Shape Optimization of Laboratory Induction Pump

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***Abstract*—The design optimization of the laboratory induction pump is carried out. The forward task is formulated as a nonlinear magnetic problem that is solved by the professional code COMSOL Multiphysics. The backward (optimal design) problem is solved by Coordinate search, BOBYQA, Monte Carlo, and Nelder-Mead algorithms implemented in COMSOL and also by some other algorithms built in OPTILAB, which is a module of open source code Agros Suite. The methodology is illustrated with an example. The result of optimization is the reduction of mass of selected parts of the pump, while the resultant force acting on the secondary element increases. Benefits of all optimization methods are discussed.**

Keywords—optimization; induction pump; FEM; statial harmonics; objective function; optimal design.

I. Introduction

Induction pump serves to deflate molten metal into any other reservoir according to the technological process. This method of transportation has a number of advantages over its competitors, for example, mechanical or vacuum pumps. The main advantages of induction pumps are noiselessness, the absence of mechanical impacts with the melt and the ability to dose the metal. The basic idea of the motion of a melt by this type of pump is the interaction of the magnetic field and currents in the metal.

The results presented in this paper are an extension of the paper [1]. In the early work, the accuracy of the obtained results was studied by various mathematical methods, and was confirmed in a physical experiment. The physical experiment was carried out on the laboratory installation, shown in Fig. 1 by the electromagnetic approximation. The electromagnetic approximation is the consideration of a liquid metal as in a solid state. This approach is often used to simplify the measurement of force in the induction pump [2-4]. This type of research neglects the presence of backflows as the extrusion of the liquid metal from the walls, due to the edge effects [4,5]. But it is worth noting, such a statement of the problem is acceptable in order to determine the correctness of the calculation of the magnetic field and to obtain the primary results.

In this article, it is proposed to consider the possibility of the design optimization of induction pumps at an example of a laboratory installation. The main aim of optimization is to reduce the dimension and weight parameters while increasing the specific forces in the secondary element. In most works related to the optimization of similar installations there is a problem with the correct description of the objective function [6-8]. Therefore, in this paper, the effect of the objective function on the optimizing parameters is considered. Also the correctness of the application of various algorithms in topological optimization is considered. The forward task is formulated as a nonlinear magnetic problem that is solved by the professional code COMSOL Multiphysics. The backward (optimal design) problem is solved by Coordinate search, BOBYQA, Monte Carlo, and Nelder-Mead algorithms implemented in COMSOL and also by some other algorithms built in OPTILAB, which is a module of open source code Agros.

Fig. 1. Ordinary laboratory bench of linear induction motor with solid secondary element

II. Formulation of Technical Problem

The induction pump is a double-sided linear induction pump (Fig.2). The primary element consists of two yokes and the coils of annular type, which are laid in the yokes slots. The back iron and a conductive secondary element, which imitates the liquid metal in the duct are located between the inductors. The axis of symmetry relative to the primary element is shown as the dashed line in Fig.2. It is worth noting that the real installation is made in the form of a double - duct linear induction pump and the Back Iron is located between the ducts. In this paper, only one duct is considered. The basic geometric parameters of the induction pump are given in Table 1.

The yoke of the primary element and back iron are made of laminated steel. The magnetization curve of which is shown in Fig. 3. Coils and conductive SE are made of copper material.

Mathematical modeling in the two-dimensional formulation of the problem is considered. The transverse edge effect in the SE is taken into account by the Bolton's coefficient (kq), as in [1, 9]. Namely, in the mathematical model, not the real value of electrical conductivity, but the equivalent one is used. The properties of materials used in modeling are given in Table.2.

TABLE I. INITIAL VALUES OF GEOMETRY

Symbol	Descriptions	Values, mm
B_z	Width of tooth	10
B_p	Width of slot	20
H_p	Height of slot	56
H_y	Height of yoke	18
δ	Thickness of gap	1
δ_{Al}	Thickness of conducting SE	10
δ_{Iron}	Thickness of back iron	11.5
B_{SE}	Width of SE	75
K	Overhang of SE	35
B_i	Width of PE	75
L	Length of PE	280
Q	Number of slots	9
q	Number of slots per pole and phase	1

TABLE II. MATERIAL PROPERTIES

Material	Property [unit]	Value
Core of PE	γ [S m^{-1}]	5000
	μ_r[-]	Fig.3
Coil of PE	γ [MS m^{-1}]	4.6
	μ_r[-]	1
Back Iron	γ [S m^{-1}]	4
	μ_r[-]	Fig.3
Conducting SE	$k_q \cdot \gamma$ [MS m^{-1}]	4.143
	μ_r[-]	1
Air	γ [S m^{-1}]	4
	μ_r[-]	1

III. DISCRIPTION OF MATHEMATICAL MODEL

In this paper, the obtained results were calculated in the Agros2D and Comsol Multiphysics programs. Specifically, the calculation of the magnetic field with nonlinearity of the magnetic permeability in steel elements was considered. The search for the optimal design of the primary element was analyzed by various optimization algorithms and objective functions.

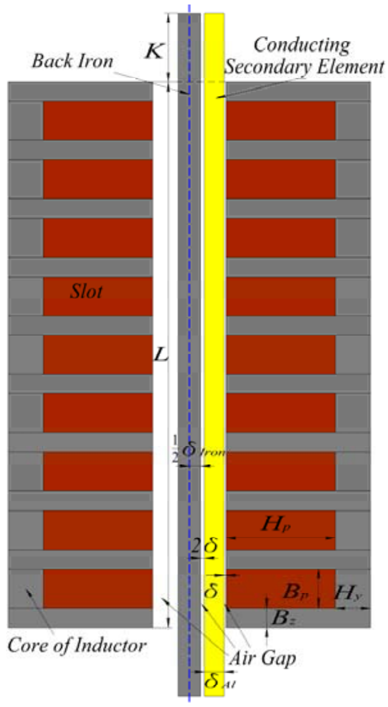

Fig. 2. Geometry of MHD-pump

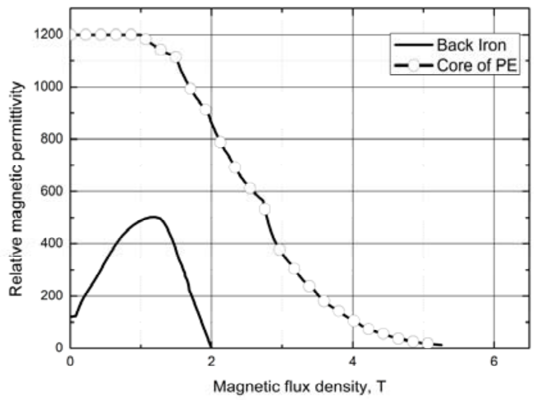

Fig. 3. Saturation curves

A. Magnetic Field

In this work traction force is the main parameter for analysis. These forces were calculated as a Lorentz's forces (1). In order to calculate this force, it is necessary to calculate the magnetic field in the region under consideration. The magnetic field analysis was carried out in the frequency domain as A-formulation (2). Equation (1) is subject to Dirichlet condition $\mathbf{A} = \mathbf{0}$ along all the boundaries of the magnetic domain.

$$F_m = \int_V (\mathbf{J} \times \mathbf{B}) \mathrm{d}V \tag{1}$$

where F_m - acting force on a conductor carrying current of density $\mathbf{J}$ whose volume is V in magnetic field $\mathbf{B}$.

$$\nabla \times (\nabla \times \underline{A}) + \mathrm{j}\mu\omega\gamma = \mu \underline{J}_{ext} \tag{2}$$

where $\underline{A}$ is the phasor of magnetic vector potential, γ - electric conductivity, μ - relative permeability, $\underline{J}_{ext}$ - harmonic current density, ω - angular frequency.

B. Optimization-Objective Function

The main aim of the work is to reduce the dimension and weight parameters and increase the forces acting on the conductive metal. There is a problem of correctly describing the objective function for this task. Therefore, it is proposed to consider three different cases of the objective functions.

In the first case (3), the objective function F_{obj} is described with respect to the traction force F_x and the mass of the primary element yoke $M_{IronOfInductor}$.

$$F_{obj} = \frac{F_x}{M_{IronOfInductor}} \rightarrow \max \qquad (3)$$

where $M_{IronOfInductor} = B_i \int_S \rho_{iron} d\mathrm{S}_{iron}$, ρ_{iron} - density of iron, S_{iron} - Area of iron primary element .

The second case considers the total minimization of the masses of the coils and the steel of the primary element yoke by means of formula (4).

$$F_{obj} = \frac{F_x}{M_{IronOfInductor} + M_{coil}} \rightarrow \max \qquad (4)$$

where $M_{coil} = L_{coil} \int_S \rho_{cu} d\mathrm{S}_{coil}$, ρ_{cu} - density of copper, S_{coil} - Area of slot , L_{coil} – length of coil

The last case of the objective function considered in this paper is described by means of formula (5). In such case, the search for the maximum of the objective function proceeds with minimizing only the masses of the inductor coils.

$$F_{obj} = \frac{F_x}{M_{coil}} \rightarrow \max \qquad (5)$$

The parameterized geometry with varying parameters during the solution is used in the model:

- $10 \text{ mm} \le B_p \le 30 \text{ mm}$
- $40 \text{ mm} \le H_p \le 60 \text{ mm}$
- $5 \text{ mm} \le B_z \le 15 \text{ mm}$
- $5 \text{ mm} \le H_y \le 25 \text{ mm}$

In the process of changing the geometry, the mesh is rebuilt, according to the configurations which satisfy to the accurate results. Maximum number of model evaluations is 100 with optimal tolerance of the objective function is equal 0.01.

IV. PERFOMANCE OF RESULTS

In this section of the work, various optimization algorithms are compared to search the optimal primary element design of the induction pump. Also the possibilities to improve the characteristics of the induction pump after optimization are analyzed.

A. Optimization study

In this paper, the mass of the coils, the mass of the inductor steel, the traction force and the length of the inductor are the main criterias estimated in this paper. The speed of search for an optimal design is estimated by the number of iterations. The efficiency of the optimal solution search for each method is analyzed by the value of the objective function.

The value in parentheses (Table 3-Table 5) shows the reduction or increase of the index in percentages relative to the original design. The results of optimization by the objective function (3) presented in Table 3 show the relevance of the application of mathematical optimization. As a result of optimization, the dimension and weight parameters were reduced and the specific force was increased. The fastest methods are BOBYQA and Coordinate search. But it is worth noting that Coordinate search significantly loses by the accuracy of determining the maximum value of the objective function.

The above is said to the optimization technique in Comsol Multiphysics. The optimization results obtained from the non-commercial open source package Agros2D have similar results with the BOBYQA method in Comsol. But it's worth noting that these algorithms implemented in Agros2D require fewer iterations to find the maximum of the target function.

TABLE III. FIRST OPT. FUNCTION (MASS IRON) – (3) GOAL FUNCTION

Method/ Criteri-on	Num ber of itera-tions	Length of induc-tor, mm	Mass of coil, kg	Mass of steel induc-tor, kg	Thrust, N	Mag-nitude of goal func-tion
BOBYQA	15	140 (50%)	2.4899 (70%)	3.6450 (75%)	10.063 (26%)	2.7607
Coordi-nate search	50	144 (49%)	2.604 (69%)	3.8407 (73%)	10.016 (25%)	2.6078
Monte Carlo	100	167.54 (40%)	4.3480(48%)	6.7068 (53%)	9.8292 (23%)	1.4656
Nestead-Melder	78	141.33 (50%)	2.5199 (70%)	3.6735 (74%)	10.056 (25%)	2.7373
BOBYQ A(Agros)	27	140 (50%)	2.4899 (70%)	3.6450 (75%)	10.151 (26%)	2.7850
BayesOp t (Agros)	8	140 (50%)	2.4899 (70%)	3.6450 (75%)	10.151 (26%)	2.7851
Limbo (Agros)	12	140 (50%)	2.4900 (70%)	3.6450 (75%)	10.151 (26%)	2.7850

The greatest increase of force after optimization was obtained by means of function (5) with minimization of the masses of the inductor coils. But at the same time, the dimension and weight parameters reduction is lower than in Table 3 and Table 4. It can be inferred that for different objective functions we will get different maximum values. Analyzing the increase of force and the reduction of the dimensions, it can be concluded that the design is optimal for this task using the objective function (3) and the algorithms BOBYQA and Nestead-Melder.

TABLE IV. SECOND OPT. FUNCTION (MASS IRON + COIL) (4) GOAL FUNCTION

Method/ Criterion	Number of iterations	Length of inductor, mm	Mass of coil, kg	Mass of steel inductor, kg	Thrust, N	Magnitude of goal function
BOBYQA	15	140 (50%)	2.4899 (70%)	3.6450 (75%)	10.063 (26%)	1.6402
Coordinate search	57	147.9 (47%)	2.5777 (70%)	4.1328 (71)	10.323 (23%)	1.5384
Monte Carlo	100	171.6 (39%)	2.9589 (65%)	5.9802 (42%)	10.454 (26%)	1.1694
Nestead-Melder	83	140 (50%)	2.49 (70%)	3.6544 (75%)	10.06 (26%)	1.6367
BOBYQA (Agros)	16	140 (50%)	2.4928 (70%)	3.6613 (70%)	10.160 (27%)	1.6510
BayesOpt (Agros)	8	140 (50%)	2.4899 (70%)	3.6450 (70%)	10.151 (27%)	1.6546

TABLE V. THIRD OPT. FUNCTION (MASS COIL) (5) GOAL FUNCTION

Method/ Criterion	Number of iterations	Length of inductor, mm	Mass of coil, kg	Mass of steel inductor, kg	Thrust, N	Magnitude of goal function
BOBYQA	22	205.7 (26%)	2.49 (70%)	13.02 (9%)	11.160 (39%)	4.482
Coordinate search	52	209.9 (25%)	2.6404 (68%)	13.47 (6%)	11.039 (37%)	4.1809
Monte Carlo	100	206.97 (26%)	2.8016 (66%)	8.352 (42%)	10.803 (35%)	3.8561
Nestead-Melder	78	209.96 (25%)	2.4899 (70%)	13.29 (7%)	11.161 (39%)	4.4824
BOBYQA (Agros)	14	194 (31%)	2.4899 (70%)	11.46 (20%)	11.241 (40%)	4.5147
BayesOpt (Agros)	22	198 (30%)	2.4899 (70%)	12.56 (13%)	12.559 (57%)	2.7851

Analyzing the results of comparing different optimization algorithms in different numerical packages (), it can conclude that the most efficient algorithm is BOBYQA and Nestead Melder for Comsol. The implemented optimization approaches in Agros2D have better performance in all comparisons.

B. Modernization of the optimal model design

The obtained optimal design is improved in this part of the work by increasing the number of slots at the same length of the inductor with a change in the connection of the winding coils. Six cases of different design are considered in Table 6:

- case I – Reference design (Table 1 and Fig.2)
- case II – Optimized design (obtained in Section 3.a)
- case III – Modernized design (an increase in Q to 18 with q = 1 and an alternation of phases in slots, like ABC-connection)
- case IV – Modernized design (case III with changing q=2)
- case V – Modernized design (case IV with connection of coil like AZBXCY)
- case VI – Modernized design (case V with changing q=1)

TABLE VI. MODERNIZING OF THE OPTIMAL DESIGN

Case	L, mm	F_x, N	M_{coil}, kg	$M_{iron\ of\ inductor}$, kg	Pole division, mm
Case I	280	8.025	8.375	14.364	90
Case II	140 (50%)	10.063 (25%)	2.4899 (70%)	3.6450 (75%)	45
Case III	275	19.692 (145%)	4.9799 (41%)	6.9863 (51%)	45
Case IV	275	31.859 (297%)	4.9799	6.9863	45
Case V	275	146.3 (1723%)	4.9799	6.9863	45
Case VI	275	87.580 (991%)	4.9799	6.9863	90

Analyzing the obtained results in Table 6, the most optimal case is 5. With this inductor design, it is possible to increase the force by 17 times, to reduce the mass of the coils by 41% and the mass of the steel by 51%.

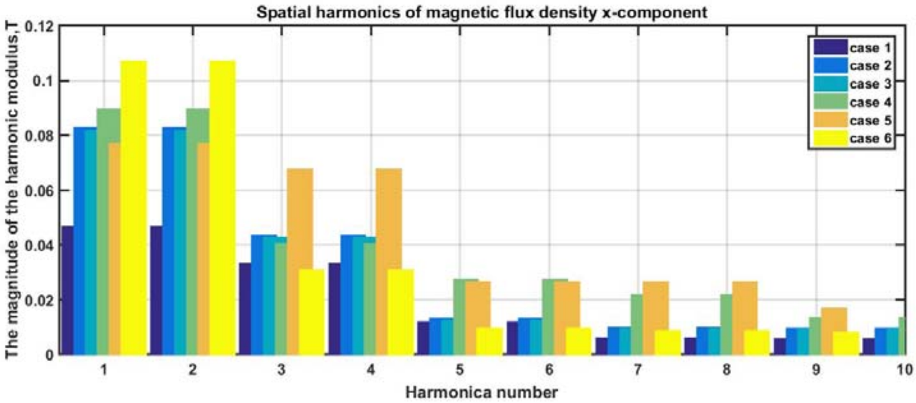

Fig. 4. Spatial harmonics of magnetic induction x-components

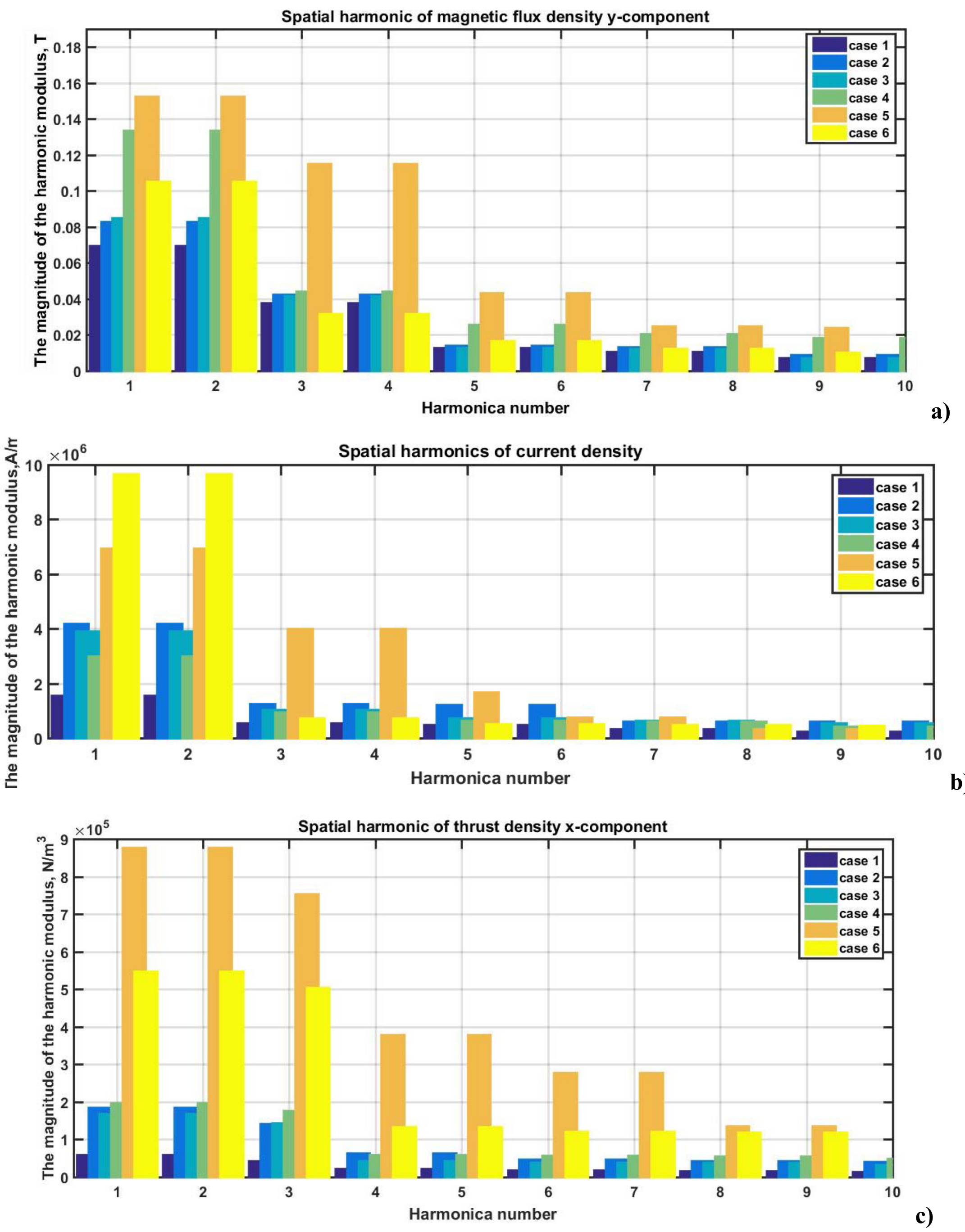

Fig. 5. Spatial harminics of magnetic flux density y-component (a), current density in conductivity secondary element (b), thrust density in secondary element (c)

In the process of optimization and modernization of the inductor design, the inductor length and pole pitch are changing, so it is difficult to compare the characteristics of the magnetic field in the SE without decomposition into spatial harmonics. In this paper, a fast Fourier transform is applied to the decomposition of spatial harmonics. Fig. 4 ambiguously characterize the optimal case of a design, unlike case 5. This is connected with the fact that the x - component of magnetic induction characterizes the levitation force, and in this work the traction force maximization is considered. Therefore, it is advisable to consider the y - component of magnetic induction and the current density in the conductive layer of the secondary element. The Fig. 5a shows that all the maximum components of spatial harmonics in cases 5 are greater than in other designs. But the harmonics spectrum of current density shown in Fig. 5, b has ambiguous conclusions. The first two harmonics are maximal in cases 6 with the number of slots per pole and phase equal to one. In this connection, the decomposition of the specific force with respect to spatial harmonics is considered (Fig. 5, c). From this graph it is possible to make a conclusion about the optimal cases of design 5.

V. Conclusion

In this paper the dimension and weight parameters of the inductor are significantly reduced with increasing specific forces. Comments are given on the best algorithms for topological optimization, both for reducing the calculation time and for search accuracy of the objective function maximum. The optimal design is modernized manually, that improves the efficiency of the laboratory installation. Integral characteristics of the magnetic field are considered as spatial harmonics, that allows to consider in more detail the optimization procedure. In future works, it is planned to extract from these spatial harmonics, the components responsible for braking force. And in the optimization process, use this criterion, for a more correct objective function.

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