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Study of a linear generator with permanent magnets converting sea wave energy into electricity

N P Georgiev¹ and R P Raychev²

¹Department of Electrical Engineering, Technical University of Sofia, Branch Plovdiv, 25 Tsanko Dystabanov Street, Plovdiv, Bulgaria
²Department of Mechanical Engineering, Technical University of Sofia, Branch Plovdiv, 25 Tsanko Dystabanov Street, Plovdiv, Bulgaria

Abstract. This paper studies the output electrical parameters of a linear generator with permanent magnets without an iron core for three types of electrical connection of its windings. Software simulations have been performed by means of ANSYS 2019 R1 and FEMM, and experimental studies of the linear generator have been carried out. A model has been obtained, which simulates the operation of the generator under study with good level of precision. The optimal scheme of connecting the generator windings, which is suitable for practical realization, has been determined.

1. Introduction

In the last quarter of a century, there has been a growing interest in devices converting the energy of the sea and ocean waves into electric power. For direct conversion of the sea power into electricity, linear generators with permanent magnets (LGPMs) are often used, which can convert the reciprocation into electrical energy [1]. These generators are divided into two types: without and with an iron core in the windings. The LGPM without an iron core are smaller in size, simpler in construction, and cheaper; their output electrical parameters are lower as well, however [2,3]. The LGPMs with an iron core in the windings, due to the low magnetic resistance, have significantly better electrical parameters [4,5] but higher harmonics are obtained with them because of the availability of an iron core [2,4,5].

The aims of the present work are: to investigate the output electrical parameters of a linear iron generator with permanent magnets without an iron core for three schemes of connecting its windings; and to determine the optimal of the three schemes of connection, most appropriate for practical realization.

The paper studies and models LGPM, which can be used to convert the offshore sea wave energy into near-shore electricity. The proposed generator is a floating element - buoy 1 on wave 2, in which a linear generator 3 is placed. The buoy is secured with a rope 4 to a weight 5, located at the seafloor – Fig. 1. Most LGPM without an iron core in the windings are composed of one or more cylindrical magnets, moving in a non-metallic cylinder, around which several coils are placed. The main disadvantage of this construction is that the magnetic fluxes, created by the permanent magnets, are small, due to the fact that they pass both through the coils and through large sections of air with high magnetic resistance.

In the proposed linear generator, the coils are stationary and placed between movable magnets, which, in turn, are fixed to iron rails as seen in Fig. 2. In this construction, the air gap is significantly reduced and together with the thickness of the coils it forms a layer of only 16 mm. Thus, the magnetic resistances are significantly reduced. At a minimum air gap, the best possible electrical parameters of the LGPM are obtained, as in [6]. Thus the magnetic fluxes across the coils increase, and thence the induced voltages and the resulting power also increase.
2. Exposition

The paper studies the output electrical parameters of a linear generator with permanent magnets without an iron core for three different schemes of connecting its four windings.

The proposed LGPM without an iron core (Figure 2) consists of: 1- a movable base on which a movable rail 2 is fixed; two П-shaped aluminum plates 3; two steel plates 4, on each of which five cylindrical permanent magnets (NdFeB32) 5 with dimensions D20xH10 mm are placed. A fixed fiberglass board 7 is attached to the aluminum plate 6, where four coils 8 with a diameter $D'_c=30$ mm, thickness $l_c=12$ mm and $N=2500$ turns with a conductor diameter $d_c=0.1$ mm are located. The movable base 1 is secured to the steel axis 9, which is supported by two steel plates 10, mounted on the lower stationary base 11. To the axis of the motor 12 is mounted a gear-belt washer 13, which transmits the rotational motion of the gear belt 14. By 15 and 16 the magnets of the magnetic brake are denoted. When the DC motor for car wipers is switched on, its rotational motion alternates direction in 1 to 5 seconds and tilts the movable base to the left and right. Thus the sea wave motion is imitated.

The moving part of the LGPM begins to reciprocate and the magnetic fluxes created by the moving magnets intersect the fixed coils and induce electromagnetic voltage in them. When the movable base is tilted to the far left or right position, the acceleration is greatest and a magnetic brake is used to avoid shocks. The magnetic brake consists of two pairs of rare earth magnets 15 and 16, which are turned with the same poles to one another.

3. Modeling and experimental studies

Modeling was performed by ANSYS 2019 R1 to obtain the maximum linear velocity $V_m$ of the mechanical system - Figure 3. Figure 4 illustrates the distribution of the magnetic field in the considered
LGPM without magnets in its stator windings, obtained by means of the finite elements method Femm 4.2.

![Figure 4. Distribution of the magnetic field.](image)

Figure 4. Distribution of the magnetic field.

Figure 5 shows the variation of the magnetic flux density along the length of one winding - $B_c$. The average magnetic flux density in the perpendicular direction for the stator winding for the considered linear generator is $B_c = 0.275$ T. Figure 6 presents the equivalent circuit of an electromagnetic harvester with a voltage rectifier at active load. In this figure $R_c$ and $L_c$ denote the active resistance and the inductance of the four connected in series windings of the electromagnetic harvester, with induced electromotive voltage $e_c(t)$ and active load resistance $R_L$. The rectified voltage over the load resistance is denoted by $U_L$.

![Figure 5. Magnetic flux density along the length of one winding.](image)

![Figure 6. Equivalent circuit of an electromagnetic harvester.](image)

The horizontal linear velocity of the considered LGPM is equal to

$$v(t) = \frac{d x(t)}{d t}$$

(1)

The magnetic flux change can be expressed by the change in the cross-section of the coil for time $A(t)$, through which the average magnetic flux density $B_c$ passes.

$$\Phi(t) = B_c A(t)$$

(2)

The change in the cross-section of the coil can be presented by its width $b$ and its moving $x$ in time

$$A(t) = b x(t)$$

(3)

From (2) and (3) the magnetic flux change in the course of time is obtained
The induced electromotive force in a single winding with \( N \) turns of the electromagnetic harvester is equal to

\[
\Phi(t) = B_i b x(t)
\]

(4)

From (4) and (5) for the induced electromotive force in one winding it is obtained

\[
e(t) = -N \frac{d\Phi(t)}{dt}
\]

(5)

With 4 coils connected in series the total electromotive force \( e_c(t) \) will be equal to (7), and its amplitude – to (8), where \( V_m \) is the maximum linear velocity

\[
e(t) = -4N B_c b \frac{dx(t)}{dt} = -4N B_c b v(t)
\]

(7)

\[
E_m = 4N B_c b V_m
\]

(8)

The active power in DC mode is calculated using the amplitude of the induced electromotive force in the coil at idle-run mode and the parameters of the equivalent circuit

\[
P_L = \left( \frac{1.41E_m R_L}{\sqrt{(R_c + R_L)^2 + (\omega L_c)^2}} \right)^2 \frac{1}{R_L}
\]

(9)

The paper considers three different connection schemes for the four windings of a linear generator, denoted by the names Circuit 1, Circuit 2 and Circuit 3 in Figure 6. Figures 7, 8 and 9 present the variation of voltage, current and power for the three connection schemes at active loads from 10 \( \Omega \) to 100 k\( \Omega \). Circuit 1 and Circuit 3 have higher than 29 V voltages at a load of 100 k\( \Omega \); Circuit 2 has a voltage lower than 24 V. The maximum current for Circuit 2 is the highest of all - 40 mA - at a low-ohm load of 10 \( \Omega \); for Circuit 3 it is 30 mA and for Circuit 1 is the least of all - 20 mA. Figure 10 shows that the active power is highest for Circuit 2 - 125 mW – at loads of 700\( \Omega \), while for Circuit 1 and Circuit 3 it is the same - 93 mW for each, but for loads of 6 k\( \Omega \) and 800\( \Omega \).

Figure 10 shows that in Circuit 2 the capacities are significantly higher for low-ohm loads of up to 1 k\( \Omega \), for Circuit 2 they are lower and for Circuit 1 they are the lowest. From the experimental studies it can be concluded that Circuit 2 has the best output electrical parameters for low-ohm loads of up to 1 k\( \Omega \) due to the higher current and active power and therefore it is more suitable for the practical realization of a linear generator with permanent magnets without an iron core.

Figure 11 shows that the obtained model simulates with good precision the operation of the studied generator in the range of variation of the load resistance from 10 \( \Omega \) to 2 k\( \Omega \), whereas the maximum relative error is \( \delta_{\text{max}} = 16.9\% \).
Figure 6.

Figure 7. Variation of voltage, current and power for Circuit 1.

Figure 8. Variation of voltage, current and power for Circuit 2.
Figure 9. Variation of voltage, current and power for Circuit 3.

Figure 10. Variation of power for Circuit 1, Circuit 2 and Circuit 3.

Figure 11. Obtained model simulates and measured powers.
4. Conclusions

Program simulations, theoretical deductions and experimental studies of the proposed linear generator with permanent magnets without an iron core have been performed for three different connection schemes of its windings. Using the ANSYS 2019 R1, the maximum linear velocity of the mechanical system has been found, and by means of Femm 4.2 the distribution of the magnetic field has been obtained. The presented model simulates with good precision the operation of the studied linear generator for the scheme of two by two connected in series windings, in the range from 10Ω to 2 kΩ, where the maximum measured power actually belongs.

The active power is highest for Circuit 2 - 125 mW – at a load of 700Ω; and the current for this circuit is at its maximum of 40 mA at a low-ohm load of 10 Ω.

From the conducted experimental studies it can be concluded that Circuit 2 - the scheme with two by two connected in series windings - has the best output electrical parameters for low-ohm loads of up to 1 kΩ, because of the higher current and active power. It is the most suitable of the three schemes for practical implementation of a linear generator with permanent magnets without an iron core.

References


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