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Optimal Design of Equivalent Linear Induction Motor Based on Taguchi Algorithm and Analysis Using Finite Element Method

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Abstract: Linear Induction motors (LIM) are widely used in industrial applications, especially in linear motion locomotive systems. These applications require high efficiency with good power factor. Mostly LIM suffer from low power factor and less efficiency. Due to this energy consumption is high and also it draws more input current. In this paper, a novel multi objective Taguchi algorithm (TA) is proposed to meet required efficiency and power factor in the design of a Linear Induction Motor. Hence, LIM dimensions can then be optimized by using a TA in an appropriate objective functions. 2-D Finite Element Method is adopted to analyze the flux density in LIM with the parameters obtained using TA. From the results it is observed that the proposed algorithm outperforms the Genetic algorithm (GA) and Particle swarm optimization (PSO) with respect to the power factor and efficiency.

Keywords: Linear Induction motor, dynamical model, Taguchi Algorithm, FEM analysis.

1. Introduction

Linear Induction motor is a special conventional rotary motor that is in use to achieve rectilinear motion rather than rotational motion. Linear Induction Motors are usually preferred for achieving linear propulsion in variety of applications due to easy maintenance, high acceleration or deceleration and produce a direct thrust without any conversion of energy. This increases efficiency, the useful life of the system and reduces maintenance costs [1]. Dr. Luciano Martins Neto [2] developed a linear induction motor phase parameter through the process of obtaining voltage and currents at the machine terminals experimentally using determination method. K. Davey [3] proposed Pulsed linear induction motors in Maglev applications to eliminate low power factor, power transfer, smaller end winding overhang, and simpler electronics.

Hofmann [4] investigated applications of a linear induction machine in railways with different coil and slot geometries. Due to noncontact operation and quick response a LIM employed experimentally in steel making plant, electromagnetic force applications to obtain high quality and high productivity in Fujisaki [5]. J.R. Wells [6] presented a linear induction motor design and mount system that are suitable for integration into an educational laboratory. Junha Kim [7] developed constrained optimization technique to reduce the attractive force and power loss strategy in a LIM for personal rapid transit (PRT) systems. H. Amirkhani [8] proposed PC based thrust estimating algorithm for LIM to control thrust, flux and also to eliminate the system from the speed measuring equipment. Haruo Noma [9] designed a digital Proactive desk with Haptic feedback to improve performance of single sided LIM and also to generate a force of more than 10 N in any direction. T.C.O. Connell [10] re-explores first-principles LIM design by implementing continuum electromechanical models.

Jianqiang Liu [11] developed loss minimize control algorithm to reduce the total copper and iron losses in variable speed and/or thrust force LIM drive by considering the end effect and attraction force. Renato Crivellari [12] discussed influence of End Effect on design parameters of Linear Induction Motor. Nilanjan Chakraborty [13] proposed dual interior point algorithm (IPA) to solve exact distance computation between convex linearly translating objects. V.P. Sakthivel, et [14] suggested multi objective PSO technique to estimate the steady-state

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equivalent circuit parameters from the IM performance characteristics. Ai-min Liu [15] established the mathematical model of multi-objective PSO algorithm based on the grain of subgroup algorithm. A. Shri [16] introduced genetic algorithm (GA) to maximize efficiency, power factor and also to reduce primary weight and end effect braking force for a LIM.

Victor G. Lopez [17] developed a discrete-time inverse optimal control to a three-phase LIM in order to meet required tracking position and also PSO is employed to improve identification and control performance. Hamid Yaghoubi [18] explained the importance of maglev transportation system in future and also designed LIM for electromagnetic aircraft launch system. Jean Thomas [19] proposed PSO to solve nonlinear and non-convex optimization problems by neglecting output and states constraints. Hasan Ravanji [20] investigated design of a ladder-type single-sided linear induction motor for various electrical machine tool applications. Hsin-Han Chiang [21] developed System on programmable chip (SoPC) based an optimized adaptive tracking control system for a LIM drive by considering unknown end effects, payload and uncertainties including the friction force. Yifei Hu [22] proposed preliminary Geometric analytical design to LIM drive under constrained conditions. Abdelkrim Sellam [26] proposed multi-machine approach to design Vector model based PMSM. Generally, the evolutionary algorithms like IPA, GA, PSO will suffer from selection of parameters and inertia weight. Due to this they take large number of iterations and more convergence time. The proposed method overcomes the short comings of above algorithms.

In this paper, section 2 presents equivalent circuit of LIM, section 3 explains Identification of LIM parameters using Taguchi method, section 4 analyze dynamical model of LIM, section 5 presents analysis of LIM using FEM based on TA and section 6 concludes the computer simulations results.

2. Equivalent Circuit model of LIM

Figure 1 shows the architecture of the LIM. LIM primary side is made-up of steel cores and secondary side made-up of the combination of aluminum sheets (nonmagnetic conductors) and back irons (magnetic conductors). An approximate equivalent circuit is used for the design analysis of desired speed flat LIM [25]. For finding the resistance of conducting sheet of secondary, the concept of surface resistivity is useful. Figure. 2 shows the approximate equivalent circuit of a LIM.

$$R_s = \frac{\rho_w l_w}{A_{wt}} \tag{1}$$

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

$$X_m = \frac{24 \mu_0 \pi f w_{se} K_w N_1^2 \tau}{\pi^2 p g_e} \tag{3}$$

$$R_r = \frac{X_m}{G} \tag{4}$$

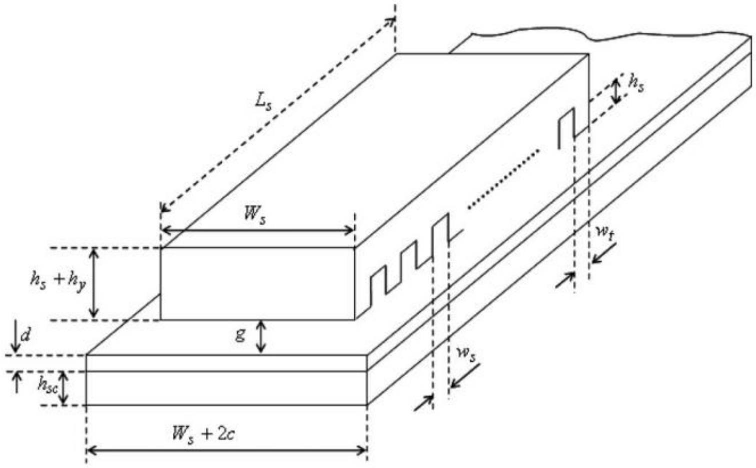

Figure 1. Architecture of a single sided LIM.

$$G = \frac{2\mu_0 f_1 \tau^2}{\pi\left(\frac{\rho_r}{d}\right) g_e} \tag{5}$$

$$F_s = \frac{m I_1^2 R_r}{\left[\frac{1}{(sG)^2} + 1\right] s V_s} \tag{6}$$

$$\eta = \frac{F_s 2\tau f_1 (1 - s)}{F_s 2\tau f_1 + 3 I^2 R_1} \tag{7}$$

$$\cos\phi = \frac{F_s 2\tau f_1 + 3 I^2 R_1}{3VI} \tag{8}$$

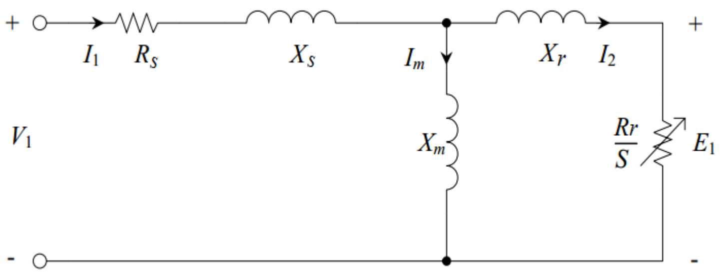

Figure 2. Equivalent circuit of a LIM.

Where, ρ_w is the copper wire volume resistivity used in the stator winding, l_w is the length of the copper wire per phase, A_{wt} is the cross sectional area of the wire, λ_s is the slot permeance, λ_d differential permeance, k_p is the pitch factor, λ_e end connection permeance, 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.

3. Identification of LIM parameters using TAGUCHI

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 (s), pole pitch (τ), aluminium thickness (d) and primary current density (J). 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. (9)

$$F_n(x_1,x_2, x_3,x_4) = \eta(s, \tau, d, J)^{k1}.p_f(s, \tau, d, J)^{k2} \tag{9}$$

As seen in Eq. (9), 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.

Table 1. Design variables of optimization problem

Parameter	units	Max.	Min.
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 ($p.f.$)	---	0.7	--

Taguchi Method is an optimization algorithm developed by Wei Chung Weng, et.al., 2007 [23]. Taguchi method is an advanced novel approach based on the orthogonal array (OA) concept and that can rapidly optimize the varying factors to meet desired specifications with degrees of freedom. Since TA is an effective analysis technique to find out the dominant control factor and its associated level, which significantly affect the experimental results. Figure 3 shows the flow chart of TA. Steps involved in the process of TA are as follows:

Step 1: Identify s, τ, d, J parameters affecting the system operation.
Step 2: Initialize the Orthogonal Array (OA) table according to the parameters.
Step 3: Define input parameters data from OA
Step 4: Define objective functions i.e., fitness functions

$$F_1= \eta(s, \tau, d, J) = \eta(x_1, x_2, x_3, x_4) \text{ and } F_2 = pf(s, \tau, d, J) = pf(x_1, x_2, x_3, x_4) \tag{10}$$

Step 5: Obtain the Matrix experiment and define its range.

$$(N_{ij})_{higher} = \frac{x_{ij} - (x_{ij})_{min}}{(x_{ij})_{max} - (x_{ij})_{min}} \tag{11}$$

$$(N_{ij})_{lowerr} = \frac{(x_{ij})_{max} - x_{ij}}{(x_{ij})_{max} - (x_{ij})_{min}} \tag{12}$$

Where, N_{ij} = Normalized values; $(x_{ij})_{max}$ = maximum value of response parameter; $(x_{ij})_{min}$ = minimum value of response parameter and x_{ij} = Value of response of i^{th} column and j^{th} row of design matrix.

Step 6: Convert the fitness value in to SN Ratio using best experiment in db i.e., $\mathcal{F}_{db} = -20\log_{10}(\textit{fitness function})$ (13)

Step 7: Check the stopping criteria and convergence, if it is satisfied goto step 11.
Step 8: Create variance response table by averaging the SN ratios for each parameter and each level

$$m = \frac{1}{n}\sum_{j=1}^{n} \mathcal{F}_{db} \tag{14}$$

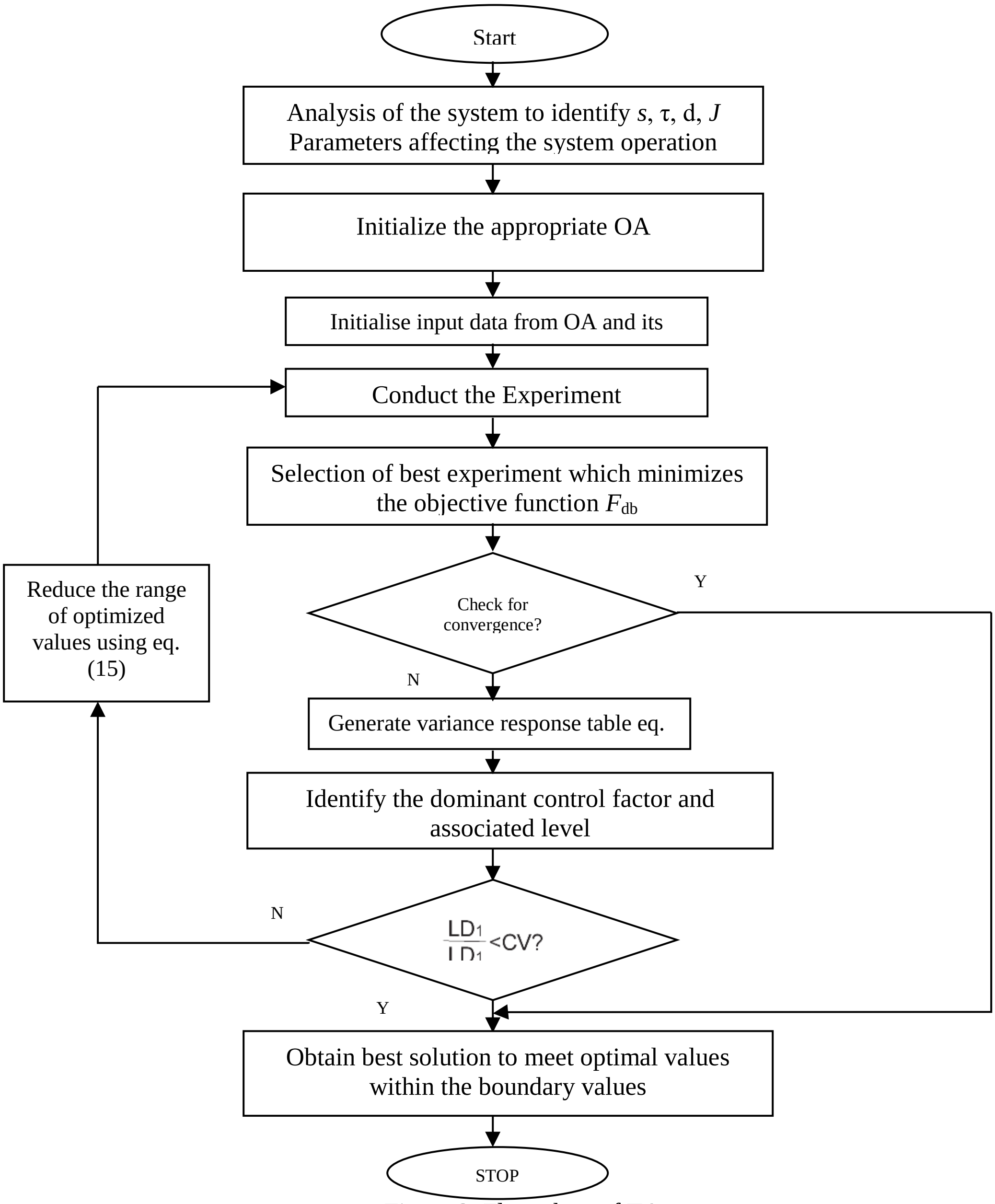

Figure 3. Flow chart of TA.

Step 9: Identify the dominant control factor and associated level according to the variance table and Conduct Confirmation Experiment.
Step 10: Check the stopping criteria and convergence, if it is not satisfied reduce the range of optimized values and then goto step 5.

$$RR(i) = \frac{Level\ Difference\ in\ (i+1)^{th}\ iteration}{1^{st} Level\ Difference} = \frac{LD_{i+1}}{LD_1} \qquad (15)$$

Step 11: Find the best solution to obtain the optimal values within the constraints.
Step 12: Stop

Table 2. Comparison of various optimization results

Method	*s*	τ	d	*J*	η	*p.f.*	t_c
IPA [13]	0.13	48.2463	4.9955	2.0154	0.658	0.551	14
GA [16]	0.1495	48.0000	4.8000	2.1000	0.67959	0.608	8.165
PSO [19]	0.1495	48.0671	4.8019	2.1000	0.68968	0.619	4.239
TA	0.1032	40.0	5.1	1.8000	0.7	0.6989	1.473

Table 2 shows, the comparison of optimized motor dimensions using Interior Point algorithm (IPA), genetic algorithm (GA), Particle Swarm Optimization (PSO) and Taguchi Algorithm (TA). From the table it is observed that the proposed method gives better optimum design parameters and hence improves the power factor and efficiency with less convergence time compared to other methods.

4. Dynamic Modeling of LIM

The dynamic model of the LIM can be expressed in the synchronously rotating frame. The dynamic model of the 3-phase star connected LIM can be described by the following differential equations [25].

$$\frac{di_{ds}}{dt} = \frac{1}{\sigma L_s}\left(-\left(R_s + \left(\frac{L_m}{L_r}\right)^2 R_r\right) i_{ds} + \sigma L_s \frac{\pi}{\tau} v_e i_{qs} + \frac{L_m R_r}{L_r^2}\phi_{dr} + \frac{P L_m \pi}{L_r \tau}\phi_{qr} v_r + V_{ds}\right) \qquad (16)$$

$$\frac{di_{qs}}{dt} = \frac{1}{\sigma L_s}\left(-\sigma L_s \frac{\pi}{\tau} v_e i_{ds} - \left(R_s + \left(\frac{L_m}{L_r}\right)^2 R_r\right) i_{qs} - \frac{P L_m \pi}{L_r \tau}\phi_{dr} v_r + \frac{L_m R_r}{L_r^2}\phi_{qr} + V_{qs}\right) \qquad (17)$$

$$\frac{d\phi_{dr}}{dt} = \frac{L_m R_r}{L_r} i_{ds} - \frac{R_r}{L_r}\phi_{dr} + \left(\frac{\pi}{\tau} v_e - P\frac{\pi}{\tau} v_r\right)\phi_{qr} \qquad (18)$$

$$\frac{d\phi_{qr}}{dt} = \frac{L_m R_r}{L_r} i_{qs} - \left(\frac{\pi}{\tau} v_e - P\frac{\pi}{\tau} v_r\right)\phi_{dr} - \frac{R_r}{L_r}\phi_{qr} \qquad (19)$$

$$F_e = K_f\left(\phi_{dr} i_{qs} - \phi_{qr} i_{ds}\right) = M\dot{v}_r + D v_r + F_L \qquad (20)$$

Where v_r is the mover linear velocity; τ is the pole pitch; *P* is the number of pole pairs; φ_{dr} and φ_{qr} be d-axis and q-axis secondary flux; i_{ds} and i_{qs} be d-axis and q-axis primary current; V_{ds} and V_{qs} are d-axis and q-axis primary voltage; 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.
5. Finite Element Analysis for LIM using TA

The validity of the design optimizations greatly depends on the accuracy of the model such as saturation, nonlinearity of materials and etc. Thus, in this section 2-D time stepping FEMM are employed to evaluate the new equivalent circuit LIM model. The optimal designed parameters of LIM are graphically analyzed with respect to flux density distribution, magnetic flux density and eddy current density using finite element analysis. The equation of magnetic field with respect to eddy currents can be written as

$$\nabla \times (\nu \nabla \times A) = J_o + J \tag{21}$$

$$J_e = -\sigma \left(\frac{\partial A}{\partial t} + grad\ \phi \right) \tag{22}$$

$$\nabla \bullet J_o = 0 \tag{23}$$

In FEM, using time-stepping analysis relative moment is measured. The force is produced by a linearly moving magnetic field acting on conductors in the fields are calculated using local virtual work method. Figure. 11 and Figure. 12 shows, the flux density distribution and graphical representation of flux lines in the analyzed LIM, respectively. Figure. 13 and Figure. 14 shows, comparison of flux density and eddy current density (J_e) of LIM.

6. Simulations Results and discussions

The novel optimization TA has been applied to meet required efficiency and power factor in the design of a Linear Induction Motor are shown in Figures. 6 to 10 and FEMM results of LIM has been shown in Figures. 11 to 14.

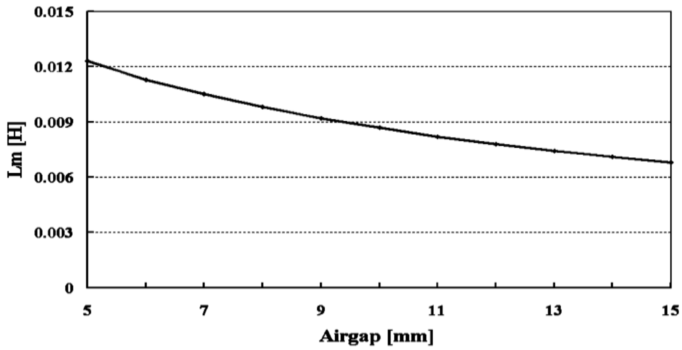

Figure 4. Magnetizing inductance according to variation of the airgap length

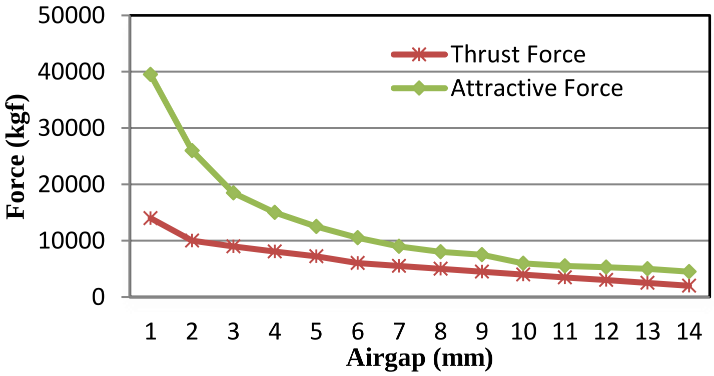

Figure 5. Forces according to variation of the airgap length

From Figure 4 and Figure 5, increase the airgap, increases the leakage flux and reluctance of the magnetic circuit and decreases the magnetizing inductance, attractive and repulsive forces.

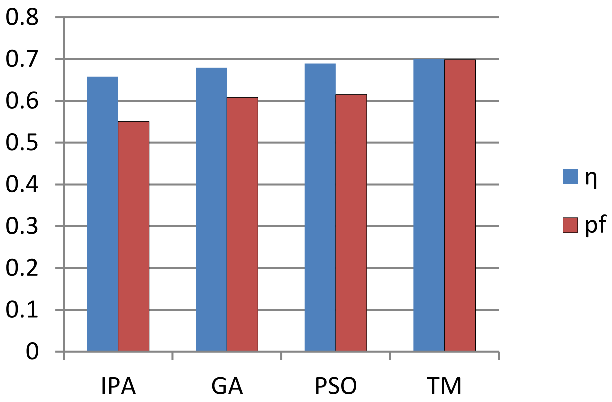

Figure 6. Comparison of efficiency and power factor between various optimization methods

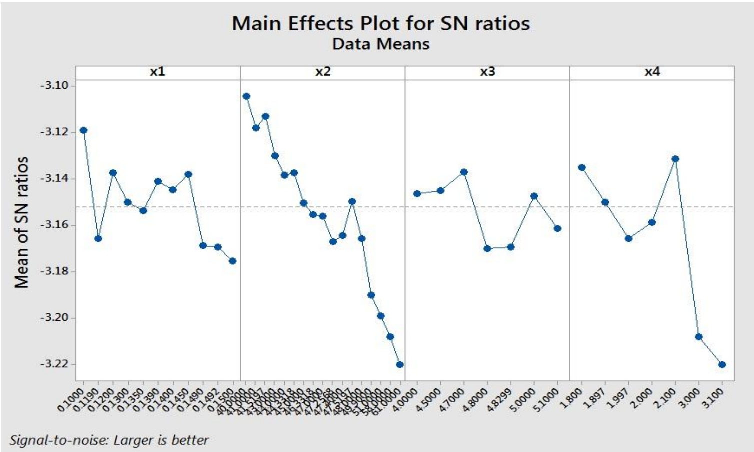

Figure. 7. Mean effects plot for SN Ratio using Taguchi optimization

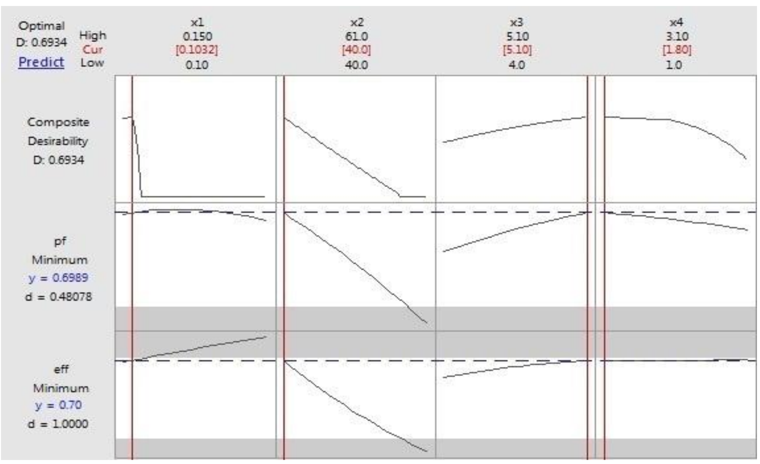

Figure. 8. Taguchi optimization plot

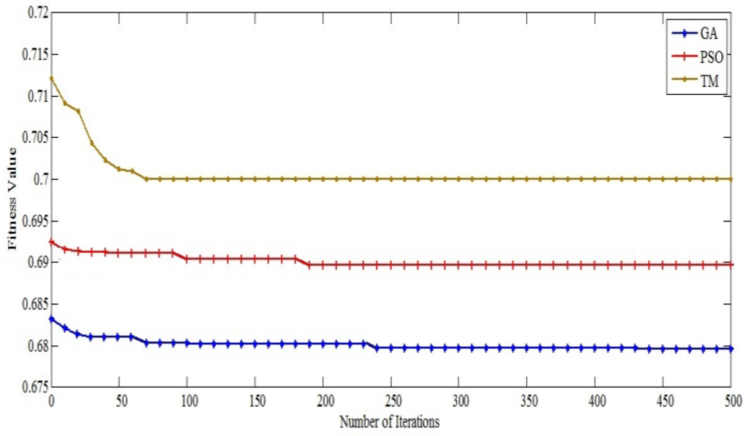

Figure 9. Comparison Fitness functions of different optimization methods

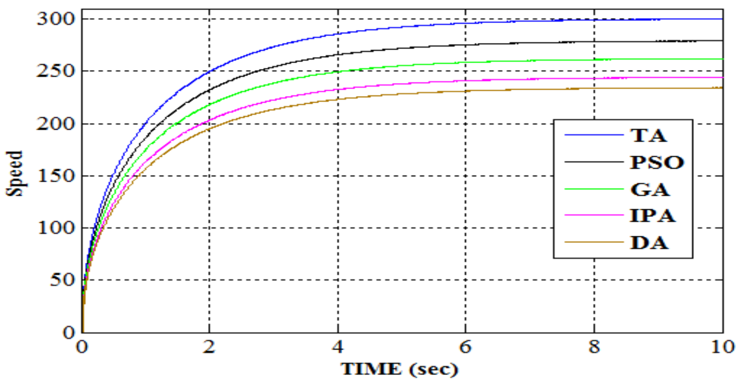

Figure. 10. Comparison of open loop LIM speed for different OPTIMIZATION METHODS

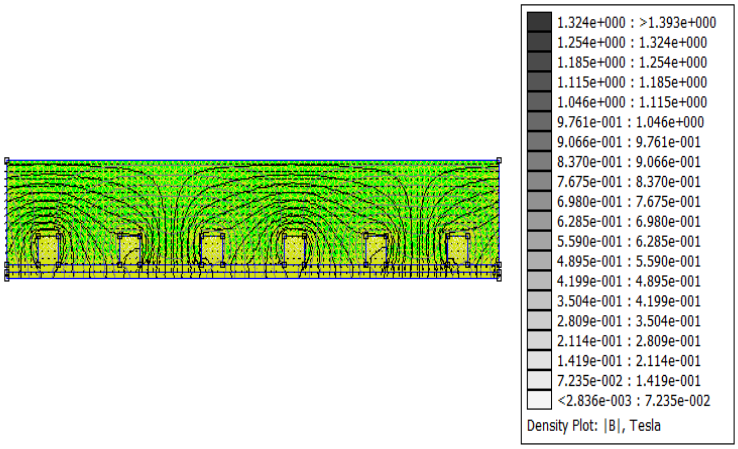

Figure 11. Flux density distribution in the LIM using Taguchi

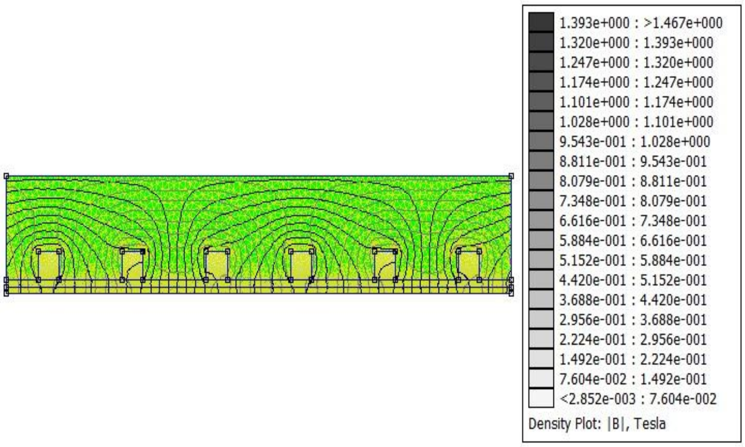

Figure 12. Flux density distribution in the LIM using PSO

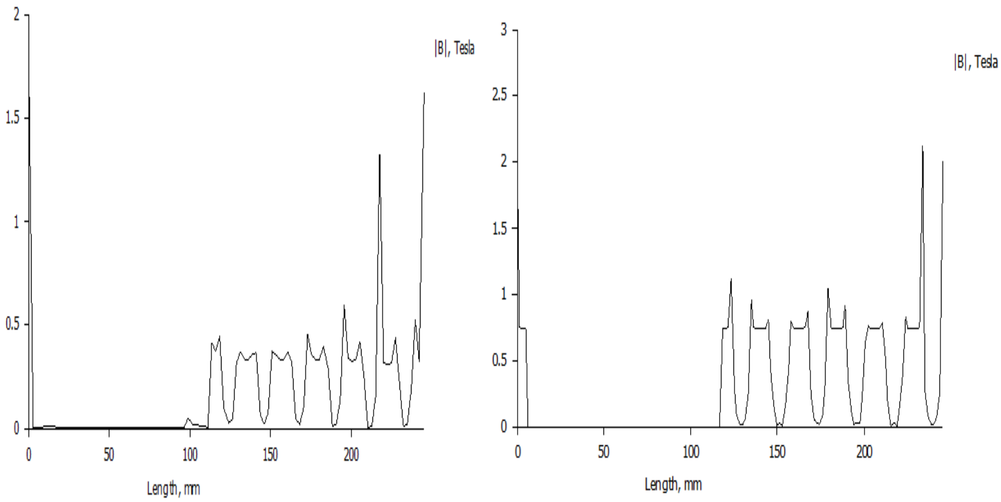

Figure 13. Magnitude of flux density LIM (Taguchi and PSO) using FEM

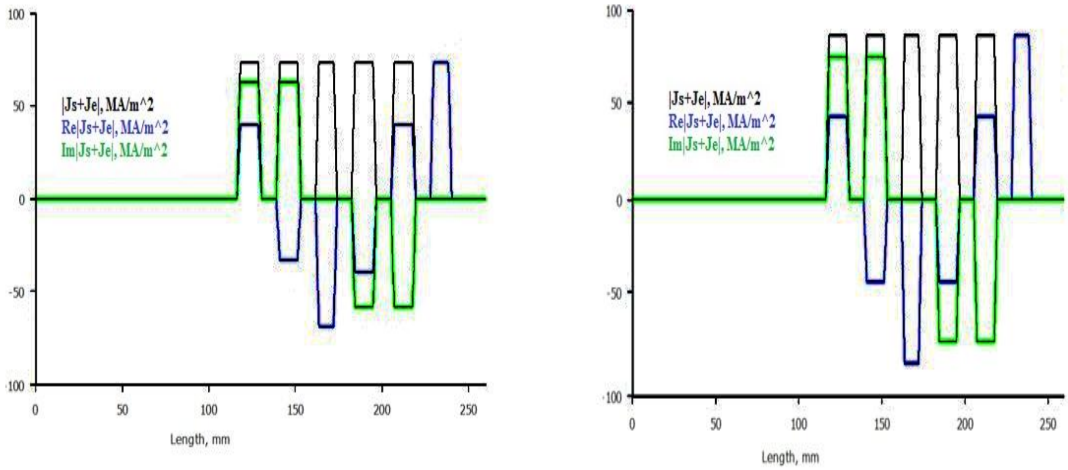

Figure. 14. Eddy current density (J_e) of LIM (Taguchi and PSO) using FEM

From Figure. 11 and Figure. 12, the flux lines are localized in front of the LIM and expand behind the LIM due to velocity effect. Figure. 13 and Figure. 14 shows, comparison of flux density and eddy current density (J_e) of LIM using FEM.

7. Conclusions

In this paper, multi-objective TA optimization method is proposed for optimized dimensions of a linear induction motor to meet the required efficiency and power factor. From the characteristics of proposed method it is observed that less air-gap have a better thrust, efficiency and less excitation current. The effect of parameters of the LIM on efficiency and power factor is observed in SN Ratio plot. Using FEMM with TA based LIM the flux and eddy current density are less when compared to FEMM with PSO based LIM. Based on the results, it can be concluded that design of LIM using TA optimization technique takes less converging time, less number of iterations to achieve desired power factor, efficiency and high speed.

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