The magnetizing field of a linear generator used to obtain electrical energy from waves energy

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Abstract. The paper studies the magnetizing magnetic field, the radial and axial forces of a linear electric generator used to convert the marine wave's energy. The study takes into account different sizes for the permanent magnets and the relative position of the moving armature over the stator and shows when the magnetizing flux is maxim. For different positions of the moving armature the radial and axial forces are computed. The magnetic field and the forces are computed on finite element method basis using FEMM.

Key words

Linear generator, permanent magnets, magnetizing field, axial forces, wave energy.

1. Introduction

A cheap method to obtain electric energy is to use the wave's energy and a linear electric generator that it is a clean energy like aeolian energy and photo-voltaic energy [1, 2]. The moving armature of the generator will be named „rotor" and is equipped with permanent magnets. The permanent magnets are also used for aeolian energy conversion [3, 4]. The permanent magnets have a torroidal form. They are placed alternatively in order to obtain an opposed magnetization at 180° for consecutive magnets. The magnetization direction is considered to be parallel with the length of the shaft. In figure 1 is depicted a longitudinal section of the generator.

The generator's shaft is made of non-magnetic steel. On the shaft are fixed 8 permanent magnets that are separated by ferromagnetic pieces. The stator has 6 radial slots in which are placed 6 flat coils of torroidal form that give a three-phase winding with 2 coil on each phase. The rotor's length is greater than the stator's one, and so the back-emf induced in stator are not diminished when the rotor is at a full displacement position in any direction. The rotor is moving along the symmetry axle with a low frequency of a few hertz equal to the one of the waves. The numerical modeling of the magnetizing field is performed with the conjugated gradient method using the FEMM software [5, 6].

The influence of the permanent magnet width over the magnetizing field for a fixed position of the rotor beside the stator and the rotor's position influence over the stator for a fixed width of the permanent magnets are analyzed.

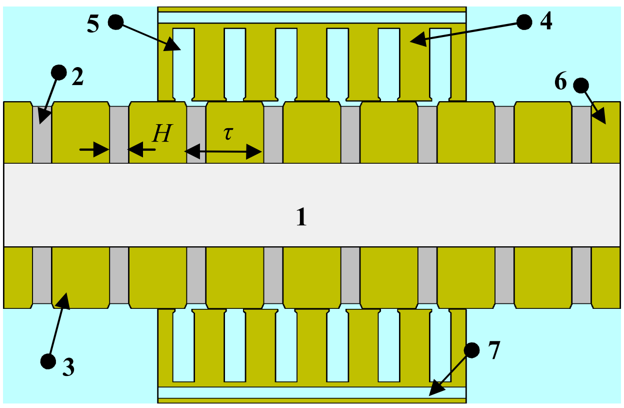

Fig. 1. The linear generator's sketch.
1 – non-magnetic shaft; 2 – permanent magnet; 3 – full ferromagnetic piece; 4 – statoric tooth; 5 – statoric coil; 6 – end ferromagnetic piece; 7 – case.

The calculation of the radial and axial forces exerted over the permanent magnets, the ferromagnetic pieces where the magnetic field runs and over the whole rotor is performed.

2. The influence of the permanent magnets width over the magnetizing field

The magnetic field is computed considering the following simplifying hypothesis: the machine is homogenous regarding electrical and magnetic properties on radial direction, the magnetizing characteristic of the ferromagnetic material is non-linear, the eddy currents losses and hysterezis losses are neglected, the reaction magnetic field given by the statoric coils are neglected.

The above presented computation hypotheses are often used in magnetic field analysis for electrical machines. The last one does not introduce significant errors because the map of the resulting magnetic field (excitation field and induced one) does not change in a great manner with the induced magnetic field. The current study aims to optimize the excitation magnetic field regarding the geometrical dimensions of the machine.

The statoric polar pitch of the linear generator is 24 mm, the rotoric polar pitch is 36 mm and the air gap 0.5 mm. The maximum displacement of the rotor is 120 mm. The oscillatory movement of the rotor is obtained using a rod-winch mechanism. The generator model is operating horizontally.

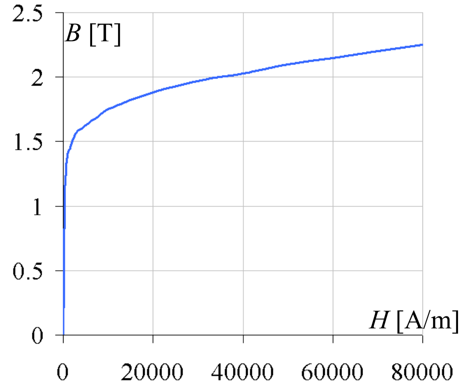

Fig. 2. The magnetizing characteristic of the ferromagnetic materials.

In Figure 2 is presented the magnetizing characteristic of the used ferromagnetic material. The permanent magnets are considered to be NdFeB and have the following specifications: coercivity H_c = 979000A/m; relative magnetic permeability μ_r = 1.049; maximum magnetic energy $B{\cdot}H_{max}$ = 40MGOe; electrical conductivity σ = 0.667 MS/m. The average speed of the rotor for half of maximum displacement is about 0.106 m/s, and the average thrust force about 4500N. The experimental model generates at stator terminals an electric power of 250 W, with a total efficiency of 52.4%.

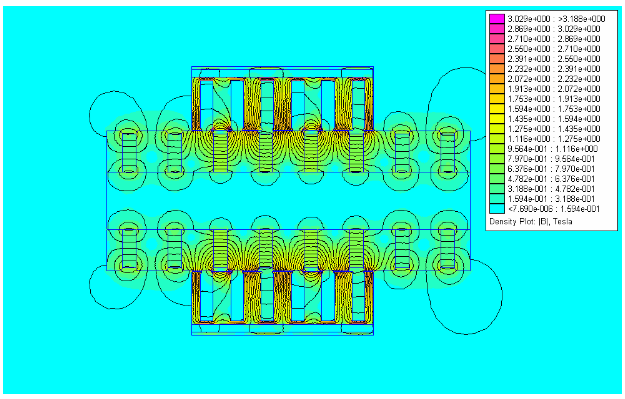

Fig. 3. The magnetizing field's map for $k = 0.3$.

The stainless steel used for the shaft has the relative magnetic permeability μ_r = 1 and the electrical conductivity σ = 1.35 MS/m.

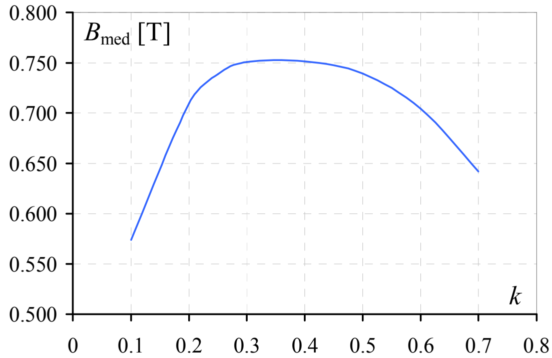

Fig. 4. The average flux density variation with the width of the magnet.

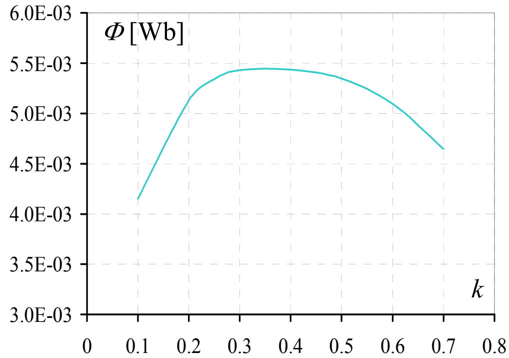

Fig. 5. The pole magnetic flux over the relative width of the permanent magnets.

The ratio between the width of the permanent magnet and the statoric polar pitch is denoted with $k = H/\tau$. This ratio influences the magnetizing field's map for a fixed position of the rotor against the stator. In Figure 3 is presented the map of the magnetizing field considering k=0.3.

For this value of k and for a lateral surface of the permanent magnet 0.007234m^2, the flux is $\Phi = 0.005403$ Wb, and the average normal flux density B = 0.748 T.

Figure 5 shows the variation of the flux for different values of k but keeping the same rotoric polar pitch of 36 mm, the same relative position of the same face of the same magnet besides the same reference point of the stator. The conclusion is that exist an optimal value for the magnet's width that generates a maximum flux. Thus for $k \in (0.28 \ldots 0.41)$ the magnetic flux is maximum.

The maximum value of k, it is not recommended due to the increased volume of the permanent magnet and thus the increased global cost of the generator.

The saturation zones are located in statoric teeth in areas towards the air gap.

Figure 4 shows the variation of the normal average flux density found in the same lateral surface of the magnet for the same values of k.

3. The influence of the rotor relative position besides the stator for the same width of the permanent magnet

The relative position is affects the map of the magnetizing field. For a fixed width of the permanent magnets (e.g. 9 mm) and for special positions of the rotor besides stator a few magnetostatic simulations are performed. Three of these positions are: position 1, corresponds to the magnet symmetry axis is the same with symmetry axis of the central statoric tooth, position 3, corresponds to the permanent magnet's symmetry axis is the same with the symmetry axis of the statoric slot and position 2, that is a median position between positions 1 and 3.

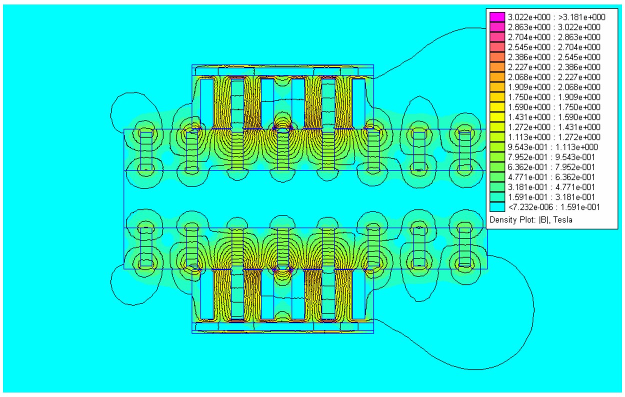

Fig. 6. The magnetizing field map for position 1 of the rotor against the stator.

In Figures 6 and 7 are presented the maps of the magnetizing field for the positions 1 and 3 respectively.
The map of the magnetizing field is strongly influenced by the permanent magnets positions. This happens due to the geometrical changes of the generator's longitudinal section.
The magnetic flux between positions 1 and 3 varies just a little because the axial magnetic field lines have the same density. The magnetic field variation between these two positions is given by:

$$\Delta\Phi[\%] = 100 \cdot \frac{53.98 - 53.43}{53.43} = 1.029\,\% \qquad (1)$$

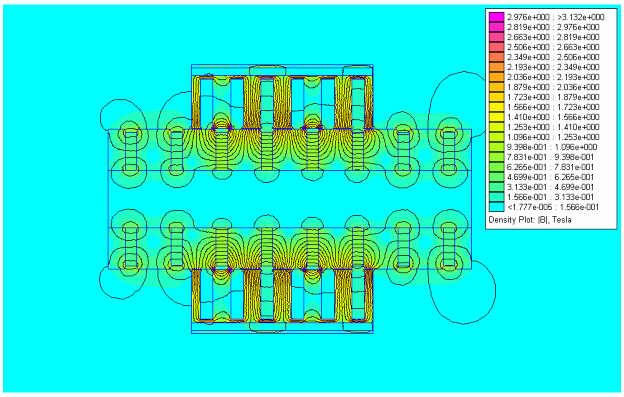

Fig. 7. The magnetizing field map for position 3 of the rotor against the stator.

In Figure 8 is shown the map of the excitation magnetic field for position 2 of the rotor, that is in the middle fo the extreme positions 1 and 3. In Figure 9 is presented a detailed view of the area marked with a rectangle in Figure 8.

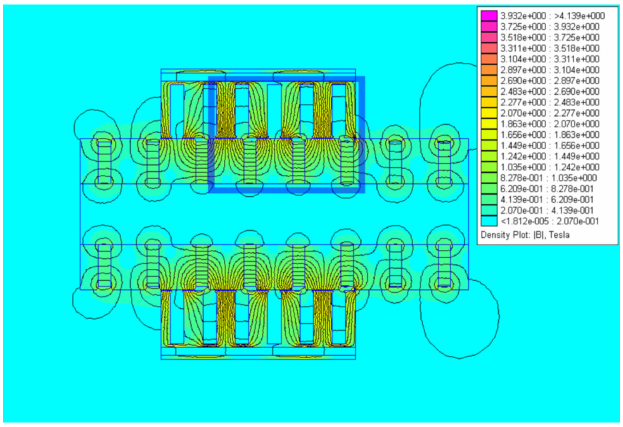

Fig. 8. The magnetizing field map for position 2 of the rotor against the stator.

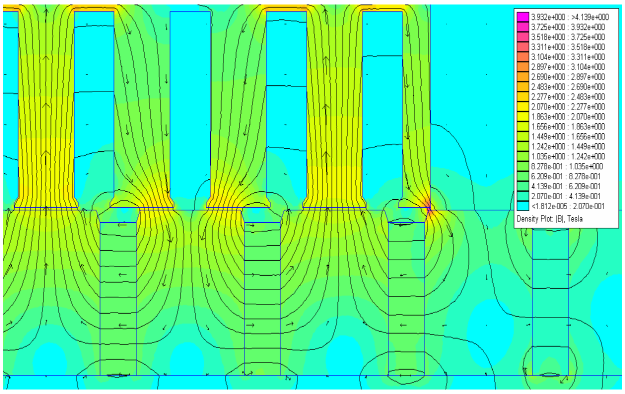

Fig. 9. Detailed view of the marked rectangle in Fig. 8.

In the case of the alignment of the magnet axis with the central statoric tooth axis *it happens a special phenomenon* as it can be seen in Figure 6. That is, the magnetic field lines of the magnet aligned with the statoric tooth, due to the symmetry, do not close along this tooth and so the flux density of this tooth is quite low about 0.15 T. In exchange, the area of the statoric tooth towards the air gap is saturated, the flux density is about 2.9 T. A lot of magnetic field lines are running through the statoric teeth in neighborhood producing saturation of the areas towards the air gap. The flux density from these zones is around 1.96T.
A similar phenomenon is taking place and for the position presented in Figure 7 where two statoric teeth are aligned with the permanent magnets and they are magnetically uncharged.

4. The computation of axial and radial forces that act over the main components of the rotor (moving armature)

The radial and axial forces acting over the parts of the rotor and over the whole rotor are computed using the Maxwell's stress tensor [7,8]. The computed forces correspond to the three chosen positions in the previous paragraph that is for a 9mm fixed width of the permanent magnets (k = 9/36 = 0.25). The rotor parts considered in the calculation of the forces are: the permanent magnet, the ferromagnetic parts from the left and right sides of the magnet and the whole rotor.

TABLE I. – Axial and radial forces acting over the different parts of the generator

Position		1	2	3
F_{a-m}	[N]	- 1.98	104.7	3.15
F_{r-m}	[N]	- 85.64	-108.3	-102.3
F_{a-x}	[N]	- 410.3	174.1	570.3
F_{r-x}	[N]	6272	6308	6211
F_{a-y}	[N]	296.4	184.9	-689.2
F_{r-y}	[N]	6389	5058	6258
F_{a-rot}	**[N]**	**17.19**	**-2610**	**- 292.2**
F_{r-rot}	**[N]**	**23.24**	**363.9**	**233.8**

The axial forces are denoted with F_a and the radial ones with F_r. The parts have the following subscripts: m – permanent magnet; x – right side ferromagnetic part; y – left side ferromagnetic part; rot – the whole rotor.
For example, F_{a-m} means the axial force exerted over the permanent magnet; F_{r-x} means the radial force that acts over the right side ferromagnetic part of the permanent magnet etc. The values of these forces are presented in Table I.
The radial forces that act over the rotor are significant but do not disturb the oscillatory movement of the mobile armature. This is because of the symmetry these forces cancel each other. The axial forces that act over the rotor parts do compensate themselves because some of them are positive and some negative. Thus, the forces that act over the rotoric parts are not relevant.
The most important influence over the movement of the rotor is given by the global axial forces that act over the whole rotor. These forces generate a step by step movement of the rotor and also to the premature usage of the bearings and operating noise.
Analyzing the values from the line before the last one it can be observed that these forces are oscillating with the relative position of the rotor against the stator. Thus, the displacement of the rotor was considered to be half of the statoric pole pitch (a distance of 12 mm) that corresponds to the extreme positions 1 and 3, defined in the previous paragraph. For this displacement that axial forces resulted positive and negative. The instantaneous variation of the **global axial force** has the maximum value of:

$$\Delta F_{a-rot} = \left[\Delta F_{a-rot}\right]_{position\ 1} - \left[\Delta F_{a-rot}\right]_{position\ 2} = \\ = 17.19 - (-2610) = 2627.19\ \text{N} \qquad (2)$$

This value is significant and outruns half of the active average force acting over the rotor. This force is due to the geometrical magnetic anisotropy of the generator. The diminishing of this force is an important issue to solve for the manufacturer of this kind of machines. It is possible to homogenize these anisotropy forces with the help of a counter-weight (a flywheel) that can be applied only if the generator is positioned vertically, the normal position for these kinds of generators.
The maximum variation of 2627.19 N for the axial force, acting over the rotor, is obtained when the rotor is moved half of the statoric pole pitch.
Positions 1, 2 and 3 of the moving armature defined in paragraph 3 correspond to the half statoric pole pitch, that is 24 / 2 = 12 mm. The rotoric pole pitch is greater than the statoric pole pitch, 36 mm. In order to study all the possible cases it has been computed the cumulative radial and axial forces acting over the moving armature when it moves with half of rotoric pole pitch, 18 mm. The global value of the axial force is only -218,9N. The conclusion drawn from here is that the axial force has the maximum variation when the rotor is moving over the distance equal to the half of statoric pole pitch.
The results obtained previously are affected by the errors of the computation method for the magnetic field and the simplifying hypothesis presented in paragraph 2.
Thus it is possible to give a physical meaning for the resultant axial forces that act on the rotor F_{a-rot}, depending on the map of the magnetic field inside the machine. So, if this magnetic field has axial symmetry in a longitudinal section then the resultant axial force is reduced. In exchange, if the field does not have axial symmetry then the force is increased. For example, in Figure 6 the field has symmetry and so the axial force is low as it can be also observed in Table I, 17.19 N. But, the magnetic field in Figure 8 is not symmetrical at all and so the axial force is high, -2610 N (see Table I).
A mitigation of the axial forces takes place at generators with a great number of permanent magnets and statoric teeth. In such cases the relative axial asymmetry is reduced.

5. Conclusion

The paper shows to the linear generators with permanent magnets manufacturers, useful information regarding the most endangered zones from a magnetic point of view. It also presents the values for the axial forces that are the dangerous ones for the generator. The optimal width of the permanent magnet is determined in order to obtain the maximum possible value for the efficiency of the generator.
The results presented in the paper are based on the computation of the magnetic field and on the forces that act over the different parts of the generator. The magnetic field was obtained using the finite element method with the help of FEMM software.

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