









$$\text{i.e., } \bar{F}_{db} = -20\log_{10}(\text{fitness function}) \quad (13)$$

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

$$m = \frac{1}{n} \sum_{j=1}^n \bar{F}_{db} \quad (14)$$

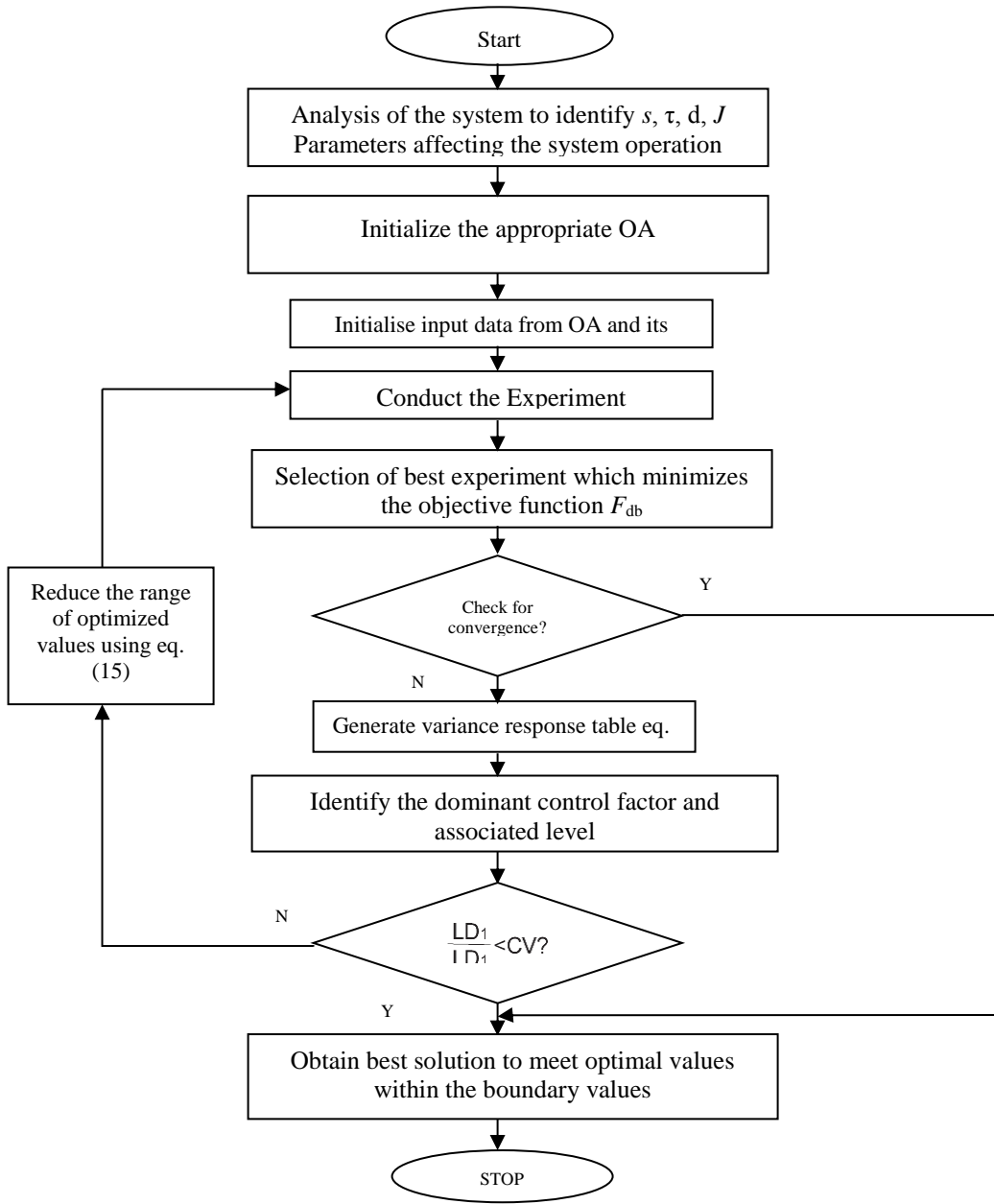


Figure 3. Flow chart of TA.

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.

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

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	$\tau$	d	J	$\eta$	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].

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

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

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

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

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

Where  $v_r$  is the mover linear velocity;  $\tau$  is the pole pitch;  $P$  is the number of pole pairs;  $\phi_{dr}$  and  $\phi_{qr}$  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

$$\nabla \times (\nu \nabla \times A) = J_o + J \quad (21)$$

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

$$\nabla \cdot J_o = 0 \quad (23)$$

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.

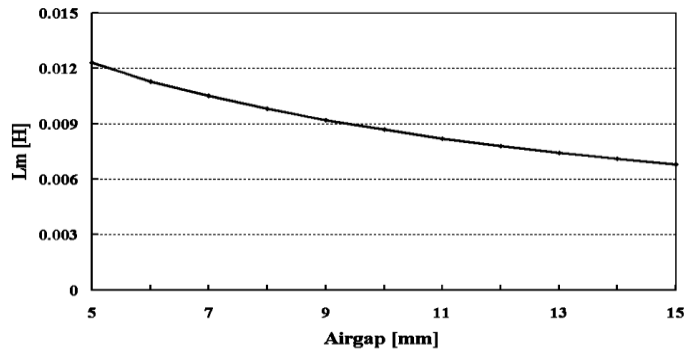


Figure 4. Magnetizing inductance according to variation of the airgap length

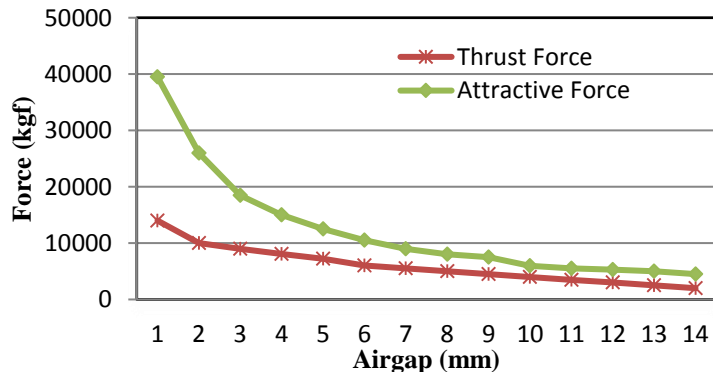


Figure 5. Forces according to variation of the airgap length

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.

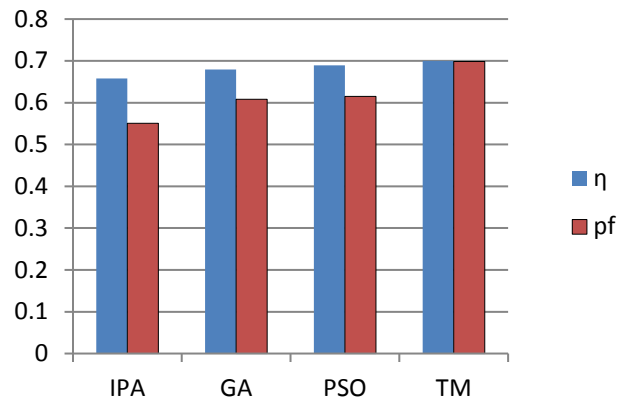


Figure 6. Comparison of efficiency and power factor between various optimization methods

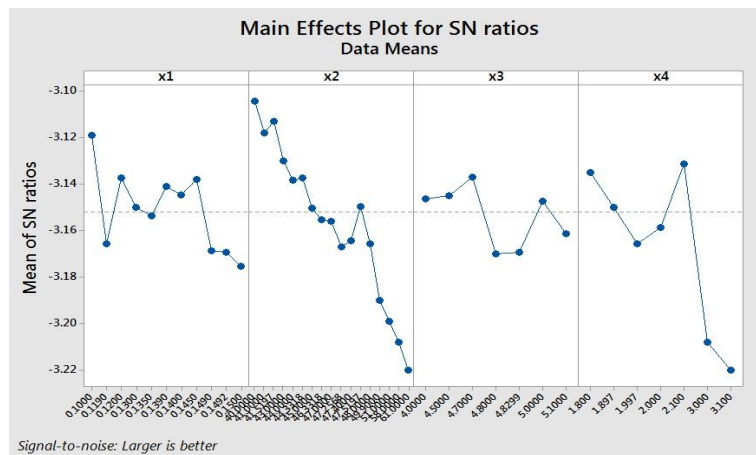


Figure 7. Mean effects plot for SN Ratio using Taguchi optimization

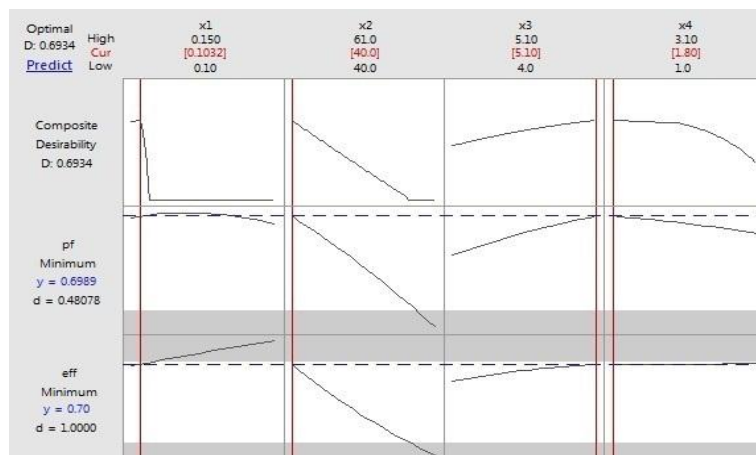


Figure 8. Taguchi optimization plot



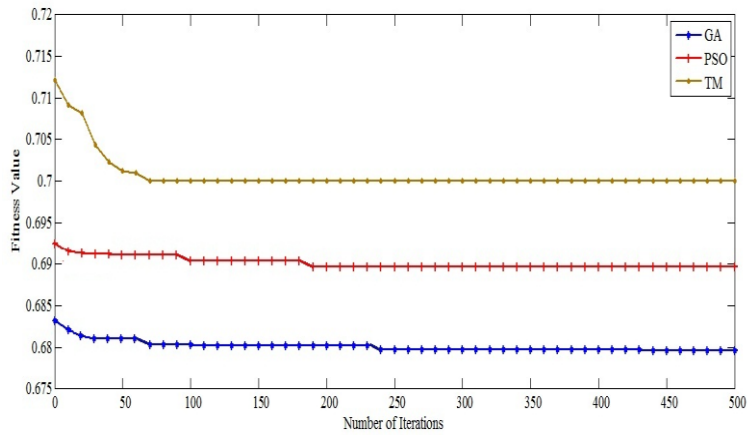


Figure 9. Comparison Fitness functions of different optimization methods

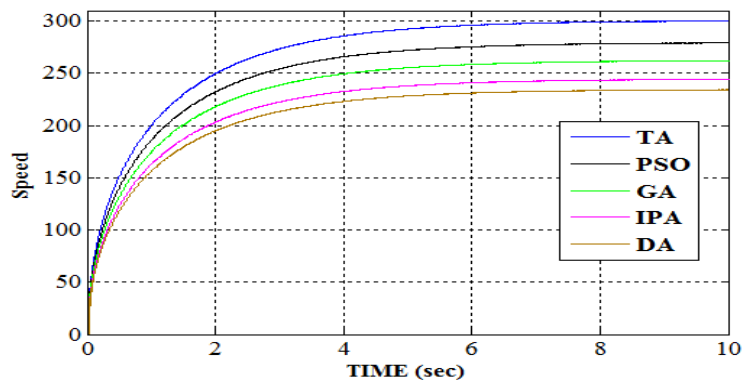


Figure. 10. Comparison of open loop LIM speed for different OPTIMIZATION METHODS

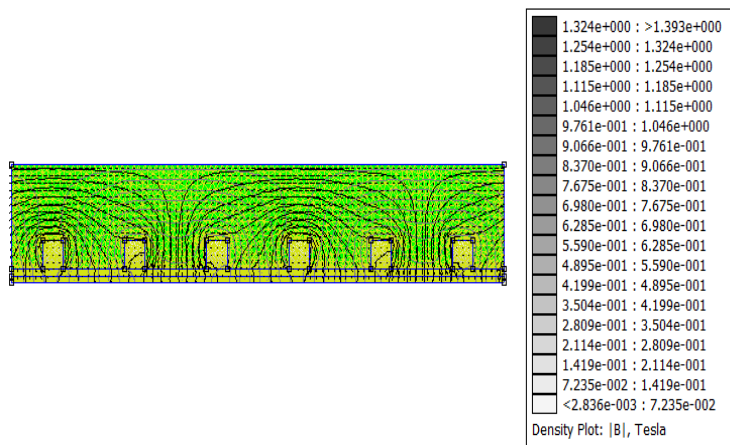


Figure 11. Flux density distribution in the LIM using Taguchi

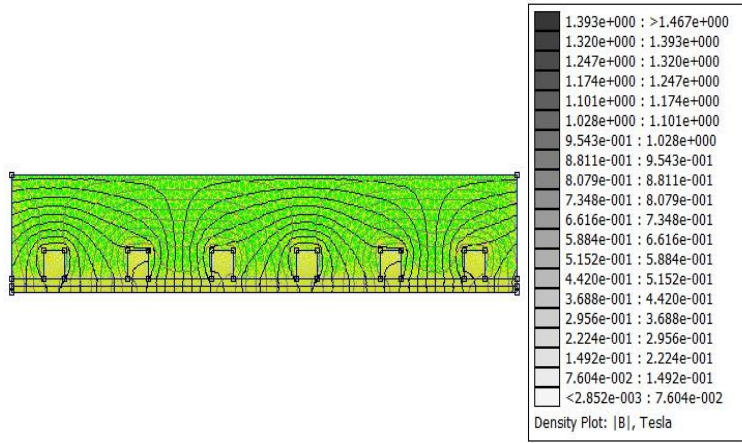


Figure 12. Flux density distribution in the LIM using PSO

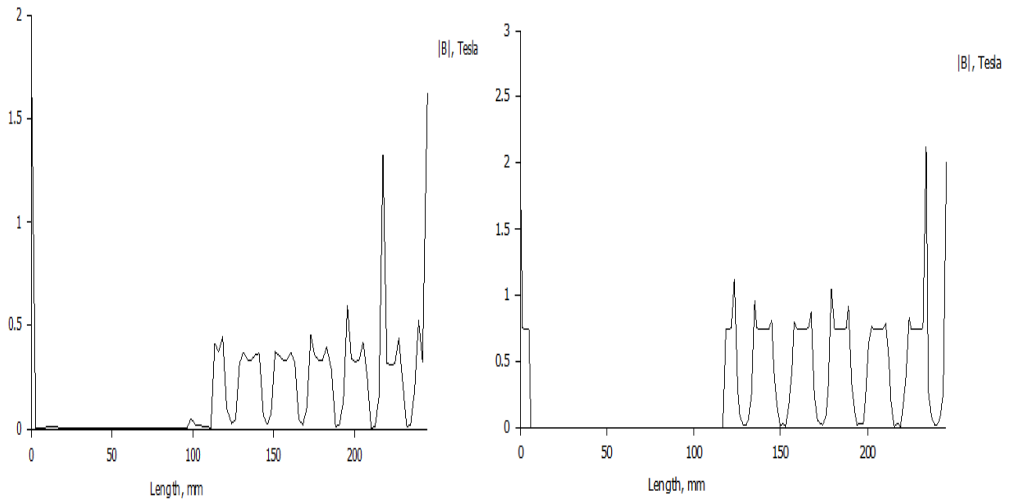


Figure 13. Magnitude of flux density LIM (Taguchi and PSO) using FEM

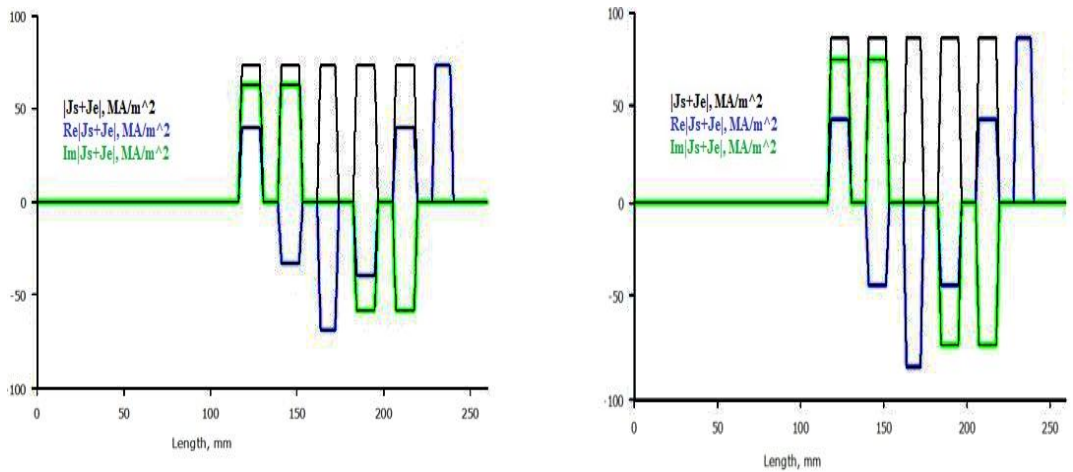


Figure 14. Eddy current density ( $J_e$ ) of LIM (Taguchi and PSO) using FEM

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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