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Design, Analysis of Linear Induction Motor based on Harmony Search Algorithm and Finite Element Method

Ch. V. N. Raja and K. Rama Sudha

Department of Electrical Engineering, A.U. College of Engineering (A)Visakhapatnam, India

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Abstract

Linear Induction motors (LIM) are used extensively in industrial applications, especially in transportation systems. These applications need high efficiency with high power factor. Mainly LIM suffer from two major drawbacks, low power factor and low efficiency. These drawbacks cause high energy consumption and high input current. In this paper, a novel Harmony Search optimization algorithm is proposed to meet required efficiency and power factor in the design of a Linear Induction Motor. Finite Element Method is adopted to analyze the flux density in LIM with the parameters obtained using HSA.

Keywords: **:** Linear Induction motor, Harmonic search Algorithm and FEM analysis

1. Introduction

Linear Induction motor (LIM), is basically an advanced version of motor that is in use to achieve rectilinear motion instead of rotational motion as in ordinary conventional motors. The stator is cut axially and spread out flat. The LIM is broadly applicable in variety of applications such as military, transportation, actuators, robot base movers elevators and etc., [1] due to easy maintenance, high acceleration/deceleration and no need of transformation system from rotary to translational motion.

Roma Rinkevicien [2] discussed application of linear induction motor in mechatronic systems. Dal-HoIm [3] describes an optimization problem using the Interior Point algorithm (IPA) to meet desired specifications. Yoon [4], optimization is performed to LIM based on starting thrust and output power input volt–ampere ratio. Rong - Jong Wai [5] developed nonlinear control strategy from lyapunov's principle to control LIM servo drive for periodic motion. Mehmet Cunkas [6] developed Genetic Algorithm (GA) program package to meet required torque efficiency and cost.

A. Hassanpour Isfahani [7] proposed a multi-objective genetic algorithm optimization method to improve both motor power factor and efficiency. Liu Ai-min [8] discussed on a Neighborhood Topology algorithm (NTA) to maintain high starting thrust and high reliability for high-voltage circuit breaker. Ismail Khalil Bousserhane [9] intended an Adaptive Backstepping controller for LIM to achieve a position and flux tracking objective under disturbance of load torque and parameter uncertainties. A. Zare Bazghaleh [10] proposed particle swarm optimization (PSO) to evaluate intensity of end effect with help of equivalent circuit method.

Ugur Hasirci [11] discussed about design, execution and nonlinear velocity tracking control of a novel maglev system for maglev trains. A. Shiri [12] derived analytical expression for braking force of LIM based on iron saturation, transverse edge effect, longitudinal end effect and skin effect. A.A. Pourmoosa [13] introduced imperialist competitive algorithm (ICA) to equivalent Linear Induction motor based on coupled-circuit model.

Maurizio Cirrincione [14] implemented an adaptive neural network based model reference system (NNMRAS) for low speed LIM drives. Adil Hameed Ahmed [15] suggested indirect field oriented voltage control to improve Linear Induction Motor Performance. Xu Qiwei [16] implemented Sliding mode observer to LIM in order to reduce the steady state error and suppress the integral saturation. Hsin - Han Chiang [17] proposed an optimized adaptive tracking control for a LIM drive by considering the uncertainties like friction force, unknown end effects and payload. Hadi Zayandehroodi [18] introduced a multi-objective cuckoo optimization algorithm (COA) enhanced to improve both efficiency and power factor.

This paper is organized as follows; section II describes Equivalent Circuit and dynamical model of LIM, section III describes Identification of LIM parameters using HSA, section IV describes FEM Analysis for LIM and section V describes the computer simulations results.

2. Machine Modelling

2.1. *Equivalent Circuit model of LIM*

Fig. 1. shows the architecture of the single sided LIM. It contains a three-phase primary and an aluminium laid sheet on the secondary back iron [7]. In 1983, J. Duncan implemented the equivalent circuit model of LIM. The per-phase equivalent circuit model of SLIM is shown in Fig. 2.

• E-mail address: ch.v.n.rajar@gmail.com

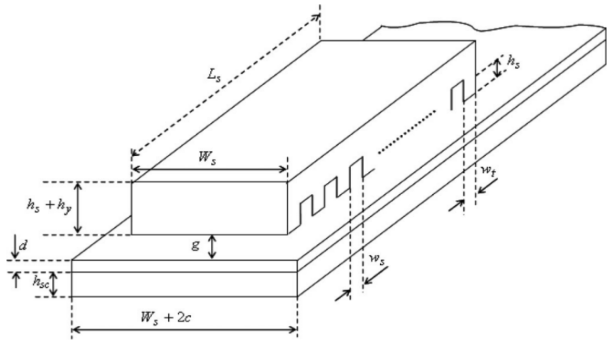

Fig. 1. Architecture of a single sided LIM

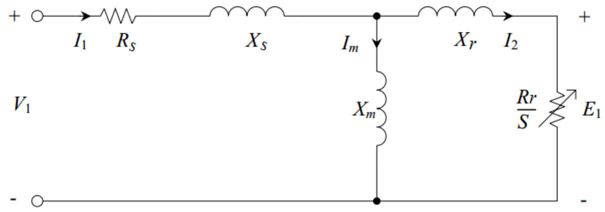

Fig. 2. Equivalent circuit of a LIM

Per-phase stator resistance $R_s = \frac{\rho_w l_w}{A_{wt}}$ (1)

Per-phase stator-slot leakage reactance

$$X_s = \frac{2\mu_0\left[\left(\lambda_s\left(1+\frac{3}{p}\right)+\lambda_d\right)\frac{W_s}{q}+\lambda_e I_{ce}\right]N^2}{p} \quad (2)$$

Slot, differential and end connection permeance are

$$\lambda_S = \frac{h_S(1+3k_p)}{12w_S}$$

$$\lambda_d = \frac{5\left(\frac{g_e}{w_S}\right)}{5+4\left(\frac{g_0}{w_S}\right)} \quad (3)$$

$$\lambda_e = 0.3(3k_p - 1)$$

Magnetizing Reactance per phase

$$X_m = \frac{24\mu_0 \pi f w_{se} K_W N_l^2 \tau}{\pi^2 p g_e} \quad (4)$$

Per-phase rotor resistance $R_r = \frac{X_m}{G}$ (5)

Goodness factor $G = \frac{2\mu_0 f_l \tau^2}{\pi\left(\frac{\rho_r}{d}\right)g_e}$ (6)

Where, ρ_w is the volume resistivity of the copper wire used in the stator winding; l_w is the copper wire length per phase; A_{wt} is the cross sectional area of the wire; k_p is the pitch factor; k_w is the winding factor; g_e is the equivalent air gap; w_{se} is the equivalent stator width; ρ_r is the volume resistivity of the rotor conductor outer layer and f_l is primary frequency.

To maintain air gap flux density below 0.5 T, then the iron losses is negligible and the thrust, the efficiency and the power factor will be given by

$$F_S = \frac{mI_1^2 R_r}{\left[\frac{1}{(sG)^2}+1\right]sV_S} \quad (7)$$

$$\eta = \frac{F_s 2\tau f_1(1-s)}{F_s 2\tau f_1 + 3I^2 R_1} \quad (8)$$

$$\cos\varphi = \frac{F_s 2\tau f_1 + 3I^2 R_1}{3VI} \quad (9)$$

Hassanpour Isfahani A, et. al., 2008 explained effect of different parameters on efficiency and power factor and hence it is necessary to employ an optimization method to achieve required specifications. Table 1 describes design variables of optimization problems for LIM.

Table 1. Design variables of optimization problem

Parameter	Symbol	Unit	Max. Value	Min. Value
Maximum thrust slip	s	--	0.1	0.3
Pole Pitch	τ	mm	40	60
Aluminium thickness	d	mm	3	6
Primary current Density	J	A/mm^2	1	3
Efficiency	η	--	0.7	--
Power Factor	$\cos\phi$	--	0.7	--

2.2. *Dynamical Modelling of LIM*

The dynamic model of the LIM is modified from traditional model of a three-phase, Y-connected LIM and can be expressed in the d-q synchronously rotating frame as [9]

$$\frac{di_{ds}}{dt} = \frac{1}{\sigma L_S}\left(\begin{array}{l} -\left(R_S+\left(\frac{L_m}{L_r}\right)^2 R_r\right)i_{ds} + \\ +\sigma L_S \frac{\pi}{\tau} v_e i_{qs} + \frac{L_m R_r}{L_r^2}\varphi_{dr} + \\ +\frac{PL_m \pi}{L_r \tau}\varphi_{qr} v_r + V_{ds} \end{array}\right) \quad (10)$$

$$\frac{di_{qs}}{dt}=\frac{1}{\sigma L_s}\left(\begin{array}{l}-\sigma L_s\frac{\pi}{\tau}v_e i_{ds}-\left(R_s+\left(\frac{L_m}{L_r}\right)^2 R_r\right)i_{qs}-\\ -\frac{PL_m\pi}{L_r\tau}\varphi_{dr}v_r+\frac{L_mR_r}{L_r^2}\varphi_{qr}+V_{qs}\end{array}\right) \quad (11)$$

$$\frac{d\varphi_{dr}}{dt}=\frac{L_mR_r}{L_r}i_{ds}-\frac{R_r}{L_r}\varphi_{dr}+\left(\frac{\pi}{\tau}v_e-P\frac{\pi}{\tau}v_r\right)\varphi_{qr} \quad (12)$$

$$\frac{d\varphi_{qr}}{dt}=\frac{L_mR_r}{L_r}i_{qs}-\left(\frac{\pi}{\tau}v_e-P\frac{\pi}{\tau}v_r\right)\varphi_{dr}-\frac{R_r}{L_r}\varphi_{qr} \quad (13)$$

$$F_e=K_f\left(\varphi_{dr}i_{qs}-\varphi_{qr}i_{ds}\right)=M\dot{v}_r+Dv_r+F_L \quad (14)$$

Secondary time constant

$$\tau_r={L_r}/{R_r}$$

Leakage coefficient $\sigma=1-\left({L_m^2}/{\left(L_sL_r\right)}\right)$ and force constant $K_f={3P\pi L_m}/{(2\tau L_r)}$

Where L_m is the magnetizing inductance per phase; L_s and L_r be primary and secondary inductance per phase; v_r is the mover linear velocity; τ is the pole pitch; P is the number of pole pairs; φ_{qr} and φ_{dr} are q-axis and d-axis secondary flux; i_{qs} and i_{ds} and are q-axis and d-axis primary current; V_{ds} and V_{qs} are d-axis and q-axis primary voltage; Where, External force disturbance be F_L, electromagnetic force be F_e, M be the total mass of the moving element and D be the viscous friction coefficient.

3. Identification of LIM parameters using HSA

In order to improve efficiency and power factor of LIM, the effective design parameters should be known. In this section design parameters are chosen as maximum thrust slip, pole pitch, aluminium thickness and primary current density. The design variables and constraints are as listed in table 1. To obtain required efficiency and power factor the objective function is defined as eq. (15)

$$f_n(x_1,x_2,x_3,x_4)=\eta(s,\tau,d,J)^{k1}.\cos\phi(s,\tau,d,J)^{k2} \quad (15)$$

Where k_1, k_2 are constants and *s*, τ, d, *J* are the variables.

As seen in Eq. (15), the power factor and the efficiency are adjusted by power coefficients to meet required performance. Minimization of f_n fulfils both objectives of the optimization. When power factor is more important, choose k_1=0, k_2= 1 and when efficiency is more important than power factor, choose k_1=1, k_2= 0. By considering k_1=k_2= 1, optimized simultaneously to meet desired efficiency and power factor.

Harmony Search Algorithm (HSA) is an optimization algorithm developed by Xiaolei Wang in 2015. HSA is an advanced process control and optimization for industrial scale systems. HSA is based on the musical process where music players manage the pitches of their instruments to find necessary harmony. Steps involved in the process of HSA are as follows:

Step 1: Assign the number of parameters to be identified for a LIM

Step 2: Initialize the HSO parameters such as harmony memory (HM), harmony memory considering rate (HMCR), pitch adjusting rate (PAR), bandwidth (BW) and maximum number of iterations for convergence.

Step 3: Define the multi objective function as

$$f_1=\eta(s,\tau,d,J)=\eta(x_1,x_2,x_3,x_4) \text{ and}$$

$$f_2=pf(s,\tau,d,J)=pf(x_1,x_2,x_3,x_4) \quad .... \quad (16)$$

Step 4: Defined the range of values for the function variables.

Step 5: Obtain functional value of initial Harmony memory.

Step 6: Set iteration counter t=0.

Step 7: Increment the iteration counter t=t+1.

Step 8: Starting of Harmony Search, if generated random value > HMCR. Then select the value of parameter randomly as,

$$x_{inew}=x_{old}+rand(0,1)*BW \quad .... \quad (17)$$

Otherwise choose harmony value from the HM and adjust the pitch as

$$x_{new}=x_{old}+BW*(rand-0.5) \quad ...(18)$$

Step 9: Update the HM of objective function and replace the worst solution with new better solution.

Step 10: Check the stopping criteria and convergence i.e., number of iteration > maximum iteration, if it is satisfied goto step 12.

Step 11: Perform for New Harmony i.e., increase the iteration count and goto step 7.

Step 12: Find the best harmony from the HM. i.e., the optimal values within the constraints.

Step 13: Stop

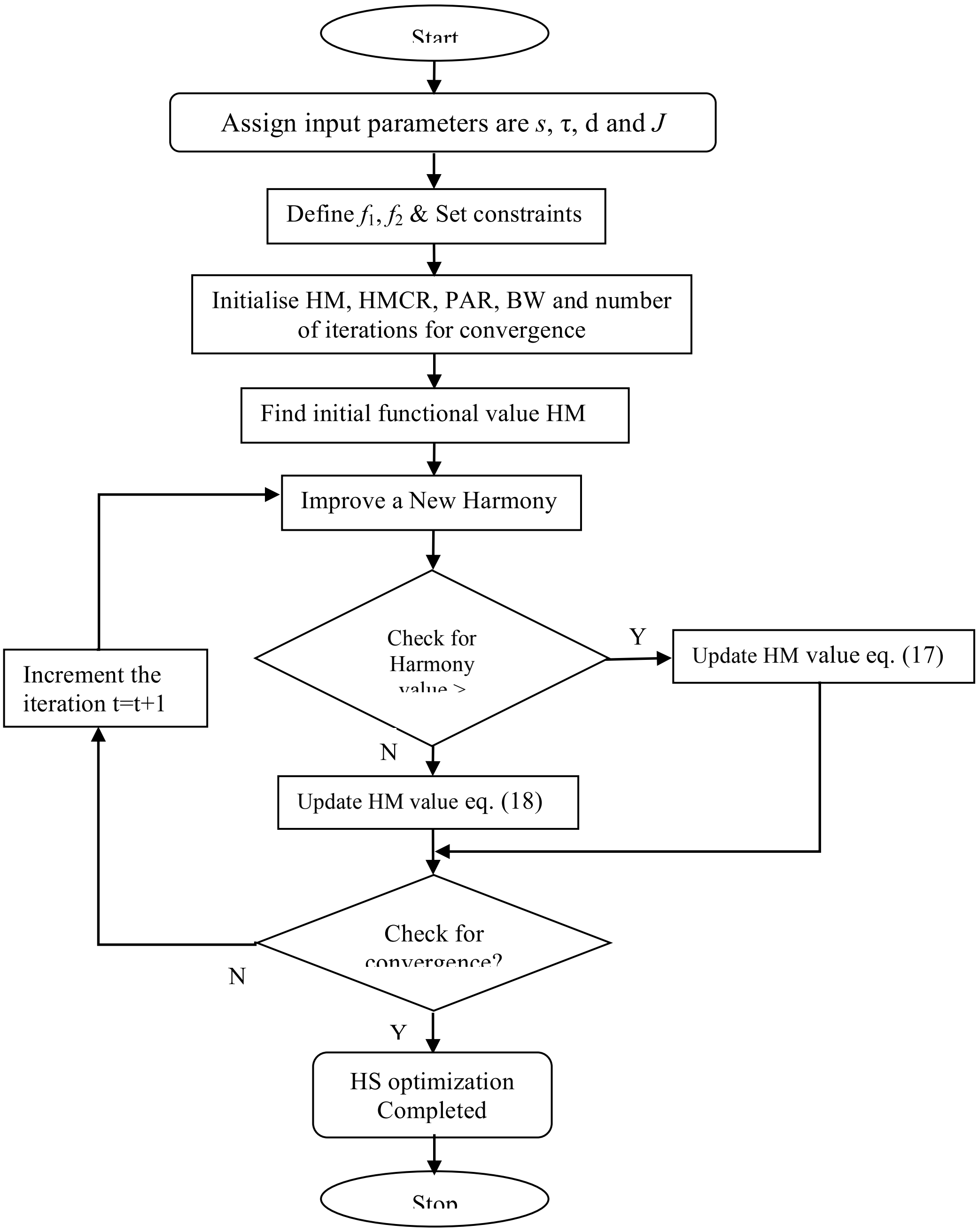

Fig. 3. Flow chart of HSA

Table 2 Comparison of various optimization results

Method	Slip	Pole pitch (mm)	d (mm)	J (A/mm^2)	H	p.f.	Convergence time (sec)
Interior Point algorithm (IPA)	0.13	48.2463	4.9955	2.0154	0.658	0.551	14
Genetic Algorithm (GA)	0.1495	48.0000	4.8000	2.1000	0.67959	0.608	8.165
Particle Swarm Optimization (PSO)	0.1495	48.0671	4.8019	2.1000	0.68968	0.619	4.239
Harmony Search Algorithm (HSA)	0.14	40.3998	4.0	2.1	0.69037	0.698	2.148

Table 2 shows, the motor dimensions and characteristics using Interior Point algorithm (IPA), genetic algorithm (GA), Particle Swarm Optimization (PSO) and Harmony Search Algorithm (HSA) optimization methods.

4. Finite Element Analysis for LIM using PSO and HSA

In this paper, the design optimizations were carried out based on the analytical model of the machine and presented in Section II. Such as the validity of the design optimizations greatly depends on the accuracy of the model. However, the model is obtained by simplifications such as considering saturation, nonlinearity of materials and etc. Thus, in this section 2-D time stepping FEM are employed to evaluate the new equivalent circuit LIM model. From the equations of the magnetic field with eddy currents can be written as

$$\nabla \text{ x } (\upsilon \nabla \text{ x A}) = J_0 + J_e \qquad (19)$$

$$J_e = -\sigma\left(\frac{\partial A}{\partial t} + grad\ \emptyset\right) \quad (20)$$

$$\nabla . J_e = 0 \quad (21)$$

Commercial computer software (CCS) is one of the most important and efficient software for 2-D FEM analysis and also to obtain numerical and graphical results. The incomplete Cholesky conjugate gradient (ICCG) method used to solve the finite-element equations. . In FEM, using time-stepping analysis the change in levitated position that is based on the current position is called relative moment is measured. The force is produced by a linearly moving magnetic field acting on conductors in the fields are then calculated using local virtual work method.

Fig. 7 and fig. 8 shows, the flux density distribution and graphical representation of flux lines in the analyzed LIM, respectively. Fig. 9 and fig. 10 shows, comparison of flux density and eddy current density (J_e) of LIM.

5. Simulations Results

The novel optimization HSA has been applied to meet required efficiency and power factor in the design of a Linear Induction Motor are shown in Figs. 4 to 6 and FEA results of LIM has been shown in figs. 7 to 10.

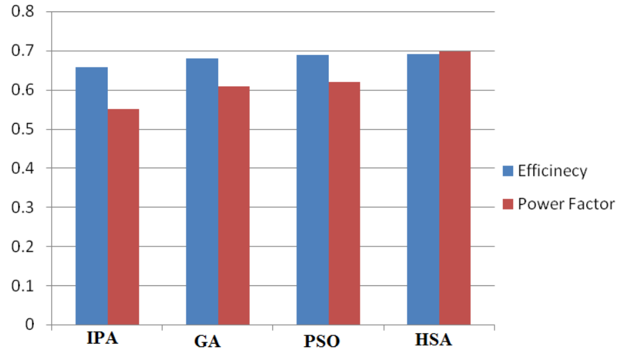

Fig. 4. Comparison of efficiency and power factor between various optimization methods

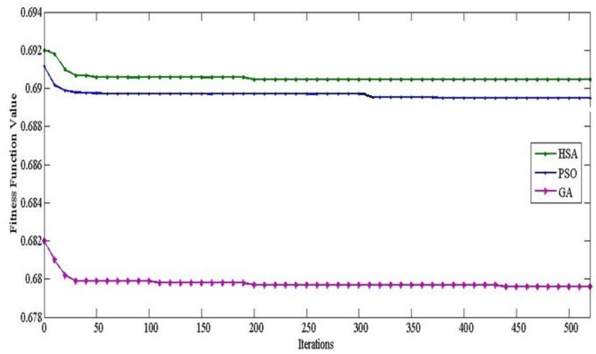

Fig. 5. Comparison Fitness functions of different optimization methods

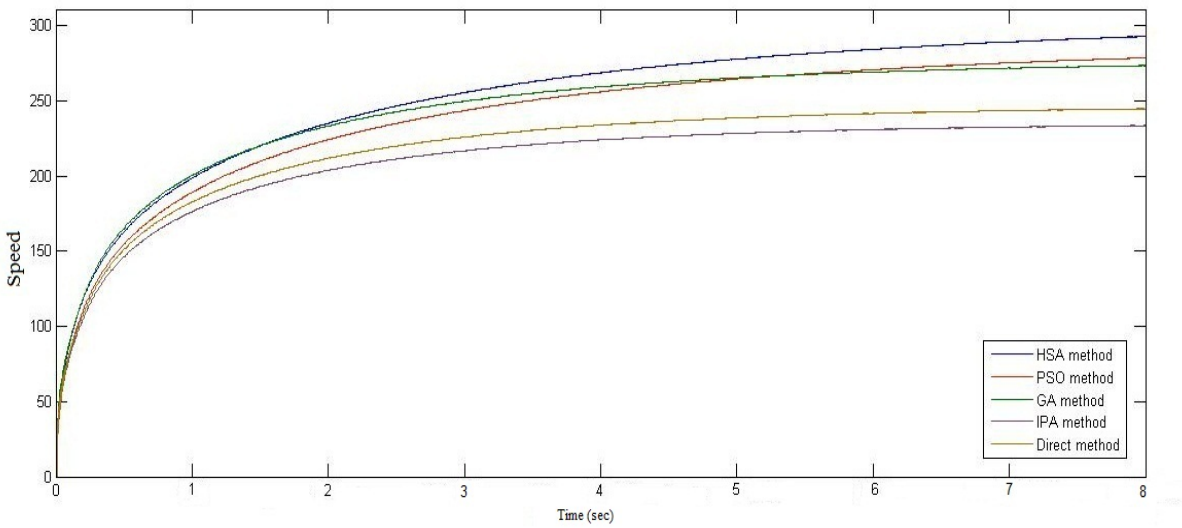

Fig. 6. Comparison of open loop LIM speed for different optimization methods

From fig. 4, Interior Point algorithm results are worst than remaining optimization methods, Genetic algorithm have 67.9% efficiency but power factor is 13.14% less than the required, particle swarm optimization have 68.9% but power factor is 11.57% less than required but HSA gives 69.04% and also reached required power factor. From fig. 5 the HSA has less number of iteration and better pattern search to reach desired optimum values as compared to GA, PSO methods. Fig. 6, shows HSA can produce higher speed as compared to other optimization methods.

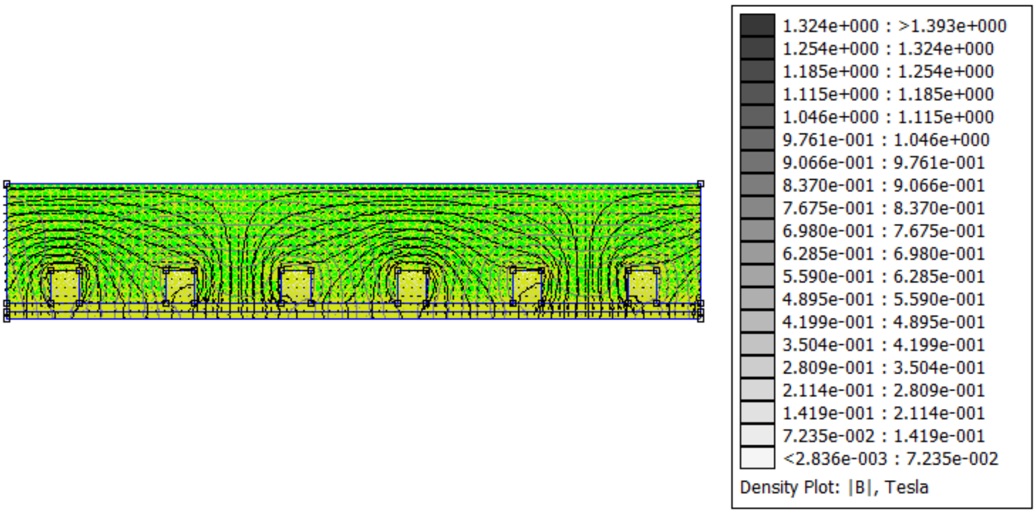

Fig. 7 Flux density distribution in the LIM using HSA

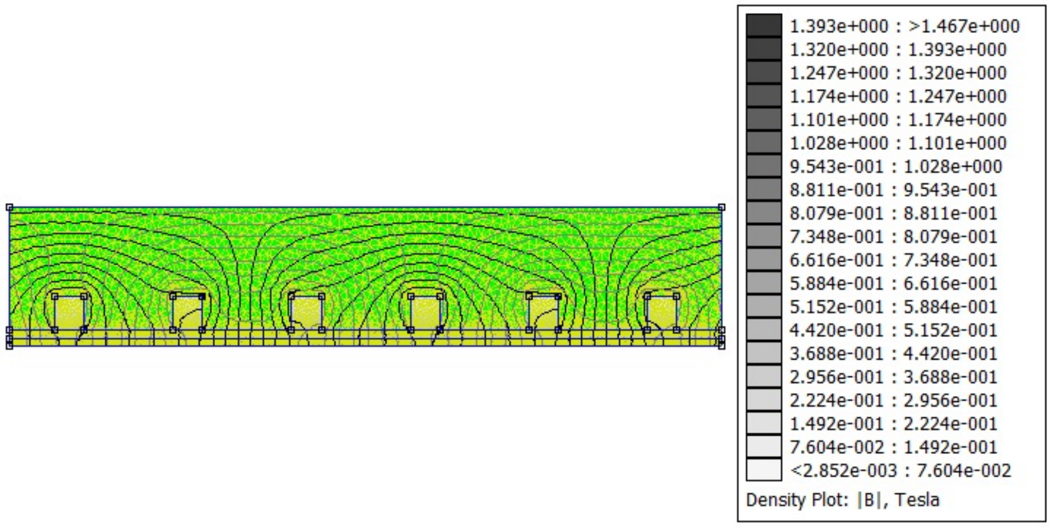

Fig. 8 Flux density distribution in the LIM using PSO

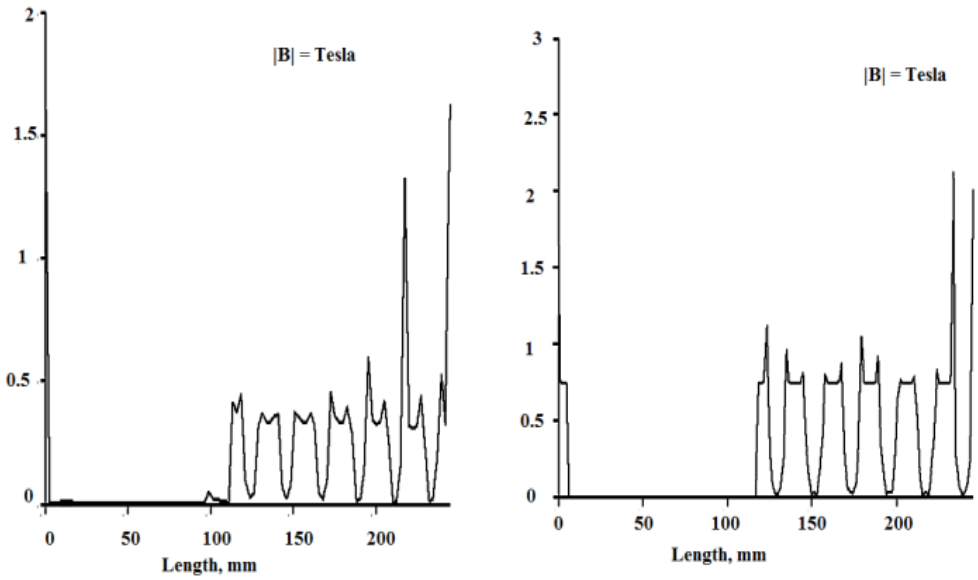

Fig. 9 Magnitude of flux density LIM (HSA and PSO) using FEM

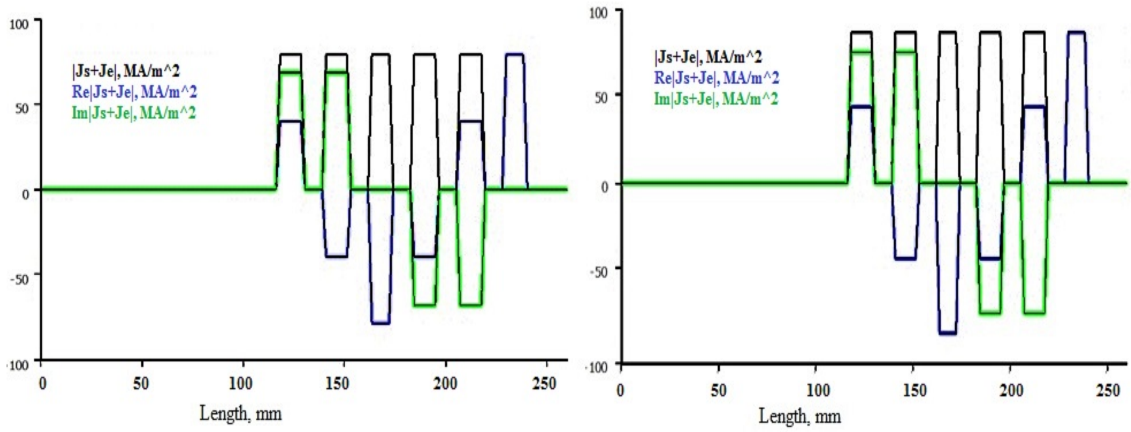

Fig. 10 Eddy current density (J_e) of LIM (HSA and PSO) using FEM

From fig. 7 and fig. 8, the flux lines are localized in front of the LIM and expand behind the LIM due to velocity effect. Fig. 9 and fig. 10 shows, comparison of flux density and eddy current density (J_e) of LIM using FEM.

6. Conclusions

In this paper, multi-objective optimization methods were used for optimized dimensions of a linear induction motor to meet required efficiency and power factor simultaneously. It is observed that, the usage of Genetic algorithm have resulted in an efficiency of 67.9% with a power factor of 13.14% less than the required. The PSO algorithm yielded an efficiency of 68.9% with a power factor of 11.57% less than the required. The usage of HSA resulted in an efficiency of 69.04% and also reached the required power factor. From FEMM analysis, HSA based LIM flux and eddy current density is less when compared to PSO based LIM. Based on the results, we conclude that design of LIM using HSA optimization technique takes less converging time, less number of iterations, desired optimum values to achieve desired efficiency, power factor and high speed.

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