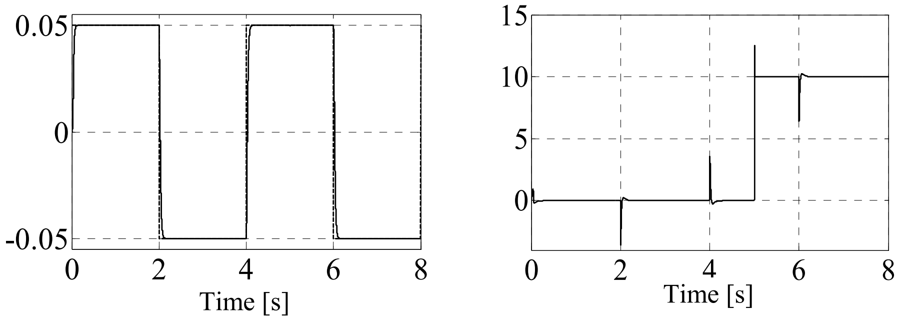

Fig. 5 – Fuzzy-sliding integral control for LIM position control with constant load force variation.

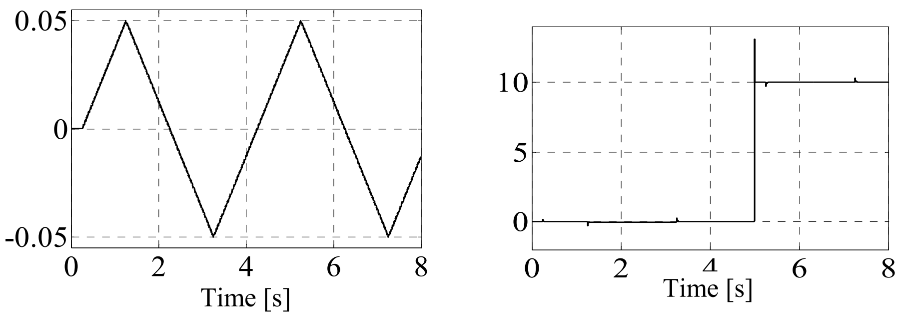

Fig. 6 – Fuzzy-sliding integral control for LIM position control with sinusoidal load force variation.

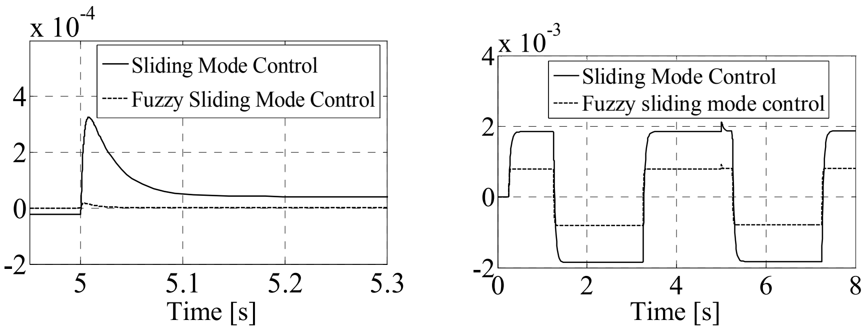

Fig. 7 – Simulated results of the comparison between the sliding mode control and fuzzy-sliding control with integral action for LIM error tracking (square and triangular).

6. **CONCLUSIONS**

This paper has demonstrated the applications of a hybrid control system to the periodic motion control of a LIM. First, a sliding mode integral controller for LIM control was designed. Moreover, a simple fuzzy inference mechanism was introduced to construct a robust control law based on the conventional sliding mode integral controller for LIM position tracking. The control dynamics of the proposed hierarchical structure has been investigated by numerical simulation. Simulation results have shown that the proposed fuzzy-sliding mode integral controller has presented satisfactory performances (no overshoot, minimal rise time, best disturbance rejection) for time-varying external force disturbances. Finally, the proposed controller provides drive robustness improvement.

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