Study of a Coupled Piezo-Electromagnetic Harvester

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Abstract - The paper presents a study of a coupled piezo-electromagnetic harvester, consisting of a piezo-harvester and an attached to it electromagnetic harvester. Modeling in ANSYS has been performed, by means of which the horizontal deviation of the mechanical system has been obtained and the accumulated charge on the electrodes of the piezo-harvester has been calculated. The magnetic field of the electromagnetic harvester has been modeled with the help of FEMM and its electromotive force (e.m.f.) has been defined. Equivalent circuits have been drawn and experiments for validation of the developed models have been conducted.

Keywords—ANSYS; FEMM; harvesters; magnets; piezo

I. INTRODUCTION

Piezoelectric and electromagnetic harvesters increasingly replace the low-consumption accumulating power-supplying devices [1]. The main advantage of the harvesters is that they do not require maintenance, and can be used in large infrastructure facilities to convert mechanical vibrations into electricity [2]. Coupled piezo-electromagnetic harvesters [3] are more and more frequently used in autonomous sensor networks as they can work separately, connected in parallel or in series [4]. Rectifying circuit, either in series or in parallel to the electric load [5] are connected to these energy converters.

A coupled harvester, consisting of a piezoelectric and an electromagnetic harvester, has been studied and modeled within the present work. The two have been studied separately, as well as connected in series or in parallel after having their voltage rectified. ANSYS R19.1 modeling of the mechanical systems of both the piezoelectric and the electromagnetic harvester has been performed. The magnetic field of the electromagnetic harvester has been modeled with the help of FEMM. Equivalent circuits of the two harvesters have been obtained. Experimental studies have been carried out to verify the modeling. The aim of the present work is to see the advantages and disadvantages of the two types of harvesters and to assess the connection scheme, giving better output electrical parameters.

II. EXPOSITION

Fig. 1 presents the construction scheme of the coupled piezo-electromagnetic harvester under consideration. It consists of a brass plate 1 with a piezo plate 3, glued to it. The brass plate is rigidly fixed to the bottom base 2. Two steel springs 4 are rigidly fixed to the upper part of the brass plate. The springs have a permanent magnet 5 fixed to them, over which a rigidly mounted winding 6 is placed and fixed in turn to the top base 7. The bottom and the top base are attached to each other by a metal fixing 8.

The piezoelectric plates are disk-type ones, made of piezoceramics PZT5A with dimensions diameter $D_p=20$ mm and thickness $T_p=0.3$ mm; the brass plate is rectangular with dimensions $28\times20\times0.3$ mm. The springs have a wire diameter $d_s=0.8$ mm, a spring diameter $D_s=7.2$ mm and a length $l_s=25$ mm. The permanent magnet is a rare earth NdFeB 37 with dimensions $20\times10\times2$ mm and weight 3.5 grams. The coil has a diameter $D_c=30$ mm and thickness $l_c=10$ mm with $N=1200$ turns with a diameter of the conductor $d_c=0.1$ mm.

The following factors have been taken into account during the simulations of the harvesters with ANSYS R19.1: the fixing, the influence of the gravity force of the concentrated mass, as well as the mechanical characteristics of the used springs, of the piezo-plate and the brass base.

Fig. 1. Coupled piezo-electromagnetic harvester
The minimum, maximum and average mechanical horizontal deviations $X$ of the mechanical system (concentrated mass - springs - glued piezo plate on a brass base) for the two-spring harvester were obtained by modeling, Fig. 2. The minimum, maximum and average horizontal deviations of the piezo plate, also obtained by modeling, are presented in Fig. 3.

The maximum charge $Q_m$, that accumulates on the electrodes of the piezo plate, having a radius $r_p$, Young’s modulus $Y$, moment of inertia $J$, transverse voltage constant $g_{31}$ and capacitance $C_p$ at no-load voltage amplitude $U_m$ and average horizontal deviation $X_m$ is

$$Q_m = C_p U_m = \frac{3g_{31}YJ}{4r_p^3} X_m$$

(1)

The equivalent circuit diagram of the piezo plate is presented in Fig. 6, whereby $J_p(t)$ denotes the current source proportional to the accumulated charge, and $C_p$ is the capacitance of the piezo plate.

The equivalent electric circuit of the piezo plate is shown in Fig. 4, where $J_p(t)$ denotes the current source proportional to the accumulated charge, and $C_p$ is the capacitance of the piezo plate.

$$J_p(t) = \frac{d}{dt} (Q_m \sin \omega t)$$

(2)

The amplitude of the induced electromotive force $E_m$ in the winding at resonance is proportional to the number of turns $N$, the difference between the maximum and minimum magnetic flux densities through the winding $\Delta B$, the frequency of mechanical oscillations $f$ and the average horizontal deviation $X_m$

$$E_m = N \Delta B 2\pi f X_m$$

(3)

In instantaneous recording, the induced electromotive force is also sinusoidal and equal to

$$e(t) = E_m \sin \omega t$$

(4)

Thus, using the calculated by FEMM magnetic flux density $\Delta B$ - Fig. 5 and (3), the amplitude of the induced electromotive force in the winding $E_m$ at no-load mode is calculated for the respective resonant frequency.

Fig. 6 shows the equivalent circuit of the electromagnetic harvester. In it, $R_c$ and $L_c$ denote the active resistance and the inductance of the winding of the electromagnetic harvester.

Fig. 7 presents the equivalent circuit of the connected in parallel piezo and electromagnetic harvesters with two voltage doublings and a common active load $R_L$. The rectified voltage on the load is expressed in this circuit by $U_L$.

$$U_L = \frac{2}{\pi} N \Delta B 2\pi f X_m$$

The rectified voltage on the load is

$$U_L = \frac{2}{\pi} N \Delta B 2\pi f X_m$$

(5)
Initially, the total current $I$ is defined as the sum of the currents from both the piezo- $I_p$ and the electromagnetic part $I_{em}$ of the harvester, and then the total power $P_L$ is found at direct-current mode.

\[ I = I_p + I_{em} \]

\[ P_L = 2R_L I^2 = 2R_L \left( I_p + I_{em} \right)^2 \]

The resulting expression $b$ denotes the total attenuation coefficient, determined using the logarithmic decay decrement $\delta$ [6], where $T$ is the period of oscillations and $E_m(t)$ is the amplitude of the measured electromotive force.

\[ b = 2m\delta \quad \delta = \frac{1}{T} \ln \frac{E_m(t)}{E_m(t+T)} \]

III. EXPERIMENTAL STUDIES

Fig. 8 presents the graphical characteristics of the relationship between the no-load voltage and the frequency of the coupled piezo-electromagnetic harvester, with its piezo and electromagnetic parts connected in parallel. The resonant frequency in this particular case is 15 Hz and the further research is conducted with the same value.

Fig. 9 illustrates the rectified voltages measured a harvester with only piezo or only electromagnetic parts. The voltages of the electromagnetic part are about twice as high as they are for the piezo part of the harvester.

Fig. 10 depicts the DC powers measured in the four studied options. The power obtained from the electromagnetic part is five times higher than the one from the piezo part of the harvester. With the series-connected piezo and electromagnetic parts the powers are significantly lower than the ones produced by only the electromagnetic part, while with the parallel-connected ones the highest powers are obtained, 20% greater than those from the electromagnetic part alone. The maximum powers in all four studied options are at a load of 10 k\( \Omega \) and they decrease when the load increases.
The maximum relative error in modeling is $\delta_{\text{max}} = 12.2\%$, i.e., the model describes well the processes in the parallel connection scheme of the coupled piezo-electromagnetic harvester.

IV. CONCLUSIONS

Theoretical derivations, program simulations and experimental studies were performed for the four studied options, namely: a harvester with only piezo or only electromagnetic parts, series-connected or parallel-connected piezo and electromagnetic parts. Modeling was performed with ANSYS R19.1 and the average horizontal deviation of both the mechanical system and the piezo plate was obtained. The magnetic field distribution for the electromagnetic harvester was obtained using FEMM 4.2. Equivalent circuits were made for both parts of the coupled piezo-electromagnetic harvester. The maximum powers in all four studied options were obtained at a load of 10 kΩ and they decrease with increasing the load. The powers obtained from the electromagnetic part are five times higher than the ones from the piezo part of the harvester. With the series-connected piezo and electromagnetic parts, the powers are significantly lower than the ones, produced by the electromagnetic part alone. The highest voltages and powers are obtained with the piezo and electromagnetic parts connected in parallel and therefore this connection scheme is the most suitable for use in practice.

REFERENCES


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