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Simulink Model of Vector Controlled Linear Induction Motor with End Effect for Electromagnetic Launcher System

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***Abstract*—Today, linear induction motors spread out in the field of transportation and many industrial fields such as railway and electromagnetic launcher systems. Especially, high efficiency control and fast dynamic response are demanded for electromagnetic launcher systems and it's well known that direct torque control scheme provides fast dynamic response for rotary induction motors. This paper describes Simulink model of direct thrust controlled linear induction motor with end effect for electromagnetic launcher system and presents a simple and effective scheme for direct thrust control of a linear induction motor. The Simulink model of single sided linear induction motor with end effect developed to realize the direct thrust control. To show the effectiveness of the improved system, simulation results are presented using commercially available software package Matlab/Simulink.**

***Index Terms*—Electromagnetic launching, Inverters, vector control, thrust control.**

I. INTRODUCTION

Various motor types used in the electromagnetic launcher systems, such as a single-sided linear induction motors (LIMs), double-sided LIMs, permanent magnet linear synchronous motor and permanent magnet brushless DC motor. The first linear motor was produced by Charles Wheatstone in 1845. There are many using areas of linear motors. In general LIMs for stand-alone applications are conveyor systems, human handling, liquid metal transport, and the accelerator, and the launcher, slow and medium-speed trains [1]. Towards the end of the 1940s the United States Navy for Westinghouse Electric Company completed successfully two aircraft launcher system. The system length and width were 425 m and 30 cm, respectively. The system needed 12 000 kW electrical power for working. The launching process continues along 300 m. At this distance, it can take between 4 to 15 minutes. Aircraft launching velocity reaches 100 m/s and remains at 125 m distance to stop [2], [3]. Yamamura made detailed studies on theoretical basics of LIMs. Both single and double-sided LIM studies were analyzed for theoretical end effect [4]. Nasar and Boldea made very extensive research on LIMs. The single-sided LIMs were examined detail in their books [5]–[7]. R. M. Pai and Boldea obtained LIM's full equivalent circuits. Also, they obtained steady-state performance characteristics, end effect, transversely with side effects and skin effect of LIM using one-dimensional, two-dimensional and three-dimensional analyzes [8]. E. R. Laithwaite used LIM to accelerate heavy weights. In his study, the LIM design was presented for moving payload of 200 kg to 1500 m distance with the velocity of 1200 m/s [9].

The driving principles of the LIMs are similar to the traditional rotary induction motor. However, its control characteristics are more complicated than novel induction motors. High performance vector control of LIMs mostly carried out in secondary flux oriented scheme has been presented in many works [10]–[13]. However, field oriented control is more complicated and requires machine parameters. In contrast to field-oriented control, traditional direct torque control requires only the accurate knowledge of the stator resistance, the stator flux and torque estimations. The control algorithm of direct torque control makes it suitable for practical implementation on embedded drive systems [14[–[16].

Compared with novel induction motors, direct thrust control (DTC) for LIM has been less researched. In the papers in literature studying vector control for LIM [17], [18], end effect was included. General views of ELS is shown in Fig. 1.

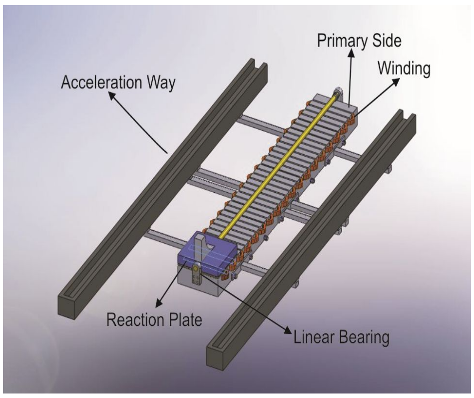

Fig. 1. General view of ELS.

The main purpose of this paper is to develop the Simulink model of DTC controlled LIM that designed for use as

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electromagnetic launcher. The rest of the paper is organized as follows. Firstly, the mathematical and the Simulink model of LIM in stationary reference frame is presented. Second, the principals of DTC including end effects are introduced. Finally, the simulation results and some results are given.

II. Mathematical Model of Linear Induction Motor

From the d-q equivalent circuit of the LIM the primary and secondary voltages equation in a stationary reference system aligned with the secondary flux are given by (1)–(8). d-q axis primary voltage equations:

$$u_{ds} = R_s i_{ds} + R_r f(Q)(i_{ds} + i_{dr}) + \frac{d}{dt}\cdot_{ds}, \tag{1}$$

$$u_{qs} = R_s i_{qs} + \frac{d}{dt}\cdot_{qs}. \tag{2}$$

d-q axis secondary voltage equations:

$$u_{dr} = R_r i_{dr} + \frac{\circledR}{2} v_r \cdot_{qr} + R_r f(Q)(i_{ds} + i_{dr}) + \frac{d}{dt}\cdot_{dr}, \tag{3}$$

$$u_{qr} = R_r i_{qr} - \frac{\circledR}{2} v_r \cdot_{dr} + \frac{d}{dt}\cdot_{qr}. \tag{4}$$

Stator and reaction plate flux vector can be calculated using the measured current and inductance as given in (5)–(8). Where L_r is leakage inductance of secondary, L_s is leakage inductance of primary and L_m refers to the magnetizing inductance. Flux linkage equations:

$$\cdot_{ds} = L_s i_{ds} + L_m (1 - f(Q))(i_{ds} + i_{dr}), \tag{5}$$

$$\cdot_{qs} = L_s i_{qs} + L_m (i_{qs} + i_{qr}), \tag{6}$$

$$\cdot_{dr} = L_r i_{dr} + L_m (1 - f(Q))(i_{ds} + i_{dr}), \tag{7}$$

$$\cdot_{qr} = L_r i_{qr} + L_m (i_{qs} + i_{qr}). \tag{8}$$

The electromagnetic torque of an LIM is usually estimated as given in (9)–(11) are manipulated each other, then to get (12). The thrust force:

$$F_e = \frac{3}{2}\frac{\circledR}{2}\frac{P}{2}\left(\cdot_{ds} i_{qs} - \cdot_{qs} i_{ds}\right), \tag{9}$$

$$f(Q) = \frac{1 - e^{-Q}}{Q}, \tag{10}$$

$$Q = \frac{D R_r P}{2 v_r L_r}, \tag{11}$$

$$F_e = \frac{3}{2}\frac{P}{2}\frac{\circledR}{2}\frac{L_m\{1 - f(Q)\}}{L_r - L_m f(Q)}\left\{\cdot_{dr} i_{qs} - \frac{L_r^2}{L_r}\frac{f(Q)}{1 - f(Q)} i_{ds} i_{qs}\right\}. \tag{12}$$

The d-q axis primary currents and secondary currents of the LIM expressed in (13)–(16):

$$i_{ds} = \frac{\{L_r - L_m f(Q)\}\cdot_{ds} - L_m\{1 - f(Q)\}\cdot_{dr}}{\{L_s - L_m f(Q)\}\{L_r - L_m f(Q)\} - L_m^2\{1 - f(Q)\}^2}, \tag{13}$$

$$i_{qs} = \frac{L_r \cdot_{qs} - L_m \cdot_{qr}}{L_s L_r - L_m^2}, \tag{14}$$

$$i_{dr} = \frac{\{L_s - L_m f(Q)\}\cdot_{dr} - L_m\{1 - f(Q)\}\cdot_{ds}}{\{L_s - L_m f(Q)\}\{L_r - L_m f(Q)\} - L_m^2\{1 - f(Q)\}^2}, \tag{15}$$

$$i_{qr} = \frac{L_s \cdot_{qr} - L_m \cdot_{qs}}{L_s L_r - L_m^2}. \tag{16}$$

Equations mentioned above used for the Simulink model of LIM. $f(Q)$ is used for end effect factor of LIM in (10). Also $f(Q)$ is used to express the end effect on magnetization factor of the LIM in the Simulink model.

III. Direct Thrust Control

The main principle of the DTC bases on to choosing the best vector voltage which makes flux rotates and produces demanded thrust. However, the DTC scheme were initially proposed for induction motor drives but over the past years it has also been applied in other motor types. The stator flux linkage and the electromagnetic thrust can be directly controlled by the selection of optimum inverter switching states. The flux and the thrust errors are kept within acceptable limits by hysteresis controllers [19].

Stator flux linkage vector is estimated using (17)–(19):

$$T_e = \frac{3}{2}\frac{P}{2}\left(\cdot_{ds} i_{qs} - \cdot_{qs} i_{ds}\right), \tag{17}$$

$$\cdot_{qs} = \int (u_{qs} - R_s i_{qs}) dt, \tag{18}$$

$$\cdot = \sqrt{\cdot_{ds}^2 + \cdot_{qs}^2}. \tag{19}$$

The electromagnetic torque of the LIM can be calculated as given in (20)

$$T_e = \frac{3}{2}\frac{P}{2}\left(\cdot_{ds} i_{qs} - \cdot_{qs} i_{ds}\right), \tag{20}$$

where P is the number of stator poles and calculation of stator flux vector region as given in (21)

$$-_{\cdot} = \tan^{-1}\left(\frac{\cdot_{qs}}{\cdot_{ds}}\right). \tag{21}$$

These estimated values are compared to reference values and the resultant errors are applied to the hysteresis comparators. According to the hysteresis comparators outputs, the estimated angle of flux linkage and using a switching table, optimum voltage vectors are selected and applied to the inverter. For the better performance of the DTC, the accurate prediction of the thrust and stator flux is important. On the other hand, the end effects influences the thrust and flux characteristics of the LIM.

The DTC scheme is consist of switching selector, PWM inverter, flux and thrust observer and electromagnetic launcher system model. Instantaneous values of flux and thrust are calculated by using transformation of measured currents and voltages of the LIM. In these calculations, all measured electrical values of the LIM must be converted to stationary d-q reference frame on the DTC scheme.

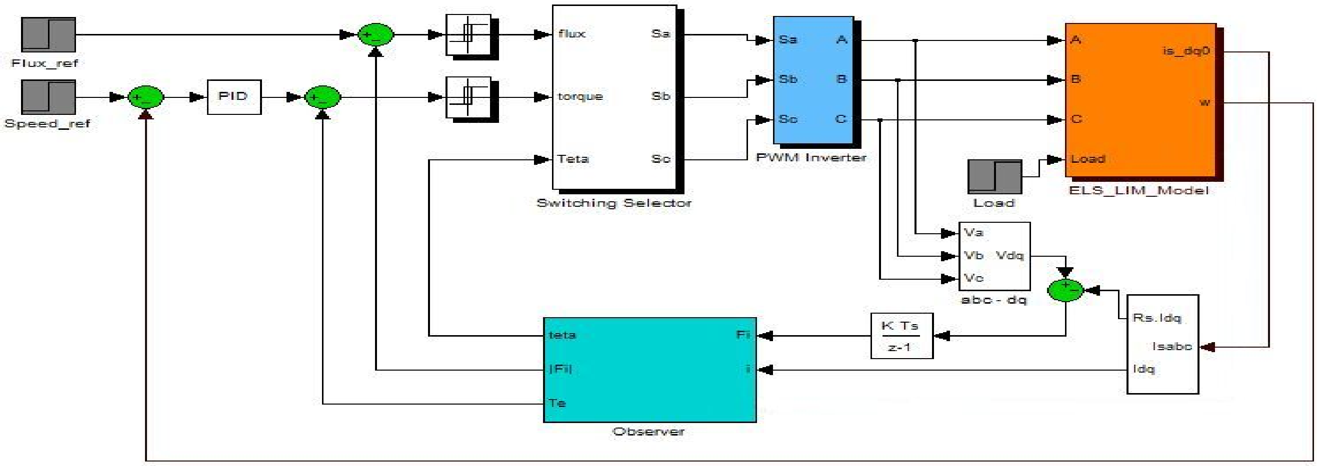

Fig. 2. DTC scheme of Linear Electromagnetic Launcher system.

The schematic representation of the proposed DTC scheme for the ELS-LIM is shown in Fig. 2.

During the simulation, the secondary d-axis reference flux is maintained constant and equal to its nominal value of 0.8 Wb. Also other LIM and simulation parameters are presented in Table I.

TABLE I. LIM AND SIMULATION PARAMETERS.

Inverter bus voltage (V)	400
Mass (kg)	2
Pole pairs	8
Pole Pitch (m)	0.15
Sampling time (s)	$1e^{-5}$
Flux reference (Wb)	0.8

IV. SIMULATION RESULTS

In this section, we demonstrate the simulation results to evaluate the dynamic performances of LIM. Thrust response, speed response and slip of LIM are realized by numeric simulation with using the Simulink interface of the Matlab environment. The simulation study consists of two parts. In the first part, the uncontrolled thrust, speed and slip are examined and in the second part, the closed loop performance of the DTC employing the improved thrust and speed is shown. In order to verify the effectiveness of the proposed scheme, simulations have been carried out on a LIM setup in the Matlab firstly.

Uncontrolled ELS thrust and DTC thrust responses are investigated in Fig. 3 and Fig. 4. Fast thrust response and rapid acceleration are important parameters for small ELS. The resistant load is 20 Nm. The exact prediction of the actual thrust is important to achieve a DTC performance. However, end effects due to core length affect the thrust characteristic. In pre-studied works investigated, thrust oscillation has large scale. This oscillation can be minimized using DTC. Thrust response is rapid in DTC. In Fig. 4, the thrust oscillation is decreased compared to Fig. 3, with using DTC.

Firstly, the dynamic thrust and speed response of the DTC system is verified under the existence of end effect. Fig. 5, (uncontrolled) and Fig. 6, (DTC) illustrates the simulation results in case assuming nominal accelerated up to 6 m/s in the 0.3 second. Also short acceleration and deceleration times are suitable for the small LIM. In Fig. 6, the speed steady state time is decreased compared to Fig. 5, with using DTC. Moreover, DTC provides small speed changed (Uncontrolled speed change=1 m/s, DTC=0.1 m/s) for ELS.

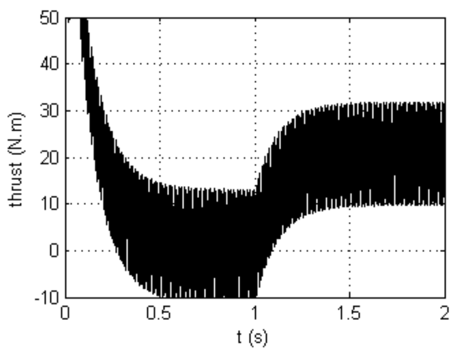

Fig. 3. Uncontrolled ELS thrust response.

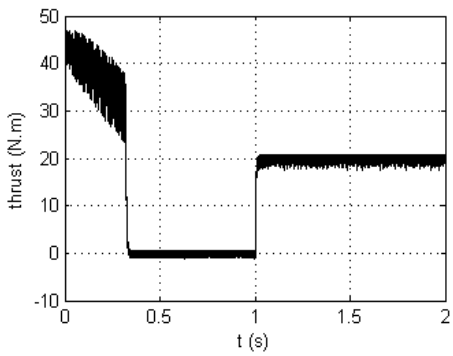

Fig. 4. DTC controlled ELS thrust response.

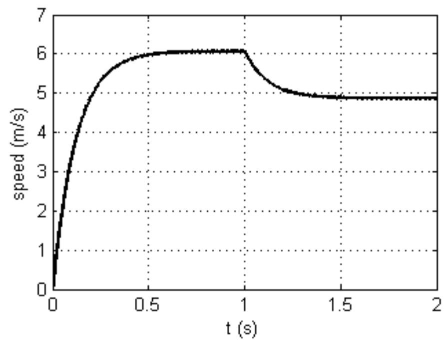

Fig. 5. Uncontrolled ELS speed response.

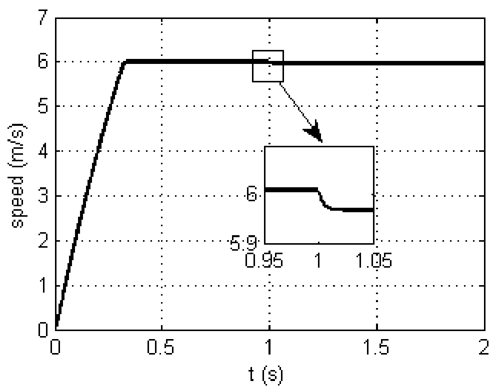

Fig. 6. DTC Controlled ELS speed response.

V. CONCLUSIONS

This paper deals with modeling of an improved DTC scheme for ELS . Many kinds of linear motors use for ELS such as permanent magnet linear motors, brushless DC motors and LIMs. However, LIMs are suitable for small ELS due to short acceleration and deceleration times. The Simulink model of single sided LIM developed to realize DTC scheme on ELS. Thrust and speed response are realized by numerical simulations with using the Simulink interface of the Matlab environment. It has been observed that the dynamic response of ELS is faster and torque ripples are reduced with the proposed method. Also purposed method provides small speed changed (Uncontrolled speed change=1 m/s, DTC=0.1 m/s) and short acceleration-deceleration times are suitable for the small ELS

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