Study of four-spring electromagnetic harvesters

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Abstract. The article considers electromagnetic harvesters, consisting of a metal plate, fixed on four springs at their lower end, and having 2 or 4 magnets. A coil is located above the magnets. Modeling by ANSYS has been done, and the horizontal deviation of the mechanical system has been obtained. With the help of FEMM, the magnetic field of the electromagnetic harvesters has been modeled and their electromotive force has been determined. Experimental studies have been performed to verify the modeling. The influence of the construction parameters on the output electric features of the studied harvesters has been considered.

1. Introduction

Sources, converting mechanical energy into electrical, such as the electromagnetic harvesters, are increasingly replacing the battery-type low power consuming power-supplying electronic devices [1, 2]. There are usually two types of magnet motion in relation to the coil in these harvesters. In the first case, the magnet moves in parallel to the coil [3] and in the second one - vertically with respect to it, often being located in its air gap [4].

Three different structures of four-spring electromagnetic harvesters are considered here, with two different masses, represented by steel plates with 2 or 4 magnets each and two different coils as well. The harvesters have a fixed coil attached to them, in parallel to which the rare earth magnets move. The aim of the present work is to study the effect of the construction parameters (such as the weight of the concentrated mass, the number of turns, the influence of the coil area, the volume of the magnets, and the size of the air gap) on the output electrical parameters of the studied harvesters.

2. Exposition

Figure 1, figure 2 and figure 3 illustrate the construction of the three four-spring electromagnetic harvesters. The following notations are used in the figures: 1 - coil; 2- rare earth magnets, 3- upper base, 4- steel plate, 5- steel springs, 6- lower base and 7 metal fastening. Springs with wire diameter \(d_s = 0.63\) mm, spring diameter \(D_s = 4.63\) mm and length \(l_s = 20\) mm are used. The steel plates are the same size and with 2 or 4 fixed permanent NdFeB37 magnets, measuring 20x10x2 mm. The first harvester has two magnets and weighs \(m_1 = 15\) grams - Figure 1; the second is with 2 magnets, spaced from each other by 8 mm - Figure 2; and the third one weighs \(m_2 = 30\) grams and has two magnets in two places, spaced from each other by a distance of 8 mm - Figure 3. The coils under study have diameters \(Dc_1 = 20\) mm and \(Dc_1 = 40\) mm, thickness \(lc = 4\) mm and \(N1 = 600\) and \(N2 = 1200\) turns with conductor diameter \(dc = 0.1\) mm.
When applying a sinusoidally varying force with a resonant frequency, the mechanical system: “mass (plate with permanent magnets) – springs” begins to oscillate in parallel with the coil. Thus the magnetic flux passes differently through the coil and creates an alternating magnetic field in a different way, thus inducing alternating electromotive force.

The studied harvesters are nonlinear mechanical oscillating systems. Their simulations made by ANSYS R19.1 take into account the fixture, the gravity effect of the plates with permanent magnets and the mechanical characteristics of the used springs. The horizontal deviation $x$ of the mechanical system “mass (plate with permanent magnets) – springs” was obtained while modeling the four-spring electromagnetic harvesters, Figure 4.

The magnetic field distribution of the three electromagnetic harvesters was obtained by means of FEMM 4.2. Figure 5 shows the magnetic field distribution for the third four-spring harvester with two spaced magnets in two places at zero horizontal deflection, and Figure 7 presents the distribution at maximum deviation. Figure 6 and figure 8 illustrate the magnetic flux density changes along the length of the harvester coil at zero and maximum horizontal deviation. From Figure 6 it can be seen that at zero horizontal deviation the normal magnetic flux density is zero, and at maximum deviation the maximum magnetic flux density $B_{\text{max}}$ is obtained.

![Figure 1. Four-spring harvester with two magnets.](image1)

![Figure 2. Four-spring harvester with two spaced magnets.](image2)

![Figure 3. Four-spring harvester with two by two spaced magnets.](image3)

![Figure 4. Deviation of the mechanical system.](image4)
Figure 5. Magnetic field distribution for a four-spring harvester with two by two spaced magnets at zero horizontal deviation.

Figure 6. Magnetic flux density along the length of the harvester coil at zero horizontal deviation.

Figure 7. Magnetic field distribution for a four-spring harvester with two by two spaced magnets at a maximum horizontal deviation.
The horizontal deviation at a sinusoidally changing force with a resonant angular frequency $\omega$ is also sinusoidal

$$x(t) = X_m \sin \omega t$$  \hspace{1cm} (1)

The horizontal oscillatory speed is equal to

$$v(t) = \frac{d}{dt} x(t) = \omega X_m \sin \left( \omega t + \frac{\pi}{2} \right)$$  \hspace{1cm} (2)

The magnetic flux can be expressed by the change in the cross section of the coil $A(t)$, through which the maximum magnetic flux density $B_{\text{max}}$ passes

$$\Phi(t) = B_{\text{max}} \frac{dA(t)}{dt}$$  \hspace{1cm} (3)

The change in the cross section $A(t)$ over time equals the horizontal deviation variation in the time $x(t)$ along the diameter $D_c$ of the corresponding coil.

$$\frac{dA(t)}{dt} = D_c \ x(t)$$  \hspace{1cm} (4)

From (3) and (4), the magnetic flux through the coil is obtained

$$\Phi(t) = B_{\text{max}} \ D_c \ x(t)$$  \hspace{1cm} (5)

The induced electromotive force in the coil of the electromagnetic harvester is

$$e(t) = -N \ \frac{d\Phi(t)}{dt}$$  \hspace{1cm} (6)

From (5) and (6) for the induced electromotive force for no-load mode, it is obtained

$$e(t) = -N B_{\text{max}} \ D_c \ \frac{d}{dt} x(t)$$  \hspace{1cm} (7)

The amplitude of the induced electromotive force in the coil is a function of the amplitude of the oscillatory speed $\omega X_m$

$$E_m = N B_{\text{max}} \ D_c \ \omega X_m$$  \hspace{1cm} (8)

The angular frequency of the forced oscillations can be expressed by the frequency $f$

$$\omega = 2\pi f$$  \hspace{1cm} (9)
From (8) and (9) for the amplitude of the induced electromotive force in the coil at a resonance it is obtained

$$E_m = N B_{max} D_c 2\pi f X_m$$  \hspace{1cm} (10)

Thus, using the magnetic flux density calculated by means of FEMM 4.2 and the given resonant frequency, number of turns, coil diameter and horizontal deviation, the amplitude of the induced electromotive force in the coil for no-load mode can be calculated for the corresponding resonant frequency.

The r.m.s. value of the induced no-load electromotive force is equal to

$$E = \frac{N B_{max} D_c 2\pi f X_m}{\sqrt{2}}$$  \hspace{1cm} (11)

Figure 9 shows the equivalent circuit of an electromagnetic harvester with voltage doubling at active load. In it, $R_c$ and $L_c$ denote the active resistance and the inductance of the electromagnetic harvester coil, $e_c(t)$ - the induced electromotive force, and $R_L$ is the active load resistance. $U_L$ indicates the rectified voltage over the load resistance.

The active power, in DC mode, is calculated using the amplitude of the induced no-load electromotive force in the coil at resonance, the voltage on the germanium diode $U_D$ and the parameters of the equivalent circuit (14).

$$P_L = \frac{1}{R_L} \left( \frac{E_m R_L}{\sqrt{\left( \frac{R_c}{b} \right)^2 + \left( \omega L_c \right)^2}} - U_D \right) ^2$$  \hspace{1cm} (12)

In the resulting expression, $b$ denotes the attenuation coefficient, which is determined by the logarithmic attenuation decrement $\delta$ \([5\), where $T$ is the oscillation periodic time and $E_{ind}(t)$ is the amplitude of the measured electromotive force

$$b = 2m \delta \quad \text{,} \quad \delta = \frac{1}{T} \ln \frac{E_m(t)}{E_m(t + T)}$$  \hspace{1cm} (13)

3. Experimental studies

Figure 10 presents the no-load rectified voltage characteristics with respect to the frequency for the first harvester with two magnets, adjacent to each other and weighing $m = 15$ grams (denoted as $m = 15g 0\text{mm}$), the second with the two spaced by 8mm magnets (denoted as $m = 15g 8\text{mm}$) and the third one, having two spaced by 8mm magnets in two places, weighing $m = 30$ grams (referred to as $m = 30g 8\text{mm}$).
Figure 10. Rectified voltage-frequency characteristics.

From the characteristics it can be seen that as the mass increases, the resonant frequency of the harvesters decreases, while the maximum no-load voltage increases. Both harvesters with equal masses of 15 g each have the same resonance frequencies, and the maximum no-load voltage for the second harvester with spaced magnets is greater by 27% than that of the third harvester with adjacent magnets.

Figure 11 shows the effect of the number of turns on the rectified voltage at load resistances in the range from 0 to 200 kΩ for a two-magnet harvester weighing \( m = 15 \) grams. The measured values at 1200 turns are twice as high as those at 600, as it can be seen from the expression for the induced electromotive force (11).

Figure 12. Active power for a harvester with two magnets weighing \( m=15 \) g.

Figure 12 shows the effect of the number of turns on the active power. The measured values at 1200 turns are four times as large as those at 600 turns, as it can be seen from the expression (14). The effect of the coil area on the rectified voltage at different load resistances is shown in figure 13. Measured values at 1260 mm\(^2\) are four times larger than those at 315 mm\(^2\), as it can be seen from the expression (10).
Figure 13. Rectified voltage for a harvester with two magnets.

Figure 14. Power for a harvester with two magnets.

Figure 14 illustrates the effect of the coil surface area on the active power. The measured values for an area of 1260 mm$^2$ are 16 times greater than those for 315 mm$^2$, as it can be seen from the expressions (10) and (12).

Figure 15 shows the effect of the number of magnets on the rectified voltage at different load resistances. The measured values for the case of two magnets in two places are slightly more than twice as large as for a two-magnet harvester, as it can be seen from the expression (10). This increase of more than 2 times is due to the fact that the air gap between the magnets and the coil has also been reduced.

The effect of the volume of the magnets on the active power is illustrated by figure 16. The measured values for the case of two magnets in two places are six times larger than for a harvester with two magnets, as it can be seen from the expressions (10) and (12).

Figure 17 shows the three measured powers for the three types of harvester structures and the results obtained from the simulation of the third harvester, having two magnets in two places.

From the theoretical and experimental studies, it can be concluded that by increasing the number of turns (from 600 to 1200), by increasing the area of the coil (from 315 to 1260 mm$^2$) and the distance between the magnets (from 0 to 8 mm), as well as by increasing the number of magnets from two to two magnets in two places, as well as by reducing the air gap from 3 to 1 mm, significant increase of the rectified voltages and active powers is achieved.
4. Conclusions

Theoretical deductions, program simulations and experimental studies of three electromagnetic harvester structures have been carried out.

Modeling has been performed (by means of ANSYS R19.1) of the four-spring electromagnetic harvesters and the horizontal maximum deviation $X_m$ of the mechanical system has been found. The magnetic field distribution of the electromagnetic harvesters has been obtained using FEMM 4.2. A simulation has been made to express the induced electromotive force. The equivalent circuitry of the electromagnetic harvesters has been drawn up and an expression has been derived for the DC power at active load.

The frequency characteristics show that as the concentrated mass increases, the resonant frequencies of the harvesters decrease, while the rectified voltages increase.

From the theoretical and experimental studies it can be concluded that by increasing: the number of turns (from 600 to 1200), the area of the coil (from 315 to 1260 mm$^2$), the distance between the magnets (from 0 to 8 mm), the number of magnets from two to four, and by reduction of the air gap, the rectified voltages and the active powers increase significantly. The third type of construction of the four-spring electromagnetic harvester, having a coil with 1200 turns and 1260 mm$^2$ area, two spaced magnets in two places (measuring 20x10x2 mm), and an air gap smaller than 1 mm, is the most appropriate type of construction for practical use, due to its best electrical output parameters.

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