

## The Vector Control Of Permanent Magnet LSM Using Sinusoidal PWM Inverter

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**Abstract**— This paper presents a vector control of nonlinear model of the Permanent Magnet Linear Synchronous Motor and modelling of a linear motor by using the analogy between the rotary motor and the linear motor. Constructional aspects of various sub-models for the permanent magnet linear synchronous motor are given and their implementation in SIMULINK is outlined. Through feedback linearization control method the PMLSM drive is designed by which the system's 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 is employed to improve the dynamic response. The SIMULINK results are presented.

**Keywords**—SPWM, Permanent magnet linear synchronous motor, feedback linearization, parks transformation, state feedback controller

### I. INTRODUCTION

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. Permanent Magnet Linear Synchronous Motor (PMLSM) is a kind of driving equipment for converting electrical energy into linear movement directly. The linear drive offers high efficiency, high reliability, high performance motion control and low vibration. 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.* Due to the improvement of fast-switching power semiconductor devices and the machine control algorithm, more precise Pulse Width Modulation (PWM) method finds particularly the growing interest. For the ac machine drive application, full utilization of the dc bus voltage is extremely important in order to achieve the maximum output torque under the all operating conditions. In this aspect it is compared with any other PWM methods for the voltage source inverter. 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).

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  $\tau$ . It does not depend on the number of poles  $2p$ .

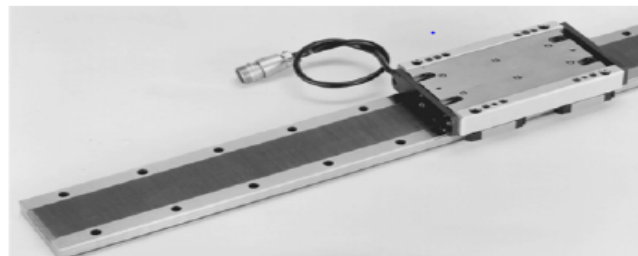


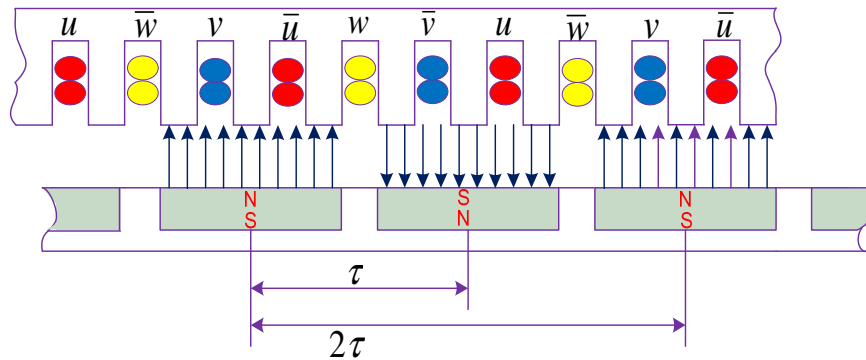
Fig.1 : permanent magnet linear synchronous motor

The linear velocity of the motor is obtained by

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

## II. ANALOGY BETWEEN THE PMLSM AND ROTARY MOTOR

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  $\pi$  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  $2\tau/3$  ( $\tau$ : pole pitch  $\rightarrow$  step between two consecutive magnetic poles of secondary) and each winding covers a distance of  $\tau$  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.

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.

### 3.1. Electrical sub model of PMLSM

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

$$V_{qs} = R_s i_{qs} + P \lambda_{qs} + \omega_e \lambda_{ds} \tag{1}$$

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

Where,

$$\lambda_{qs} = L_{qs} i_{qs} \tag{3}$$

$$\lambda_{ds} = L_{ds} i_{ds} + \lambda_{PM} \tag{4}$$

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

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

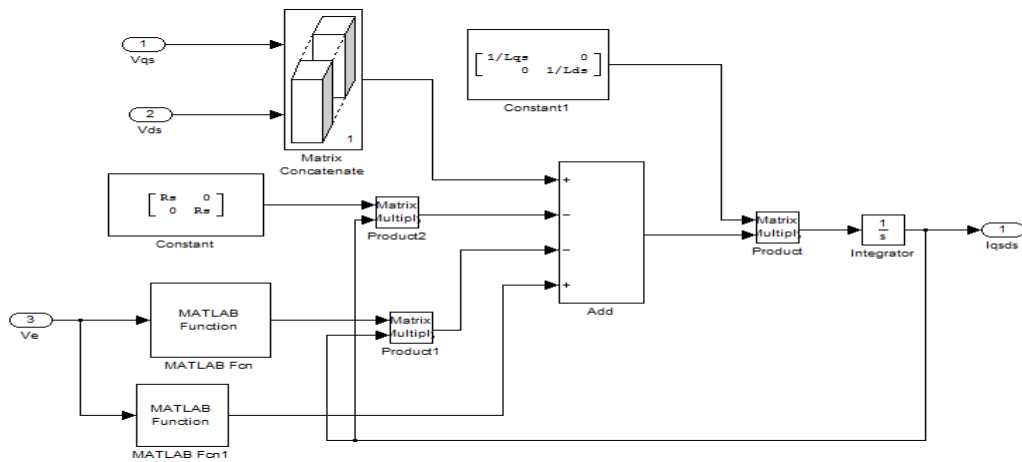
$$V_{ds} = R_s i_{ds} + L_{ds} P i_{ds} - \omega_e L_{qs} i_{qs} \tag{6}$$

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

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

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

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



*Fig-3 : Electrical Sub Model of PMLSM*

### 3.2. Thrust sub model of PMLSM

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

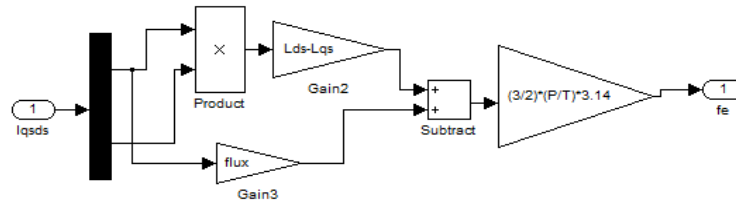


Fig-4 : Electromagnetic Thrust sub model

Where flux =  $\lambda_{PM}$

### 3.3.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

$$\frac{V_e}{F_e - F_l} = \frac{1}{MS + B}$$

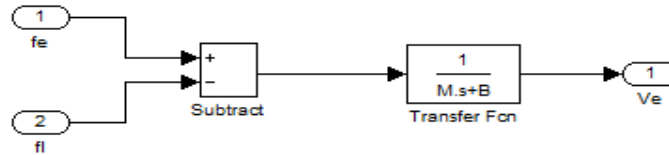


Fig-5: Mechanical Sub Model of PMLSM

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.

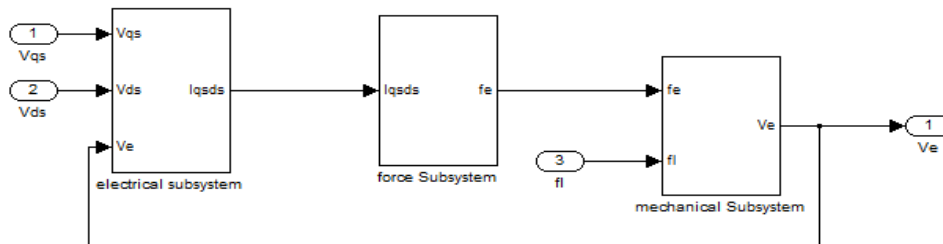


Fig.6: PMLSM overall Model in SIMULINK

## 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.

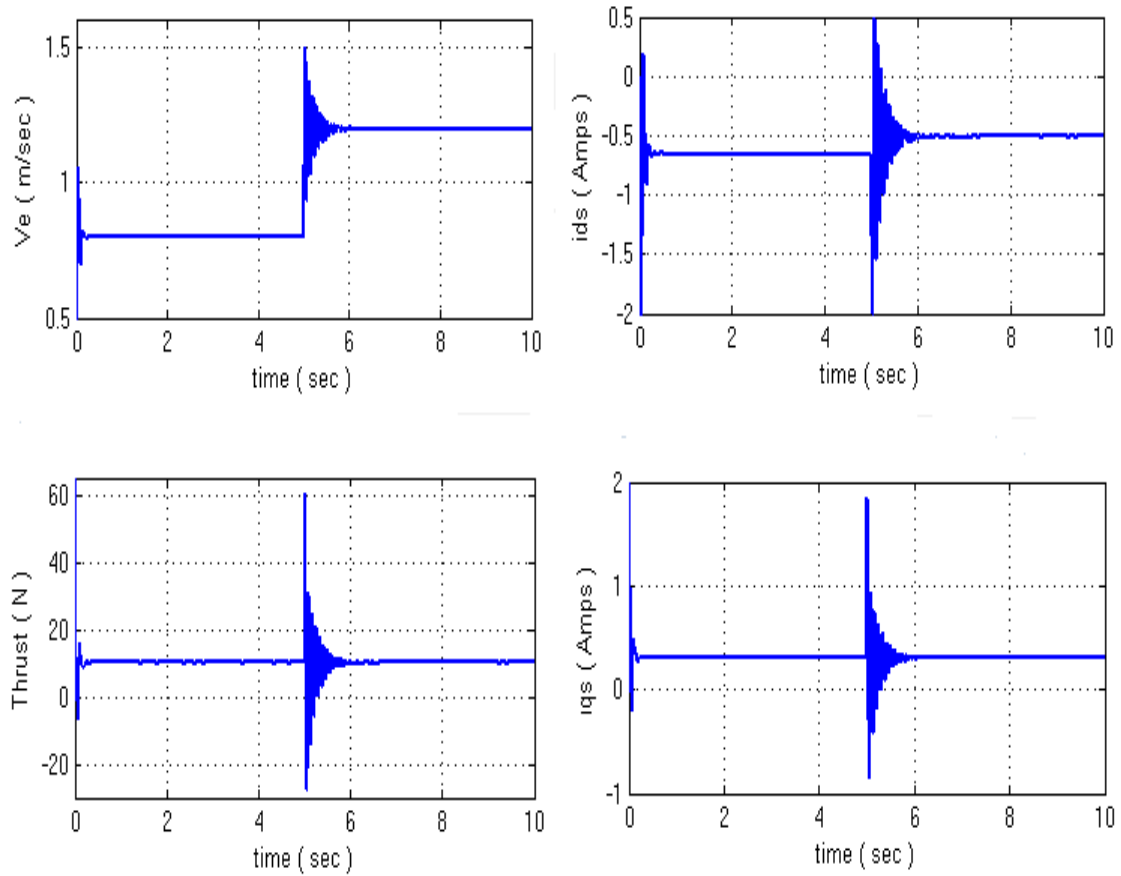


Fig-7. Simulation results of PMLSM for step change in speed from 0.8 m/s to 1.2 m/s at 5<sup>th</sup> sec at constant thrust of 10N

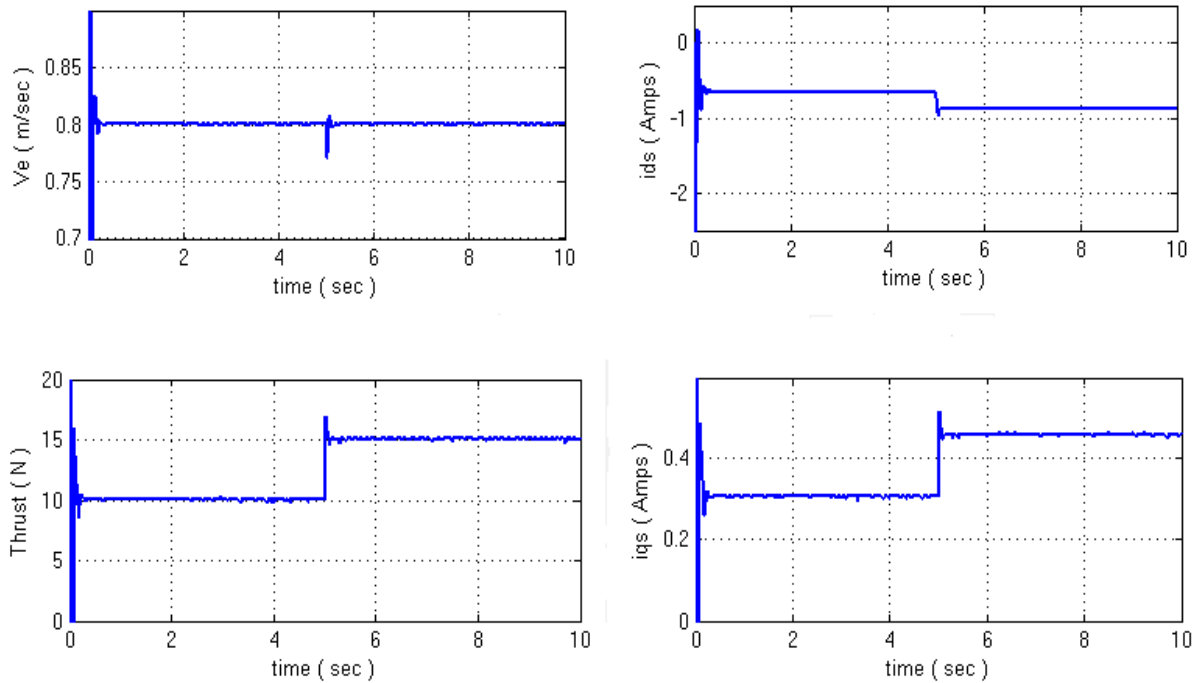


Fig.8 : Simulation results of PMLSM for step change in thrust from 10N to 15 N at 5<sup>th</sup> sec at constant Speed of 0.8m/s.

## 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  $i_d^*$  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 desired 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.

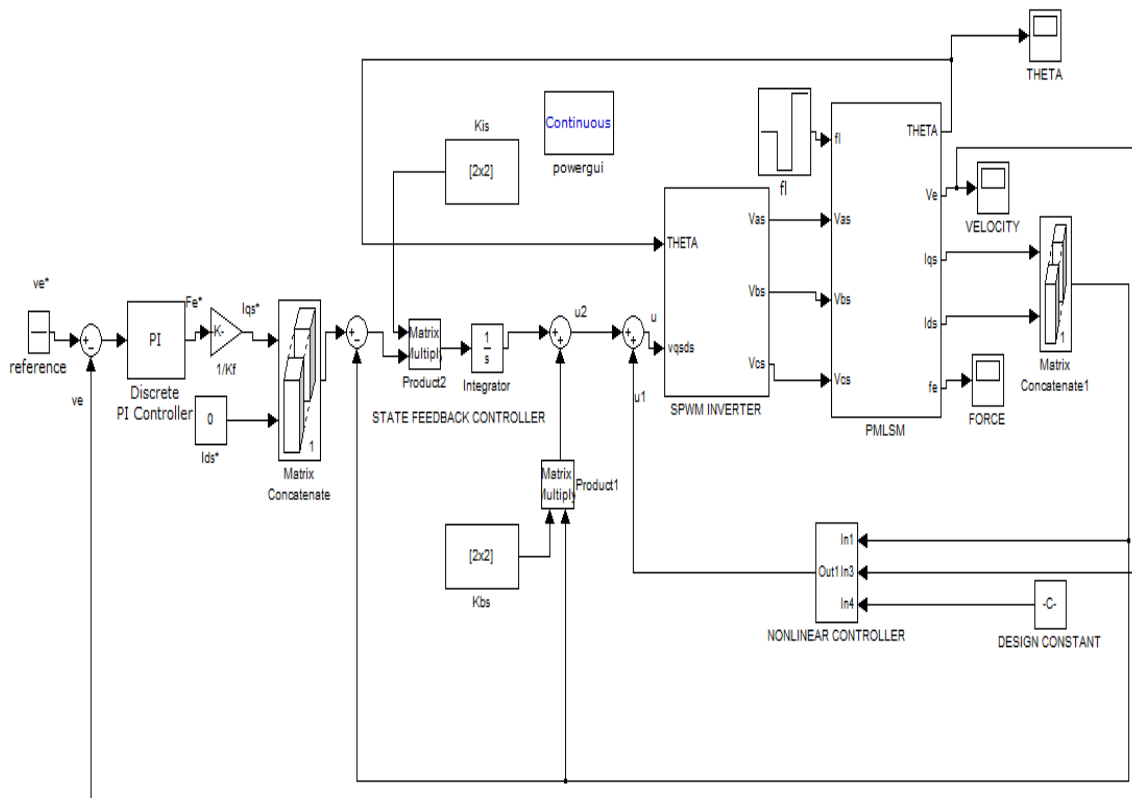
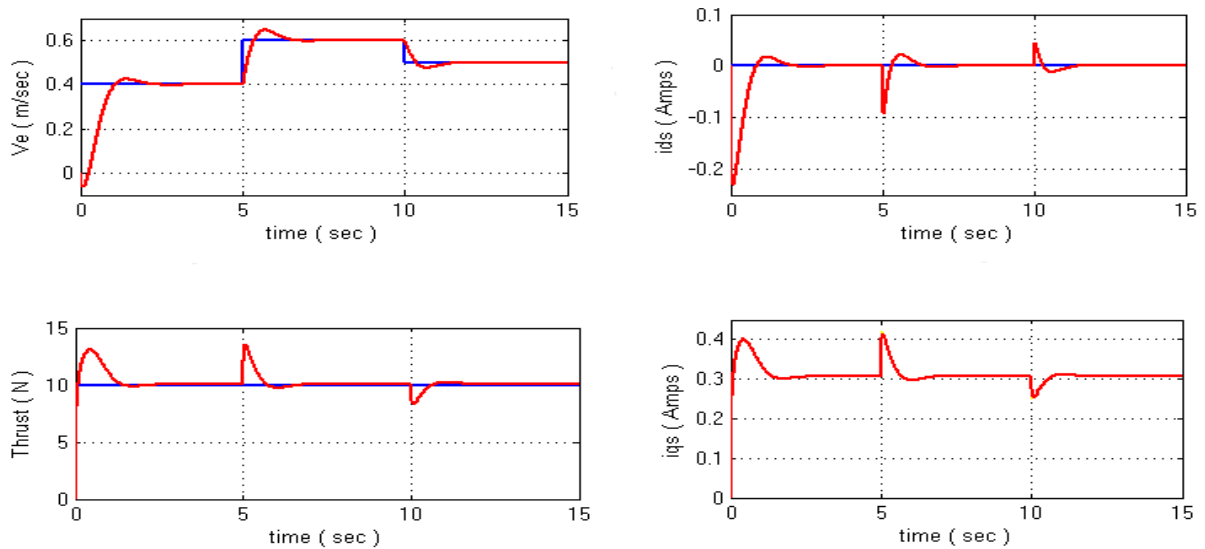


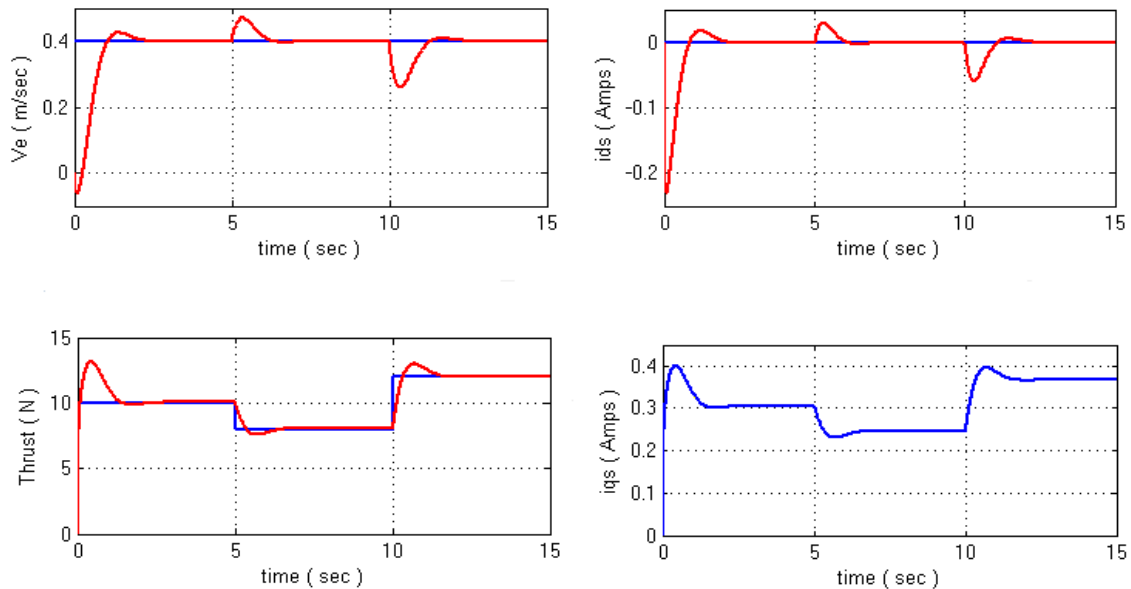
Fig.9 : Closed loop Simulink Diagram

## 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 5<sup>th</sup> sec and from 0.6 to 0.5 at 10<sup>th</sup> sec at constant thrust of 10N



**Fig.11** Simulation results of PMLSM for Step change in thrust from 10 to 8 at 5<sup>th</sup> sec and from 8 N to 12N at 10<sup>th</sup> 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.

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