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Modelling, Simulation and Nonlinear Control of Permanent Magnet Linear Synchronous Motor

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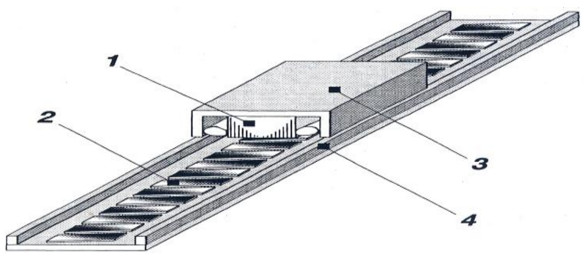
Abstract: This paper describes a nonlinear model of the Permanent Magnet Linear Synchronous Motor and an analogy between the rotary motor and the linear motor. Constructional details of various sub-models for the permanent magnet linear synchronous motor are given and their implementation in SIMULINK is outlined. A novel control of PMSM is designed by which the system nonlinearity is cancelled. In addition, a linear state feedback control law based on pole placement technique to achieve zero steady state error with respect to reference current specification is employed to improve the dynamic response. The extensive simulation is performed through MATLAB SIMULINK.

Keywords: Dynamic Modelling; Permanent magnet linear synchronous motor

I. INTRODUCTION

In today's competitive industrial environment, a tremendous amount of resources are dedicated to simple, optimal, and efficient solutions for the process automation, machine tool and material handling systems. Linear motors can give machine tools linear motion directly without indirect coupling mechanisms such as gear boxes, chains and screws. In particular, permanent magnet direct drive motors are becoming more and more popular in machine automation nowadays. The advantages of permanent magnet motor drives are their gearless structure, excellent control Characteristics like high speed, high acceleration and the most importantly, high motion precision and better efficiency. PMLSMs are used in lifts, paper machines, propulsion units of ships, windmills *etc*.

In PMLSM, the moving part (mover) of which consists of a slotted armature and three-phase windings, while the surface permanent magnets (SPMs) are mounted along the whole length of the path (stator).



1 -armature, 2 - PMs
3 -carrier, 4 - guiderail

Fig.1 : permanent magnet linear synchronous motor

LSMs operating on the principle of the travelling magnetic field, the speed v of the moving part is equal to the synchronous speed v_s of the travelling magnetic field depends only on the input frequency f (angular input frequency $\omega = 2\pi f$) and pole pitch τ. It does not depend on the number of poles 2p.

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$$v = v_s = 2f\tau = \frac{\omega}{\pi}\tau$$

This paper is organized as follow: Section I gives the Introduction of the Permanent Magnet Linear Synchronous Motor. Section II is helpful to understand the analogy between permanent magnet linear synchronous motor and rotary motor . Section III explains the System dynamic modeling of motor. Section IV show the performance of open loop motor and Section V describes closed loop system and Section VI show the performance of closed loop motor the last section concludes the paper and followed by the references.

II. ANALOGY BETWEEN THE PERMANENT MAGNET ROTARY SYNCHRONOUS MOTOR AND THE PMLSM

The electrical model of the PMLSM can be obtained by analogy to a permanent magnet rotary synchronous motor, as shown in Fig. 2. For a rotary motor, the three armature windings shift one another by an electrical angle of $2\pi/3$, and each winding covers an electrical angle of π in the stationary reference.

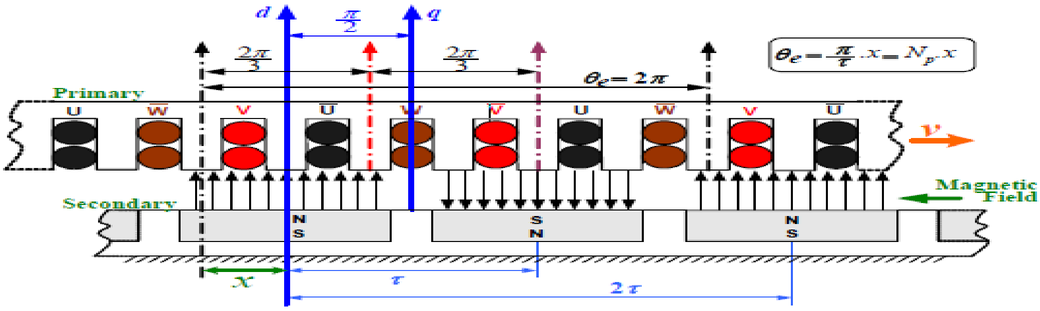

Fig 2 : Electrical model of the PMLSM

By analogy, the stator armature windings of a PMLSM shift one another by a distance of $2\tau/3$ (τ: pole pitch → step between two consecutive magnetic poles of secondary) and each winding covers a distance of τ in the linear reference frame.

The electrical angle along which the primary of the PMLSM moves in the linear reference frame can be expressed by

$$\theta_e = N_p x \, ; \; N_p = \frac{\pi}{\tau}$$

Here, N_p is the electrical position constant of the PMLSM.

TABLE I. EQUIVALENCES OF ELECTRICAL ANGLE AND ELECTRICAL ANGULAR SPEED

	Rotary motor	PMLSM
Electrical angle (θ_e)	$\theta_e = N_p\theta$	$\theta_e = N_p x$
Electrical angular speed (ω)	$\omega = N_p\Omega$	$\omega = N_p v$

With the rapid development in computer hardware and software, new simulation packages which are faster and more user friendly are now available. This paper discusses the use of one such product, the SIMULINK software of MATLAB, in the dynamic modeling of the PMLSM. The main advantage of SIMULINK over other programming software is that, instead of compilation of program code, the simulation model is built up systematically by means of basic function blocks. Through a convenient graphical user interface (GUI), the function blocks can be created, linked and edited easily using menu commands, the keyboard and an appropriate pointing device (such as the mouse). A set of machine differential equations can thus be modeled by interconnection of appropriate function blocks, each of which performing a specific mathematical operation. Programming efforts are drastically reduced and the debugging of errors is easy. Since SIMULINK is a model operation programmer, the simulation model can be easily developed by addition of new sub-models to cater for various control functions. As a sub-model the PMLSM could be incorporated in a complete electric motor drive system.

III. DYNAMIC MODEL OF PMLSM USING SIMULINK

A generalized dynamic model of the PERMANENT MAGNET LINEAR SYNCHRONOUS MOTOR consists of an electrical sub-model to implement the three-phase to two-axis (3/2) transformation of stator voltage and current calculation, a thrust sub-model to calculate the developed electromagnetic thrust, and a mechanical sub-model to yield the rotor or mover velocity.

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III. 1. ELECTRICAL SUB-MODEL OF THE PMLSM

The voltage equations for the permanent magnet synchronous motor in synchronously rotating reference frame are

$$V_{qs} = R_s i_{qs} + P\lambda_{qs} + \omega_e \lambda_{ds} \qquad (1)$$

$$V_{ds} = R_s i_{ds} + P\lambda_{ds} - \omega_e \lambda_{qs} \qquad (2)$$

Where,

$$\lambda_{qs} = L_{qs} i_{qs} \qquad (3)$$

$$\lambda_{ds} = L_{ds} i_{ds} + \lambda_{PM} \qquad (4)$$

By substituting eq no's (3) & (4) in equations (1) & (2) respectively, we get

$$V_{qs} = R_s i_{qs} + L_{qs} P i_{qs} + \omega_e L_{ds} i_{ds} + \omega_e \lambda_{PM} \qquad (5)$$

$$\mathbf{V_{ds} = R_s i_{ds} + L_{ds} P i_{ds} - \omega_e L_{qs} i_{qs}} \qquad (6)$$

By rearranging equations (5) & (6) ,then

$$P i_{qs} = \frac{V_{qs}}{L_{qs}} - \frac{R_s}{L_{qs}} i_{qs} - \omega_e \frac{L_{ds}}{L_{qs}} i_{ds} - \omega_e \frac{\lambda_{PM}}{L_{qs}}$$

$$P i_{ds} = \frac{V_{ds}}{L_{ds}} - \frac{R_s}{L_{ds}} i_{ds} + \omega_e \frac{L_{qs}}{L_{ds}} i_{qs}$$

$$\begin{bmatrix} \dot{i}_{qs} \\ \dot{i}_{ds} \end{bmatrix} = \begin{bmatrix} \frac{1}{L_{qs}} & 0 \\ 0 & \frac{1}{L_{ds}} \end{bmatrix} \left[\begin{bmatrix} V_{qs} \\ V_{ds} \end{bmatrix} - \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} - \begin{bmatrix} 0 & \omega_e L_{ds} \\ -\omega_e L_{qs} & 0 \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} + \begin{bmatrix} -\omega_e \lambda_{PM} \\ 0 \end{bmatrix} \right]$$

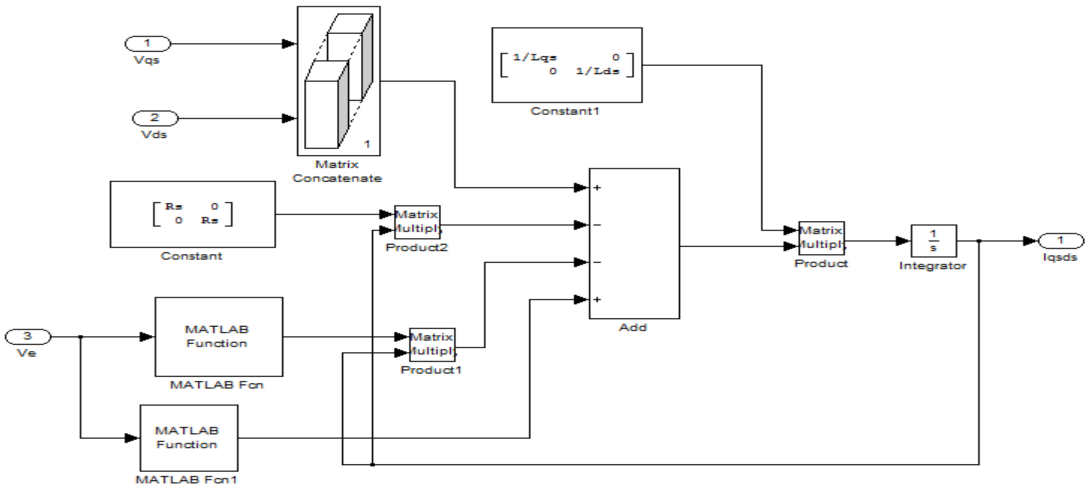

Fig-3 : Electrical Sub Model of PMLSM

III. 2. THRUST SUB-MODEL OF PMLSM

$$F_e = \frac{3}{2}\frac{\pi}{\tau} P\left[\lambda_{PM} i_{qs} + \left(L_{ds} - L_{qs}\right) i_{ds} i_{qs}\right]$$

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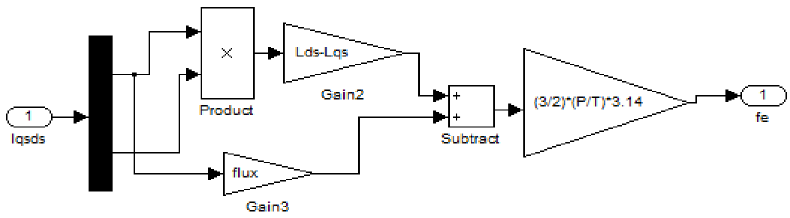

Fig-4 : Electromagnetic Thrust sub model

Where flux = λ_{PM}

III. 3. MECHANICAL SUB-MODEL OF PMLSM

$$F_e - F_l = M\dot{V}_e + BV_e$$

By taking laplace transform of above equation we obtain

$$F_e - F_l = MSV_e + BV_e$$

$$F_e - F_l = (MS + B)V_e$$

From which the ratio, $\frac{V_e}{F_e - F_l}$ is obtained as

$$\frac{V_e}{F_e - F_l} = MS + B$$

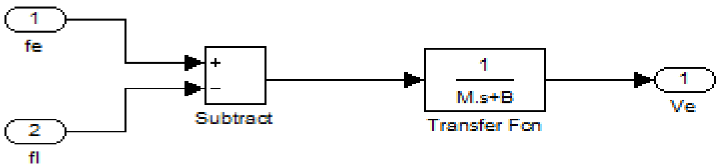

Fig-.5: Mechanical Sub Model of PMLSM

The electrical sub-model in Fig-3, the thrust sub-model in Fig-4, the mechanical sub-model in Fig-5, are grouped together to form the PMLSM model as shown in Fig-6.

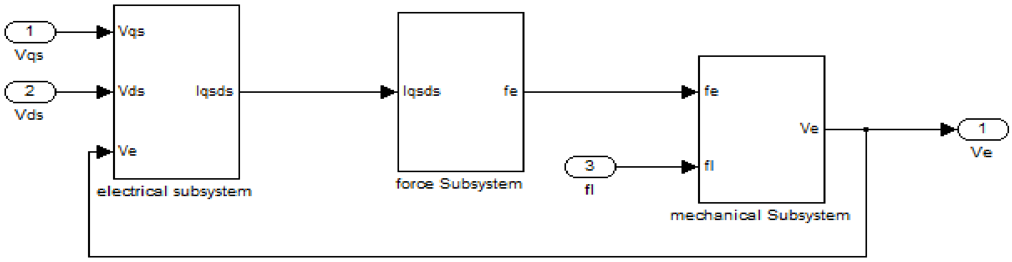

Fig.6: PMLSM overall Model in SIMULINK

IV. OPEN LOOP RESULTS

Open loop simulation results for step change in speed at constant Load Thrust shown in fig-7 and for step change in Load Thrust at constant speed is shown in fig-8.

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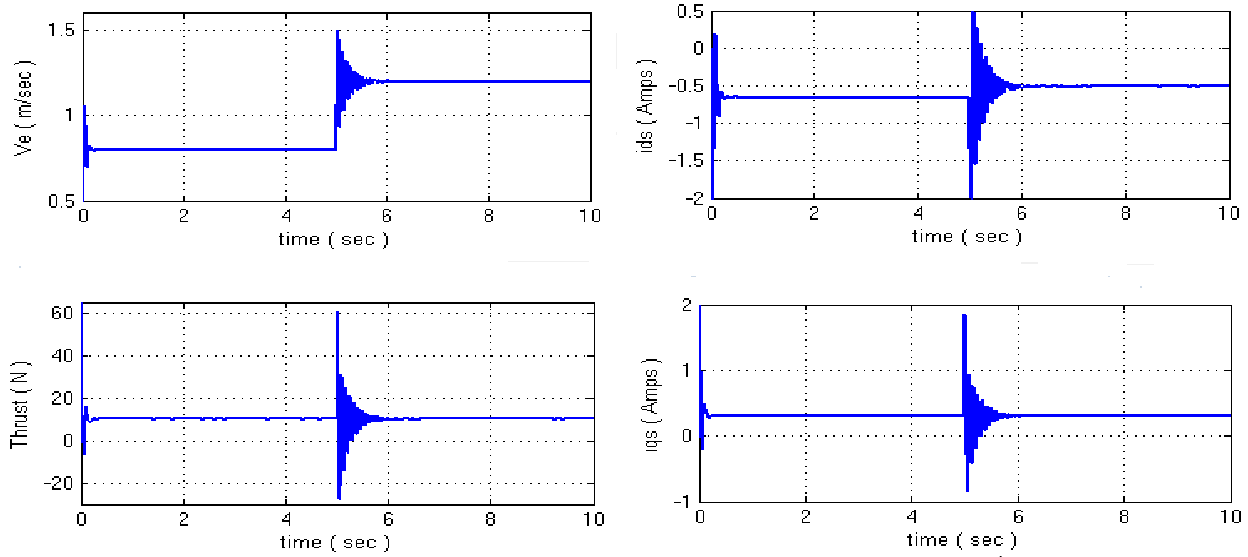

Fig-7. Simulation results of PMLSM for step change in speed from 0.8 m/s to1.2 m/s at 5th sec at constant thrust of 10N

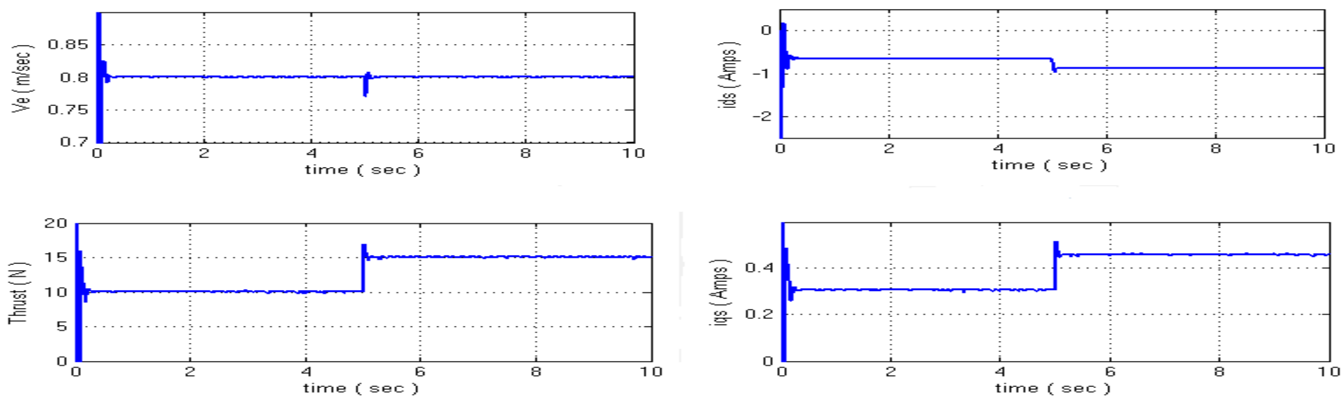

Fig.8 : Simulation results of PMLSM for step change in thrust from 10N to 15 N at 5th sec at constant Speed of 0.8m/s.

V. CLOSED LOOP CONTROL SYSTEM

In this paper, the proposed controller represented in the conventional two-loop structure for the motor drive is shown in Fig.9. The outer loop is the speed controller, the output of which is the reference value of the thrust F_e^*. In field oriented control algorithm thrust is controlled by the q-axis current component. Hence the reference value of the currents i_q^* is computed from reference thrust while id* is zero.

The inner loop is the current controller which consists of a nonlinear controller by which the system nonlinearity is canceled using exact feedback linearization. The eigen values of the resulting linear systems are shifted by state feedback to appropriate locations in order to achieve the desire dynamic performance. Since the main task of the current controller is to follow reference thrust set by outer speed loop. For this purpose, the state feedback design is augmented with integral of output errors .

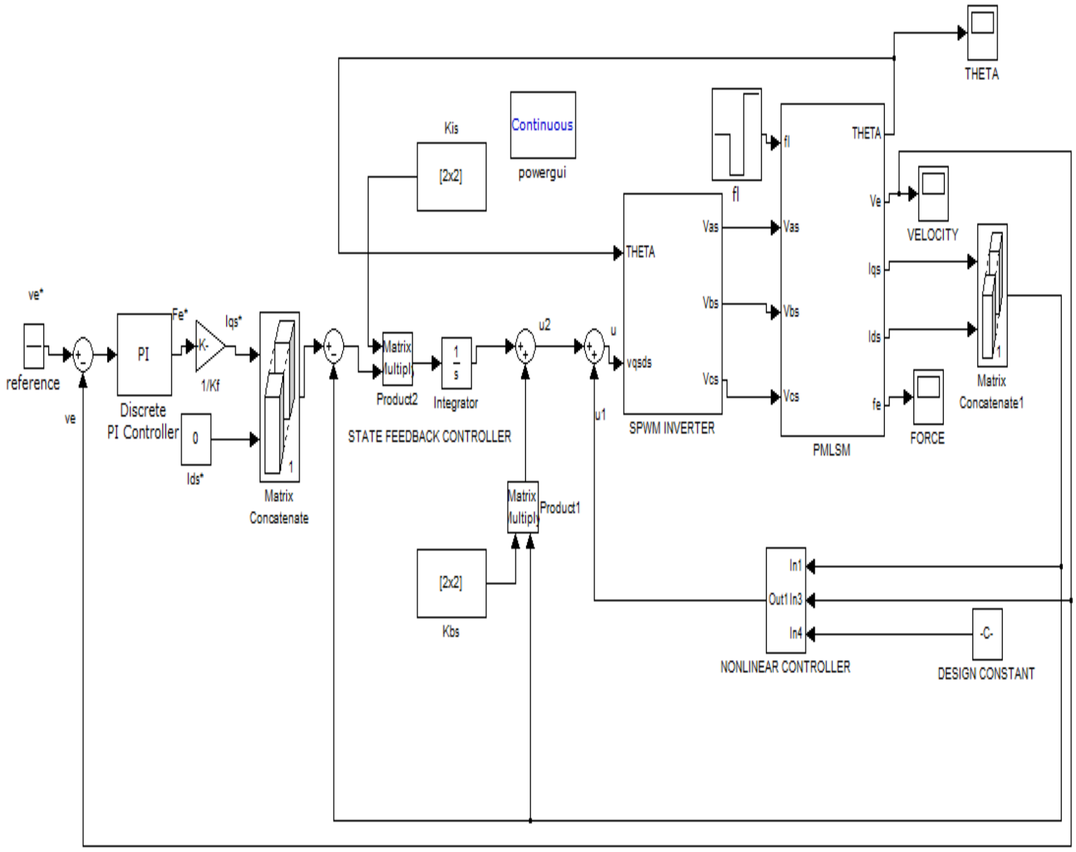

Fig.9 : Closed loop Simulink Diagram

VI. CLOSED LOOP CONTROL RESULTS

Closed loop simulation results for step change in speed at constant thrust of 10N shown in Fig-10. Simulation results for step change in thrust at constant speed are shown in Fig-11.

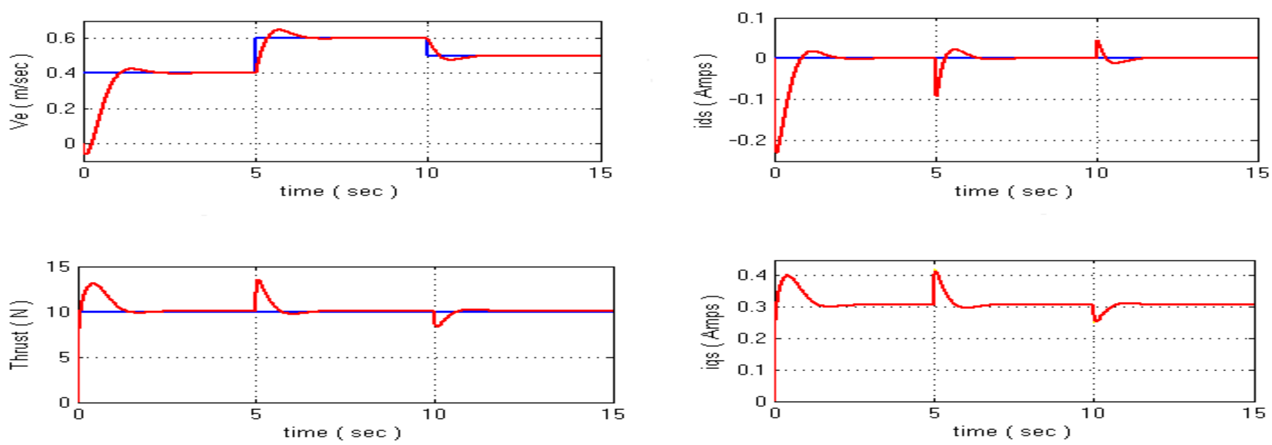

Fig.10 Simulation results of PMLSM for step change in Speed from 0.4 to 0.6 at 5th sec and from 0.6 to 0.5 at 10th sec at constant thrust of 10N

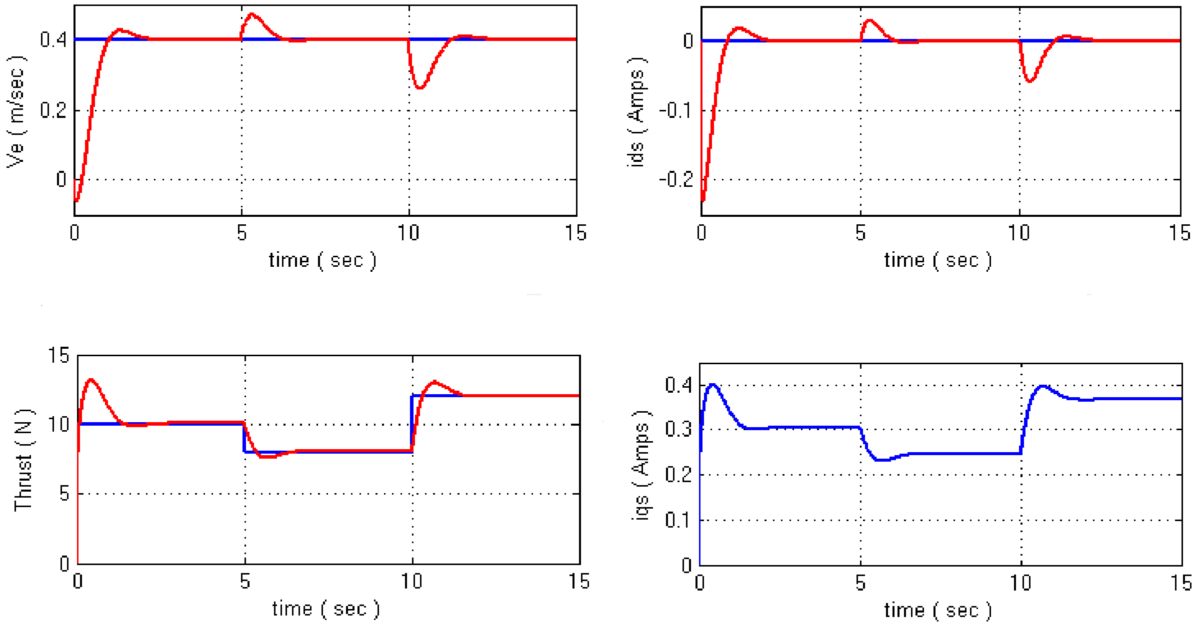

Fig.11 Simulation results of PMLSM for Step change in thrust from 10 to 8 at 5th sec and from 8 N to 12N at 10th sec at constant speed of 0.4m/sec

VII. CONCLUSION

In this paper we have used SIMULINK software of MATLAB to test the dynamic model of PMLSM at open loop & closed loop control. A generalized approach to the design of the speed control of Linear synchronous Motor has been presented by which the system nonlinearity is cancelled. In addition, a linear state feedback control law based on pole placement technique to achieve zero steady state error with respect to reference current specification is employed to improve the dynamic response. The closed loop control simulation shows good results. The predicted current step responses agreed well with the measurements and less overshoots were observed.

SIMULATION PARAMETERS

The permanent magnet linear synchronous motor chosen for the simulation studies has the following parameters:

L_{ds} (Stator direct-axis inductance)	=	0.0131 mH
L_{qs} (Stator quadrature-axis inductance)	=	0.0131 mH
R_s (Stator winding resistance)	=	2.1 0hmS
λ_{PM} Permanent magnet flux linkage	=	0.1391 webers
τ = pole pitch	=	20 mm
M (mass of the mover)	=	4.5 kgs

VIII. NOTATIONS USED

V_{ds}, V_{qs} $d\&\, q$ AXIS STATOR VOLTAGES RESPECTIVELY

i_{ds}, i_{qs} $d\&\, q$ AXIS STATOR CURRENTS RESPECTIVELY

$\lambda_{ds}, \lambda_{qs}$ $d\ \&q$ AXIS STATOR MAGNETIC FLUXS RESPECTIVELY

λ_{PM} PERMANENT MAGNET FLUX LINKAGE

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L_{ds}, L_{qs}	d& q AXIS STATOR INDUCTANCES RESPECTIVELY
RS	STATOR RESISTANCE
M	TOTAL MASS OF THE MOVING ELEMENT SYSTEM
$F_{e,}F_L$	ELECTROMAGNETIC , EXTERNAL DISTURBANCE (OR) THRUSTS RESPECTIVELY
f_e	ELECTRIC FREQUENCY
τ	POLE PITCH
V	LINEAR VELOCITY OF THE MOVER
v_e, v_e^*	ELECTRIC , REFERENCE ELECTRIC LINEAR VELOCITYS RESPECTIVELY
V_m	MECHANICAL LINEAR VELOCITY
B	VISCOUS FRICTION AND IRON-LOSS COEFFICIENT
P	NUMBER OF POLE PAIRS

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BIOGRAPHY

Dr. K. Alice Mary was born on 24th day of April 1959, received BE from Govt.BDT CE&T, Davanagere , Karnataka, India in 1981, ME in the year 1989 from IIT-Roorkee and PhD from IIT-Kharaghpur in the year 1998. She is in teaching profession from 1981 onwards and now working as Professor and Principal of Vignan's institute of information technology, Visakhapatnam. To her credit, she received many prestigious awards for her achievements in academic performance at national level. Her research interests are control system applications to power electronics and machine drives.

B.Arundhati was born on 19th day of March 1968, received BE from University college of Engineering, Burla, Sambalpur, Orissa, India in 1991, M.Tech in the year 2005 from JNTU,Hyderabad and pursuing PhD from JNTU, Hyderabad. Presently working as Asso. Professor and HOD-EEE of Vignan's institute of information technology, Visakhapatna,India. Her research interests are Linear motors & control system applications to power electronics and machine drives.

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