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Application of an imperialist competitive algorithm to the design of a linear induction motor

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ABSTRACT

In this paper a novel optimization algorithm based on imperialist competitive algorithm (ICA) is used for the design of a low speed single sided linear induction motor (LIM). This type of motors is used increasingly in industrial process specially in transportation systems. In these applications having high efficiency with high power factor is very important. So in this paper the objective function of design is presented considering both efficiency and power factor. Finally the results of ICA are compared with the ones of genetic algorithm and conventional design. Comparison shows the success of ICA for design of LIMs.

1. Introduction

Linear induction motors (LIMs) are widely used in rapid transportation systems and they obtain thrust directly without gear, link or axial mechanism. LIMs also have many other advantages such as simple structure and easy maintenance.

There is much work on the design of linear induction motors has been reported in [1–4]. Such design of the linear induction motor has been performed based on different drawbacks of it. Two major disadvantages of LIMs are low power factor and low efficiency. But there are not enough works on them.

In [5] optimization is based on some characteristics such as end effect, transverse edge effect and normal force. In this reference sequential quadratic programming (SQP) method is used to optimize output volt–ampere, primary weight and cost of secondary. In [6] optimization is done based on starting thrust and output power to input volt–ampere ratio.

Ref. [7] describes the optimization problem using the finite element method and the sequential unconstrained minimization technique (SUMT). Thrust is taken as an objective function in order to maximize thrust under a constant current drive. In [8] optimization of the stator-winding arrangement for magnetic levitation (Maglev) systems is discussed.

In [9] an optimum design of LIM based on efficiency and power factor as an objective function is discussed. In this reference genetic algorithm is used to optimize the design.

The objective of this paper is to present an optimal design of a low speed single sided linear induction motor using imperialist competitive algorithm. Both power factor and efficiency are chosen as objective function. Proposed method for optimization has some advantages, such as simplicity, accuracy, and time saving. In the comparison with genetic algorithm the results of ICA are more reliable and optimized.

2. Machine model

Fig. 1 shows the topology of the proposed LIM [9]. It consists of a three-phase primary and an aluminum laid sheet on the secondary back iron [9]. A simple equivalent circuit for LIMs is shown in Fig. 2 [9]. The parameters of the equivalent circuit can be obtained as follows [9]:

$$X_m = \frac{12\mu_0\omega_l a_e K_w^2 \tau N_{ph}^2}{\pi^2 p g_{ei}} \tag{1}$$

$$X_1 = \frac{2\mu_0\omega_l}{p} N_{ph}^2 \times \left[\left(\lambda_s\left(1+\frac{3}{2p}\right)+\lambda_d\right)\times\frac{2a}{q}+\lambda_e l_{ce}\right] \tag{2}$$

$$R_1 = \frac{1}{\sigma_c}\left(\frac{4a+2l_{ce}}{N_{ph} I}\right) J_c N_{ph}^2 \tag{3}$$

$$R_2' = \frac{12 a_e K_w^2 N_{ph}^2}{\tau d p \sigma_{ei}} \tag{4}$$

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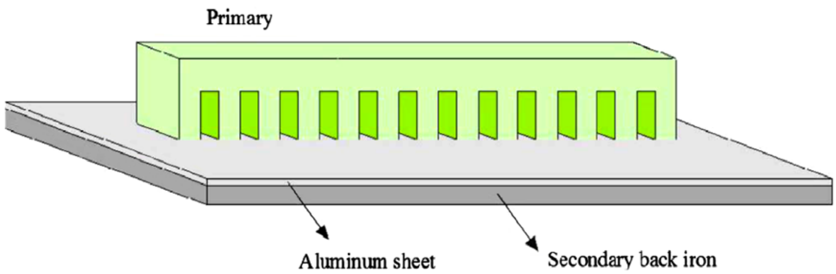

Fig. 1. Topology of a single sided LIM [9].

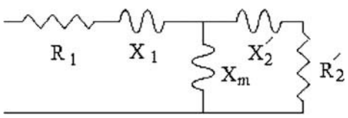

Fig. 2. Equivalent circuit of a LIM [9].

where a is primary width, a_e is effective primary width, d is Al sheet thickness, g_{ei} is modified air gap length, I is primary phase current, J_c is primary winding current density, K_w is primary winding factor, l_{ce} is end connect length, N_{ph} is winding turns number, p is pole pairs number, q is slot per pole per phase, s is slip, μ_0 is air permeability, σ_{ei} is modified aluminum conductivity, σ_c is Cu conductivity and τ is pole pitch.

The goodness factor, one of the most important indicators in design procedure, is then given by [9]:

$$G = \frac{2f_l\mu_0\sigma_{ei}d\tau}{\pi g_{ei}} \quad (5)$$

where f_l is primary frequency. If we keep 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 [9]:

$$F_x = \frac{3I^2R_2'}{2sf_l\tau\left[\left(\frac{1}{sG}\right)^2+1\right]} \quad (6)$$

$$\eta = \frac{F_x2\tau f_l(1-s)}{F_x2\tau f_l + 3I^2R_1} \quad (7)$$

$$\cos\varphi = \frac{F_x2\tau f_l + 3I^2R_1}{3VI} \quad (8)$$

The value of motor parameters is presented in [11]. It is shown in [9] that different parameters have different effect on efficiency and power factor and it is necessary to use an optimization program to achieve an optimal design. In next sections the optimization problem is solved using ICA.

Table 1
Design constrains [9].

Parameter	Symbol	Unit	Minimum value	Maximum value
Maximum thrust slip	s	–	0.1	0.5
Aluminum thickness	d	mm	1	4
Primary width/pole pitch	a/τ	–	0.5	4
Primary current density	J_c	A/mm^2	3	5
Efficiency	η	–	0.35	–
Power factor	$\cos\varphi$	–	0.3	–

3. Optimization problem

Because we want to compare the ability of ICA with genetic algorithm in optimization problems, we choose the same objective function as [9]. In [9] design variables are chosen as the primary winding current density (J_c), the primary width to pole pitch ratio (a/τ), the aluminum sheet thickness (d), and the maximum thrust slip (s). The constraints are as listed in Table 1 which are the same as what considered in [9].

To obtain an optimal design considering both power factor and efficiency, the objective function is defined as follows [9]:

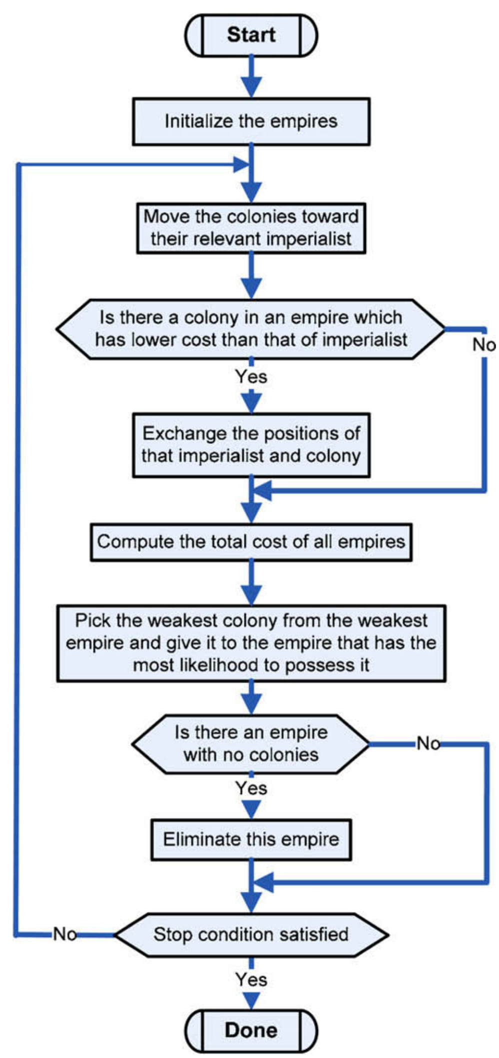

Fig. 3. Flowchart of the imperialist competitive algorithm (ICA) [10].

Table 2
Optimization results and conventional motor parameters.

Parameter	Conventional design [9]	GA [9]			ICA		
		Opt. 1	Opt. 2	Opt. 3	Opt. 1	Opt. 2	Opt. 3
Efficiency	0.36	**0.393**	0.325	**0.327**	**0.4901**	0.4345	**0.4461**
Power factor	0.32	0.3	**0.42**	**0.415**	0.5729	**0.6463**	**0.6295**
Maximum thrust slip	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Aluminum thickness	2	1.4	1.7	1.7	1	1	1
Primary width/pole pitch	2	2.5	3.9	3.9	2	4	4
Primary current density	4	3	5	5	3	5	4.01

Bold values show the objective function of the optimization problem.

$$J_\tau(x_1,\ldots,x_n) = \eta(x_1,\ldots,x_n)^{k_1} \cdot \cos\varphi(x_1,\ldots,x_n)^{k_2} \quad (9)$$

where k_1 and k_2 are constant and $x_1, \ldots, x_n$ are design variables. When efficiency is more important than power factor, we can choose $k_1 = 1$, $k_2 = 0$ and when power factor is more important, these constants will be selected as $k_1 = 0$, $k_2 = 1$. By considering $k_1 = k_2 = 1$ both efficiency and power factor will be optimized simultaneously. These three problems are called optimal 1, optimal 2 and optimal 3, respectively. On the other hand, since in imperialist competitive algorithm the objective function (cost function) will be minimized, the inverse of (9) is regarded as objective function.

As mentioned in [9] the minimum value of the efficiency and power factor is chosen close to their initial values of the non-optimized motor. Therefore, we can be sure that neither the efficiency nor the power factor has been deteriorated.

4. Imperialist competitive algorithm

Imperialist competitive algorithm (ICA) is a new evolutionary algorithm for optimization. This algorithm starts with an initial population. Each population in ICA is called country. Countries are divided in two groups: imperialists and colonies. In this algorithm the more powerful imperialist, have the more colonies. When the competition starts, imperialists attempt to achieve more colonies and the colonies start to move toward their imperialists. So during the competition the powerful imperialists will be improved and the weak ones will be collapsed. At the end just one imperialist will remain. In this stage the position of imperialist and its colonies will be the same. The flowchart of this algorithm is shown in Fig. 3 [10]. More details about this algorithm are presented in [10].

As mentioned before in this optimization problem the objective function is the inverse of (9). Optimization variables are the Al sheet thickness (d), primary winding current density (J_c), slip (s) and primary width to pole pitch ratio (a/τ). The number of countries is 200 and the number of imperialists is 8.

5. Results

Table 2 shows the motor dimensions and characteristics using conventional, genetic algorithm, and ICA design optimization methods. Conventional motor parameters and genetic algorithm search results are given from [9]. Table 2 and Fig. 4 depict that maximum efficiency is obtained in the first optimization process (optimal 1) for both genetic algorithm and ICA. But ICA result is higher than GA one. Furthermore, the maximum of power factor is gained in optimal 2 and also, ICA result is better than GA. In the case of optimal 3, in comparison with conventional design genetic algorithm improved the power factor about 1.3 times. But, it collapses the efficiency about 0.9 times. On the other hand ICA improved both power factor and efficiency about 1.97 and 1.24 times respectively which have considerable increase. It is important to mention that ICA in all optimization problems (optimals 1–3) improved both efficiency and power factor in the comparison with conventional design and of course in each problem the main objective function is much more optimized. Although genetic algorithm in the case of optimal 1 and optimal 2 has improved efficiency and power factor respectively but in each case it has collapsed the other characteristic. For example in optimal design 1 the efficiency has been increased from 36% to 39.5% but power factor has been decreased from 0.32 to 0.3. So ICA is more reliable than genetic algorithm in calculating optimized motor parameters.

Fig. 5 shows the enhancement of objective function during different iterations in these three optimization problems using genetic algorithm [9]. As shown in this figure in the best situation, GA receives to optimal response after 50 generation. The enhancement of these objective functions using imperialist competitive algorithm is shown in Fig. 6. As mentioned before the objective function of ICA is selected as the inverse of GA one and Fig. 6 depicts the mean and minimum cost of all imperialists versus iteration. It shows, the global minimum of the function is found at the first iteration. But in the worse case (optimal design 1) until iteration 5, other imperialists are also in good positions and are able to compete. Then they start to collapse one by one, at iteration 5 only one of them is alive; one that has reached the global minimum sooner (see Fig. 4).

6. Finite-element analysis

In this section 2-D time stepping FEM is employed to validate the optimization results. First, the geometry of the cross section

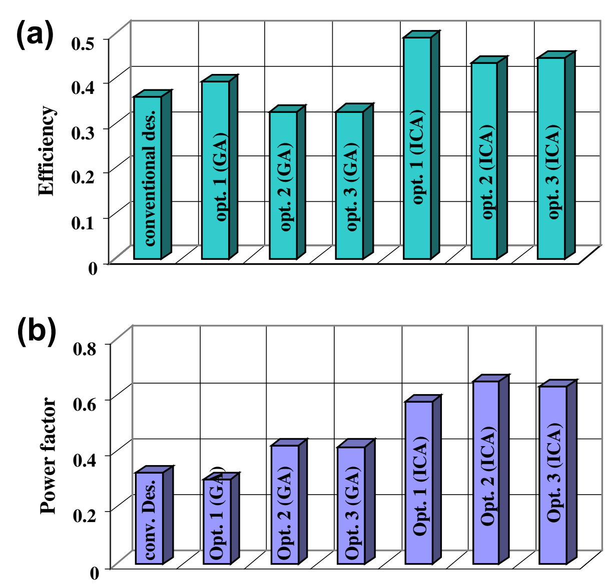

Fig. 4. Comparison of: (a) efficiency and (b) power factor between conventional design, optimal design with genetic algorithm and ICA.

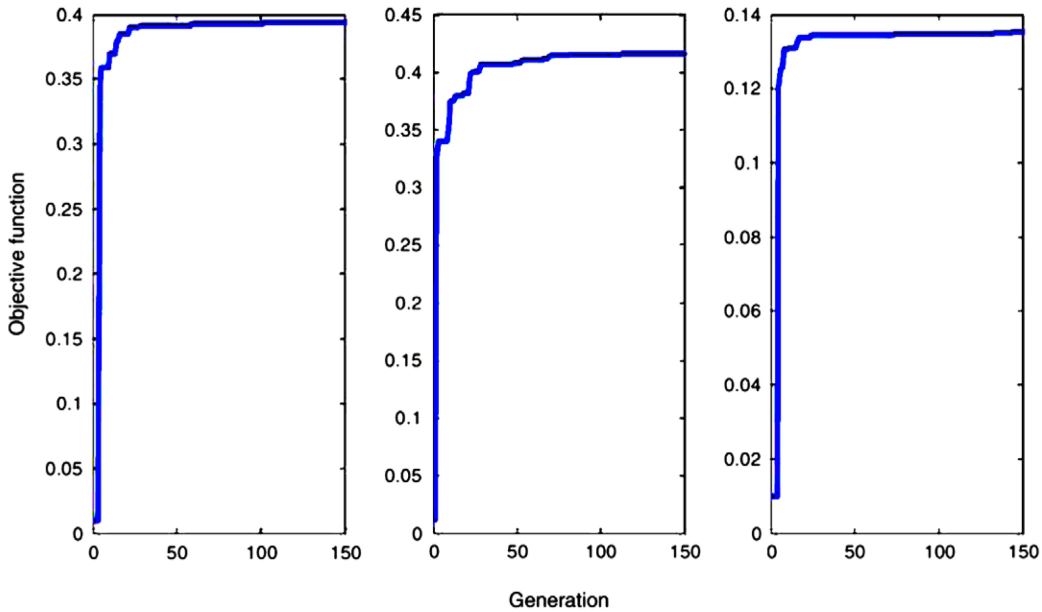

Fig. 5. Improvement of objective function using genetic algorithm (from left to right optimal designs 1, 2 and 3) [9].

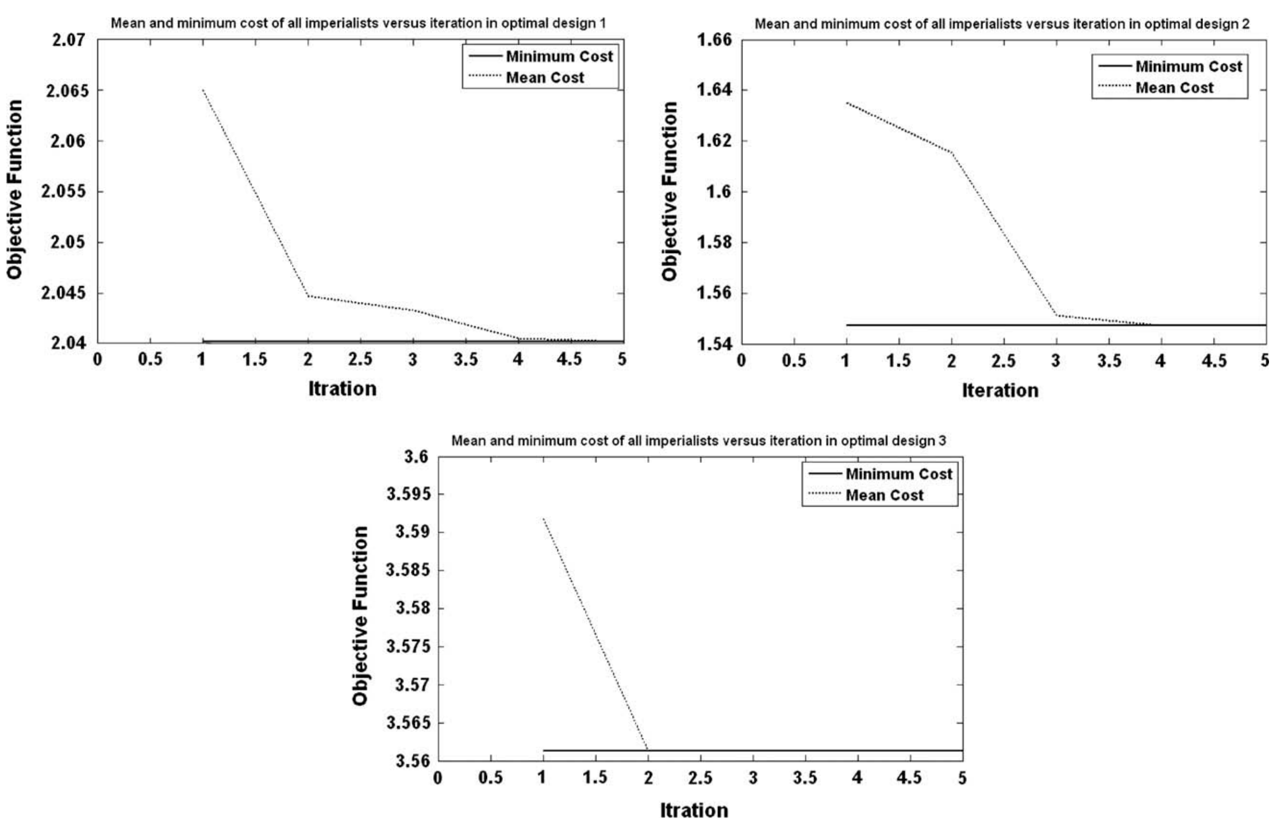

Fig. 6. Mean and minimum cost of all imperialists versus iteration in these three optimization problems.

of the machine is defined. Then the materials of the different sections are assigned and boundary conditions are defined. After making meshes and solving the problem, the results of the analysis such as flux, flux density distribution, etc. are observed.

2-D FEM is carried out for the both third optimal design using genetic algorithm and imperialist competitive algorithm and graphical results are obtained. Figs. 7 and 8 show the flux density distribution and graphical representation of flux lines in the analyzed LIM, respectively.

7. Conclusions

Linear induction motors have many advantages that cause to increase their application. But they have two major disadvantages, low power factor, and low efficiency. In this paper imperialist competitive algorithm is used to optimize both efficiency and power factor. Optimization is done in three cases. At first just the efficiency is optimized and in the second one just power factor is considered. In the final study both efficiency and power factor are

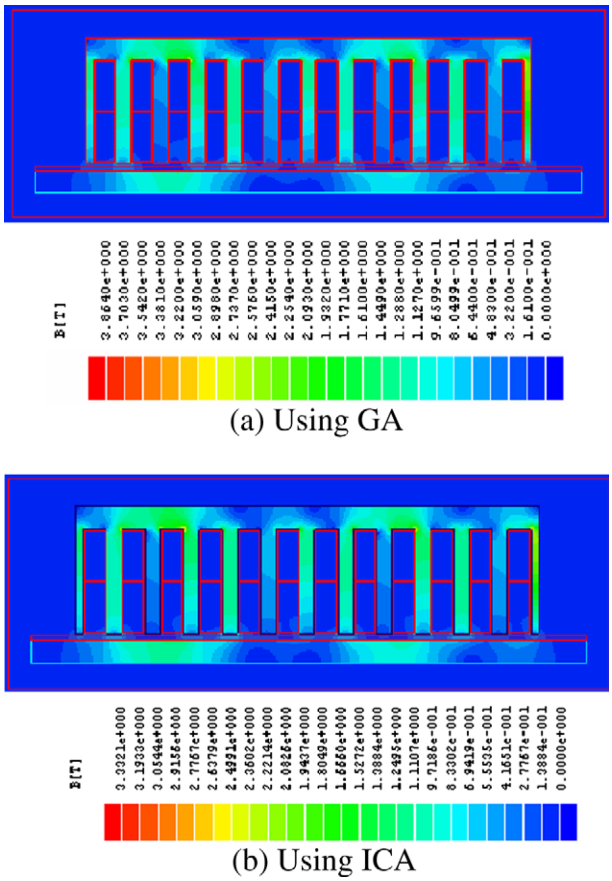

Fig. 7. Flux density distribution in the LIM for the case of optimal design 3.

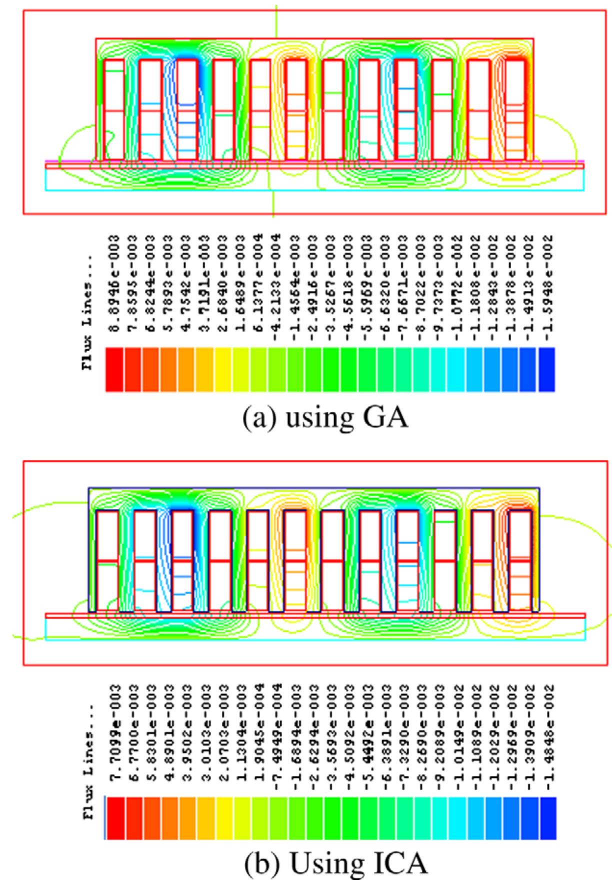

Fig. 8. Flux lines in the LIM for the case of optimal design 3.

regarded. The optimization results in all problems are compared with the ones of genetic algorithm. This comparison shows that in all cases the results of ICA are more optimized than genetic algorithm and the number of its iteration is less than genetic algorithm.

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