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Optimization Of Reciprocating Linear Generator Parameters

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Abstract

This paper performs a linear generator optimization parameters, the criterion of which is the maximum magnetic flux in the gap at the simultaneous reduction of the permanent magnet weight (with a fixed size of a stator). The calculations are performed by the software package Ansys Maxwell, using the finite element method for the solution of field problems. In order to solve the problem an analytically calculated model was taken as a starting point. This model contained the error of the dimensions determination which were adjusted to satisfy the given output characteristics and the volume of material consumption in comparison with the dimensions calculated later in Ansys Maxwell. The calculations were based on the search for the minimum dimensions of permanent magnets functional dependence from the value of the current induced in the windings. After a certain number of iterations the extremum of this function is reached, indicating the obtaining of such dimensions at which a given current will be reached. During the study of maximum magnetic flux obtaining terms four types of assembly were considered - the magnets buried in a translator, the magnets attached to a translator, the assembly based on the Halbach design and the assembly with the axial magnetization vector magnets. The study results determined the linear dimensions of a given power generator components and the topology of the translator - permanent magnet system was chosen.

Keywords: linear generator, neodymium magnets, small power, efficiency increase, Halbach assembly

1. ITRODUCTION

The workflows of some machinery and mechanisms that use an electric drive, suggest the use of a working body reciprocating movement. These are the piston pumps and compressors, some types of power tools (nail guns), pressing equipment and so on. G. Typically this type of motion organization using the conventional electric motors between a working body and a drive motor requires the installation of an additional mechanical device that converts a rotary motion into a reciprocating one [1]. This may be a crank mechanism, a cam-shaft with a pusher, etc. Naturally, an additional element in the electric drive leads to increased losses, the increase of dimensions, cost and in some cases reduces the reliability of an entire device. Thus, for the above-mentioned cases, the refusal from the additional converting mechanical assembly and the creation of a direct reciprocating motion drive becomes a very attractive one. This drive must contain an electric motor of reciprocating motion, which is best of all agreed with the working body of the driven device according to the nature of the motion. The industrial applicability of the electric motors in this configuration became possible after the development of industrial manufacture of permanent magnets made of rare minerals such as neodymium Nd, samarium Sm, and the alloys thereof. The motors, using permanent magnets as an excitation system, surpassed the collector DC motors by specific torque 2 times, and the asynchronous motors were surpassed 1.2-1.6 times [2]. The successful use of permanent magnets in these cases allows to be sure that in this task the creation of sufficient magnetic flux for small generators and motors will be possible. One may expect that the use of a rotor with permanent magnets made of rare minerals leads to the decrease of engine mass dimensions, to the increase of efficiency and the improvement of its thermal state. The relevance of the performed research was determined by the energy strategy of Russia, in particular the escalation task of a limited power engineering for some non-electrified areas of the country.

2. OPTIMIZATION TECHNIQUES

The optimization of any device involves the replacement of the existing relations to another one, which would demonstrate the required input or output parameters on a new qualitative and quantitative level [3]. It is natural from an economic point of view, try to reduce the consumption of active materials while maintaining or increasing (which is the best way) of the entire mechanism productivity. From a technical point of view, the problem is reduced to the choice of an inductor and a stator length, the number of pole pairs and the parameters of the mechanical oscillating inductor system. Besides, the choice of the rational lengths for a stator and an inductor is important to determine the dimensions of a linear generator and to obtain maximum capacity. If the length of a stator is less than the length of an inductor, all conductors of the stator winding will participate in the electromechanical energy conversion. The drawback of this design is the increased consumption of the permanent magnet material, which leads to an increased cost of an excitation system.

Since this work was carried out by taking into the industrial use, then the optimization technique is applied for a practically significant case, namely for the generator the inductor of which should not go beyond the stator and the inductor oscillation amplitude should be 120 mm. This requirement is described by the condition $l_{st} = l_{ind} + A$, where l_{st} is the length of a stator, l_{ind} is the length of an inductor, A is the magnet oscillation amplitude. To obtain the desired value of the desired frequency EMF $f_u = k_p f$ the length of an inductor is defined as $l_{ind} = 2p\tau$, where p is the number of pole pairs, determined by the desired frequency value of the output voltage and the oscillation frequency f. In order to improve the generator characteristics of the number of pole pairs, i.e. the maximum number of magnets is selected.

The analysis is performed by the comparison of inductor different topologies which results in the obtaining of the optimal geometrical dependencies from the maximum magnetic flux in the gap between an inductor and a stator. The most expensive material in the linear device is neodymium magnets, consequently, their coordinates, as well as the coordinates of the air gap remain relatively tightly fixed. Thus, the linear dimensions undergo some variation. It is proposed to manufacture a titanium inductor. Titanium has high strength characteristics. It is a nonmagnetic material and is processed easily.

2.1 GENERAL PROVISIONS

The analysis of the value relationships is held in the software package AnsysMaxwell, using the method of finite elements method for the expansion of field problems.
The field solver of AnsysMaxwell program operates with Maxwell's basic differential equations.

Ampere's law:

$$\nabla \times H = J, \tag{2.1.1}$$

where J is the current density, H is the magnetic field strength.

Gauss theorem:

$$\nabla \cdot B = 0, \tag{2.1.2}$$

wherein the magnetic flux density B is associated with H by the following equation

$$B = \mu \cdot H$$

For isotropic materials, the magnetic permeability is the function of the magnetic flux density:

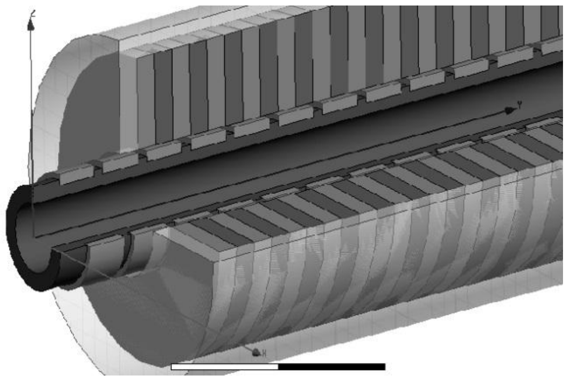
$$\mu = \frac{B}{B(H)}$$

The flux density may be expressed via a vector potential A as follows:

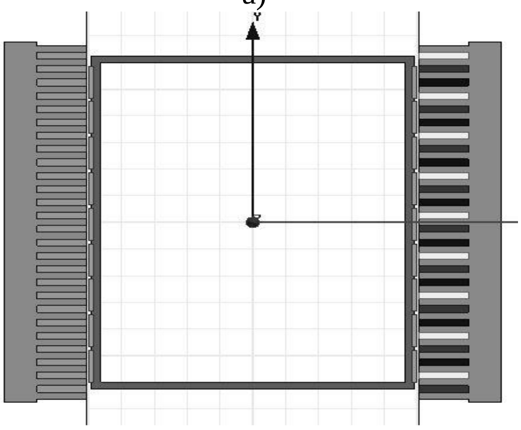
$$B = \nabla \cdot A$$

The finite element method uses the equations (2.1.1) and (2.1.2) to solve $\nabla \times (\frac{1}{\mu(B)}\nabla \times A)$ taking into account the characteristics of isotropic materials.

First of all it is necessary to clarify the model, the research of which is performed in Ansys Maxwell. Since the shape of the linear generator is a cylinder - an axial-symmetric solid body, then it makes no sense to make calculations in 3D coordinates, since this requires some impressive computing powers. Besides, the calculation of a three-dimensional model makes a number of errors in the calculation results, increases the time and the probability of failure during calculations. The choice of a two-dimensional cross-section, which is also an axially symmetric body is a reasonable one. Thus, it is enough to calculate the half-section of a volume model. The transition from the calculation of a magnetic field in a cylindrical coordinate system to a Cartesian one is performed through the modification of Maxwell equations which is performed automatically in Ansys Maxwell [4]. The technique of a two-dimensional finite element modeling of design details with uniformly distributed geometric components around the circumference is confirmed experimentally by comparing with the results of three-dimensional model calculations. The sequence of the calculation model transformation is shown by Figure 1.



a)



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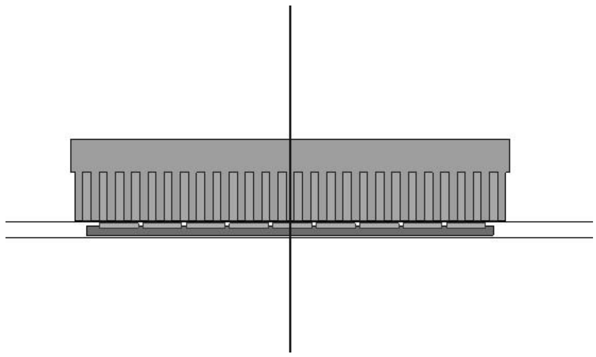


c)

Fig. (1). The sequence of calculation model transformation: calculation model (a), longitudinal section (b), half of a longitudinal section (c).

During the analysis the effect of an inductor and a stator geometric dimensions on the magnitude of the magnetic flux value in the air gap was taken into account. For this several parameters were varied in order to derive the dependences of induction change. It is proposed to use a Halbach assembly in an optimized generator as it is necessary to ensure a uniform distribution of magnetic flux in the active part only, since its presence in an empty translator is pointless [5], [6], [7]. The Halbach assembly represents the set of individual magnets, the changing magnetization vectors of which are modified so that the resulting field superposition of an assembly individual parts of the assembly ideally provides a complete absence of a magnetic flux on one side and a double magnetic flux on the other side. These transformations may be easily understood with the reference to the Mallinson's drawings [8] (Figure 2).

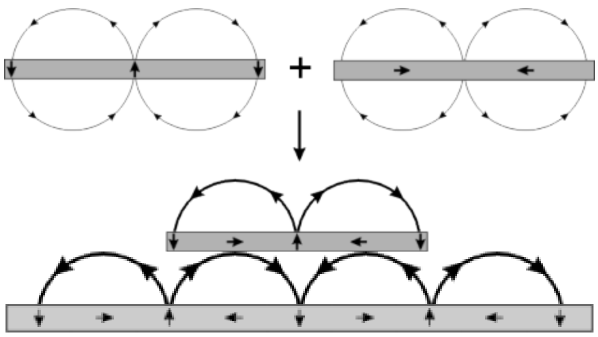


Fig. (2). Mallinson's drawings.

In Ansys Maxwell such a magnetic flux distribution is presented in the following way (figure 3).

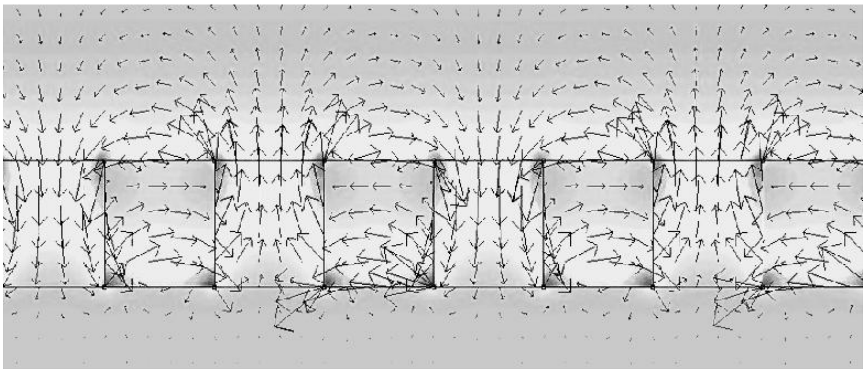


Fig. (3). Magnetic flux distribution in Halbach assembly.

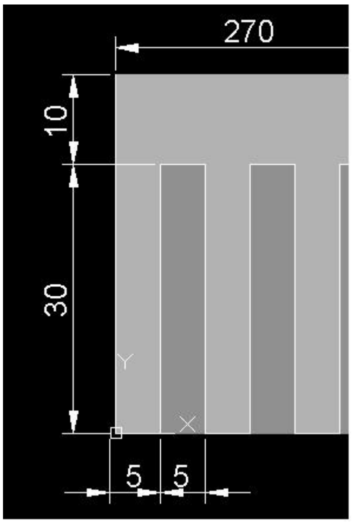
The magnitude of an air gap throughout the whole analysis is a fixed value of 1.5 mm. Therefore, the change of a magnet height is possible only in the direction of a translator, which would affect the depth of immersion. The width of magnets is limited only by the length of a translator and the distance between two adjacent magnets.

2.3. COMPARISON OF COMPONENT PART TOPOLOGIES

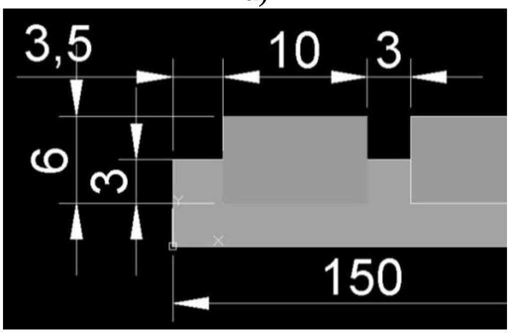
To reduce the cost of a generator it is necessary to reduce the consumption of active materials by performing a preliminary analysis of their value. Thus, the cost of steel makes 130 rubles/kg, the cost of copper makes 260 rubles/kg, the cost of titanium makes 1450 rubles/kg, the cost of neodymium magnets makes 22000 rubles/kg [9]. The main contribution to a device cost reduction will be the decrease of neodymium magnets weight. The previously mentioned things should be taken into account - they try make a generator with the largest possible number of poles (magnets). Therefore, the resizing of magnets is possible only by width at a fixed value of an air gap [10].

The solution of inverse problems is impossible by a finite element method. You can't find the geometric dimensions, knowing the necessary output values [11]. In this case, one performs analytical calculations. Such calculations were carried out preliminary in the package MatLab. They allowed to determine the geometrical dimensions of an engine and the amount of current strength (30 A) at which the required power of 10 kW is developed. The resulting geometrical dimensions used in the further analysis are shown by figure 4. The permanent magnets of an inductor should create the magnetic field strength in the stator windings during a motion with the current of 30 amps. Since AnsysMaxwell operates only with a current density, the magnetic field strength and magnetic induction the current strength may be calculated using the Ampere's theorem:

$I_{S\Gamma} = \oint_{\Gamma} \vec{H} \cdot \vec{d}s,$ where Γ is a closed circuit, SΓ is an open surface bounded by Γ.



a)



b)

Fig. (4). The dimensions of stator (a), translator with magnets (b).

2.4. DETERMINATION OF MAXIMUM MAGNETIC FLUX CREATION TERMS.

The figures 5 and 6 show two options for magnet mounting - recessed and attached ones, respectively. The structure at which the magnets are recessed in a translator, is more reliable, since the support reaction force is increased [12]. Where a magnetic assembly may be attached without in a translator without any immersion, while maintaining the operational loads, the weight of the latter one is reduced [13], [14]. A lighter translator, reducing the inertia of a generator moving part is preferable. Talking into account the complexity of magnets mounting on a translator without any immersion, the construction with the notches for magnets is selected. Technologically, the process of creating this kind of a translator is not particularly difficult - it is an alternate putting of titanium rings and magnets on a hollow cylindrical titanium dummy.

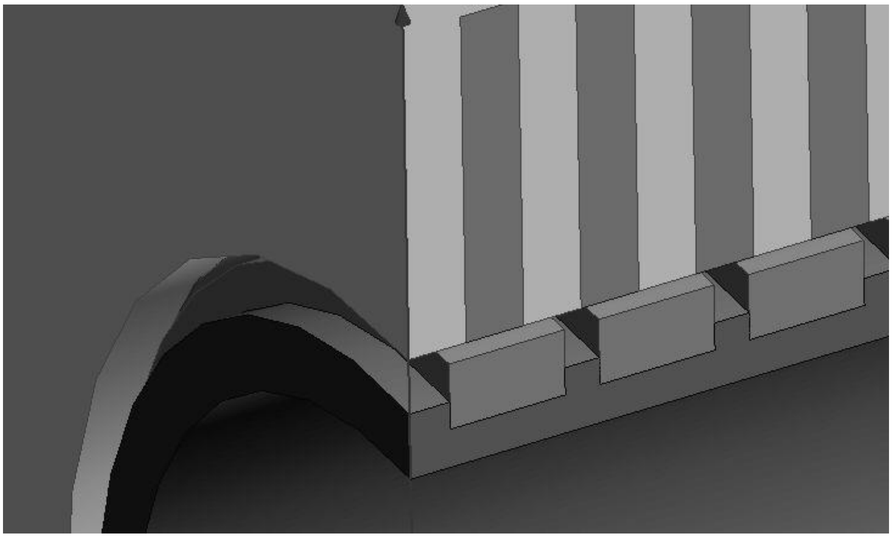


Fig. (5). Recessed magnets.

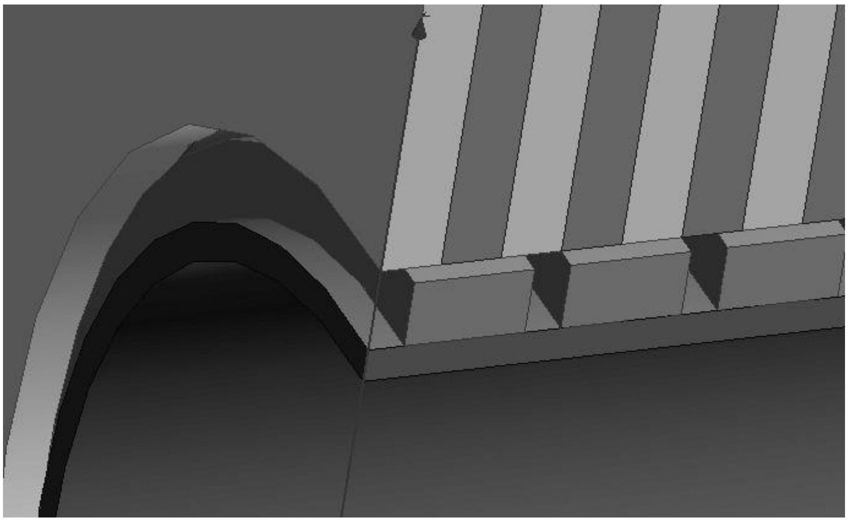


Fig. (6). Attached magnets.

Let's analyze the distribution of magnetic flux at axially magnetized magnets. Figure 7 shows the distribution pattern of the magnetic induction and the calibration scale (maximum value multiplier - 10^{-2}).

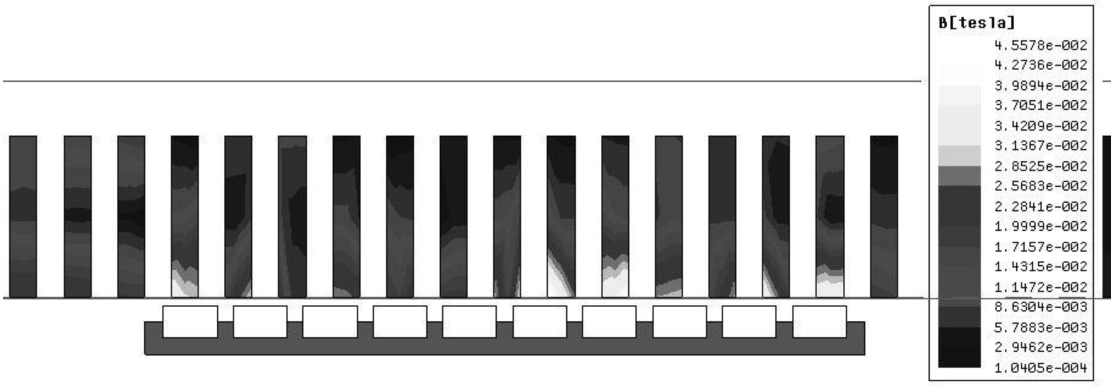


Fig. (7). The distribution of the magnetic induction at axially magnetized magnets.

During the analysis of the Halbach assembly flow the following scheme is used. It indicates the direction of the magnetization vectors. Each subsequent vector is obtained from the preceding one by multiplying it with 0,8j, where $j = e^{j90^{\circ}}$. Thus, the vector makes one turn clockwise within five turns, thus the assembly consists of five sections [15] and [16]. At ten magnets the sixth magnet has the magnetization vector, which coincides with the vector of the second magnet, the seventh coincides with the third one, and so on [17]. Figure 8 shows the vector directions of a single assembly, and Figure 9 is the picture of the magnetic induction distribution (maximum multiplier value - 10^{-1}).

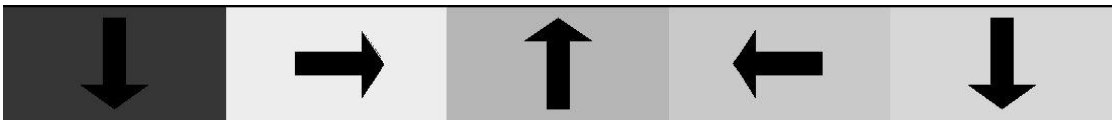


Fig. (8). Variable magnetization vectors of Halbach assembly.

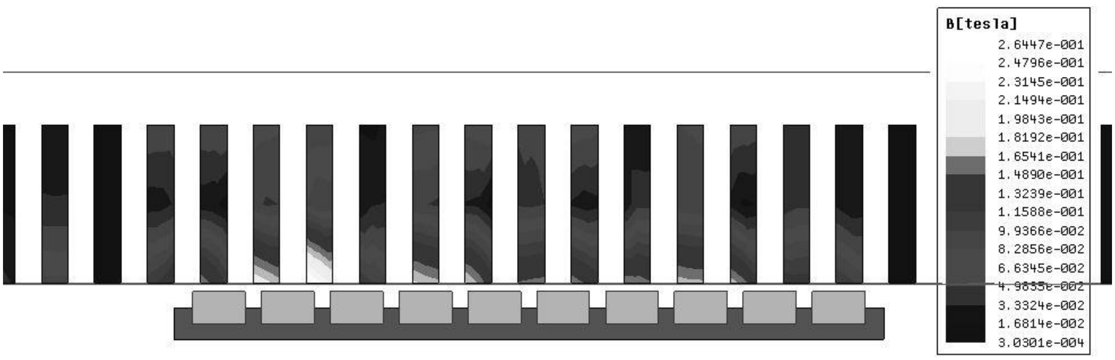


Fig. (9). Distribution of magnetic induction using Halbach assembly.

Comparing the density of magnetic induction distribution on Figure 7 and 9, we may conclude that the greatest magnetic flux is achieved using Halbach assembly. The translator topology does not change the flow due to the non-magnetic properties of titanium. Taking into account all mentioned above, a translator with recessed magnets assembled in the Halbach assembly is chosen.

3. CONCLUSIONS

This article describes the way of a reciprocating linear generator parametres optimization according to the example of a limited dimension generator development. The choice of specific parameter values is conditioned by a currently developing prototype of a small-sized generator. At the same time, the application of this technique is not limited to the case described in the article, and it may be used when considering other computational tasks in the area of linear motors and generators.

The production of an electric generator prototype and the performance of experimental studies is planned during the next stage of operations in accordance with the calculated parameters.

CONFLICT OF INTERESTS

The author confirms that the presented data do not contain any conflict of interest.

ACKNOWLEDGEMENTS

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