Design Optimization of Linear Induction Motor for Improved Efficiency and Power Factor

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***Abstract*-Linear electrical motors (LMs) are increasingly used in industry applications to develop linear motion. However, they suffer from two major drawbacks i.e. low efficiency and low power factor which cause more energy consumption, a rise in input current and occupation of transmission lines capacity. This paper presents a multi objective optimization method to improve both efficiency and power factor, simultaneously. For this purpose, the analytical model of machine is employed to calculate the efficiency and power factor. Motor parameters and dimensions are then optimized using genetic algorithm and an appropriate objective function. The results show an enhancement in motor performance. Finally, time stepping finite element method is used to evaluate the analytical results. The comparison of results validates the method.**

I. INTRODUCTION

Linear electrical motors (LMs) offer numerous advantages over rotary ones in linear motion developing, notably absence of mechanical gears and transmission systems, which results in higher efficiency, higher dynamic performance and improved reliability [1]. Among various types of linear motors, linear induction motor LIM gains a specific attention due to its simple structure and low cost [2,3]. Using an aluminum sheet instead of aluminum bars existing in rotary ones makes LIM structures to be simpler.

Desirable performance of LIMs requires optimizing its design and control. Design optimization of LIMs has been considered in many researches so far [4-8]. Cost, primary weight, starting force and winding design are the main focus of optimization in these researches. However, efficiency and power factor (PF) have not been given enough attention, while low efficiency leads to more energy consumption and low PF causes more occupation of transmission line capacity and non optimal using of inverter. In most cases improving in the efficiency or PF has an adverse effect on the other one. Therefore a compromising is needed between efficiency and PF. In order to achieve this goal a multi objective optimization is employed in this paper. First an analytical model is presented for the LIM. An effective objective function regarding the efficiency and PF is then proposed and genetic algorithm is used to optimize design parameters. Finally the 2D time stepping nonlinear finite element method (FEM) is carried out to evaluate the design optimization.

II. MODEL OF LINEAR INDUCTION MOTOR

Equivalent circuit for the LIM is shown in Fig. 1. Parameters of this circuit can be obtained as follows:

$$X_m = \frac{12\mu_0 \omega_1 a_e k_{w1}^2 \tau N_{ph}^2}{\pi^2 p g_{ei}} \tag{1}$$

$$a_e = a + \frac{g_0}{2} \tag{2}$$

$$X_1 = \frac{2\mu_0 \omega_1}{p}\left[\left(\lambda_s\left(1+\frac{3}{2p}\right)+\lambda_d\right)\cdot\frac{2a}{q}+\lambda_e l_{ce}\right]N_{ph}^2 \tag{3}$$

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

$$R_2' = \frac{12 a_e k_{w1}^2 N_{ph}^2}{\tau d p \sigma_{ei}} \tag{5}$$

for the secondary sheet $X_2' \approx 0$. Edge Effect is neglected. Saturation, air gap leakage and skin effect are taken into account by modifying air gap length and conductivity of Al sheet as follows:

$$\sigma_{ei} = \frac{\sigma}{k_{sk}} + \frac{\sigma_i \delta_i}{k_{tri} d} \tag{7}$$

$$g_{ei} = k_l k_c \left(1+k_p\right) g_0 \tag{8}$$

where $g_0 = g_m + d$ and $K = k_l k_{sk} k_c k_p$

Therefore, Goodness factor, one of the most important indicators in design procedure, is then given by:

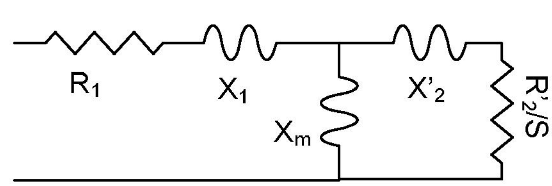

Fig. 1. Equivalent Circuit of LIM

$$G = \frac{2 f_l \mu_0 \sigma_{ei} d \tau}{\pi g_{ei}} \tag{9}$$

Equivalent current sheet of primary windings, J_m, is found from following relationship:

$$J_m = \frac{\sqrt{2} m N_{ph} I k_w}{p \tau} \tag{10}$$

Therefore the amplitude of first component of flux density in the air gap is found as follows:

$$B_{g1} = \left| \frac{j \mu_0 J_m}{\pi \frac{g_m}{\tau} \left(1 + jsG\right)} \right| \tag{11}$$

If we keep air gap flux density in the range of 0.2 to 0.5T the iron losses is negligible so the thrust, efficiency and power factor are given by:

$$F_x = \frac{3 I^2 R_2'}{2 s f_l \tau \left[\left(\frac{1}{sG} \right)^2 + 1 \right]} \tag{12}$$

$$\eta = \frac{F_x 2 \tau f_l \left(1 - s\right)}{F_x 2 \tau f_l + 3 I^2 R_1} \tag{13}$$

$$\cos \varphi = \frac{F_x 2 \tau f_l + 3 I^2 R_1}{3 V I} \tag{14}$$

Symbols definitions appear in appendix.

III. Optimization Problem

Some of the LIM parameters and dimensions are selected as design variables. Design variables are determined through an optimization procedure. In this paper, design variables are primary winding current density, motor width to pole pitch ratio, aluminum sheet thickness and slip. To have a more realistic design, some constraints are applied to design variables listed in Table I. Nominal thrust, input voltage and frequency, and mechanical velocity -the main constant specifications in the design procedure- are 128 N, 220 V, 50 Hz, and 2.5 m/s respectively.

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

$$J_\tau \left(x_1, x_2, \ldots\right) = \eta \left(x_1, x_2, \ldots\right) \cdot PF \left(x_1, x_2, \ldots\right) \tag{15}$$

Table I
Constraint Applied to Design Variables

Design Variable	Min	Max	Unit
d	1	4	mm
a/τ	0.5	4	-
s	0.1	0.5	-
J_c	3	5	A/mm^2

where x_1,x_2, … are design variables. As seen in the eq. (15) the importance of efficiency and power factor are supposed to be equal. Maximization of J_τ fulfils simultaneously both objectives of the optimization. Such an objective function provides a higher degree of freedom in selecting appropriate design variables. Genetic algorithm is employed to search for maximum value of J_τ [9].

IV. Results

A. Optimization

A three-phase linear induction motor with Al sheet for handling materials is chosen as the basis of design optimization. The minimum value of efficiency and PF in the algorithm is chosen as their initial values of the non-optimized motor. Therefore, we can make sure that neither efficiency nor PF have been deteriorated. Genetic algorithm is then employed to search optimal values of design variables. The number of initial population is 25.

Fig. 3 shows the enhancing of objective function during the different generations. The specifications of initial and optimal motor are listed in Table 2. Complete specification of initial motor and optimized motor will be presented in full paper.

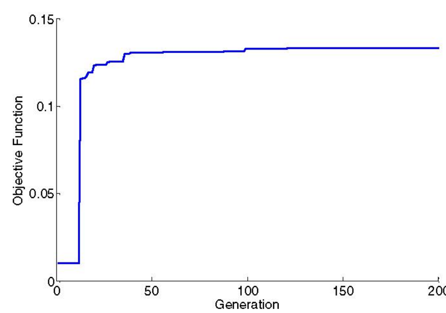

Fig. 2. Improvement of objective function

Table II
Specification of Optimal Design Candidates

Specification	Optimized motor	Initial motor
Efficiency	0.352	0.350
Power Factor	0.378	0.307
Obj. Func.	**0.13**	0.10
d	2.2mm	2 mm
a/τ	6.2	2
s	0.5	0.5
J_c	3.1 A/mm^2	4.25 A/mm^2

B. FEM Evaluation

The design optimizations in this work were carried out based on the analytical model of the machine presented in section II. Therefore, validity of the design optimizations greatly depends on the accuracy of the model. However, the model is obtained by some simplifications such as ignoring end and edge effects. Thus, it is necessary to evaluate the extent of model accuracy. In this section two-dimensional time stepping finite element method (FEM) is employed to validate the model. 2D-FEM is carried out and numerical and graphical results are obtained. The iron loss is also included in FEM. Fig. 3 and 4 show flux density distribution and graphical representation of flux lines in the LPMS motor respectively. The optimized design is simulated and its specifications are obtained by the FEM. Results of analytical method and FEM are compared in Table 3. It is seen that the results of analytical model are close enough to the results of FEM.

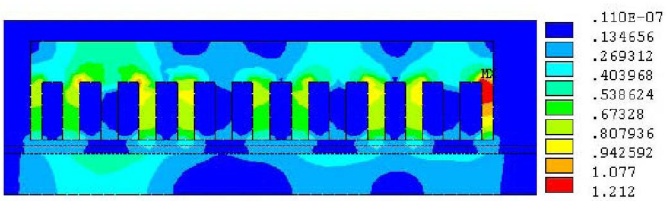

Fig. 3. Flux density distribution

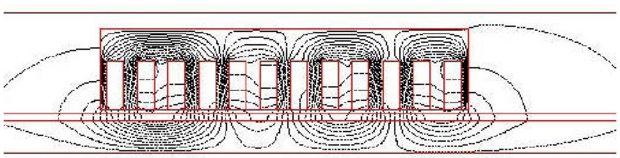

Fig. 4. Flux lines

TABLE III
COMPARISON OF ANALYTICAL AND FEM RESULTS

Optimized motor	Analytical	FEM
Efficiency	0.352	0.343
Power Factor	0.378	0.385
Obj. Func.	0.133	0.134

V. CONCLUSION

The multi objective optimization method has been applied to linear induction motor to improve both efficiency and power factor simultaneously. Motor parameters and dimensions have been optimized using genetic algorithm. It is seen that the power factor increases up to 7% whereas efficiency is improved only 0.2%. The objective function is improved about 3%. The results are then verified by finite element method.

ACKNOWLEDGMENT

The authors wish to thank the Center of Excellence on control and intelligent processing at the University of Tehran for supporting this research.

APPENDIX

List of Symbols

Primary width	a
Effective primary width	a_e
1st harmonic of air gap flux density	B_{g1}
Tooth flux density	B_y
Yoke flux density	B_t
Al sheet thickness	d
Primary frequency	f_1
Thrust	F_x
Goodness factor	G
Mechanical air gap	g_m
Magnetic air gap	g_0
Primary phase current	I
Equivalent layer current density	J_m
Primary winding current density	J_c
Carter factor	k_c
Flux leakage factor	k_l
Iron saturation factor	k_p
Skin effect factor	k_{sk}
Primary winding factor	k_w
Primary winding factor for 1st harmonic	k_{w1}
End connect length	l_{ce}
Phase number	m
Winding turn number	N_{ph}
Pole pairs number	p
Iron loss	P_{iron}
Slot per pole per phase	q
Primary resistance	R_1
Secondary resistance referred into primary	R_2'
Slip	s
Primary inductance	X_1
Secondary inductance referred into primary	X_2'
Air permeability	μ_0
Al Conductivity	σ_{Al}
Cu Conductivity	σ_c
Pole pitch	τ
Primary angular frequency	f

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