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AC/DC power conversion improvement of rotational electromagnetic energy harvesting using piezoelectric elements for active rectification

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Abstract

In the present work, a cooperative hybrid energy harvester for scavenging ambient vibrations is presented. The proposed energy harvesting system exploits both piezoelectricity and electromagnetism to harvest rotational energy. More precisely, while the electromagnetic device is devoted to energy harvesting, the piezoelectric element is actually used for efficiently converting the energy of the former. Indeed, in order to improve the electromagnetic transducer's AC/DC conversion efficiency, a half-wave voltage doubler where the piezo element is driving MOSFETs is employed. Such a motivation is actually explained by the much lower conversion abilities of the piezoelectric transducer compared to the electromagnetic one in the considered structure. Simulation and experimental validations are presented, demonstrating the improvement of the energy conversion efficiency of the electromagnetic transducer.

1. Introduction

The recent expansion of wireless sensors networks (for instance, in the framework of IoT) along with the development of ultralow power consumption devices have been driving research on microgenerators converting ambient energy into electricity, and hence, the development of energy harvesting systems. Among the commonly utilized ambient energy sources (thermal, solar, radiofrequencies, etc.), kinetic energy has drawn great attention due to its high power density and ubiquity. In order to efficiently extract this form of energy on a small sale, micro-rotational energy harvesters have been developed in the last decade [1]. Rotational energy harvesting based on piezoelectric and electromagnetic conversion are the most commons ones. However, the use of piezoelectric systems in such configuration have usually been demonstrated to be less efficient than electromagnetic transducers due to their typical low power levels. On the other hand, the typical output voltage of electromagnetic systems (order of magnitude of mV), suffers from low AC/DC power conversion efficiency. A recent approach to increase the power conversion efficiency of low-power systems, is to integrate different power sources on the same system and use one of the transducer for diode biasing [2]. Nevertheless, previous works focused on systems exploiting available energies from different sources at very different frequency levels, which light not be available in all kinds of environment. Hence, in this work, a hybrid cooperative electromagnetic-piezoelectric energy harvester extracting the same energy source is proposed. The work focuses on the power conversion efficiency improvement of the electromagnetic transducer employing MOSFETs powered by the piezoelectric system.

2. Motivation and principles

The system is derived from the rotational energy harvesting system previously developed by H. Fu et al. [3] consisting of a rotating host with a cuboidal magnet (5x5mm) placed on it. A piezoelectric cantilever beam is installed below the rotating host, with a tip magnet placed at its free end. The magnetic force between the driving magnet and the tip magnet plucks the beam periodically, making it vibrate at its resonance frequency in a frequency-up conversion manner. In order to further exploit the available energy source of the system, a coil is also placed above the rotating host: the variation of the magnetic flux induced from the movement of the rotating magnet thus causes a voltage to be induced in the coil. In order to have a prelaminar evaluation of the possible power that can be extracted by the two transducers, the AC power outputs have then been measured, showing one order of magnitude of difference between the piezoelectric (10 μW) and the electromagnetic transducer (208 μW), demonstrating the inefficiency of piezoelectric systems for directly harvesting energy in rotational systems compared to electromagnetic ones. However, although the power that can be extracted from the electromagnetic system is potentially higher, the voltage output levels are lower than the typical diode threshold voltage (0.6 V), thus leading to high power losses when rectifying the AC voltage to a DC stage (as sensors need to be powered by DC voltage). To overcome this issue and increase the AC/DC power conversion efficiency of the electromagnetic transducer, typical diodes used for rectification can be replaced by MOSFETs that can be powered by the piezoelectric system.

The resulting circuit is illustrated in Fig. 1 and it consists of a half-wave voltage doubler employing p-MOS and n-MOS transistors. It is then important that the negative and positive peaks of the piezoelectric and electromagnetic voltage waveforms are well synchronized in order to properly activate the MOSFETs.

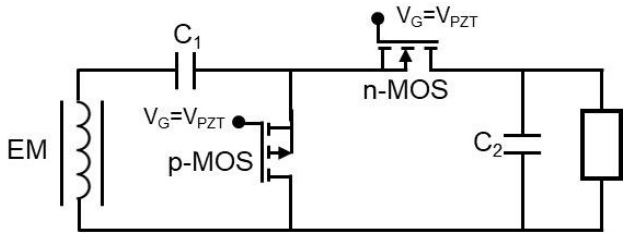

Fig. 1. Circuit schematic

2. Simulation and experimental validation

As a first validation process of the cooperative piezoelectric-electromagnetic energy harvesting system, LTspice simulations have been conducted. Simulated waveforms in the transient state are shown in Fig. 2, depicting the open circuit electromagnetic voltage and the resulting rectified signal when considering MOSFETs, Schottky diodes and standard silicon diodes.

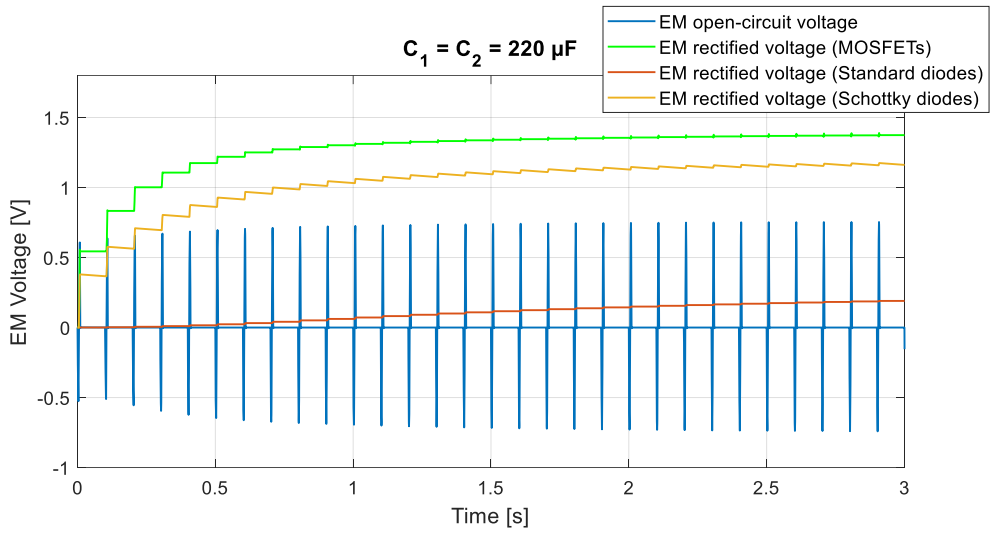

Fig. 2. Simulated waveforms

Then, the system has been experimentally validated. In order to achieve voltage peaks synchronization, the rotating host have been divided in two layers, the bottom layer containing two magnets (facing opposite polarity with respect to the piezoelectric magnet) and the top layer containing one magnet (responsible of the magnetic flux change seen by the coil) as shown in Fig. 3. The two bottom magnets are responsible of a wider amplitude of the piezoelectric voltage peaks, so that they occur at the same instant of the electromagnetic voltage peaks.

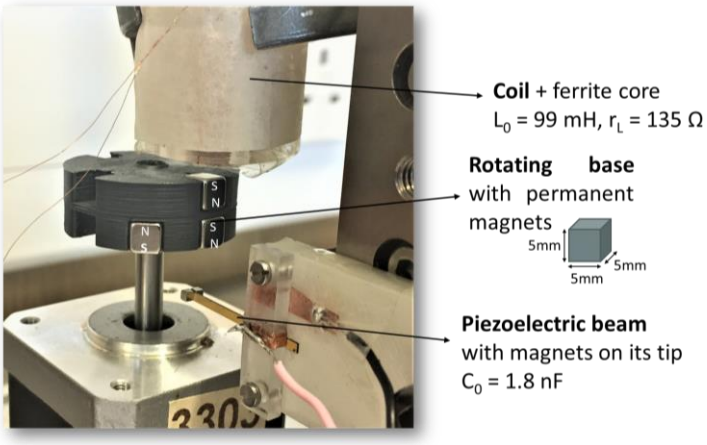

Fig. 3. Structure set-up

Fig. 4 depicts the experimental waveforms of the hybrid system along with the rectified signals when considering MOSFETs (ZVNL120A, ZVP4424A), Schottky diodes (BAT48) and standard diodes (IN4148) when no load is connected to the circuit. Subsequently, the DC power with a connected load have been measured considering the three different rectification methods, as shown in Fig. 5. It is evident from the plot how the rectification in the hybrid cooperative case allows obtaining relatively higher power conversion efficiencies, particularly when compared with the non-hybrid techniques. Table I gives a comparison among the maximum output powers and the conversion ratio between the DC output power (P_{DC}) and the AC electromagnetic power (P_{AC}) of the analysed techniques.

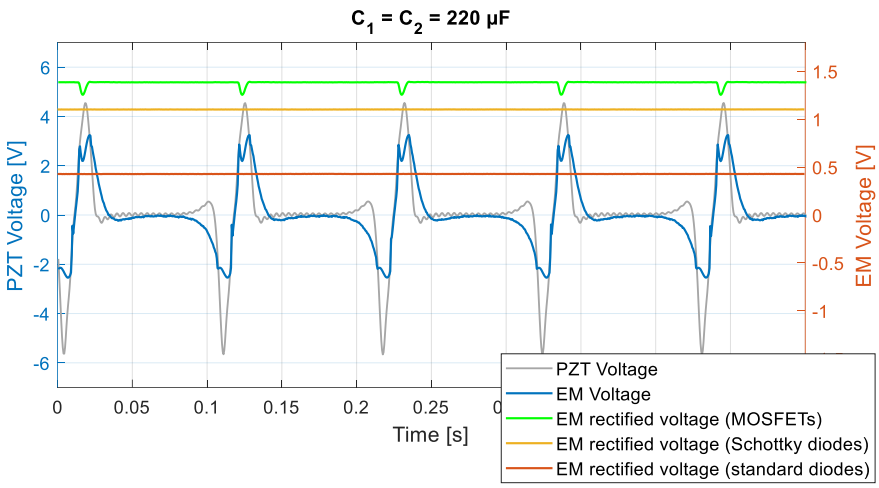

Fig. 4. Experimental waveforms

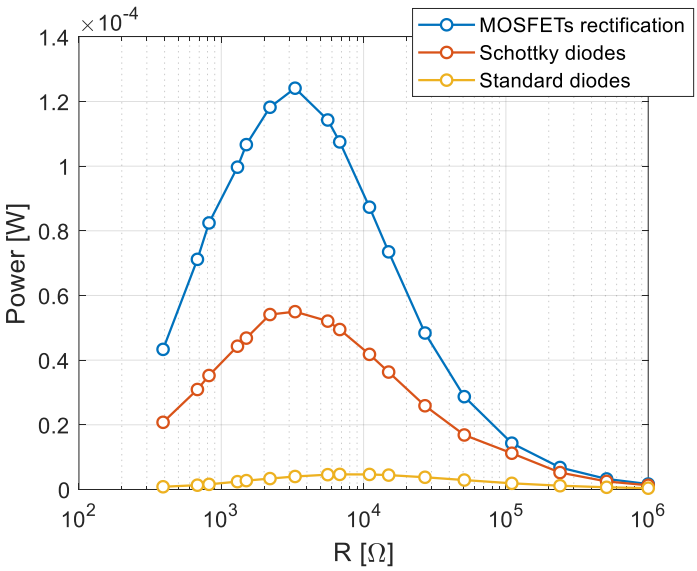

Fig. 5. Experimental harvested powers

Table 1. Output power levels comparison

Technique	Pmax	$\eta = P_{DC}/P_{AC}\ x100$
Hybrid cooperative rectification	124 µW	60 %
Schottky diodes rectification	55 µW	26 %
Standard diodes rectification	4.65 µW	2.25 %

4. Conclusion

The proposed work presented a hybrid cooperative electromagnetic-piezoelectric energy harvesting system for rectification purposes. The electromagnetic system is connected to a half-wave voltage doubler circuit employing MOSFETs powered by the piezoelectric transducer. LTspice simulations and experimental results have demonstrated the improvement of the energy conversion efficiency of the electromagnetic transducer with respect to non-hybrid and hybrid standard case.

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