Cascade Position Control of Linear Reluctance Motor Fed by SVPWM VSI with Fuzzy Logic Controller

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***Abstract*- A two-axis dynamic model of linear reluctance motor (LRM) is presented in this paper. The cascade position control with fuzzy logic controller is used to track the position of LRM fed by space vector pulse width modulation (SVPWM) inverter. The simulation results gained using Matlab/Simulink software show that the proposed motor model can give good performance in trackng the position reference using the proposed cascade controller.**

Key words: LRM, Cascade control, Position control.

I. INTRODUCTION

In recent years, linear motors have gained considerable attention in applications for linear motion such as modern laser cutting, robotic assembly systems and transportation. The direct-drive linear motor systems have many advantages compared with traditional (indirect) drive rotary motor systems coupled with lead screws or toothed belts. The electromagnetic force from linear motor can be applied directly to the payload without any mechanical transmission that usually imposes mechanical limitations on velocity. As a result, the system can operate with higher acceleration and velocity to achieve higher accuracy that is now only limited by the bandwidth of the position measurement system or by the power electronics system. In addition, the linear motor drive systems provide less friction, no backlash, low mechanical maintenance and longer lifetime[1,2].

Every electrical rotating machine can be built in its linear version to satisfy the requirements of particular applications. Generally, if the end effects are disregarded, the behavior and performance of the linear motor can be deduced from those of the originate rotating motor. Therefore, high thrust density has to be expected from the linear reluctance motor. Therefore linear reluctance motors can be alternative for linear induction motors with less secondary loss, less end effect, and constant thrust force in different speeds[3].

Linear motors used in the industrial drives are predominantly position controlled because the translation range of motion is limited. Three-phase linear motor models are good for motor analysis under different operating conditions, but they are inappropriate for the control synthesis. Namely, their variables are linearly dependent. For the control synthesis two-axis linear motor dynamic model are namely used[4].

In this paper, a nonlinear three-phase dynamic LRM motor model in general form is presented first. The three-phase LRM model is transformed into a d-q reference frame defined by the axes of minimum and maximum magnetic reluctances. MATLAB/SIMULINK package is employed for the simulation of the two-axis LRM model fed by space vector pulse width modulation voltage source inverter SVPWM VSI, and controlled by cascade position control with fuzzy logic controller.

II. CONSTRUCTION OF LINEAR RELUCTANCE MOTOR

The armature has a three-phase winding with geometric symmetry per phase, used to create the traveling field on the armature whose poles are asymmetric. The reaction rail of the LRM motor is composed of magnetically salient segments[4-6]. The length of the segment is equal to the armature pole pitch. By arranging the segments to gether any length of the reaction rail can be reached. Each segment consists of semicircular lamellas cut out from electrical steel sheet. A filling is used to make the segment compact. The linear reluctance motor prototype is schematically shown in Fig.1.

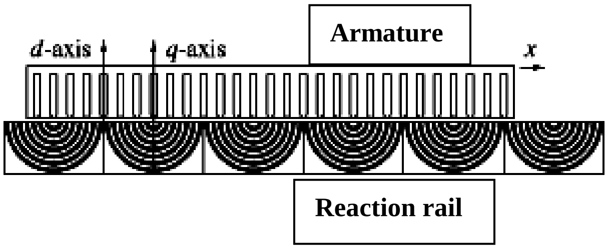


Fig.1.A cross sectional schematic diagram of LRM.

III. MATHEMATICAL MODEL OF THREE-PHASE LRM

The electrical part of a three-phase Y-connected LRM is mathematically described by the following equations:

$$v_{abc} = R_{abc} \cdot i_{abc} + \frac{d}{dt}\lambda_{abc} \qquad (1)$$

where,

$$v_{abc} = [v_a \quad v_b \quad v_c]^T \qquad (2)$$

$$i_{abc}=\begin{bmatrix} i_a & i_b & i_c \end{bmatrix}^T \tag{3}$$

$$R_{abc}=\begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \tag{4}$$

$$\lambda_{abc}=\begin{bmatrix} \lambda_a & \lambda_b & \lambda_c \end{bmatrix} \tag{5}$$

$$\lambda = L.i \tag{6}$$

The motor thrust force equation is:

$$f_{dx}=\frac{1}{2} i_{abc}^T \frac{\partial L_{abc}}{\partial x} i_{abc} \tag{7}$$

where,
λ_{abc} is the flux linkage of the primary.
x is the position of the primary.
f_{dx} is the motor thrust force.
R is the primary phase resistance.
v_a, v_b, v_c and i_a, i_b, i_c are the voltages and currents of the primary.
$\lambda_a, \lambda_b, \lambda_c$ are the flux linkages of the primary.
The matrix of of inductances L_{abc} is[4]:

$$L_{abc}=\begin{bmatrix} L+L_2C_1 & L_2C_3 & L_2C_2 \\ L_2C_3 & L+L_2C_2 & L_2C_1 \\ L_2C_2 & L_2C_1 & L+L_2C_3 \end{bmatrix} \tag{8}$$

where,

$$C_1=\cos(\frac{2\cdot\pi}{\tau_p}x) \tag{9}$$

$$C_2=\cos(\frac{2\cdot\pi}{\tau_p}x+\frac{2\cdot\pi}{3}) \tag{10}$$

$$C_3=\cos(\frac{2\cdot\pi}{\tau_p}x-\frac{2\cdot\pi}{3}) \tag{11}$$

τ_p is the armature pole pitch.

$$L=L_{s\ell}+\frac{3}{2}L_o \tag{12}$$

$L_{s\ell}$ is the phase leakage inductance of the primary due to the self flux-linkage which does not cross the air gap.
L_o is the average of the second harmonic component of self inductance due to the self flux-linkage crossing the air gap.
L_2 is the magnitude of the second harmonic component of self inductance due to the self flux-linkage crossing the air gap.
L_o and L_2 can be calculated as[4]:

$$L_o=N^2\left(\frac{1}{S_d}+\frac{1}{S_q}\right) \tag{13}$$

$$L_2=N^2\left(\frac{1}{S_d}-\frac{1}{S_q}\right) \tag{14}$$

where,
N denotes the number of turns of a single phase coil on the primary.
S_d is the minimum magnetic reluctance.
S_q is the maximum magnetic reluctance.

IV. TWO-AXIS MODEL OF LRM

The two-axis d-q model of a LRM can be derived from the three-phase model by using the transformation matrix to transform the voltage and current vectors from three phase to d-q reference frame as follows**:**

$$\begin{bmatrix} i_d \\ i_q \\ i_o \end{bmatrix}=T\cdot\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{15}$$

$$\begin{bmatrix} v_d \\ v_q \\ v_o \end{bmatrix}=T\cdot\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{16}$$

where,
v_d, v_q are the d-q reference frame voltages.
i_d, i_q are the d-q reference frame currents.
T is the transformation matrix and can be shown as[7]:

$$T=\sqrt{\frac{2}{3}}\cdot\begin{bmatrix} \cos(\frac{\pi}{\tau_p}x) & \cos(\frac{\pi}{\tau_p}x-\frac{2}{3}\pi) & \cos(\frac{\pi}{\tau_p}x+\frac{2}{3}\pi) \\ -\sin(\frac{\pi}{\tau_p}x) & -\sin(\frac{\pi}{\tau_p}x-\frac{2}{3}\pi) & -\sin(\frac{\pi}{\tau_p}x+\frac{2}{3}\pi) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \tag{17}$$

The zero component of current i_o equals zero due to the star connection.

$$V_{dq}=R_{dq}.i_{dq}+\begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix}.\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix}+ \omega.\begin{bmatrix} 0 & -L_q \\ L_d & 0 \end{bmatrix}.\begin{bmatrix} i_d \\ i_q \end{bmatrix} \tag{18}$$

$$R_{dq}=\begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix}=R_{abc} \tag{19}$$

The electromagnetic thrust force of a three phase LRM can be written as[4,8]:

$$F_e=\frac{\pi}{\tau_\rho}\left(L_d-L_q\right)i_d i_q \tag{20}$$

In addition, linear motor mechanical equation is:

$$m\frac{d^2x}{dt^2}=F_e-F_\ell-b\frac{dx}{dt} \tag{21}$$

The inductances of the LRM is given as[4]:

$$L_d = L_{s\ell} + \frac{3}{2}(L_o + L_2) \qquad (22)$$

$$L_q = L_{s\ell} + \frac{3}{2}(L_o - L_2) \qquad (23)$$

Where,

L_d is the direct axis inductance.

L_q is the quadrature axis inductances.

m is the mass of the primary.

F_ℓ is the load force.

b is the coefficient of friction.

τ_p is the primary pole pitch.

$\omega = 2\pi f$ rad/sec.

V. SIMULINK MODEL REPRESENTATION OF THE TWO-AXIS LRM

MATLAB/SIMULINK package is employed for the simulation of the two-axis LRM model. The d-q model of the motor which is given by Eqs.(18-21) are simulated using Simulink software as shown in Fig.2.

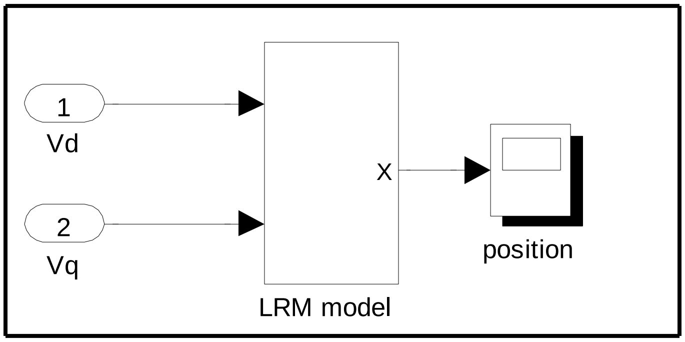


Fig.2 Implemented Simulink block model of two-axis LRM.

The internal construction of LRM model block of Fig.2 is shown in Fig.3.

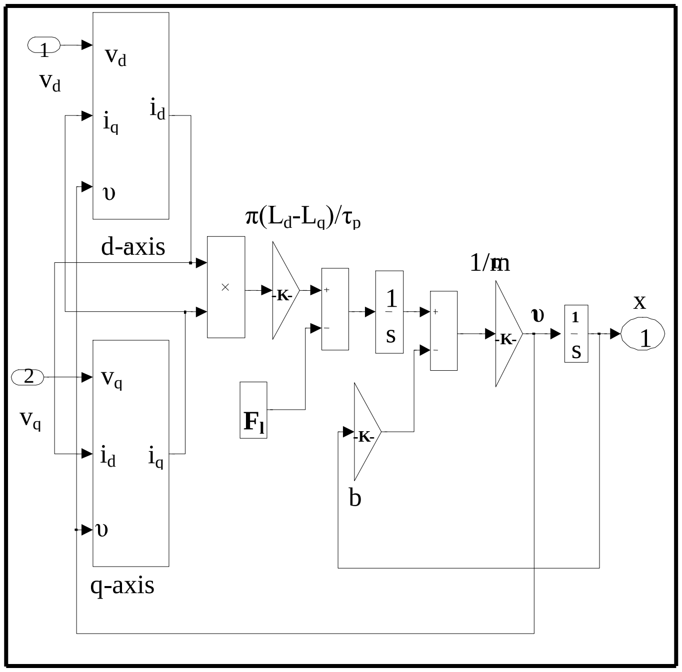


Fig.3 Internal construction of the LRM model block .

VI. POSITION CONTROL OF LRM

To achieve high performance motion control with LRM, a position sensor is typically required[5]. The motor Simulink model fed by (SVPWM) inverter and the control circuit is shown in Fig.4.

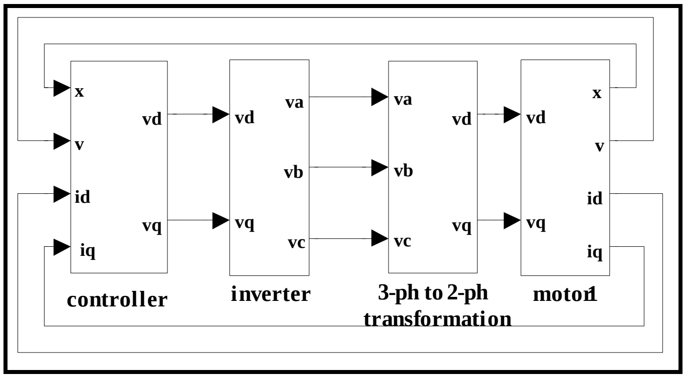


Fig.4 Implemented Simulink model of LRM fed by SVPWM inverter.

A. The Cascade Controller

The conventional position control of a LRM is a cascade control. The control structure is characterized by three serial control loops: Position loop, velocity loop, and current loop. In position loop, the input of the position controller is the position error signal. While the input of the velocity controller is the velocity error which is the difference between the output of position controller and the derivative of actual position. The input of the current controller is the difference between the output of velocity controller and the feedback current The internal construction of the first block in Fig.4 represents the cascade controller. The details of this controller is given in Fig.5.

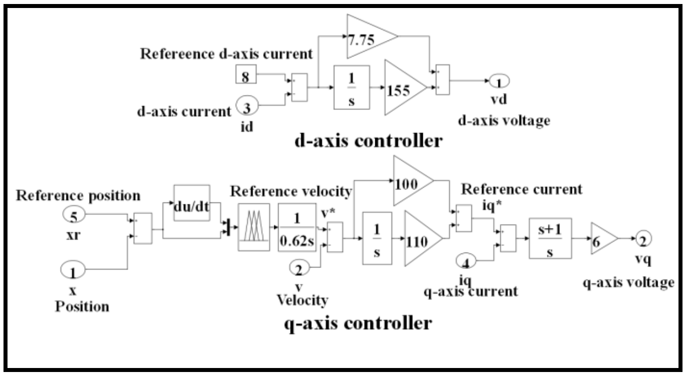
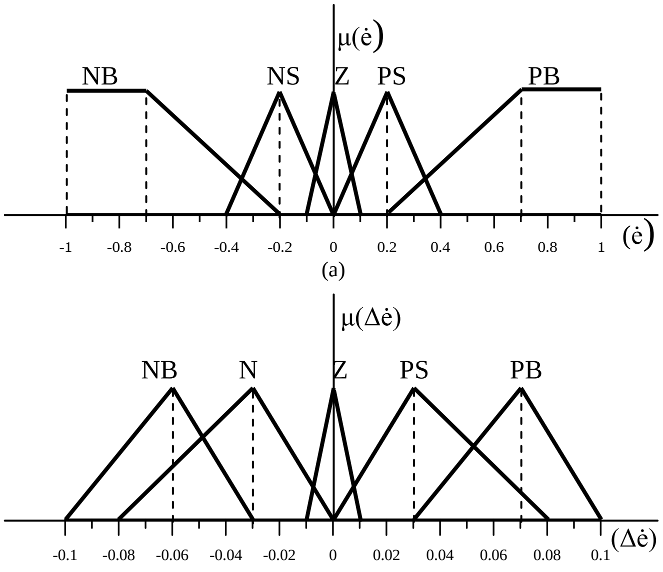


Fig.5. Implemented Simulink model of cascade position controller with FLC of the LRM.

The inputs of FLC in Fig.5 are the position tracking error between the reference position and the mover position (e = x^*- x) and the change of error (Δe). These two inputs are normalized to be between ±1 and ±0.1 for (e) and (Δe) respectively.
The input variables membership functions are shown in Fig.6.



(a)

(b)

Fig.6 The membership functions of: (a) The normalized synchronized position error.(b) The normalized change of position error.

where,
ė is the normalized error.
Δė is the normalized change of error.

The inference engine executes 25 rules (5*5) as shown in Table-I

TABLE-I

CONTROL RULES

ė Δė	**NB**	**NS**	**Z**	**PS**	**PB**
NB	PB	PS	PS	PS	Z
NS	PS	PS	PS	Z	NS
Z	PS	PS	Z	NS	NS
PS	PS	Z	NS	NS	NS
PB	Z	NS	NS	NS	NB

In the present work a zero-order Sugeno model, is used. The output level z is a constant *(a=b=0).*

B. Space Vector Pulse Width Modulation SVPWM VSI Inverter.

The second block represent the SVPWM VSI inverter. The concept of space vector is derived from the rotating field of AC machine which is used for modulating the inverter output voltage. In this modulation technique the three phase quantities can be transferred to their equivalent 2-phase quantity either in synchronously rotating frame or stationary frame. From this 2-phase component the reference vector magnitude can be found and used for modulating the inverter output[9].

VII. THE SIMULATION RESULTS

Implemented Simulink model of LRM shown in Fig.4, is tested using Matlab software facilities to verify the ability of tracking the nonlinear reference position signal as in eq.24[4] shown below. The data of the used motor are shown in Appendix-1

$$x^* = \frac{0.25}{2\pi}\left[2\pi t - \sin(2\pi t)\right] \tag{24}$$

where,

x^* is the reference position. t is the time.

The results of machine testing with 250N load to track the reference position trajectory are shown through Figs. 7 to 9.

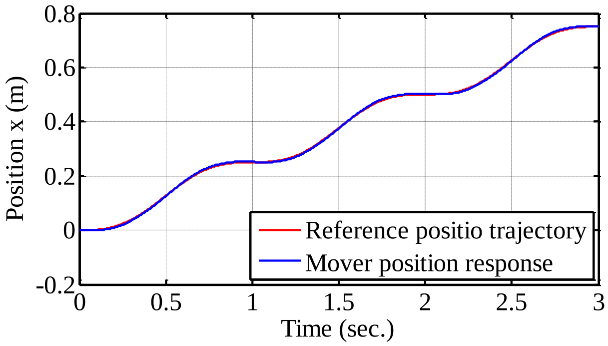


Fig.7 Mover position response with 250N load.

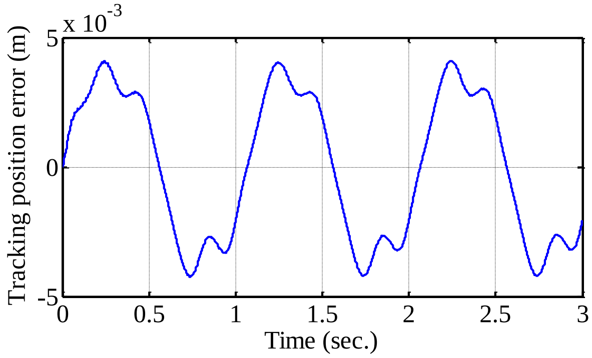


Fig.8 Tracking position error with 250N load.

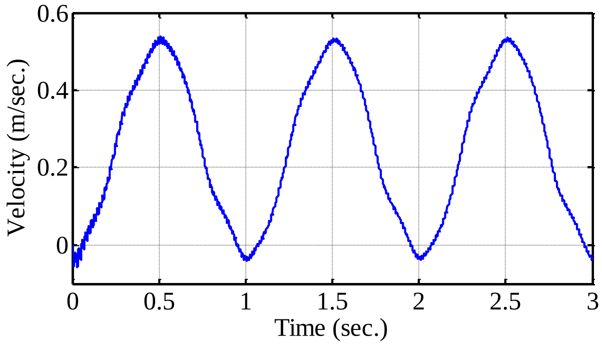


Fig.9 Mover velocity with 250N load.

These results show that the motor tracks well the reference position with small position error when using fuzzy logic controller in the position control circuit of the machine. The oscillation in the position error and the velocity is due to the oscillation in the reference position.

VIII. CONCLUSIONS

This paper has presented a linear reluctance motor model fed by SVPWM inverter and controlled using cascade controller with FLC to track the position reference trajectory. The motor can track the reference position using fuzzy logic control in the cascade controller with small position error. To improve the dynamic response of the machine the feed forward controller can be used.

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APPENDIX

Parameters and Rating of Linear Reluctance Motor

Parameter	**The Value**	**Unit**
Rated voltage	300	Volt
DC bus voltage	500	Volt
L_d	0.11	H
L_q	0.026	H
R	1.1	Ω
m	105	kg
b	123.5	Ns/m
τ_p	0.07224	m