OPTIMAL DESIGN OF EQUIVALENT LINEAR INDUCTION MOTOR BASED ON HARMONY SEARCH ALGORITHM AND ANALYSIS USING FINITE ELEMENT METHOD

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Abstract

Linear Induction motors (LIM) are used extensively in industrial applications to develop linear motion, 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 multi objective Harmony Search optimization algorithm (HSA) 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 HSA in an appropriate objective functions. 2-D Finite Element Method is adopted to analyse the flux density in LIM with the parameters obtained using HSA.

Keywords: FEM analysis, FEMM software, Dynamical model, Harmonic search Algorithm, Linear Induction motor, MATLAB 2013a.
1. Introduction

Linear Induction motor (LIM) is 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, etc., [1] due to easy maintenance, high acceleration/deceleration and no need of transformation system from rotary to translational motion.


Isfahani et al. [7] proposed a multi-objective genetic algorithm optimization method to improve both motor power factor and efficiency. Also analysed the effect of parameters on power factor and efficiency. Liu et al. [8] discussed on a Neighborhood Topology algorithm (NTA) to maintain high starting thrust and high reliability for high-voltage circuit breaker. Bousserhane et al. [9] intended an Adaptive Backstepping controller for LIM to achieve a position and flux tracking objective under disturbance of load torque and parameter uncertainties. Ravanji and Nasiri-Gheidari [10] proposed multi objective genetic algorithm (GA) to design equivalent single sided LIM for machine tool applications and also analysed the obtained parameter values using a 2-D finite-element method.


This paper is organized as follows; Section 2 describes Equivalent Circuit, Section 3 describes Identification of LIM parameters using HSA, Section 4 describes the dynamical model of LIM, Section 5 describes FEM Analysis for LIM and Section 6 describes the computer simulations results.
2. Machine Modelling

Figure 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].

**Fig. 1. Architecture of a single sided LIM.**

**Equivalent Circuit model of LIM**

In 1983, Duncan implemented the equivalent circuit model of LIM. The per-phase equivalent circuit model of SLIM is shown in Fig. 2.

**Fig. 2. Equivalent circuit of a LIM.**

\[
R_s = \frac{\rho}{A_{wl}} \frac{L_w}{l_w} \quad (1)
\]

\[
X_s = \frac{2\mu_0\pi}{p} \left[ \left( \lambda_s \left( 1 + \frac{3}{p} \right) + \lambda_d \right) \frac{W}{q} + \lambda_e I_{ce} \right] N^2 \quad (2)
\]
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\[ \lambda_s = \frac{h_s (1 + 3k_p)}{12w_s} ; \quad \lambda_d = \frac{5 \left( \frac{g_e}{w_s} \right)}{5 + 4 \left( \frac{g_w}{w_s} \right)} \quad \text{and} \quad \lambda_e = 0.3(3k_p - 1) \quad (3) \]

\[ X_m = \frac{24 \mu_0 \pi f s e K_w N_1^2 \tau}{\pi^2 p g_2} \quad (4) \]

\[ R_r = \frac{X_m}{G} \quad (5) \]

\[ G = \frac{2 \mu_0 f_1 \tau^2}{\pi \left( \frac{p_r}{d} \right) g_e} \quad (6) \]

\[ F_s = \frac{m l_r^2 R_r}{\left[ \frac{1}{(sG)^2 + 1} \right] s V_s} \quad (7) \]

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

\[ \cos \phi = \frac{F_s 2 \tau f_1 + 3 l_r^2 R_1}{3VI} \quad (9) \]

Isfahani et al. [7] 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>
<thead>
<tr>
<th>Parameter</th>
<th>Max.</th>
<th>Min.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum thrust slip (s)</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>Pole Pitch (( \tau ))</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>Aluminium thickness</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Primary current Density</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Efficiency (( \eta ))</td>
<td>0.7</td>
<td>--</td>
</tr>
<tr>
<td>Power Factor</td>
<td>0.7</td>
<td>--</td>
</tr>
</tbody>
</table>
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, the 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. (10)

\[
f_{n}(x_1, x_2, x_3, x_4) = \eta(s, \tau, d, J)k_1, p_f(s, \tau, d, J)k_2
\]  

(10)

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 Wang et al. in 2015 [19], Fig. 3. 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:

i. Assign the number of parameters to be identified for a LIM.

ii. Initialize the HSA parameters such as HM, HMCR, PAR, BW and maximum number of iterations for convergence (shown in Table 2).

iii. Define the multi objective function as

\[
f_1 = \eta(s, \tau, d, J) = \eta(x_1, x_2, x_3, x_4) \\
f_2 = p_f(s, \tau, d, J) = p_f(x_1, x_2, x_3, x_4)
\]  

(11)

iv. Defined the range of \( s, \tau, d \) and \( J \) values for the function variables.

v. Obtain functional value of initial Harmony memory.

vi. Set iteration counter \( t=0. \)

vii. Increment the iteration counter \( t=t+1. \)

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

\[
x_{\text{new}} = x_{\text{old}} + \text{rand}(0,1) \ast BW
\]  

(12)

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

\[
x_{\text{new}} = x_{\text{old}} + BW \ast (\text{rand} - 0.5)
\]  

(13)

i. Update the HM of objective function and replace the worst solution with new better solution.

ii. Check the stopping criteria and convergence, i.e., number of iteration> maximum iteration, if it is satisfied go to step (xii).

iii. Perform for new Harmony, i.e., increase the iteration count and go to step (vii).
iv. Find the best harmony from the HM, i.e., the optimal values within the constraints.

v. Stop.

![Flowchart of HSA](image)

Table 2. Parameters of harmony search algorithm.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harmony Memory Size</td>
<td>10</td>
</tr>
<tr>
<td>Harmony Memory Acceptance rate</td>
<td>0.9</td>
</tr>
<tr>
<td>Pitch Adjustment Rate</td>
<td>0.5</td>
</tr>
<tr>
<td>Band Width</td>
<td>randomly</td>
</tr>
</tbody>
</table>

Table 2 describes the parameters of HSA. From Table 3 it is observed that the proposed HSA method shows better results with respect to maximum thrust slip (s), pole pitch (τ), aluminium thickness (d) and primary current density (J).
4. Dynamical Modelling of LIM

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

\[
\begin{align*}
\frac{d\phi_{dr}}{dt} &= \frac{L_m R_f}{L_f} i_{ds} - \frac{R_f}{L_f} \phi_{dr} + \left( \frac{\pi}{\tau} v_e - P \frac{\pi}{\tau} v_r \right) \phi_{qr} - R_f \frac{R_f}{L_f} \phi_{qr} \\
\frac{d\phi_{qr}}{dt} &= \frac{L_m R_f}{L_f} i_{qs} - \left( \frac{\pi}{\tau} v_e - P \frac{\pi}{\tau} v_r \right) \phi_{dr} - R_f \frac{R_f}{L_f} \phi_{qr} \\
F_e &= K_f \left( \phi_{dr} i_{qs} - \phi_{qr} i_{ds} \right) = M v_r + D v_r + F_L
\end{align*}
\]

5. Finite Element Analysis for LIM using GA 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, 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

\[
\nabla \times (\nabla \times A) = J_o + J \\
J_e = -\sigma \left( \frac{\partial A}{\partial t} + \text{grad}\ \phi \right) \\
\nabla \cdot J_o = 0
\]

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.
6. Simulations Results and discussions

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.

From Fig. 4, Interior Point algorithm results are worse than remaining optimization methods, Intelligent simulated Annealing optimization have 66.95% with a power factor of 13.86% less than required, Genetic algorithm have 67.9% efficiency but power factor is 13.14% less than the 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 ISA, GA methods. Figure 6 shows HSA can produce higher speed as compared to other optimization methods.

Figures 7 and 8 show the density of flux distribution and analysis of LIM graphical flux lines representation, respectively. Figures 9 and 10 shows, comparison of flux density and eddy current density ($J_e$) of LIM. From Figs. 7 and 8, the flux lines are localized in front of the LIM and expand behind the LIM due to velocity effect. Figures 9 and 10 show comparison of flux density and eddy current density ($J_e$) of LIM using FEM.
Fig. 6. Comparison of open loop LIM speed for different optimization methods.

Fig. 7. Flux density distribution in the LIM using HSA.

Fig. 8. Flux density distribution in the LIM using GA.
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Fig. 9. Comparison Magnitude of flux density in LIM using FEM.

(a) HSA method.  (b) GA method.

Fig. 10. Eddy current density ($J_e$) in LIM using FEM.

(a) HSA method.  (b) GA method.

7. 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. From Table 3, the maximum thrust slip raises the power factor and efficiency. Increase in the primary width to pole pitch ratio leads to an increase in the power factor and a reduction in the efficiency. If the aluminum thickness decreases then efficiency and the power factor values increases. Current density increases the power factor and reduces the efficiency of LIM. From Fig. 4, the usage of intelligent simulated Annealing algorithm have resulted in an efficiency of 66.95% with a power factor of 13.86% less than the required. The GA algorithm yielded an efficiency of 67.9% with a power factor of 13.14% less than the required. The usage of HSA...
resulted in an efficiency of 69.14% and also reached the required power factor. From FEMM analysis, HSA based LIM flux and eddy current density is less when compared to GA based LIM, which implies HSA based LIM, consumes less energy and has less input current. 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.

<table>
<thead>
<tr>
<th>Nomenclatures</th>
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<td>$A_{wt}$</td>
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<td>$d$</td>
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<td>$F_e$</td>
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<table>
<thead>
<tr>
<th>Greek Symbols</th>
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<tbody>
<tr>
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<td>$\phi_{d}$</td>
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<tr>
<td>$\phi_{q}$</td>
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<tr>
<td>$\eta$</td>
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<tr>
<td>$\lambda_d$</td>
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<tr>
<td>$\lambda_e$</td>
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</table>
\( \lambda_s \) Slot permeance
\( \rho_r \) Volume resistivity of the rotor conductor outer layer, \( \Omega \cdot \text{m} \)
\( \rho_w \) Copper wire volume resistivity, \( \Omega \cdot \text{m} \)
\( \tau \) Pole pitch, m

**Abbreviations**
- COA: Cuckoo optimization Algorithm
- FEM: Finite Element Method
- GA: Genetic Algorithm
- HM: Harmony memory
- HMCR: Harmony memory considering rate
- HSA: Harmony Search Algorithm
- ICA: Imperialist competitive Algorithm
- IPA: Interior Point Algorithm
- ISA: Intelligent simulated Annealing
- LIM: Linear Induction Motor
- NTA: Neighborhood Topology Algorithm
- PAR: Pitch adjusting rate

**References**


