Study of linear generators with and without rotating permanent magnets in their stator windings

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***Abstract*—The paper examines linear generators with and without rotating magnets in their stator windings. A three-dimensional model in dynamic mode has been synthesized with the help of ANSYS R19.1. The influence of the dimensions of the permanent magnets in the double sided translators on the electrical parameters of the generators has also been analyzed. Experimental studies of the generators have been performed to prove the accuracy of the simulation model.**

***Keywords*—ANSYS, linear generator, rotating magnets.**

I. Introduction

Concerns about climate change, rising oil prices and rising government subsidies are leading to increased investment in renewable energy.

Permanent magnet linear generators (PMLGs), which directly extract energy from sea waves, are part of the solution to these problems [1]. Their action is based on the conversion of reciprocating motion into electricity. There are two types of PMLGs - with and without an iron core in the windings. The ones without an iron core in their windings are with a simpler construction and cheaper, and the electric power obtained with them is lower [2,3,4,7].

In the case of the linear generators with an iron core in the windings, higher electric power is obtained because of the small reluctance [4,5] but due to the availability of an iron core, higher harmonics appear [2,4,5].

The aim of the present work is to study and compare the main electrical parameters of linear generators with and without permanent rotating magnets in the stator windings at permanent translational magnets, different in volume.

II. Exposition

Fig. 1 shows the structural diagram of the two linear generators under consideration - without and with rotating magnets in their stator windings. A similar generator with rotating magnets in the stator windings is considered in [8]. Their main components are: 1 - windings, 2 - rotating magnets, 3 - steel plates of the translator, 4 - permanent translational magnets, 5 and 6 - aluminum plates, 7 and 8 – magnets, creating a magnetic brake, 9 - steel plates, 10 - movable rail and 11 - base. As the waves move, the movable part of the PMLG performs a reciprocating motion, which creates a moving magnetic field and an electromotive force is generated in the windings.

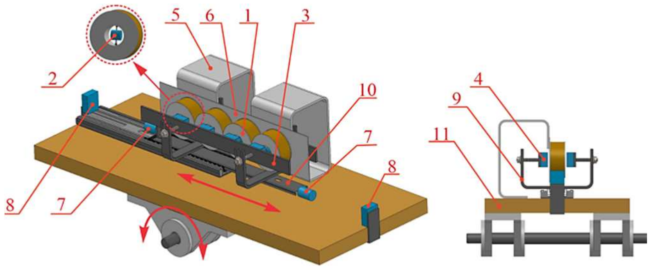

Fig. 1. Structural diagram of linear generators with and without rotating magnets in their stator windings.

Fig. 2 shows the positions of the magnetic poles for the studied cases.

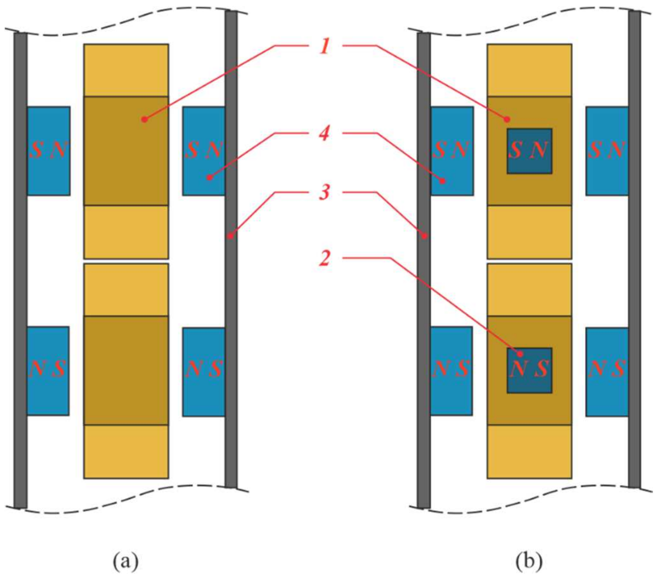

Fig. 2. Positions of the magnetic poles for the studied cases: (a) without rotating magnets; (b) with rotating magnets.

When modeling the generators in dynamic mode with the help of ANSYS R19.1, first the mechanical problem was solved, and then the magnetic one. The distribution of the magnetic field in both linear generators is shown as it follows: in Fig. 3 – for the generator with rotating magnets in its stator windings; and in Fig. 4 – for the generator without permanent magnets in the stator windings. The electrical problem was also solved, and the electromotive forces induced in the windings of the two generators were obtained at idle run mode.

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The simulation model was used to study the influence of the translational magnets' thickness on the output electrical parameters for the two linear generators. The windings used had a diameter D = 50 mm, thickness H = 16 mm, number of turns N = 1400 and wire diameter d = 0.3 mm.

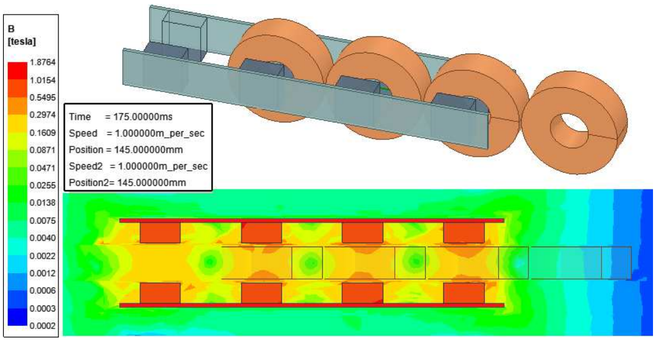

Fig. 3. Distribution of the magnetic field for the generator without rotating magnets in the stator windings and thickness h = 10 mm of the magnets in the double-sided translator.

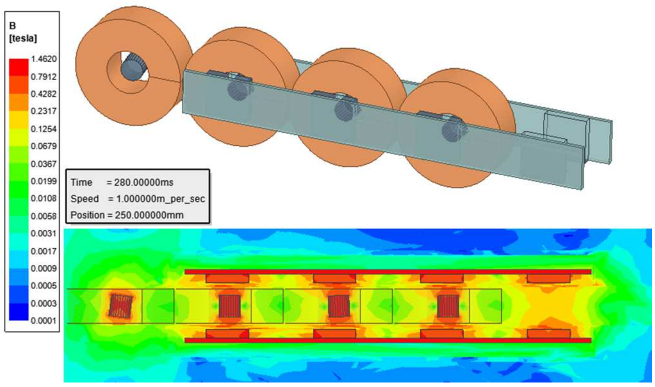

Fig. 4. Distribution of the magnetic field for the generator with rotating magnets in the stator windings and thickness h = 4 mm of the magnets in the double-sided translator.

Fig. 3 shows the distribution of the magnetic field in the PMLG without rotating magnets for the case when the translational magnets are 10 mm thick (h = 10 mm), and Fig.4 shows the situation for the generator with rotating magnets and translational magnets with a thickness of h = 4 mm.

After solving the electrical problem, the electromotive force of 4 series-connected windings at idle run mode was obtained. It is presented in: Fig. 5 - for the PMLG without rotating magnets and translational magnets with thickness h=10mm, and in Fig. 6 - for the generator with rotating magnets and translational magnets with thickness h=4 mm.

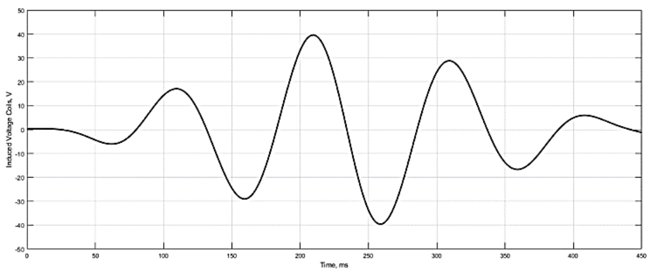

Fig. 5. Electromotive force at idle run mode for the PMLG without rotating magnets, having translational magnets with thickness h = 10 mm.

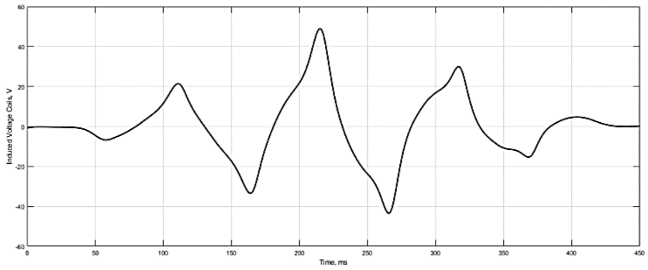

Fig. 6. Electromotive force at idle run mode for the PMLG with rotating magnets and with 4 mm thick translational magnets (h = 4 mm).

The equivalent circuit diagram for the two PMLGs (with and without rotating magnets) is shown in Fig. 7.

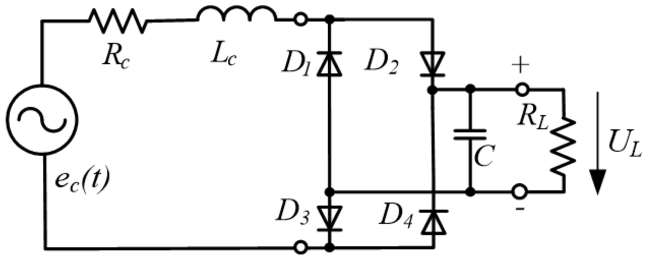

Fig. 7. Equivalent circuit diagram for the two PMLGs.

With the help of the obtained from the ANSYS R19.1 simulation instantaneous idle run electromotive forces $e_c(t)$, the rectified electromotive forces E for 4 series-connected windings are calculated (1). Using these electromotive forces and the parameters of the equivalent circuit, the active powers in DC mode are found [6]:

$$P_L = \frac{E^2 R_L}{(R_C+R_L)^2+(\omega L_C)^2} \tag{1}$$

III. Experimental Research

Figures 8 and 9 show the measured voltages and currents of a generator with translational magnets with 20 mm length and width and thicknesses h = 2, 4, 8 and 10 mm, respectively, and without rotating magnets in the stator windings. The active powers for these magnets and the powers, obtained from the simulation at thickness h = 10 mm, are presented in Fig. 10.

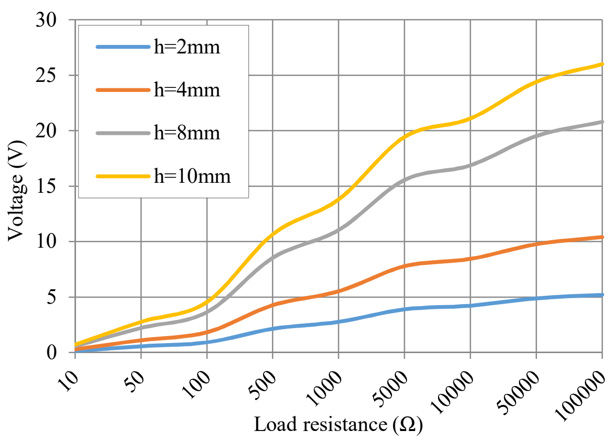

Fig. 8. Voltages in a generator without rotating magnets and with translational magnets with thickness h = 2, 4, 8 and 10 mm.

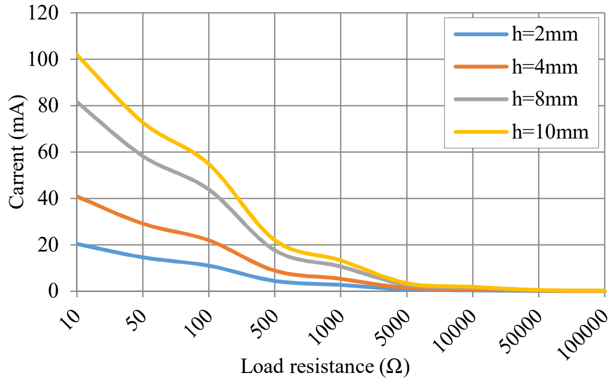

Fig. 9. Currents in a generator without rotating magnets and with translational magnets with thickness h = 2, 4, 8 and 10 mm.

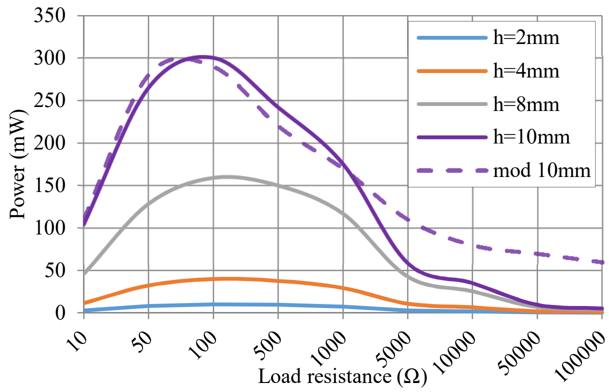

Fig. 10. Active powers in a generator without rotating magnets and with translational magnets with thickness h = 2, 4, 8 and 10 mm.

From the obtained experimental results it can be seen for both generators that when the thickness and volume of the translational magnets are increased, the voltages and currents increase proportionally, and the increase for the power is quadratic. The highest powers are obtained at a load resistance of 100 Ω for all types of magnet dimensions. In the case when the translational magnets have the largest thickness h = 10mm the highest power of 300 mW is obtained. The presented model is adequate for load resistances from 10 to 3000 Ω, and the maximum relative error is δ_{max} = 13.5%.

The graphs in Figures 11, 12 and 13 illustrate the voltages, currents and active powers depending on the load resistances of the generator with rotating magnets in its stator windings. The overall dimensions of the used magnets are: translational magnets - 20 mm length and width and thickness h = 2 or 4 mm; while the rotating magnets are h_{mr}=10 thick and have a diameter d_{mr}=10 mm.

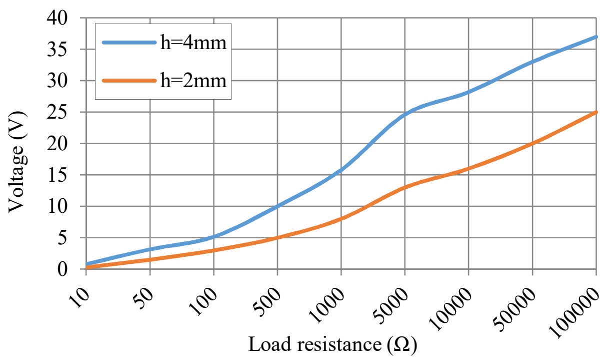

Fig. 11. Voltages of a generator with translational magnets with thickness h = 2 and 4 mm in case of no rotating magnets in the stator windings.

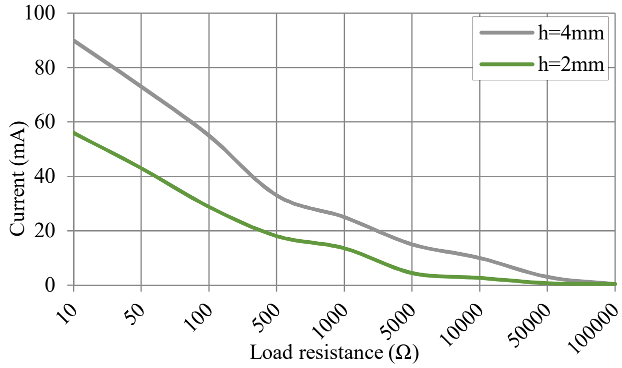

Fig. 12. Currents of a generator with translator magnets with thickness h = 2 and 4 mm when there are rotating magnets in the stator windings.

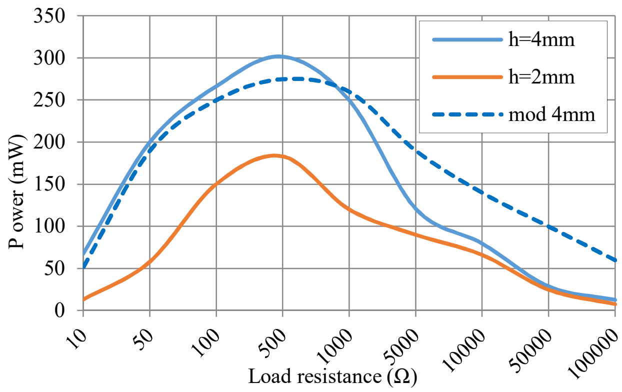

Fig. 13. Power of a generator with translational magnets with thickness h = 2 and 4 mm when there are rotating magnets in its stator windings; and the obtained during the simulation power for translational magnets with thickness h = 4 mm.

When analyzing the experimental results for the linear generator with rotating magnets in its stator windings, it can be seen that the tendency, related to the influence of the translational magnets' thickness is preserved: as the thickness increases, the voltages and currents go up proportionally, and the increase in the power is quadratic. Maximum power of 303mW is measured at a load resistance of 500Ω, when the thickness of the translational magnets is h = 4 mm. When magnets with greater thickness are used, h = 8 and 10 mm, this leads to significant increase in the resistance force caused by the interaction of the two fields - the axial one of the translational magnets and the rotational field of the rotating magnets, respectively. Therefore, these studies are not presented here. Modeling was only performed for a linear generator with rotating magnets in its stator windings, having translational magnets with thickness h = 4 mm. The presented model is valid for load resistances from 10 to 3000Ω, usually in the operating mode range for these generators. The maximum relative error is δ_{max} = 9.5%.

TABLE I. MEASURED MAXIMUM VOLTAGES, CURRENTS AND POWER FOR BOTH TYPES OF GENERATORS.

Linear generator	**U_{max} , V**	**I_{max} , mA**	**P_{max} , mW**	**Price, €**
With rotating magnets	37	90	303	12
Without rotating magnets	26	103	300	25

When comparing the characteristics of the two generators, it can be seen that their electrical parameters are similar, as the maximum powers are almost equal. An advantage of the linear generator with rotating magnets is that the presence of these magnets in the stator windings significantly reduces the reluctance as they reduce the air sections. This allows using much smaller translational magnets, twice reducing, in turn, the cost of the linear generator.

IV. CONCLUSIONS

In the experimental studies of the two linear generators - with and without rotating magnets in their stator windings - it is noticeable that with increasing the thickness and volume of the translational magnets, the voltages and currents increase proportionally, and the power increases quadratically. The maximum powers for the two generators are almost the same, being 300 mW at a load resistance of 100Ω for the generator without rotating magnets with 10 mm thick translational magnets. For the generator with rotating magnets the power is 303mW at a load resistance of 500Ω, when the thickness of its translational magnets is only 4 mm.

The obtained model simulates with good accuracy the operation of the studied generator with rotating magnets.

Both types of PMLGs have similar electrical parameters. An advantage of the linear generator with rotating magnets in its stator windings is the significant reduction of the reluctance. This allows the use of much smaller translational magnets, which, in turn, halves the cost of this linear generator.

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