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.


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.
\[ F_S = \frac{\frac{m l^2 R_r}{\tau f_1^2}}{s V_S} \left[ \frac{1}{(s g)^2} + 1 \right] \]  \hspace{1cm} (7)

\[ \eta = \frac{F_2 \tau f_1 (1-s)}{F_2 \tau f_1^2 + 3l^2 R_i} \]  \hspace{1cm} (8)

\[ \cos \phi = \frac{F_2 \tau f_1 + 3l^2 R_i}{3V_I} \]  \hspace{1cm} (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   | \( s \) | --     | 0.1        | 0.3       |
| Pole Pitch       | \( \tau \) | mm    | 40         | 60        |
| Aluminium        | d      | mm    | 3          | 6         |
| Primary current  | \( J \) | A/mm² | 1          | 3         |
| Density          | \( \eta \) | --    | 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]

\[
\frac{d}{d t} \left( \begin{array}{c}
R_s + \frac{l_m}{l'_r} R_r \\
R_r
\end{array} \right) i_d + \left( \begin{array}{c}
\sigma l_s \frac{\pi}{\tau} v_e i_q s + \frac{l_m}{l'_r} R_r \phi d r \\
\frac{P l m \pi}{L_r \tau} \phi q r \nu r + V_d s
\end{array} \right)
\]  \hspace{1cm} (10)
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, aluminum thickness and primary current density. The design variables and constraints are as listed in Table 1. To obtain required efficiency and power factor, choose \( k_1=0, k_2=1 \) and \( \eta=0.5 \) when power factor is more important, choose \( k_1=1, k_2=0 \). By considering \( k_1=k_2=1 \), optimized simultaneously to meet desired efficiency and power factor.

Identification of LIM parameters using HSA

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

\[
f_1 = \eta(s, \tau, d, J) = \eta(x_1, x_2, x_3, x_4) \quad \text{and} \quad f_2 = p(s, \tau, d, J) = p(x_1, x_2, x_3, x_4) \quad \ldots \quad (16)
\]

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 \( > \text{HMCR} \). Then select the value of parameter randomly as,

\[
x_{\text{new}} = x_{\text{old}} + \text{rand}(0,1) \times \text{BW} \quad \ldots \quad (17)
\]

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

\[
x_{\text{new}} = x_{\text{old}} + \text{BW} \times \text{rand} - 0.5 \quad . \quad \ldots \quad (18)
\]

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

<table>
<thead>
<tr>
<th>Method</th>
<th>Slip</th>
<th>Pole pitch (mm)</th>
<th>d (mm)</th>
<th>J (A/mm²)</th>
<th>H</th>
<th>p.f.</th>
<th>Convergence time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interior Point algorithm (IPA)</td>
<td>0.13</td>
<td>48.2463</td>
<td>4.9955</td>
<td>2.0154</td>
<td>0.658</td>
<td>0.551</td>
<td>14</td>
</tr>
<tr>
<td>Genetic Algorithm (GA)</td>
<td>0.1495</td>
<td>48.0000</td>
<td>4.8000</td>
<td>2.1000</td>
<td>0.67959</td>
<td>0.608</td>
<td>8.165</td>
</tr>
<tr>
<td>Particle Swarm Optimization (PSO)</td>
<td>0.1495</td>
<td>48.0671</td>
<td>4.8019</td>
<td>2.1000</td>
<td>0.68968</td>
<td>0.619</td>
<td>4.239</td>
</tr>
<tr>
<td>Harmony Search Algorithm (HSA)</td>
<td>0.14</td>
<td>40.3998</td>
<td>4.0</td>
<td>2.1</td>
<td>0.69037</td>
<td>0.698</td>
<td>2.148</td>
</tr>
</tbody>
</table>

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

$$\nabla \times (\mu \nabla \times A) = J_0 + J_e$$

(19)
\[ J_e = -a \left( \frac{qA}{\dot{q}_t} + \text{grad} \, \varphi \right) \]  \hspace{1cm} (20)

\[ \nabla \cdot J_e = 0 \]  \hspace{1cm} (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.

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
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.

References