Finite element analysis of combined magnetoelectric-electrodynamically vibration energy converter

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Abstract. In this paper we report on the design and optimization of a novel combined vibration energy harvester based on the use of electrodynamic and magnetoelectric (ME) principles to increase the energy outcome of an electrodynamic harvester without significantly increasing its size. Thereby the most important aspect is the dependence of magnetic flux variation on design parameters, as it is the decisive effect for energy conversion. Magnetic circuit form and magnetization are optimized for maximizing energy outcome. We conclude that better magnetic flux variation is reached for a magnetic circuit formed with two magnets stacked one within the other using the same magnetization. Results illustrate that the use of combined converter enables to enhance the performance of simple electrodynamic or ME converter.

1. Introduction
Harvesting energy from natural sources to power wireless devices present a big interest for research. In particular, due to the availability of vibration energy, harvesting energy from vibration sources is investigated based on electrostatic, electrodynamic [1, 2], piezoelectric [3, 4] and magnetoelectric [5, 6] principles. Developed converters have some advantages but present also some limitations such as the size, energy density and system reliability.
To improve vibration energy converter performance, different solutions are developed such as the enhancement of the electronic to improve the converter performance [7]. Also, the use of multi harvesters based on the same principle [8, 9] are investigated which enable to improve the working frequency for the converter but lead to a bulky system.
Another interesting solution is the use of combined converter based on different principles especially electrodynamic, magnetoelectric and piezoelectric [10, 11]. This method enables to enhance the energy outcome for the system and its life time. Until now, combined converters based on electrodynamic and piezoelectric present some limitations due to the aging problem of the piezoelectric material receiving an external excitation and the needed volume to realize such solution. For the combination of electrodynamic and ME principles, developed system based on cantilever beam enables to improve the converter energy outcome but still have some limitations such the size of the whole system and life time because of using the cantilever beam.
In this context, this work presents an alternative combined vibration converter based on electrodynamic and ME principles. The developed system is formed with a magnetic spring, magnetic circuit, magnetoelectric transducer and coil. This work is devoted to evaluate the
behavior of the combined vibration energy converter using finite element analysis. It is organized in three main sections. In section 1, the developed converter design is presented. In section 2, a finite element analysis model is investigated to optimize the ME transducer behavior. At the end, comparison for the combined converter with single ME or electrodynamic converter is developed.

2. Design of the combined energy converter

Combined converter design based on electrodynamic and ME principles is proposed as shown in Figure 1.(a). The electrodynamic principle is based on the relative movement between magnets and coil which leads to generate energy based on Faraday’s Law. For the ME principle, it consists on the placement of a ME transducer formed with two magnetostrictive (MS) layers and one piezoelectric in between, in a variable magnetic field environment. Due to the presence of vibration, the changing of the magnetic flux leads to a deformation on the MS layers. Receiving this stress, piezoelectric layer placed between two MS layers generates energy. In the developed concept, the magnets movement is ensured by the use of magnetic spring principle for better robustness.

![Figure 1. (a) Proposed design for the electrodynamic-magnetoelectric converter, (b) Magnetic Force for the magnetic spring](image)

The system consists on the use of magnetic spring formed with two magnets with the size of 8 mm of diameter and 2 mm of thickness placed in repulsive direction to transmit the external vibration source. The top magnet is attached to the moving part. Magnetic circuit formed with cylindrical magnets for the ME transducer is also fixed to the moving part. Second magnet, ME transducer and coil are attached to the fixed part.

For the magnetoelectric transducer, rectangular geometry is selected based on previous realized work. It is formed with two magnetostrictive layers with the size of 6 mm of length, 4 mm of width and 1 mm of thickness and one piezoelectric layer in between with the size of 7 mm of length, 4 mm of width and 1 mm of thickness.

Magnetic circuit form, size, polarization and positions are optimized to get better performance from the converter. The housing coil is placed surrounding the ME transducer with the size of 8 mm of outer diameter, 25 mm of length and 0.5 mm of thickness. The total volume for the converter is 20 cm³. Static position for the moving part is determined by the calculation of magnetic force for the magnetic spring depending on the distance between the magnets as shown in Figure 1.(b).
3. Simulation results and discussions

3.1. Definition of the finite element model

Figure 2 presents the developed finite element model for this study. The magnetic circuit is defined using cylindrical magnets. In between, we define the composite formed by two MS layers and one PZT layer. NdFeB and copper materials are used for the magnets and coil respectively. For the magnetic transducer, Terfenol-D and PZT-5H materials are used for the MS and piezoelectric layers respectively. Terfenol-D is used due to its high MS performance and its nonlinear behavior is defined using HB curve [12] from which the magnetic field \( H \) is determined relative to the magnetic flux density value. The MS layers are polarized along their length and PZT along the thickness which enables to get better performance for the MS layers. The induced voltage for the converter is related directly to the variation of magnetic field through the MS layers and coil. For that, we concentrate on the evaluation of magnetic field variation relative to different parameters such as magnetic circuit form, size and magnetization.

3.2. Optimization of magnetic circuit

The MS layers behavior is evaluated depending on different parameters. We start with the evaluation of the suitable magnetic circuit by comparing three possibilities, which consist on the use of one disc magnet (Figure 3.(a)), two separated discs magnets from each MS layer side (Figure 3.(b)) or two magnets stacked one within the other (Figure 3.(c)). The magnets size is fixed to 8 mm of diameter and 1 mm of thickness for the use of one disc magnets and to 4 mm of diameter and 1 mm of thickness for the use of two separated discs magnets. For the use of two stacked magnets, the influence of the ring magnet size is studied. Simulations are conducted for

![Figure 2. Defined finite element model for the converter](image)

![Figure 3. Proposed magnetic circuit for the converter (a) one disc magnet (b) two discs magnets (c) two magnets stacked one within the other](image)
an inner disc magnet with the size from 1.6 mm to 7.8 mm. Results show that the use of two separated discs magnets leads to the decrease of the magnetic flux density to 0.6 T as maximum (Figure 4.b) comparing to the use of only one disc magnet (Figure 4.(a)). Using two magnets stacked one within the other, same behavior is reached than the use of one disc magnet with a more higher magnetic flux density level.

We conclude that the use of ring magnet with 8 mm of inner diameter, 3.2 mm of outer diameter and 1 mm of thickness and an inner disc with the size of 3.2 mm of diameter and 1 mm of thickness enables to reach better magnetic flux density level. This is due to the concentration of magnetic flux density lines which are surrounding the MS layers.

![Figure 4](image)

**Figure 4.** Variation of magnetic flux density for bottom and top MS layers relative to the magnets position along z axis (a) one disc magnet (b) two discs magnets (c) two magnets stacked one within the other for one layer with same and repulsive magnetization

Taking into account the obtained results for the magnetic flux density variation through the bottom and top MS layers, the static position for the magnets is fixed to 18.5 mm along z axis. Figure 4.(c) presents the influence of the magnets polarization on the magnetic flux density variation. The magnet movement is limited to 2 mm. In the case of repulsive direction, magnetic flux density is limited to 0.23 T which is four time less than the reached magnetic flux density using same magnetization. We conclude that the use of two stacked magnets with same magnetization for the magnetic circuit enables to enhance the magnetic flux variation through the MS layers.

3.3. Comparison of combined magnetoelectric-electrodynamic with simple electrodynamic or magnetoelectric converter

After the determination of optimal magnetic circuit and magnetization, influence of the two principles combination is studied. Magnetic field evaluation is illustrated in Figure 5. Results show that combined converter enables to enhance the magnetic field level especially for the case of electrodynamic converter. The magnetic field is increased by 125 Oe through the coil comparing to the case of electrodynamic converter. For the magnetoelectric transducer, a small difference is observed. Therefore, due to the increase of the magnetic field through the combination of the two principles, electrodynamic-magnetoelectric converter is able to reach better performance comparing to the use of single electrodynamic or ME converter.
4. Conclusion
In this paper, optimization of combined vibration converter based on electrodynamic and ME principles is investigated. Mechanical design for the combined converter composed with magnetic spring, magnetic circuit, one ME transducer and a coil is proposed. For this purpose, the used ME transducer is formed with two MS layers (Terfenol-D) and one PZT layer in between. Through the realized finite element analysis, magnetic flux density variation through the transducer and the coil is evaluated. Results show that the use of magnets with same magnetization enables to reach higher magnetic field variation than repulsive magnetization. Finally, an enhancement of magnetic flux density is reached through the coil and the the ME transducer while combining the two principles comparing to a simple electrodynamic or ME converter.

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