

Optimal Operation of Linear Induction Motor Based on PSO-PID Controller

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Abstract: Recently, Particle Swarm Optimization (PSO) technique has been utilized in different electrical drives for velocity control. This study proposes this technique for online tuning PID controller parameters used to drive the Linear Induction Motor (LIM). A three phase inverter based on Sinusoidal Pulse Width Modulation (SPWM) technique is employed to obtain the required output voltage supplied to the main windings of the LIM to control the velocity with minimum harmonics and good characteristics. The end effect is taken into account in dq axis equivalent circuit. The simulation results proved that the proposed controller is more effective to improve the performance of the motor.

Key words: Linear induction motor, modeling and simulation, PWM inverter, PSO algorithm, PID controller, velocity control

INTRODUCTION

LIM's are utilized in wide range in the industrial automation including conveyor systems, actuators, material handling, Modern trains and robot base movers, etc., with a good performance (Bousserhane *et al.*, 2009). The essential principle of the LIM is similar that to the Rotary Induction Motor (RIM) but are different in the some inherent characteristics such as longitudinal end-effect, transversal edge-effect and normal force. A LIM is acquired by imagine the process of cutting and unrolling a rotary IM. The flat motor result a linear torque which is called thrust instead of producing rotary torque from a RIM. LIMs can be produce various thrust ranging from several Newton's to thousands of Newton's. Actually, all types of motors can have possible linear configurations but the LIM has many advantages such as high velocity operation, high starting thrust, simple mechanical devices, reduction of mechanical friction and so on (Bousserhane *et al.*, 2009). Also, the LIM's produce a direct linear motion without the need for a motion transformation (gearbox) from rotating to linear. Therefore, they have been the study and analysis this motors are wide attention.

The equivalent q-axis electrical circuit for the LIM is same as to the q-axis electrical circuit for a RIM. In this case, the end effects does not affect on the parameters but the end effects is affects during entry and exit from the linor in respect to the primary. While, the equivalent

d-axis electrical circuit related with a RIM circuit, so that, cannot be used in the analysis of a LIM. Therefore, the ends effects was considered as a function of velocity (Thomas and Hansson, 2013; Anand and Ashok, 2011). In most applications of LIM a short primary and infinite linor (secondary) are used where the primary continuously entering a new secondary region leads to hold the surprise increase of the magnetization flux permeation by permitting a progressive aggregation of the magnetizing field density in the gap.

The principle operation of LIM is similar to RIM but due to the end effect the control are more complicated and also, the parameters of the motor are changing due to the change of operating conditions. In recent years increasing the method control to LIM because of the need for controllers with high performance and more robustness, especially with the need to high precision in many applications (Thomas and Hansson, 2013). A three phase inverter with SPWM are used to control the velocity of linear induction motor. PWM technique are described by fixed amplitude pulses with diverse duty cycles for each period. To obtain the required output voltage from the inverter, the width of these pulses are adjusted. SPW method is widely used to control the motors and inverter application due a good performance with minimizing the harmonic contents (Thomas and Hansson, 2013). In this study, an optimal PID controller is utilized to control the velocity of LIM using PSO algorithm which is used to learning online the parameters

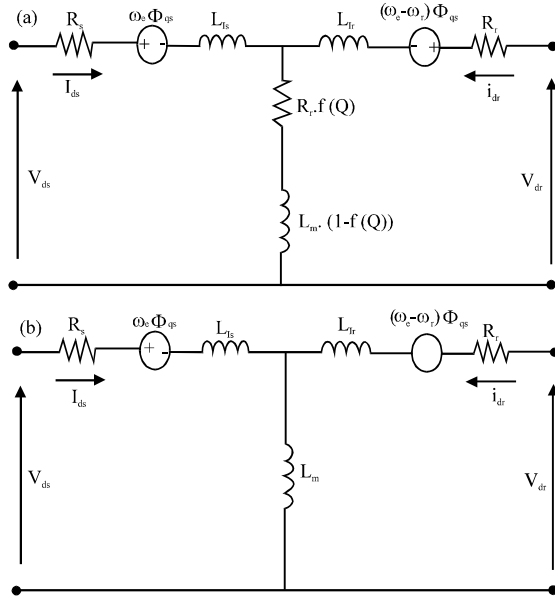


Fig. 1: The LIM equivalent circuit taking into account the end effect: a) d-axis equivalent circuit; b) q-axis equivalent circuit

of the PID controller. The performance of this controller reduced the output error and give better response under operating conditions. The Simulink Models of linear induction motors are built in MATLAB/Simulink. The simulation results contain the of velocity control and inverter output to verify the control system.

Mathematical model of LIM: There is a similarity between the dynamic model of the linear IM and the rotary three phase IM. Sophistically the dynamic model of LIM is based on influence the end effect of parameter in its equivalent circuit Anand and Ashok, 2011; Boucheta *et al.*, 2009; Da Silva *et al.*, 2003; Hairik and Hassan, 2009). The quadrature axis equivalent part of LIM is similar to its corresponding quadrature axis equivalent rotary IM. Therefore, the end effects will be small in q-axis while its contribution has the a dominate in d-axis. A linoric path of currents will influence by the air gap flux and consequently decreases the flux in the direct axis of rotor Φ_{dr} . As a result, the direct axis equivalent circuit of the rotary IM cannot be used in the model of LIM because of the consideration of the end effects. Figure 1 and 2 shows the dq-axis equivalent circuit with taking into account the end effect.

From the d-q equivalent circuit, the voltage equations in a synchronous reference frame aligned with the linor flux are given by Anand and Ashok (2011), Boucheta *et al.* (2009), Da Silva *et al.* (2003), Hairik and Hassan (2009):

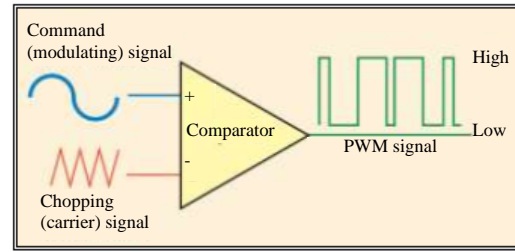


Fig. 2: SPWM technique

$$V_{ds} = R_s i_{ds} + R_r f(Q)(i_{ds} + i_{dr}) + p\lambda_{ds} - \omega_e \lambda_{qs} \quad (1)$$

$$V_{qs} = R_s i_{qs} + p\lambda_{qs} + \omega_e \lambda_{ds} \quad (2)$$

$$V_{dr} = R_r i_{dr} + R_r f(Q)(i_{ds} + i_{dr}) + p\lambda_{dr} - \omega_{sl} \lambda_{qr} \quad (3)$$

$$V_{qr} = R_r i_{qr} + p\lambda_{qr} + \omega_{sl} \lambda_{dr} \quad (4)$$

Where the flux linkage components are given as follows:

$$\lambda_{ds} = L_{ls} i_{ds} + L_m (1-f(Q))(i_{ds} + i_{dr}) \quad (5)$$

$$\lambda_{qs} = L_{ls} i_{qs} + L_m (i_{qs} + i_{qr}) \quad (6)$$

$$\lambda_{dr} = L_{lr} i_{dr} + L_m (1-f(Q))(i_{ds} + i_{dr}) \quad (7)$$

$$\lambda_{qr} = L_{lr} i_{qr} + L_m (i_{qs} + i_{qr}) \quad (8)$$

where, V_{ds} , V_{qs} , V_{dr} and V_{qr} are d, q-axes primary and secondary estimated voltages, i_{ds} , i_{qs} , i_{dr} and i_{qr} are d, q axes primary and secondary estimated currents, λ_{ds} , λ_{qs} , λ_{dr} and λ_{qr} are d, q axes primary and secondary estimated flux linkage, R_s and R_r are the resistance of the primary and secondary windings, respectively, per phase, L_m , L_s and L_r are the mutual, primary and secondary self-inductances, respectively, per phase, L_{ls} and L_{lr} are primary and secondary leakage inductances, respectively, per phase, ω_e , ω , and ω_{sl} are the primary, secondary and slip electrical frequency, respectively.

The Q factor is a function of the primary length and the velocity of the LIM, according to influence the end effect which can be described as:

$$(Q) = \frac{DR_r}{(L_m + L_{lr})v} \quad (9)$$

Therefore:

$$f(QQ) = \frac{1-e^{-Q}}{Q} \quad (10)$$

The end effect is affected by increasing or decreasing the velocity and the primary length, so that, the magnetization current of the LIM is changed. This changing can be calculated quantitatively in terms of the magnetization inductance as follow:

$$L'_m = L_m(1-f(QQ)) \quad (11)$$

The thrust force is given by Boucheta *et al.* (2009):

$$F_e = \frac{3\pi P}{2\tau_p} (\lambda_{ds} i_{qs} - \lambda_{ds} i_{qs}) = M.v' + D.v + F_L \quad (12)$$

Where:

- D = The primary length
- v = The velocity (m/sec)
- P = The number of pole pairs
- τ_p = The pole pitch
- F = The electromagnetic thrust force
- M = Total mass of the moving element

Modeling of pwm three phase inverter: Three-phase voltage source inverter provide the required voltage and required frequency input to the motor according to PWM technique. PWM is an internal control method takes the signal from the external control method. There are several methods of PWM techniques for voltage-sourced inverters. An appropriate technique of pulse width modulation has to be employed to obtain the suitable output voltage to be fed to the motor. In this study, a SPWM is used to give better performance (Islam *et al.*, 2013; Janak and Kaur, 2014).

In SPWM technique a sine wave are compared with triangular carrier wave to generate PWM pulse. In three phase inverter, the reference signals are three sinusoidal waves which have 120° difference in phase between them. The reference signals frequency is taken according to the output inverter frequency, 50/60 Hz a high frequency (usually several kHz) is taken for the carrier signal (usually triangular signal). The comparison of the two signals generates the pulses signal which are used to drive the inverter switches as shown in Fig. 2.

The pulse will give to each gate of the three inverter according to switching sequence to obtain the required voltage to the LIM as shown in Fig. 3.

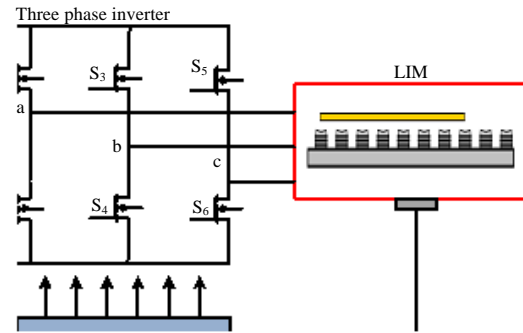


Fig. 3: LIM with three phase inverter

Algorithm for particle swarm optimization technique: PSO is a population based on computational technique inspired from the simulation of gregarious behavior bird flocking, fish schooling and swarm theory. PSO is a method utilized to explore the search space of a given problem to find the optimal solution according to the particular objective. The technique has been developed to be powerful in solving problems with complex and nonlinear systems, multi-dimensional and non-differentiable systems through learning.

PSO algorithm is one of the evolutionary computation methods for solving optimization problems. This technique can be utilized to control the velocity of LIM that includes particular objective function to give optimal results. In this algorithm, each individual solution is called a particle. Every particle have an initial velocity which are flow in the search space with dimensions the problem. The initial velocity of each particle is constantly updated by the own previous experience and experience of neighboring particles in its swarm to select the best position for itself which called the personal best position (called the Pbest). When a particle in the whole swarm have the best position in the swarm which is called the global best position (gbest). Where the best previous position of any particle is called local best position (lbest).

The swarm direction of a particle is determined by the set of particles neighboring the particle and its previous experience to decide whether the best solution is accomplished according to the objective function where the best previous position giving the minimum fitness value.

The performance of each particle is determined using a fitness function that differs depending on the optimization problem (Sedighzadeh and Masehia, 2009; Sharaf and El-Gammal, 2009; Niknafs *et al.*, 2014; Obed and Saleh, 2014). For a multi-dimensional problem,

the velocity and position of each particle in the swarm are updated using the following equations:

$$v_i^{k+1} = w.v_i^k + c_1.R_1.(lbest_i - x_i^k) + c_2.R_2.(gbest_i - x_i^k) \quad (13)$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \quad (14)$$

Where:

x_i^k, v_i^k = The instant position and speed of particle i at iteration k , respectively

w = The inertia weight

c_1 and c_2 = The acceleration constants and

R_1, R_2 = A random variables between 0 and 1

$$w = w_{max} - \frac{(w_{max} - w_{min})}{iter_{max}} \quad (15)$$

Where:

w_{max} and w_{min} = The maximum and minimum weights

$iter_{max}$ = The maximum number of iterations

The objective functions considered are based on the desired criterion. The selection of the criteria depends on the system and the controller. In this study, a multi-objective function is used to find the optimal solution with a minimum speed error based on the minimum Integral of Squared Error (ISE) criterion and minimum overshoot (M_p follow (Sharaf and El-Gammal, 2009; Obed and Saleh, 2014; Saleh and Obed, 2014):

$$\text{Fitness function} = \min(\text{ISE}) + \min(M_p) \quad (16)$$

Where:

$$\text{ISE} = \int e^2(t) dt \quad (17)$$

$$M_p = v_{max} - v_{ref} \quad (18)$$

$$e(i) = v(i) - v_{ref}^{(i)} \quad (19)$$

Where:

v = The actual velocity and

v_{ref} = The desired velocity of linear induction motor

According to the above, the flow chart of the PSO algorithm can be shown in Fig. 4.

Velocity control of linear induction motor based on pso-pid controller: The main objective of the proposed controller is to the linear velocity control of the LIM drive to track the set velocity reference. The drive system

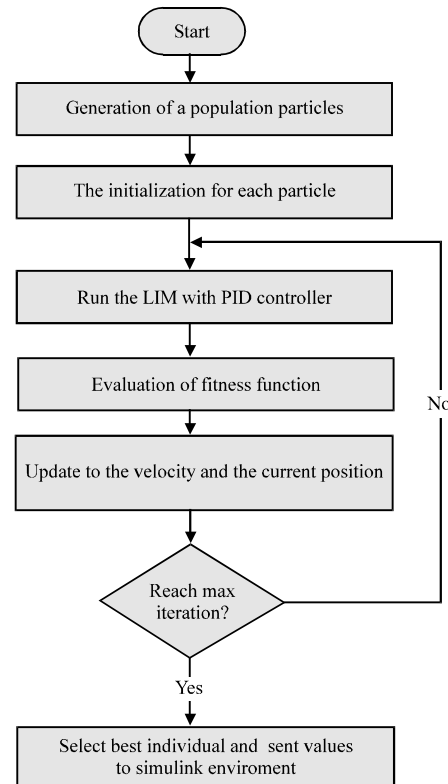


Fig. 4: General flow chart of PSO

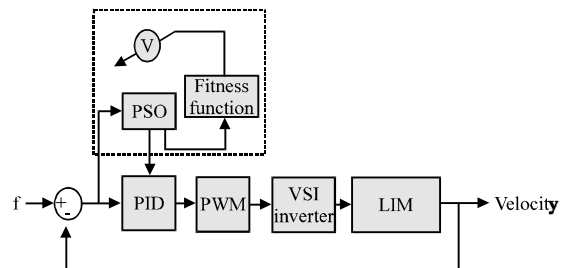


Fig. 5: Block diagram of LIM with online tuning PI controller based on PSO algorithm

consists of three inverter which is switching by SPWM technique according to the control signal which is given from PID controller to obtain the required voltage to track the velocity desired. It is recommended to minimize the switching frequency of the inverter switches. The parameters of the PID controller are tuning using particle swarm optimization.

In this study, the PID controller based on PSO algorithm is used to control the velocity of LIM in wide range and to provide better performance than conventional PID controller. Figure 5 shows the block diagram of the LIM with online tuning PID controller based on PSO algorithm.

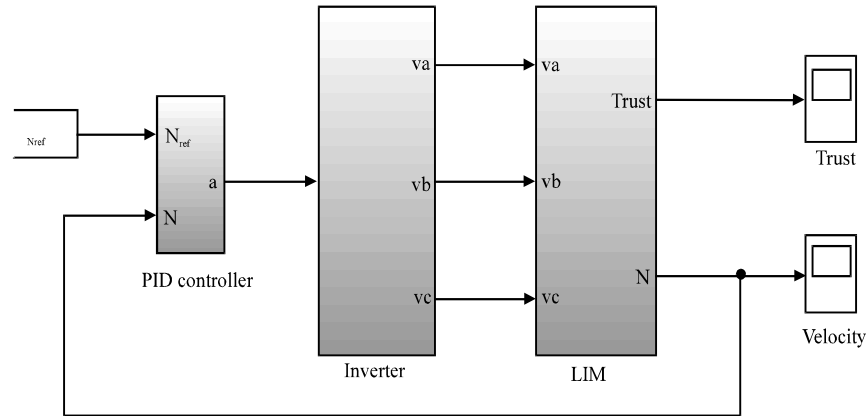


Fig. 6: The overall model of LIM motor drive system

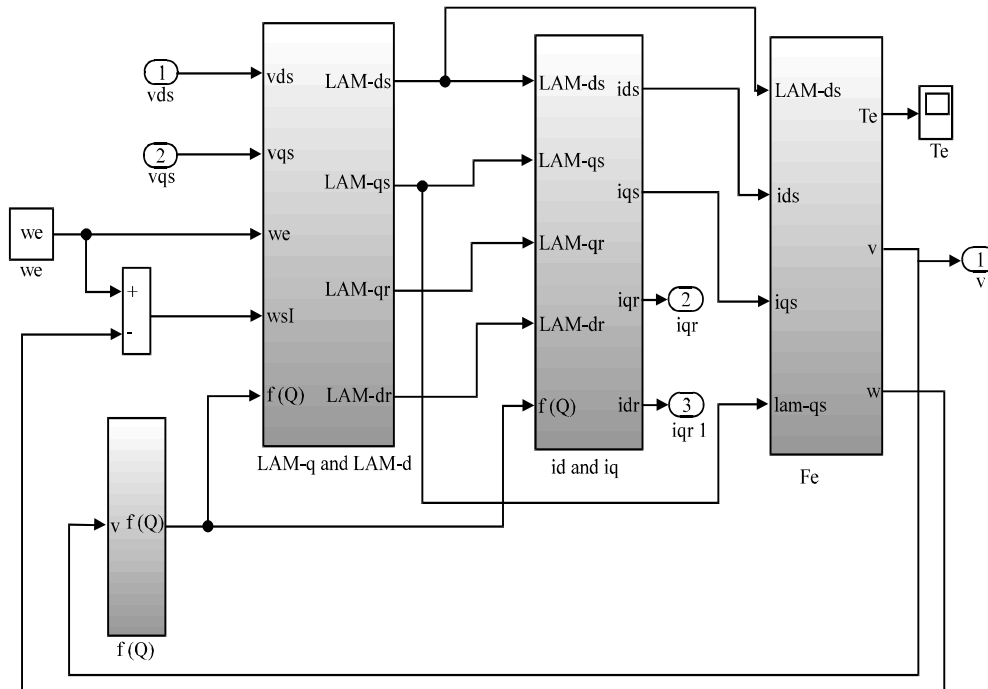


Fig. 7: The Simulink Model of the LIM motor

According to the training, the following PSO parameters that are used for training the PID controller to give the better performance:

- The member of each particle is K_p , K_i and K_d
- No. of birds = 60
- Maximum iteration number = 40
- Inertia weight factor $w = 0.9$
- Acceleration constant $c_1 = 1.8$ and $c_2 = 2$

Simulink implementation for linear induction motor velocity control based on PID-PSO controller: The complete Simulink Model of LIM drive system is shown in Fig. 6. The Simulink Model of the LIM can be construct in MATLAB, according to the given mathematical Eq. 1-12 as shown in Fig. 7. The three phase inverter can be implemented according to the SPWM technique as shown in Fig. 8. Where the SPWM technique can be built as shown in Fig. 9. The speed is controlled by controlling the amplitude of output voltage of the inverter using SPWM method.

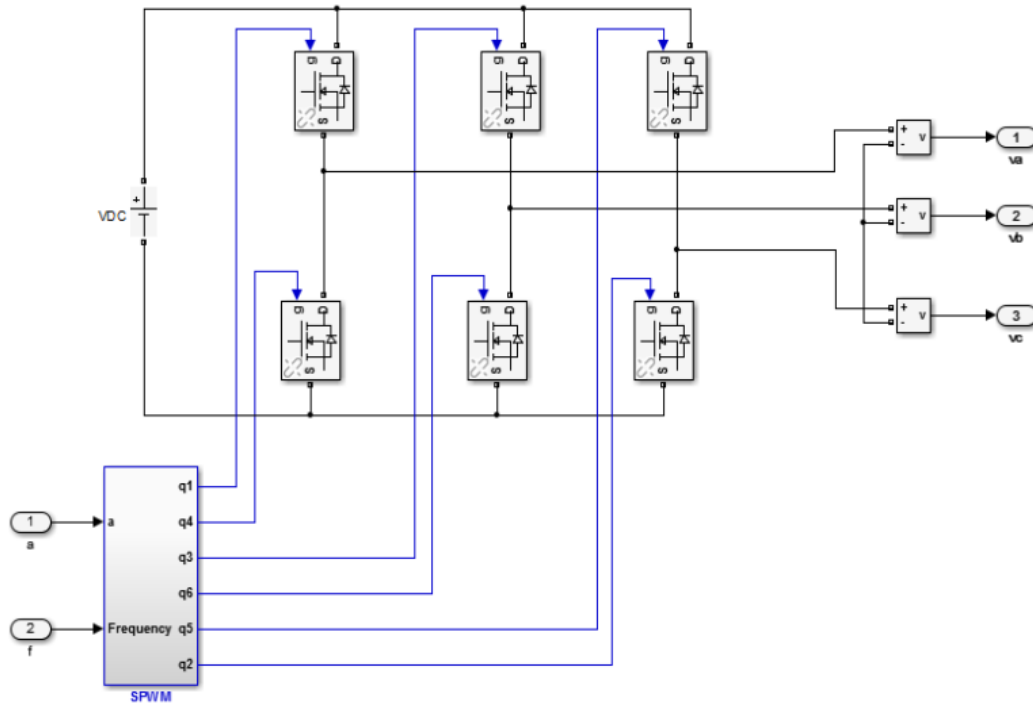


Fig. 8: The Simulink Model of SPWM three phase inverter

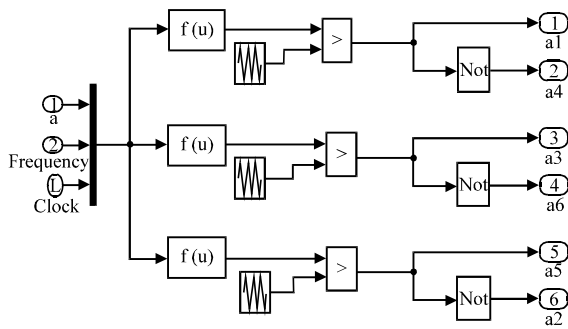


Fig. 9: The Simulink Model of SPWM technique

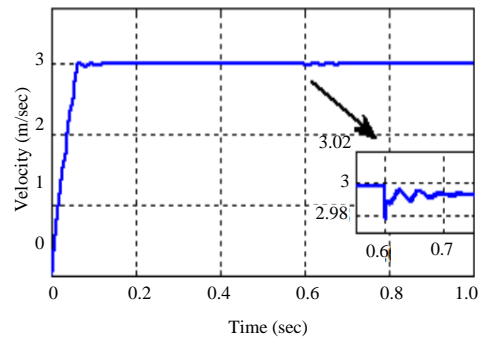


Fig. 10: The velocity response under all conditions

RESULTS AND DISCUSSION

The velocity control of LIM drive system with optimal PID controller using PSO algorithm is implemented in Simulink/MATLAB program, Version 2012b which uses the 4 order Runge-Kutta-Gill method for Simulink setting. The simulation period that assumed in this model is 1 sec. The simulation results for the following cases are presented and discussed:

Performance under no load and load conditions: To validate the control strategy, the linear speed response is fixed at the reference speed 3 (m/sec) with no load condition and a sudden thrust of 200 N is added at t = 0.6 sec as shown in Fig. 10. The developed thrust during no

load and load condition is shown in Fig. 11. Figure 12 and 13 show the d-q components of primary current at no load and load condition. Figure 14 and 15 show the d-q components of secondary current at no load and load condition. The F(Q) function for the same starting and loading conditions is shown in Fig. 16 and 17 show the linear velocity response with PID-PSO controller and with trail and error PID controller.

Step change in reference speed: In this case, a step change of the velocity response of the LIM are tested as shown in Fig. 18. The motor is driven at 3 m/sec for free acceleration and the reference velocity increases until reach its rated at 4 m/sec at 0.4 sec and a sudden thrust

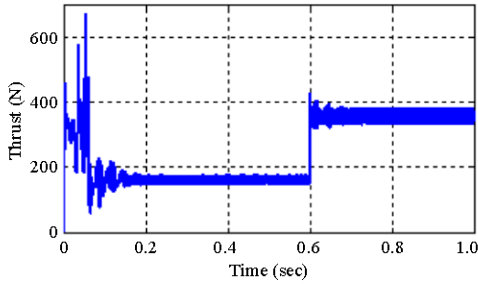


Fig. 11: Developed thrust force of the LIM

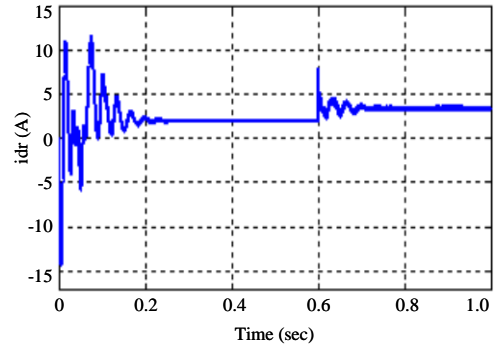


Fig. 15: D-axis component for Secondary current at all conditions

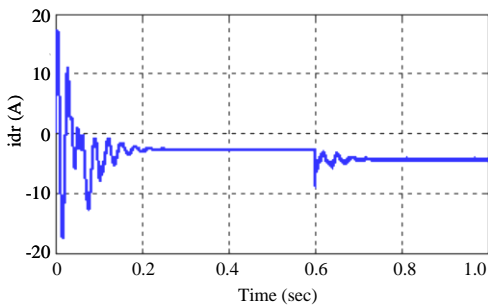


Fig. 12: Q-axis component for primary current at all conditions

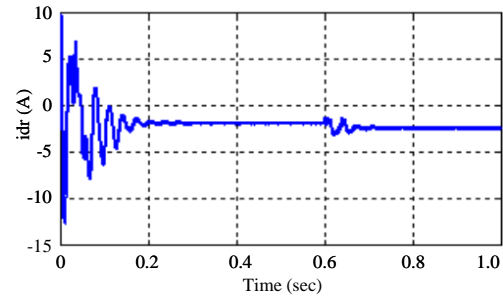


Fig. 16: The $f(Q)$ function

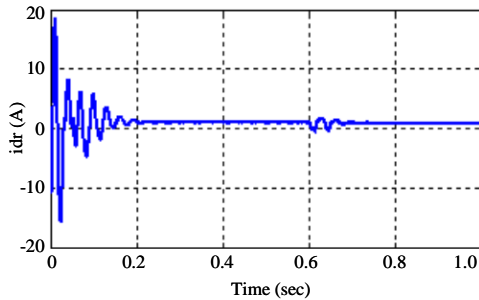


Fig. 13: D-axis component for primary current at all conditions

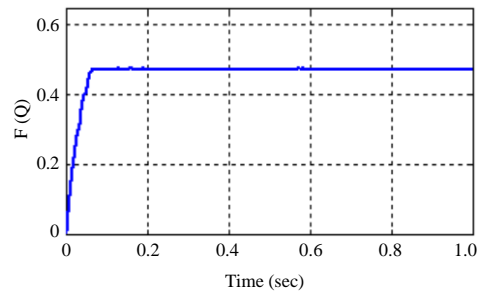


Fig. 17: The linear velocity response with PID-PSO controller and with rail and error PID controller

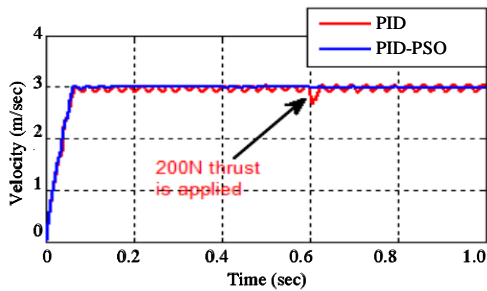


Fig. 14: Q-axis component for Secondary current at all conditions

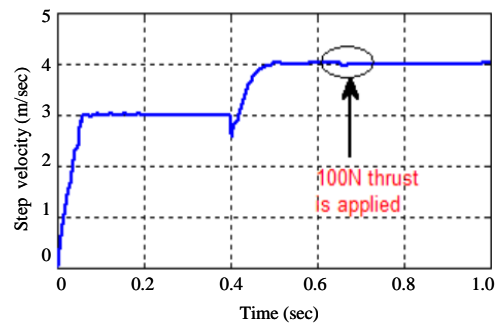


Fig. 18: The step velocity response under no load

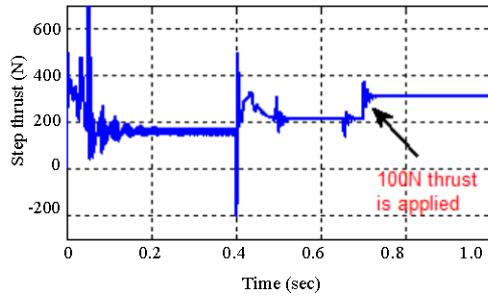


Fig. 19: The developed thrust during the step change of the velocity

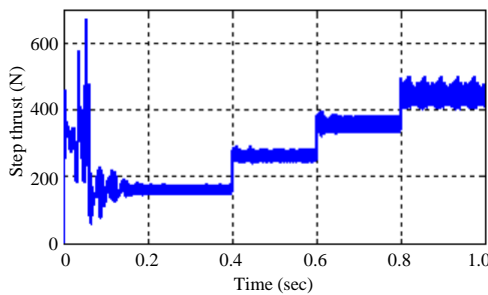


Fig. 20: The step change in the developed thrust

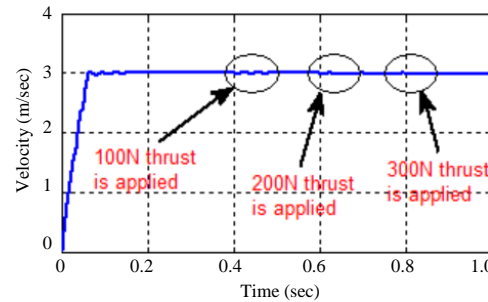


Fig. 21: The linear velocity response during the step change in the thrust

of 100 N is added at $t = 0.7$ sec. while the developed thrust during the step change of the velocity is shown in Fig. 19.

Step change in load torque: In this case, the linear velocity response is fixed at the reference speed 3 (m/sec) and the load is being changed from no load at starting and a sudden thrust of 100 N is added at $t = 0.4$ sec and increases 100 N every 0.3 sec. Where the linear velocity is kept constant with step change in the load. Figure 20 shows the step change in the developed thrust. Figure 21 shows the linear velocity response during the step change in the thrust.

CONCLUSION

In this study, a proposed optimal PID controller based on particle swarm optimization technique which is used to control the velocity of LIM. PSO technique is applied to tuning the parameters of PID controllers. With used Sinusoidal Pulse Width modulation (SPWM) in speed control of LIM drive. The velocity response shows improvement in overshoot, rising time, settling time and steady state error. Moreover, the drive provides a flexible and robust.

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