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Sliding Mode Control Strategies for Speed Control of Linear Induction Motor Drive

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Abstract: The mover speed control of a linear induction motor(LIM) using a sliding mode control design is proposed, in this paper. Considering the end effects. First, the indirect field-oriented control LIM is derived, considering the end effects. The sliding mode control design is then investigated to achieve speed- and flux-tracking under load thrust force disturbance. The numerical simulation results of the proposed scheme present good performances in comparison to that of the classical sliding mode control.

Keywords: Linear Induction Motor, Field-Oriented Control, Sliding Mode Control, End Effects, Compensation.

I. INTRODUCTION

Currently, linear induction motors (LIMs) are widely used in many industrial applications, including transportation, conveyor systems, actuators, material handling, pumping of liquid metal, sliding-door closers, and others, with satisfactory performance [1, 2]. The most obvious advantage of a linear motor is that it has no gears and requires no mechanical rotary-to-linear converters. Linear electric motors can be classified into the following,motors, induction motors (IM), synchronous motors, stepping motors, and others. An 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 [1-4]. The driving principles of an LIM are similar to those of a traditional rotary induction motor (RIM); however, its control characteristics are more complicated. The motor parameters are time-dependent because of changes in the operating conditions, such as the speed of the mover, temperature, and rail configuration. Moreover, significant parameter variations exist in the reaction rail resistivity, the dynamics of the air gap, slip frequency, phase unbalance, saturation of the magnetizing inductance, and end effects [1-3, 5]. Therefore, its mathematical model is difficult to derive completely.

An equivalent circuit modeling of an LIM is not simple as that of a rotary motor because of the existence of the end effect. In RIMs, a sufficiently accurate equivalent circuit model can be made because of the pole-by-pole symmetry. However, in LIMs, the pole symmetry argument is not preserved because the electrical conditions change at the entry and exit point because of the end effect [6-8]. A significant amount of research has been conducted for the modeling of the dynamic performance of the LIM and all significant variations have been taken into consideration [1, 2, 4, 5]. However, uncertainties continue to exits, which are usually composed of unpredictable plant parameter variations, external load disturbance, unmodeled and nonlinear dynamics, in practical applications of the LIM. Most of the existing models of an LIM depend on field theory [6-10]; hence, they cannot be directly applied for vector control. Many researchers have derived “per-phase” equivalent circuits reflecting the end effect [6-8]. The field theory was utilized in developing the lumped parameter of the LIM model [7-9], wherein end effect, field diffusion in the secondary sheet, skin effect, and back-iron saturation were considered. However, the resulting lumped-parameter models were very complicated for practical use in modeling and control.

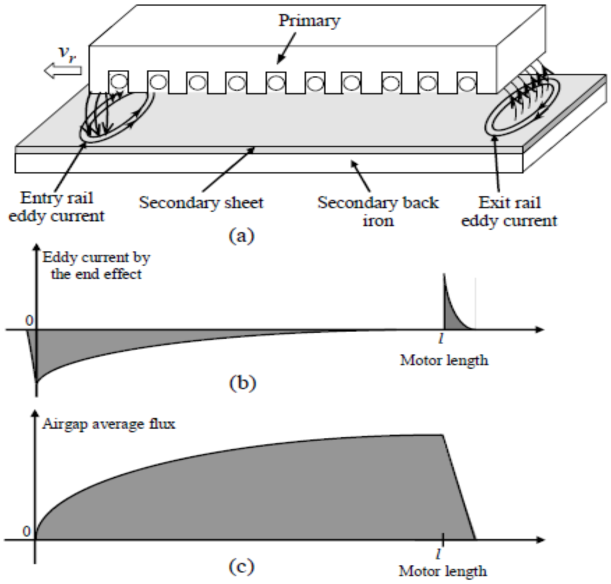


Fig.1. (a) Eddy current at the entry and exit of the air gap for a given velocity; (b) Polarity and decaying profile of the entry and exit eddy currents; (c) Air gap flux profile.

To resolve the unique end-effect problem, speed dependent scaling factors are introduced to the magnetizing inductance and series resistance in the d-axis equivalent circuit of the RIM to correct the deviation caused by the end effect [10]. In contrast, a thrust correction coefficient introduced by [11] can be used to calculate an actual thrust to compensate for the end effect. A related method to deal with the problem is the introduction of an external force corresponding to the end effect into the RIM model to provide a more accurate modeling of an LIM considering the end effect. The authors proposed a new type of end-effect compensator. The proposed method is based on the new concept that the end effect can be compensated only by supplying the eddy current synchronizing with the LIM frequency in front of the LIM. In the present paper, a sliding mode controller based on indirect field orientation is proposed for LIM speed control while considering end effects. The proposed controller is applied to achieve a speed- and flux-tracking objective under parameter uncertainties and disturbance of load thrust force.

II. INDIRECT FIELD-ORIENTED CONTROL OF THE LIM

The primary (mover) of the adopted three-phase LIM is simply a “cut-open-and-rolled-flat” rotary-motor primary. The secondary generally consists of a sheet conductor using aluminium with an iron back for the return path of the magnetic flux. The primary and secondary form a single-sided LIM. Moreover, a simple linear encoder is adopted for the feedback of the mover position. Fig. 1(a) shows a conceptual construction of an LIM. In an LIM, as the primary moves, the secondary is continuously replaced by a new material that tends to resist a sudden increase in flux penetration and only allows a gradual build up of the flux density in the air gap. To obtain a suitable LIM equivalent circuit, quantifying the effects of the entry and exit of new material on the air gap flux distribution known as the end effect will be necessary. When the primary of an LIM does not move, there is no difference in the equivalent circuits of LIM and RIM, because the contribution of the end effects will be relatively small and can be neglected. However, if the primary coil of LIM moves, a new field penetrates into the reaction rail in the entry area, whereas the existing field disappears at the exit area, thereby creating the eddy current in the reaction rail. The eddy current in the entry grows very rapidly to mirror the primary current, nullifying the primary magneto motive force (MMF) and reducing the flux to nearly zero at entry [6-8]. At the same time, the eddy current generates dragging force at the exit area, which reduces the hauling ability of the motor.

The density profile of the eddy current along the length of LIM is depicted in Fig. 1(b) [6-8]. Hence, the resulting MMF, and thereby air gap flux, is something similar to that shown in Fig. 1(c). The spatial distribution of the magnetic flux density along the length of the primary is dependent on the relative velocity between the primary and the linor (secondary). For a zero relative velocity, the LlM can be considered to have an infinite primary. In this case, the end effects may be ignored. The end-effect dynamic because of the relative motion between the primary and the secondary causes additional thrust attenuation, which may decrease the main thrust force of the LIM. At low speed, the additional thrust attenuation are small; at high speed, the additional thrust attenuation becomes significant [6-10]. The end effects behave differently at the entry and exit ends of the LIM. The currents induced in the secondary at the entry end decay more slowly than at the exit end because of a larger time constant. Duncan used the parameter Q to simulate this effect associated with the length of the primary. To a certain degree, he quantified the end effects as a function of the velocity v_r as described by Eq. (1) [7-10]:

$$Q = \frac{l \cdot R_r}{L_r \cdot v_r} \tag{1}$$

where l is the primary length.

III. SPEED CONTROL OF LIM USING SLIDING MODE CONTROL

Variable structure control (VSC) with sliding mode (SMC) is one of the effective nonlinear robust control approaches because it provides system dynamics with an invariance property to uncertainties once the system dynamics are controlled in the sliding mode [20-25]. The first step of SMC design is to select a sliding surface that models the desired closed-loop performance in state variable space. The control is then designed such that the system state trajectories are forced to the sliding surface and to stay on it. The system state trajectory in the period of time before reaching the sliding surface is called the reaching phase. Once the system trajectory reaches the sliding surface, it stays on it and slides along it toward the origin. The system trajectory sliding along the sliding surface toward the origin is the sliding mode. The insensitivity of the controlled system to uncertainties exists in the sliding mode, but not during the reaching phase. Thus, the system dynamic in the reaching phase continues to be influenced by uncertainties. Without loss of generality, consider the design of a sliding mode controller for the following second order system: $\ddot{x} + a_1\dot{x} + a_2x = b.u$, where u(t) is the input to the system, and b>0 is assumed. A possible choice for the structure of a sliding mode controller is [7].

$$u = u_{eq} + k \cdot sgn(s) \tag{2}$$

where u_{eq} is called the equivalent control, which dictates the motion of the state trajectory along the sliding surface. k is a constant, representing the maximum controller output required to overcome parameter uncertainties and disturbances; and s is called the switching function because the control action switches its sign on the two sides of the switching surface s = 0.

$$s = \dot{e} + \lambda \cdot e \tag{3}$$

where $e = x_d - x$ and x_d are the desired states; λ is a constant; and sgn(s) is the signum function:

$$sgn(s) = \begin{cases} -1 & s < 0 \\ 1 & s > 0 \end{cases} \tag{4}$$

To ensure that the system trajectories move toward and stay on the sliding surface s = 0 independent of the initial condition. In practice, using a sign function often causes chattering. One solution is to introduce a boundary layer around the switching surface.

$$u = u_s + u_{eq} \tag{5}$$

Where

$$u_s = k.sat\left({}^{s}/_{\xi}\right) \tag{6}$$

and where the constant factor ξ defines the thickness of the boundary layer, and sat (·) is a saturation function defined as

$$sat\left({}^{s}/_{\xi}\right) = \begin{cases} sgn\left(\frac{s}{\xi}\right) & \left|\frac{s}{\xi}\right| \geq 1 \\ \frac{s}{\xi} & \left|\frac{s}{\xi}\right| < 1 \end{cases} \tag{7}$$

The characteristic of u_s versus s is shown in Fig. 2.

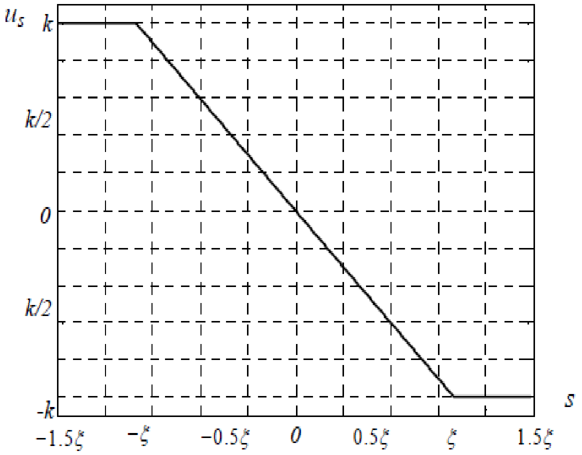


Fig. 2. Discontinuous control action of the SMC control law (u_s).

The LIM has a significant nonlinear behavior, such as the coupling between the motor speed and the electrical quantities; the model parameters such as the mover mass and the friction coefficient may also not be exactly known. At the same time, the load thrust is always unknown. Other factors may also influence the LIM system. For example, the LIM is often influenced by parameter uncertainties because of the end effects, unmodelled dynamics, and external disturbances. The need for controllers with high performance and guaranteed robustness has increased during the last decade, especially with the requirement of high precision in real applications. This section describes the design procedure of the robust nonlinear control via the SMC for LIM control, considering the end effects. The objective of this controller is to obtain the LIM control laws so as to achieve high quality speed tracking performance. The design of the proposed sliding mode controller for an LIM mover speed control involves the following steps:

Design of Sliding Mode Speed Controller:

To control the speed of the LIM, the sliding surface is defined as follows:

$$s(v_r) = v_r^* - v_r \tag{8}$$

Differentiating $s(v_r)$ with respect to time gives

$$\dot{s}(v_r) = \dot{v}_r^* - \dot{v}_r \tag{9}$$

Considering the motion equation of the LIM defined, the time derivative of sliding surface can be written as

$$\dot{s}(v_r) = \dot{v}_r^* - \left(\frac{3}{2}\frac{PL_m(Q)\pi\cdot\emptyset_{dr}^*}{M\cdot h\cdot L_r(Q)}.\, i_{qs} - \frac{D}{M}v_r - \frac{F_L}{M}\right) \tag{10}$$

We take

$$i_{qs} = i_{qs}^{equ} + i_{qs}^{n} \tag{11}$$

During the sliding mode and at steady-state conditions, $s(v_r) = 0$, $\dot{s}(v_r) = 0$, and $i_{qs}^n = 0$; the equivalent control action can be defined as follows:

$$i_{qs}^{equ} = \frac{2}{3}\frac{hML_r(Q)}{\pi PL_m(Q)\emptyset_{dr}^*}\left(\dot{v}_r^* + \frac{D}{M}v_r + \frac{F_L}{M}\right) \tag{11}$$

During the convergence mode, the condition $s(v_r)\cdot\dot{s}(v_r) < 0$ must be verified, thereby guaranteeing motion of the state trajectory to the manifold. Substituting (11) into the time derivative of the sliding surface $\dot{s}(v_r)$ yields

$$\dot{s}(v_r) = -\frac{3}{2}\frac{\pi PL_m(Q)\emptyset_{dr}^*}{hML_r(Q)} i_{qs}^n \tag{12}$$

The discontinuous control action can be given as

$$i_{qs}^n = k_{iqs}\cdot sat(s(v_r)/\xi_v) \tag{13}$$

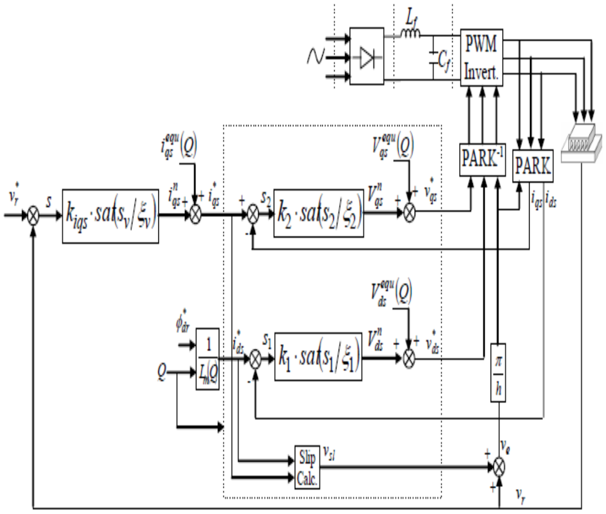
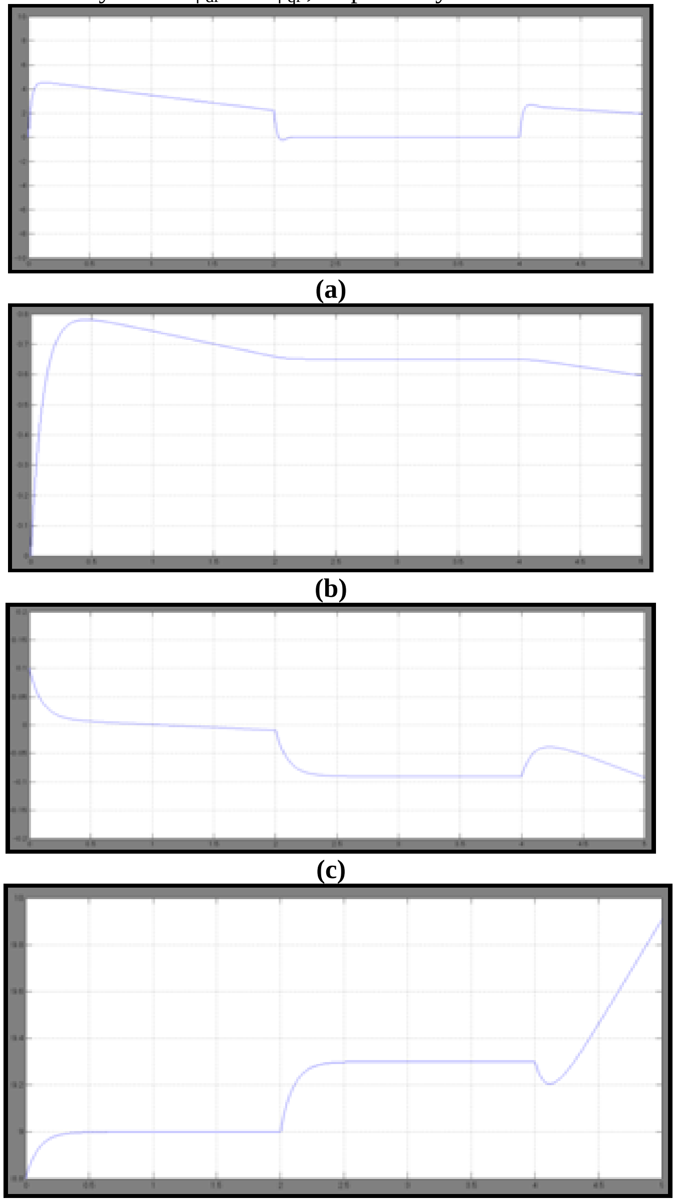


Fig.3. Block diagram of sliding mode speed and currents control of LIM with end effects compensation.

To verify the system stability condition $(s(v_r)\cdot\dot{s}(v_r) < 0)$, choosing a strictly positive gain k_{iqs} is sufficient. The current loops are often the internal regulated loop in a field-oriented controlled LIM. The global performance of the drive is strongly dependent on the performance of current control. Therefore, precise and fast current control is essential to achieve high static and dynamic performance for the FOC of LIMs. If the secondary currents are not adjusted precisely and do not have fast dynamics to the reference values, cross-coupling will occur between the motor thrust and the primary flux, thereby degrading the performance of the FOC.

IV. SIMULATION RESULTS

Simulations were carried out in MATLAB/SIMULINK to demonstrate the effectiveness of the proposed control scheme for speed control of the LIM. The block diagram of the proposed control system is shown in Fig. 3. The proposed control system mainly consists of a linear induction motor, a ramp comparison current-controlled pulse width modulated (PWM) inverter, a slip velocity estimator, an inverse park, IFOC bloc based on sliding mode current controller, and a speed feedback control loop that contains a sliding mode controller. The simulated results of the SMC system without compensation on end effects for rectangular shape-thrust are shown in Fig. 4. The thrust is depicted in Fig. 4(a), and the direct secondary current i_{ds} is depicted in Fig. 4(d). Figs. 4(b) and 4(c) show the direct and quadratic secondary fluxes φ_{dr} and φ_{qr}, respectively.



(a)

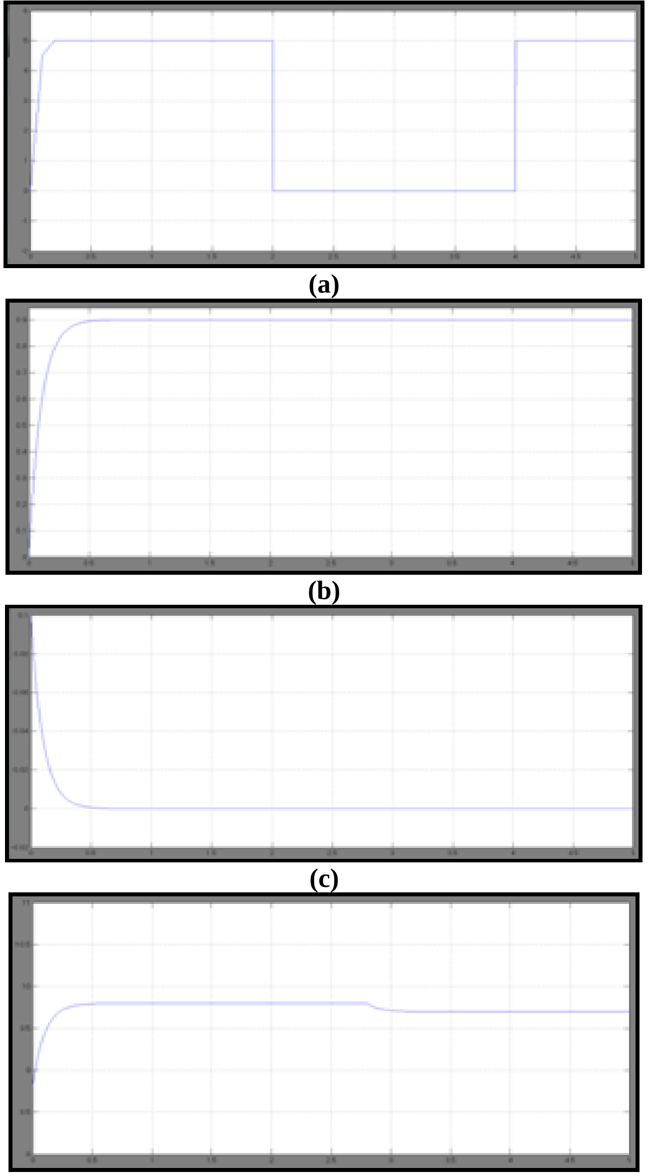
(b)

(c)

(d)

Fig.4. Simulated results of the decoupling obtained by SMC without end effects compensation.

The fig 5 shows simulation results with compensation



(a)

(b)

(c)

(d)

Fig.5. Simulated results of the decoupling obtained by SMC with end effects compensation.

V. CONCLUSION

The present paper demonstrates the application of a nonlinear SMC system for the speed control of an LIM, considering end effects. First, an IFOC of LIM is designed, considering the end effects. Moreover, a SMC design technique is investigated to achieve a thrust-, flux-, and speed-tracking objective under disturbance of load thrust force. The control dynamics of the proposed hierarchical structure were investigated through numerical simulation. The proposed sliding mode controller with end effects compensation presented satisfactory performances and provided desirable decoupling between flux and thrust. However, the proposed scheme needs an adaptive control law or an estimation of the end effect and magnetizing inductance.

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