# Field oriented & State Feedback control of a Permanent Magnet linear Synchronous motor in High Performance Motion system

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**Abstract -**
Field oriented (or vector) control is the most popular AC machine control method and is widely used in high-performance industrial applications of electric drives. Field Orientated Control allows precise controllability and excellent transient behavior when used to control the motor by manipulating the angle and amplitude of the torque and speed producing current vectors. A novel control of PMSM is designed by which the system nonlinearity is canceled. 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, while at the same time improving the dynamic response. The extensive simulation is performed through MATLAB and is validated through experimental results.

**Keywords-** Permanent magnet Linear synchronous motor (PMLSM); field oriented control, State feedback control

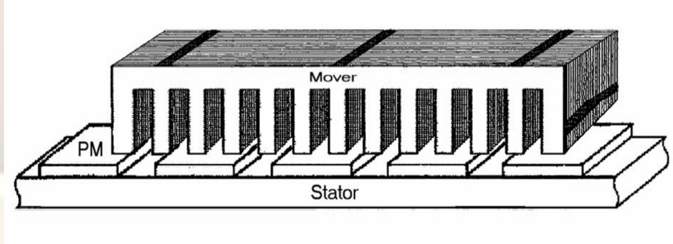
## I. Introduction

In today's highly competitive manufacturing environment, a tremendous amount of resources are dedicated to developing optimal, simple, and efficient solutions for the process automation, assembly automation, and material handling processes .Unlike rotary motors, high-performance linear motors can give machine tools linear motion directly without indirect coupling mechanisms such as gear boxes, chains and screws (Fig.1). 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, better 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). The linear motor is an old invention, but it is only recently that, as a result of the

development of permanent magnets and their reduced costs, permanent magnet linear motors have become a viable alternative to rotating motors fitted with linear transmission. A linear motor provides linear motion without the potential complications associated with pneumatics and hydraulics, and simplifies the mechanical structure of transmission, eliminating the contact-type nonlinearities caused by backlash and compliance. Additionally, the main benefits of a linear motor include high force without sacrificing speed or precision. Linear motors are therefore the most natural choice in applications where accurate positioning is needed.




**(Fig :1 Permanent magnet linear synchronous motor)**

In this paper, the proposed controller represented in the conventional two-loop structure for the motor drive is shown in Fig.4. The outer loop is the speed controller, the output of which is the reference value of the thrust $F_e^*$. From this value, the reference values of the currents, viz $i_q^*$ and $i_d^*$ are computed. In the field oriented control by setting the power factor angle to be equal to the torque angle, resulting in complete decoupling between the armature flux and the field flux, thus, producing a dc motor like behavior.

The inner loop is the current controller which consists of a nonlinear controller by which the system nonlinearity is canceled. In addition, a linear state feedback control law based on pole placement technique including the integral of output error (IOE) is used. The state feedback control requires the knowledge of all states. Therefore, the inaccessible damper winding currents need to be estimated. However, such observers are usually developed based on linearized system model around nominal operating conditions making it difficult to assess large signal stability of the systems.

## II. Dynamic Model Of Pm Linear Synchronous Motor

The d-q voltage equations for PMLSM in rotor reference frame are given by,

$$u_d = R_a i_{ad} + \frac{d\psi_d}{dt} - \omega\psi_q \qquad (1)$$

$$u_q = R_a i_{aq} + \frac{d\psi_q}{dt} + \omega\psi_d \qquad (2)$$

Where $u_d$ and $u_q$ are the terminal voltage $\psi_d$ and $\psi_q$ are the armature winding flux linkages and $i_{ad}$ and $i_{aq}$ *are* the armature currents in the d and q-axis components .

The synchronous speed in a linear motor is

$$\omega = \frac{\pi v_s}{\tau} \qquad (3)$$

where $\tau$ is the pole pitch. $v_s$ is linear synchronous velocity

The equivalent circuit of the PMLSM is in Figure 2.

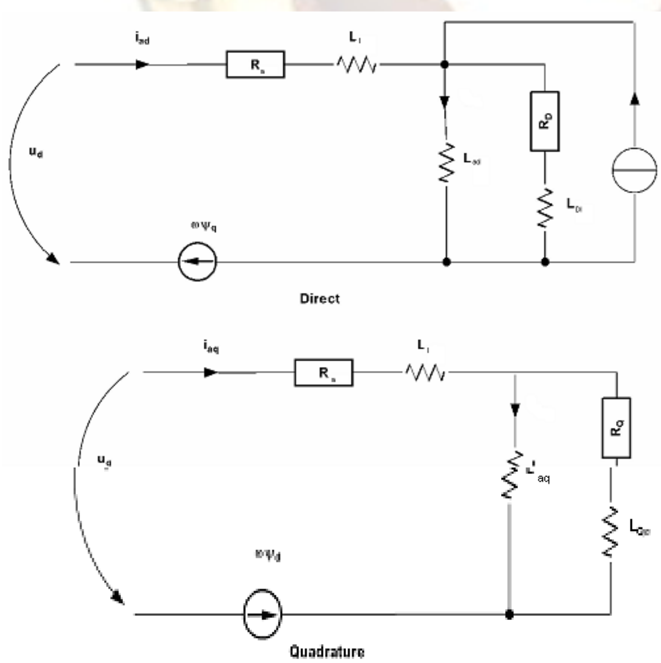



**Figure 2**. Equivalent circuit of a PMLSM.

$$\psi_d = L_{sd} i_{ad} + L_{ad} i_D + \psi_{pm} \qquad (4)$$

$$\psi_q = L_{sq} i_{ad} + L_{aq} i_Q \qquad (5)$$

$$\psi_D = L_{ad} i_{ad} + L_D i_D + \psi_{pm} \qquad (6)$$

$$\psi_Q = L_{aq} i_{aq} + L_Q i_Q \qquad (7)$$

Where $L_{sd}$ and $L_{sq}$ are the d and q-axis components of the resultant armature inductance, $L_D$ and $L_Q$ are the d and q-axis components of the damper winding inductance, $L_{ad}$ and $L_{aq}$ are the d and q-axis components of the magnetizing inductance and $\psi_{pm}$ is the flux linkage of the permanent magnet per phase.

A rotary synchronous motor has a cage damper winding embedded in pole shoe slots .In Linear synchronous motor ,It would be difficult to furnish PMs with a cage winding so that the damper has the form of an aluminum cover or solid steel pole shoes.

The voltage equations of the short-circuited damper winding are

$$0 = R_D i_D + \frac{d\psi_D}{dt} \qquad (8)$$

$$0 = R_Q i_Q + \frac{d\psi_Q}{dt} \qquad (9)$$

The electromagnetic thrust of a PMLSM with p pole pairs is the electromagnetic power, *P*elm divided by the linear velocity $v_s$ .

$$F_e = \frac{3}{2} p \frac{\pi}{\tau} \left[ \psi_{pm} + (L_{sd} - L_{sq}) i_{ad} \right] i_{aq} \qquad (10)$$

The end effect can be included by multiplying the thrust by a coefficient *k end* < 1 which takes into account the thrust reduction due to the end effect. Thus

$$F_e = \frac{3}{2} p K_{end} \frac{\pi}{\tau} \left[ \psi_{pm} + (L_{sd} - L_{sq}) i_{ad} \right] i_{aq} \qquad (11)$$

## III Control System Design

### A) Design of the PI Controller

The output of the PI controller is the reference thrust $F_e^*$, from which the reference currents, $i_q^*$ and $i_d^*$ for stator winding can be generated. $F_l$ is the load thrust.
The design of the gain constants of this controller is as follows

$$p\omega_r = \frac{\pi}{\tau} * \frac{1}{M}[F_e - F_l] - \frac{B}{M}\omega_r$$

The controller equation is

$$F_e^* = k_p e + k_i \int_0^t e dt \qquad (12)$$

Where,

$$e = (\omega_e - \omega_r)$$

$\omega_e$ is the set (reference) speed, and $k_p$ and $k_i$ are the proportional and integral gains of the controller respectively.

The controller gains, $k_i$ and $k_p$ are obtained as,

$$k_i = M\omega_n^2 \qquad (13)$$

$$k_p = 2M\xi\omega_n - \beta \qquad (14)$$

The value of $\xi$ is usually determined from the requirement of permissible maximum overshoot and $\omega_n$ determines the time response.

**B) FIELD ORIENTATION CONTROL**

The field-oriented control is based on the Blashke method of vector control which is here applied for Linear synchronous motor drives, replacing the expensive DC motors. PMLSM require very complex control algorithms, because there is no linear relationship between the stator current and either the torque or the flux. This means that it is difficult to control the speed or the thrust, because of the transients until the motor reaches its new stationary state. The controller keeps the amplitude of the rotor flux constant so that only its direction could be changed. The field-oriented theory offers a suitable method for optimal control of the PMLSM motors. The most often used method is the one with the rotor flux orientation because of the simple structure of the control loops and command variable calculation.

In the present vector control the direct axis current $i_{ad}$ is set to zero, as shown in Fig.3
Reference Thrust

$$F_e^* = \frac{3}{2} pK_{end} \frac{\pi}{\tau}\left[\psi_{pm} i_{aq}\right] \qquad (15)$$

This means that the angle $\psi$ between the armature current and q-axis always remains at 0° and the thrust is proportional to the armature current $i_a = i_{aq}$. However, the motor runs always at a lagging power factor in field oriented control.

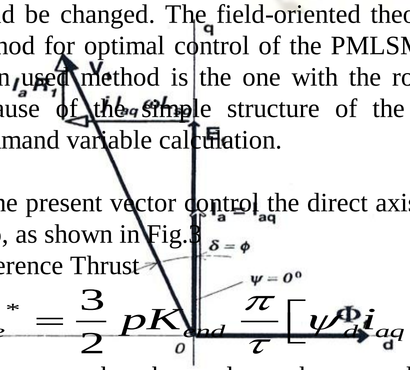


**Fig 3** Phasor diagram of PMLSM for $i_{ad}$=0

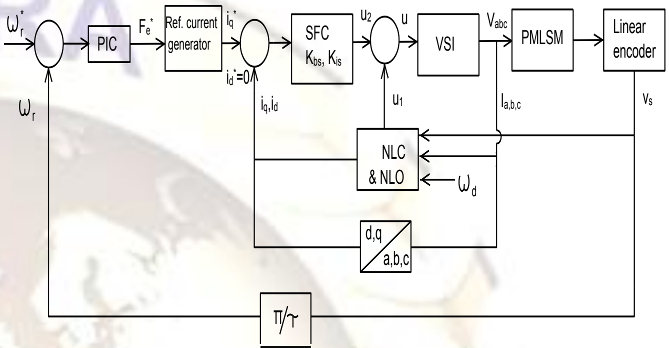



**Fig-4** Control scheme of PMLSM

**III. Reference Current generation**

The generated electrical thrust is a function of the states, i.e., the stator and rotor (field and damper) currents of the linear synchronous motor, which are nonlinear, thus, there is a great deal of flexibility in the choice of the reference values for these currents.

**(a) Taking torque angle ( δ) as a specification**

Referring to phasor diagram of a Salient pole PMLSM

$$\tan\delta = \frac{-u_d}{u_q} \qquad (16)$$

Substituting $u_d$ and $u_q$ from equation (1) & (2), we get

$$\tan\delta = \frac{\omega L_{aq} i_{aq} - R_a i_{ad}}{R_a i_{aq} + \omega L_{ad} i_{ad} + \omega\psi_{pm}} \qquad (17)$$

From equation (11)

$$i_{aq} = \frac{F_e}{\frac{3}{2} pK_{end} \frac{\pi}{\tau}\left[\psi_{pm} + (L_{sd} - L_{sq}) i_{ad}\right]} \qquad (18)$$

Substituting (18) in (17) and simplifying yields

$$i_{ad}^* = \frac{-q_2 \pm \sqrt{q_2^2 - 4q_1 q_3}}{2q_1} \qquad (19)$$

Where

$$q_1 = 3\frac{\pi}{\tau}(L_{sd} - L_{sq})(-R_a - \omega L_{ad}\tan\delta) \qquad (20)$$

$$q_2 = 3\frac{\pi}{\tau}(L_{sd} - L_{sq})\omega\,\psi\tan\delta + 3\psi(-R_a - \omega\,L_{ad}\tan\delta) \quad (21)$$

$$q_3 = 3\omega\,\psi^2\tan\delta + (-R_a\tan\delta - \omega\,L_{aq})F_e^* \quad (22)$$

The value of $i_{aq}^*$ is obtained by substituting the value of $i_{ad}^*$ from (19) in (18).

**(b) Taking internal angle ($\psi$ ) as a specification**

$$i_{aq}^* = \frac{-3\psi \pm \sqrt{9\psi^2 + 12F_e^*(L_{sd} - L_{sq})\tan\psi}}{6(L_{sd} - L_{sq})\tan\psi} \quad (23)$$

The value of $i_{ad}^*$ is obtained by substituting the value of $i_{aq}^*$ from (23) in (18).

The power factor of a permanent magnet linear motor is varied from lagging to leading values through unity by setting ψ from a positive to negative value through zero.

## IV. Results And Discussions

The simulation results for step change in speed w.r.t to a frequency of 6 to 10 Hz at constant load torque=1N.m for a) desired δ, b) desired ψ, c) field oriented case is shown in Figure 5, which clearly indicates that there is change in $i_{qs}$ and $i_{ds}$ currents of stator for delta variation when compared to ψ variation and FOC. This clearly implies for a wider change in dynamic performance of the system.

There is marginal changes in δ and ψ and hence ϕ which indicates that for a value of load torque $T_l$ there is a corresponding δ . The maximum value of δ is found to be 74º. The thrust obtained at this value is the maximum pull out thrust beyond which the system goes in to instability. The thrust developed in field oriented case is of large value compared to arbitrary cases of δ and ψ respectively.

Simulation results for step change in load torque from 1 to 3 N-m at a speed corresponding to a frequency of 6 Hz is shown in fig 6. The performance of field oriented case is found to be better compared to arbitrary cases of δ and ψ.

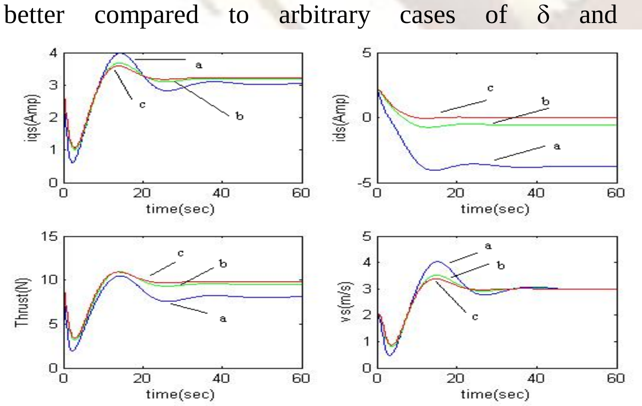



**Figure 5:** Simulation results for step change in speed wrt to a frequency of 6 to 10 Hz at constant load torque=1N.m for a) Desired δ, b) desired ψ, c) field oriented case

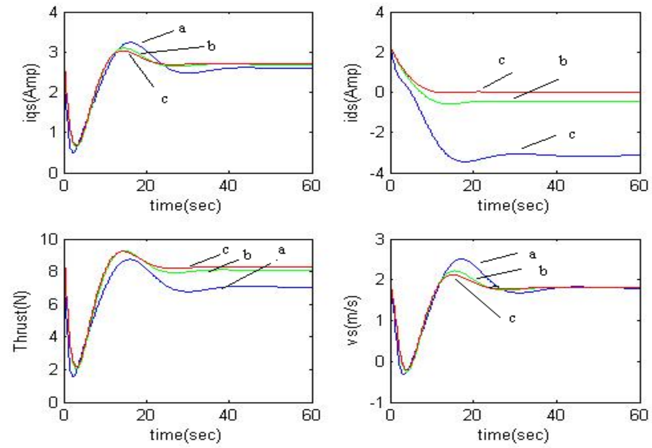



Figure 6: Simulation results for step change in load torque from 1 to 3 N-m at a speed corresponding to a frequency of 6 Hz for a) Desired δ, b) desired ψ, c) field oriented case

**Machine rating and parameters of the PMLSM**

| | |
|---|---|
| Nominal force Fe=154N | Nominal power =3910W |
| Rated speed Ve= 4.5m/s, | Rated current= 4.6A |
| Resistance per phase=2.1 Ω | Inductance =3.1 mH |
| Mass of forcer =1.5Kg | Pole pitch=20mm |
| Force constant=23.2 N/A | Voltage constant=27V/m/s |

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