HARVESTING VIBRATION ENERGY BY ELECTROMAGNETIC INDUCTION

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Abstract **–This paper presents some aspects about the operation and design of a harvesting generator of electricity from ambient vibration by electromagnetic induction method. For experimental tests of the generator was designed and developed a electromagnetic shaker original and controllable in frequency and amplitude. Harvesting generator is designed to work at low frequencies, close to ambient vibration, but can be adapted to work at high values of frequency. The operating principle consists to move a magnetic component inside a coil. Mobile magnetic component has in its structure rare earth permanent magnets, NdFeB. Currently they are the best performing, due to high energy density which retains the properties for a long period. At the outside of the enclosure which houses the magnets, it is a coil with two windings connected in phase opposition. A novelty in this area wich we are trying to implement is using a ferrofluid as lubricating agent attached to permanent magnets. The ferofluids are dispersion of magnetic particles (~10nm) in a liquid base. The number of these particles is very high, a reference value is 10^{23} particles per cubic meter. These magnetic fluids have common properties of liquids, but also act as the magnetic material. Due to metal particles in its composition, it appears as a ring around the mobile magnets, as their friction with the housing of the generator is much smaller. After experimental tests it was found an increased efficiency by around 25% for cases in which it was used the ferrofluid. Measurements were made with harvesting generator in horizontal and vertical position.**

Keywords: *convert electricity from vibration, energy harvesting, harvesting generator by electromagnetic induction.*

1. INTRODUCTION

Over recent years there has been a growing interest development of miniaturized system and micro electromechanical systems (MEMS), in this way, with great efforts, reached to reduce energy consumption at these devices in order mW to order μW [1]. Applications such as medical implants, sensors in buildings, sensors used in military applications, wireless sensors networks, environmental monitoring, sensors which give information about the condition and maintenance requirements of various industrial equipment, structural monitoring sensors are just a few of many examples [1-3]. The supply of power to such systems is realized through batteries, but they present some disadvantages such as: are large in size, have a limited lifetime, contain dangerous substances for the environment and sometimes are hard to replace. A potential and promising alternative solution to batteries is the usage of miniature renewable power supply. Therefore, devices who convert energy from existing sources into electricity are used.

These devices can be used to replace or charge the existing battery and increase the lifetime of the system [1,3-5]. Renewable energy sources can be: solar, thermal, acoustic, mechanic and others. Of all the renewable energy sources, solar energy is the most efficient and widespread. There are also cases in which this energy sources it is not handy reason for that is need to find solutions to power various devices. The alternative in many cases is mechanical energy as a source to obtain electricity, the reason why our interest is focused on vibration sources.

2. HARVESTING ENERGY GENERATORS FROM VIBRATIONS

Harvesting energy generators from vibration, as alternative energy sources, have become increasingly widespread because vibrations are common.

Harvesting energy from vibration can be achieved by several methods such as: electrostatic (capacitive), piezoelectric and electromagnetic (inductive) [6].

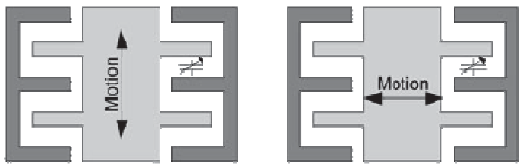
2.1. Electrostatic generator to harvest energy form vibration

Electrostatic conversion is the use of two plates that move relative to each other, separated by a dielectric, forming a variable capacitor (Fig. 1).

The armatures transfer energy stored in capacitor realizing in this way the mechanism of conversion mechanical energy into electricity [7]. If using a flat rectangular capacitor with parallel electrodes, the voltages across the capacitor is given by:

$$V = \frac{Qd}{\varepsilon_0 lw} \tag{1}$$

Where:
-Q is the load capacitor
-d is the distance between the plates
-l is the length of plate
-w is the width of plate
- ε_0 is the dielectric constant for free space



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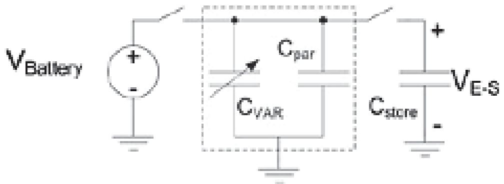

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Figure 1: a) Principle of electrostatic conversion scheme, b) electrostatic conversion equivalent circuit.

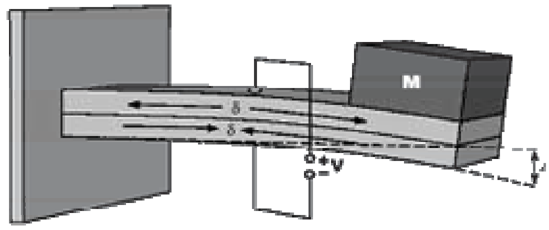
The main disadvantage of these generators is given by the need for a separate power source to initiate the process, because the capacitor must be charged with an initial voltage in order to get the start of the conversion process. Another disadvantage is the difficulty of manufacturing these converters because capacitor electrodes must not come into contact and thus short circuit the system. A big advantage of electrostatic converters is given by their compatibility with microelectronics.

2.2. Piezoelectric generator to harvest energy from vibration

Piezoelectric generators are made of piezoelectric materials. These materials are capable of generating electrical charge when a mechanical load is applied to them.
If the piezoelectric material is subjected to mechanical stress periodic or sinusoidal due to external vibration, then in this material can be measured a voltage (Fig. 2).
If a resistive load is attached to the piezoelectric generator, the voltage generated will be discharged on the load and the average power is defined by the formula:

$$P = \frac{{V_{load}}^2}{2R_{load}} \tag{2}$$

A big advantage of these generators is given by the high value of the voltage generated, and a disadvantage is given by its incompatibility with microelectronics.



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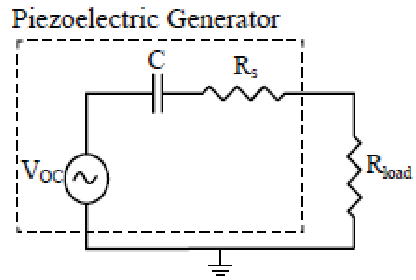


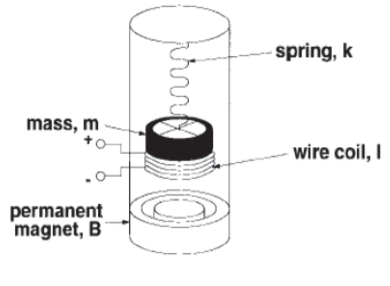
Figure 2: a) Principle of piezoelectric conversion scheme b) piezoelectric conversion equivalent circuit.

2.3. Electromagnetic generator to harvest energy from vibration

Electromagnetic conversion consists in converted mechanical energy into electricity by relative moving of a magnet inside a coil. These generators can be realized in different ways. A first example is a generator which move a mobile magnet with a spring, as in Fig. 3a [8]. A second example shows a generator who moves a mobile magnet through a console as shown in Fig 3b [9]. Another constructive known method in building inductive generators is the use of fixed magnets, oriented with same pole to the moving magnet. This latter case is used by us and presented in detail in Chapter 3.
The main advantage of these generators is that they are easily designed and build, because there is no contact between the parts which improves reliability.

3. HARVESTING SISTEM

Scheme of energy harvesting system of vibration is shown in Fig. 4 and its structure has the following components: sinusoidal signal generator of low frequency, power amplifier, vibration generator (shaker), harvesting generator of vibration, oscilloscope to determine the voltage, load resistance and a micro-ammeter.



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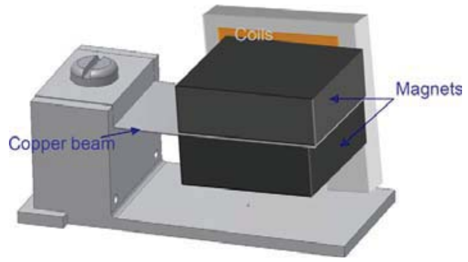

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Figure 3: a) Principle of electromagnetic generator scheme with spring; b) Principle of electromagnetic generator scheme with console.

3.1. Vibration generator

Due to the need of a vibration source it was built a vibration generator where we can control both amplitude and vibration frequency.

The shaker is shown in Fig. 5 and contains two magnets coupled attractive, mobile relative to the housing and fixed on a shaft non-magnetic with two ferromagnetic discs. The shaft is kept in equilibrium by two fixed magnets inside the cap. At the upper end portion the shaft has a threaded portion that allows assembly harvesting generator. There two caps serve and the bearings for shaft vibration. Through the thread, the caps can modify the distance between the magnets and thus is allowed to execute a more ample movement. Mobile magnets are ring shaped and have outer diameter of 19 mm, inner diameter of 9.5 mm and 6.4 mm height. Fixed magnets are also ring shaped to allow the shaft to passage through the interior of these. These have an outer diameter of 15 mm, inner diameter of 6 mm and a height of 6 mm. At the exterior it was built a coil of the CuEm ϕ 0.6 mm. Each winding has 700 turns and resistance of 7 Ω. These are connected in series and phase opposition.

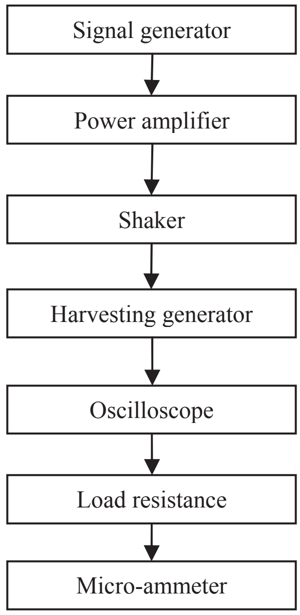

Figure 4: Principle scheme of the harvesting energy system from vibration.

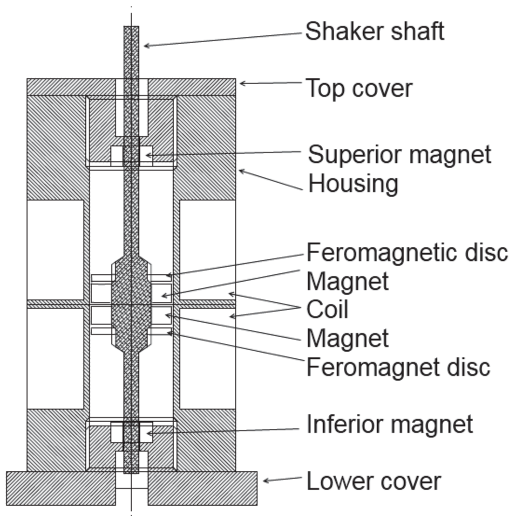

Figure 5: Principle of vibration generator scheme.

3.2. ELECTROMAGNETIC GENERATOR WITH MAGNETIC LEVITATION

A schematic diagram of the electromagnetic generator is presented in Fig. 6. From a functional principle point of view, it is similar to a shaker, but the conversion process is reversed.

The electric system presented is a simply first order L-R circuit with the impedance of the coil in series with the load resistance.

The operating principle of the device is as it follows: when the housing is vibrated by a dynamic mechanical force from outside causes a relative motion of the mobile magnet in relation to the housing. This relative oscillating motion causes a variation magnetic flux inside the coil. Using Faraday's law the voltage induced in the coil is obtained:

$$\varepsilon = -\frac{d\phi_B}{dt} \tag{3}$$

where: ε is voltage induced and Φ_B is magnetic flux
The amplitude of this voltage is proportional to the displacement speed of mobile magnets relative to the coil.

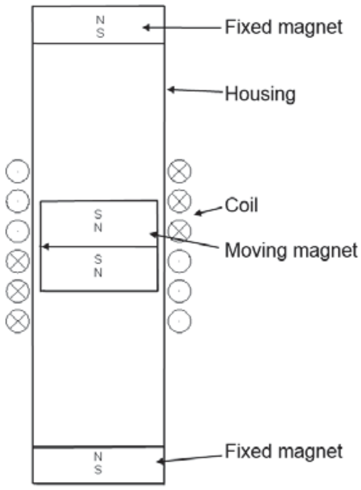

Figure 6: Principle of harvesting generator scheme.

The most important parameters that influence the design of such a system are size and conversion efficiency.
In Fig. 7 it is shown a section through the harvesting generator. It consist of two fixed magnets at the end of housing and two mobile magnets inside with same pole oriented to fixed magnets. Fixed magnets are ring shaped with outer diameter of 10 mm, inner diameter of 4 mm and height of 5 mm. Mobile magnets are disc shaped with diameter of 15 mm and height of 8 mm. These magnets have two rings of ferrofluid at extremities. At the outside of the housing is placed a coil with two windings connected in phase opposition. Each winding has 6000 turns of wire CuEm of ϕ 0.15 mm and a resistance of 0.6 kΩ. Generator housing is made of plexiglass. Caps can be moved outside, so allow mobile magnets to execute more ample moves in case of large amplitude vibrations. Also, the coil windings are made on individual support and the distance between them can be modified if the magnets have an increased stroke.
Permanent magnets used are made from rare earth, neodymium more precisely, and are known as the NdFeB or Neo. They are the strongest magnets known and are made of an alloy composed of neodym, iron and boron to form $Nd_2Fe_{14}B$ tetragonal structure.

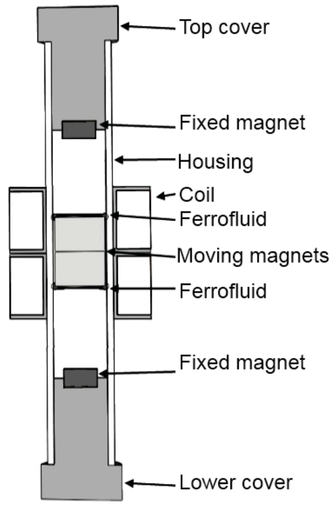

Figure 7: View in section for experimental model of harvesting generator.

Rare-earth permanent magnets have good thermal stability of magnetic characteristics to variations of temperature (Curie temperature Tc~300-400°C), high magnetic energy per unit volume (BH 300 kjoule/m^3), remanent induction (Br) over 1 T, magnetic coercitive field (Hc) over 100kA/m and manufacturing technology is relatively simple.
In the operation of harvesting generator a very important rol consists of ferrofluid or magnetic fluid. Magnetic fluid can be obtained using a variety of liquids including mention water, glycerin, hydrocarbons, silicones and other. They have a wide range of value of viscosity, moisture, density, surface tension and other physical and chemical properties. A magnetic fluid is non-magnetic in the absence of a magnetic field, but show strong magnetic properties in presence of a magnetic field, but having no hysteresis. Magnetic fluids using both the specific properties of liquids and solid specific magnetic properties.

3.2.1. Analytical calculation of the generator

In order to determine and anticipate practical performance electromechanical and magnetic of the generator the following analysis is made:
Consider the system shown in Fig. 6, mobile magnets of mass m and elasto-magnetic constant k_{em}. Elasto-magnetic constant is obtained by the equation:

$$k_{em} = \frac{\Delta F}{\Delta x} \tag{4}$$

where F is the force of repulsion resulting from mobile and fixed magnets and Δx is displacement of mobile magnets. Repulsion force can be expressed as: [10]:

$$F = k\left(\frac{1}{(x+h)^2} + \frac{1}{(x+2d)^2} - \frac{2}{(x+d)^2}\right) \quad (5)$$

where k and h are constants, x is the distance between the magnets faces and d is the axial length of magnets. We consider variable y for moving the housing. For a sinusoidal excitation [5]:

$$y = Y \sin \omega t \quad (6)$$

where Y is the amplitude of vibration and ω is pulsation vibration, we get the differential equation of motion:

$$m\ddot{z} + c\dot{z} + k_{em}z = m\omega^2 Y \sin \omega t \quad (7)$$

where z is the relative displacement of mass in raport to housing:

$$z = (x - y) \quad (8)$$

and c is the damping coeficient. The solution to equation (7) is given by equation:

$$z = \frac{m\omega^2 Y}{k - m\omega^2 + j\omega c} \sin \omega t \quad (9)$$

The instantaneous electrical power, P_i, generated by the system is:

$$P_i = c_e \dot{z}^2 \quad (10)$$

where c_e is part of the damping assigned to electromagnetic force interaction, mobile magnets-coil current.
Hence the magnitude of the generated power $|P_i|$, is:

$$|P_i| = c_e \left|\frac{mY\omega^3}{(k - m\omega^2) + j\omega c}\right|^2 \quad (11)$$

The generated power can be written as:

$$P = \frac{m\varsigma_e Y^2 \left(\frac{\omega}{\omega_n}\right)^3 \omega^3}{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left[2\varsigma\left(\frac{\omega}{\omega_n}\right)\right]^2} \quad (12)$$

where:

$$\omega_n = \sqrt{\frac{k}{m}} \quad (13)$$

is the natural pulsation of the system, si:

$$\varsigma_e = c_e / 2m\omega_n \quad (14)$$

is the electromagnetic damping factor. The overall damping of the system, ς, includes losses due to friction, ς_f, air resistance, etc. and is given by:

$$\varsigma = \varsigma_e + \varsigma_f = \frac{c}{2m\omega_n} \quad (15)$$

The voltage, e, and current, i, generated by system are described by equations:

$$e = \phi\dot{z} - i(R_c + j\omega L_c) \quad (16)$$

$$F_e = \phi i \quad (17)$$

where F_e, is the force generated by the electromagnetic couplig (Laplace force), R_c, and L_c are the resistance and inductance of the coil and ϕ is the transformation factor:

$$\phi = NBl \quad (18)$$

where N is the number of turns, B is magnetic induction, and l is the average length of a spiral coil (πD).

If the current is through a load of resistance R_L, the electrical generated force will be:

$$F_e = \frac{\phi^2 \dot{z}}{R_L + R_c + j\omega L_c} \quad (19)$$

Hence the electrical damping will be:

$$c_e = \frac{\phi^2}{R_L + R_c + j\omega L_c} \quad (20)$$

For the frequencies where the inductive impedance is much lower than resistive impedance, the electromagnetical damping factor will be:

$$\varsigma_e = \frac{\phi^2}{2m\omega_n(R_L + R_c)} \quad (21)$$

For the case when $\omega \approx \omega_n$, and substituting from equation (21) into equation (12), will obtain the maximum electrical power generated as:

$$P = \frac{\phi^2 Y^2 \omega_n^2}{8\varsigma^2(R_L + R_c)} \quad (22)$$

3.2.2. Experimental determinations

Experimental tests were divided into two categories initially, depending on the position of harvesting generator. It works in both horizontal and vertical position. When used in horizontal position, because its weight, mobile magnets are supported by the generator housing and at the time of vibration they have a great friction with the cylinder walls, reason for the system efficiency is reduced and dropped for

the moment this method. For the case when we use the generator in vertical position, mobile magnets are always in levitation and friction with cylinder walls are much smaller than the case when the generator work in a horizontal position where they are much reduced by using ferrofluid.
In the measurements made it was tried to keep a low frequency and low amplitude, these are the parameters especially meet in nature.
Thus, for a frequency of around 5 Hz and amplitude of 4-6 mm it was obtained an output voltage of 12 V. For a load of 1kΩ it was obtained an output power of about 1.44 mW.
Some other tests have been made using other types of magnets, both mobile and fixed, but the best results were obtained when using magnets described above. For example, there have been used mobile ring shaped magnets under the same conditions of frequency and amplitude and they had lower results although due to the form the drag was small.
For the future it is taken into consideration redesigning the harvesting generator for minimizing its dimensions and increasing its efficiency.

4. CONCLUSIONS

The documentary study about harvesting energy from environmental vibration, showed that there is a growing trends towards other renewable energy sources than those normally used to date.
If the harvesting process of energy, such as solar or wind is well done, it can be said that the harvesting energy from vibration is still in infancy. Even if these generators are not powerful they are specially designed for use in places hard to reach, usually for feeding sensor systems, having available a source of infinite power. Taking into consideration that the vibrations and movements which produce vibrations are always present in the environment, this dimension of the renewable energy can be a significant factor of interest for the future
In this paper it was studied the harvest of the energy from vibrations. It was designed and built a generator that is based on relative movement of a permanent magnet in relation to a coil.
Experimental tests were performed for a low vibration frequency, so the generator is capable to produce useful power of 1.44 mW at a frequency of 5 Hz for a load resistance of 1 kΩ.
The advantage of this device is that has low cost of production, no maintenance required and is able to harvest energy in a wide range of frequencies.

Acknowledgments

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References

[1] I. Sari, T. Balkan, H. Kulah, *An electromagnetic micro power generator for wideband environmental vibrations*, Sensors and Actuators A 145, 2008, pp 405-413.

[2] P. Glynne-Jones, M.J. Tudor, S.P. Beeby, N.M. White, *An electrormagnetic, vibration-powered generator for intelligent sensor systems*, Sensors and Actuators A 110, 2004, pp 344-349.

[3] E.P. James, M.J. Tudor, S.P. Beeby, N.R. Harris, P. Glynne-Jones, J.N. Ross, N.M. White, *An investigation of self-powered systems for condition monitoring applications*, Sensors and Actuators A 110, 2004, pp 171-176.

[4] D. Zhu, S. Roberts, M.J. Tudor, S.P. Beeby, *Design and experimental characterization of a tunable vibration-based electromagnetic micro-generator*, Sensors and Actuators A 158, 2010, pp 284-293.

[5] M. El-Hami, P. Glynne-Jones, N.M. White, M.Hill, S.Beeby, E. James, A.D. Brown, J.N. Ross, *Design and fabrication of a new vibration-based electromechanical power generator*, Sensors and Actuators A 92, 2001, pp 335-342.

[6] S. Chalasani, J. M. Conrad, *A survey of energy Harvesting sources for embedded system*, IEEE SoutheastCon 2008, pp 442-447.

[7] S. Joseph Roundy, *Energy scavenging for wireless sensor nodes with a focus for vibration to electricity conversion,* PhD Thesis, The University of California, Berkeley, 2003.

[8] R. Armirtharajah, A. P. Chandrakasan, *Self-powered signal precessing using vibration-based power generation,* IEEE Journal of Solid States Circuit, Vol 33, No 5, 1998, pp 675-679.

[9] S. Kalkarni, E. Koukharenko, R. Torah, J. Tudor, S. Beeby, Design, fabrication and test of integrated micro-scale vibration-based electromagnetic generator, Sensors and Actuators A 145-146, 2008, pp 336-342.

[10] S. Defrancesco, V. Zanetti. *Experiments on magnetic repulsion*. American Journal of Physics 51,1983.