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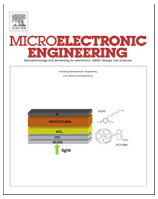

A hybrid micro vibration energy harvester with power management circuit

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ABSTRACT

In this paper, a hybrid micro vibration energy harvester based on piezoelectric and electromagnetic transduction mechanisms is developed and tested, which improves total output power and voltage in low frequency and small amplitude vibration environment. It contains a MEMS piezoelectric (PZT) cantilever array with an integrated Si proof mass, an NdFeB magnet attached to the free end of the cantilever beam, and one multi-layer micro coil fabricated using standard PCB technology placed on the fixed bottom. A mathematical model is established to calculate the output power from the hybrid energy harvester. The optimum size of the device's structure is obtained based on the finite element analysis. Experimental test results show that the maximum output power of 40.62 μW can be drawn from the hybrid energy harvester with the optimal load resistance under the vibration of 0.2 g acceleration at the resonant frequency of 55.9 Hz. The more power output can be generated than a stand-alone piezoelectric or electromagnetic device, and the output voltage is increased by using the MEMS PZT cantilever array architecture. In order to regulate the output voltage of energy transducer, a low power consumption power management circuit integrated with AC–DC rectifier and DC–DC buck converter is designed and applied in wireless sensor nodes. The test results prove that the hybrid energy harvester can provide a stable output power supply voltage of 3.6 V for wireless sensor node.

1. Introduction

Vibration energy harvesting has emerged as one of the amazing alternative approaches to battery for supplying power to wireless sensor nodes (WSN) [1–3]. Many literatures have proposed various vibration energy harvesters. However, most of them usually adopt single energy conversion mechanism, such as piezoelectric [4–8], electrostatic [9–11] and electromagnetic transduction [12–15]. The traditional MEMS vibration energy harvester based on stand-alone transduction mechanism can only generate a couple of microwatts power, and also have low output voltage (hundreds of mV). In order to supply power effectively for WSN using vibration energy harvesting technique, the output voltage and power of the energy transducer based on MEMS must be increased.

To improve the energy conversion efficiency and increase power density of energy harvester, the hybrid energy harvester based on multi-transduction mechanisms has received great attention [16–19]. Shan et al. [17] presented an energy harvester using a piezoelectric and suspension electromagnetic mechanism to enlarge the frequency bandwidth and obtain a larger energy output, but energy harvester was designed based on meso-scale architecture, and its comparatively large volume limits the application fields. Yang et al. [18] investigated a hybrid energy harvester integrated with piezoelectric and electromagnetic energy harvesting mechanisms. However, the maximum output voltage is only 0.84 V, which is difficult to be used for supplying power for the subsequent load. Rahman et al. [19] developed and examined another hybrid energy harvester that integrates with piezoelectric and electromagnetic transducer. The energy harvester used four pole magnets to produce stronger magnetic field over a stationary coil, which generated total maximum power of 5.8 mW at its resonant frequency. Similarly, it also has big volume because both piezoelectric and electromagnetic transducers are designed and fabricated based on macro-scale architecture. It is obvious that the above reported hybrid energy harvesters have great enhancement in total power output by increase the volume of transducer. Accordingly, this paper proposes a hybrid vibration energy harvester with features of lower work frequency, higher output

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voltage and more output energy. It consists of a MEMS PZT cantilever array, an NdFeB permanent magnet and multi-layer printed circuit board coils which coverts ambient kinetic energy to electricity using both piezoelectric and electromagnet conversion mechanisms. Hence, higher output power density by using hybrid energy conversion mechanisms is achieved and higher output voltage is obtained by using five PZT cantilever array instead of traditional single cantilever structure, respectively. Moreover, in order to regulate the output voltage of energy transducer, a low power consumption power management circuit integrated with AC–DC rectifier and DC–DC converter is designed and applied in wireless sensor nodes.

This paper is organized as follows. Section 2 presents the mathematical model and output power analysis of hybrid energy harvester. Structure design and optimization based on finite element analysis are discussed in Section 3. The power management circuit is proposed in Section 4. The experimental test results are illustrated in Section 5. Finally, conclusions are given.

2. Mathematical model and design analysis

2.1. Second-order spring-mass-damper model

As shown in Fig.1, the hybrid piezoelectric–electromagnetic energy harvester can be simplified as a second-order spring-mass-damper system, which consists a proof mass m, a spring k, a mechanical damping b_M, a piezoelectric damping b_P and an electromagnetic damping b_{EM}. X and Y represent the spring deflection and the input displacement, respectively. The differential equation of the movement of the mass with respect to the energy harvester can be described by Eq. (1).

$$m\frac{d^2x(t)}{dt^2}+b\frac{dx(t)}{dt}+kx(t)=m\frac{d^2y(t)}{dt^2} \tag{1}$$

This can be written in the form after the Laplace transform as:

$$ms^2x(s)+bsx(s)+kx(s)=ma(s) \tag{2}$$

where $a(s)$ is the Laplace expression of the acceleration of the vibration, it is equal to be $d^2y(s)/ds^2$. Thus the transfer function of a vibration-based micro-generator is

$$\frac{x(s)}{a(s)}=\frac{1}{s^2+\frac{b}{m}s+\frac{k}{m}}=\frac{1}{s^2+\frac{\omega_r}{Q}s+\omega^2} \tag{3}$$

where $Q=\sqrt{km}/b$ is the quality factor, $\omega=\sqrt{k/m}$ is the resonant frequency, and k is the stiffness.

As mentioned above, damping in vibration energy harvester consists of mechanical damping and electrical damping including piezoelectric and electromagnetic damping. The overall damping factor of the system ζ_T is given by Eq. (4).

$$\zeta_T=\frac{b}{2\sqrt{mk}}=\frac{b_M+b_P+b_{EM}}{2\sqrt{mk}}=\zeta_M+\zeta_P+\zeta_{EM} \tag{4}$$

where ζ_M is the mechanical damping factor, ζ_P is the piezoelectric damping factor, and ζ_{EM} is the electromagnetic damping factor, respectively.

2.2. Output power of piezoelectric energy harvester

For a basic piezoelectric unimorph cantilever energy harvester, the induced voltage across the PZT material under open circuit condition can be written as [17]

$$V_P=\frac{-d_{31}t_p\sigma_{beam}}{\varepsilon_p} \tag{5}$$

where σ_{beam} is the stress produced in the structure, t_p, d_{31} and ε_p are material properties of PZT material, representing the thickness of the PZT layer, the piezoelectric strain constant, and the dielectric constant of the PZT material, respectively. The average effective stress per unit length induced in the vibrating beam subjected to a bending moment $M(x)$ is

$$\sigma_{beam}=\frac{1}{L}\int_0^L\frac{M(x)d}{I}dx \tag{6}$$

where L is the length of the beam, d is the maximum distance from the neutral axis, I is the moment of inertia, and x is the direction along the length of the beam. The moment $M(x)$, considering the beam to be in resonance can be evaluated as

$$M(x)=(K_{beam}Y)\cdot x=\frac{ma}{2(\zeta_M+\zeta_P)}\cdot x \tag{7}$$

$$m=\frac{k}{\omega^2} \tag{8}$$

In the case of a cantilever beam, k can be calculated by expression Eq. (9).

$$k=\frac{3EI}{L^3} \tag{9}$$

$$\sigma_{beam}=\frac{1}{L}\int_0^L\frac{\frac{ma}{2(\zeta_M+\zeta_P)}\cdot x\cdot d}{I}dx=\frac{3Ead}{4L^2(\zeta_M+\zeta_P)\omega^2} \tag{10}$$

$$\zeta_p=\frac{3}{16R_L}\left(\frac{d_{31}^2t_p^2EC^2}{I\varepsilon_p^2L\omega}\right) \tag{11}$$

where R_L is the load resistance, C is the capacitance of the PZT material, and E is the modulus of the piezoelectric unimorph cantilever beam. According to the above expressions, the output power from the piezoelectric energy harvester can be written as

$$P_P=\frac{9}{64}\frac{Eac}{L^2(\zeta_M+\zeta_P)\omega^2} \tag{12}$$

2.3. Output power of electromagnetic energy harvester

The output power of a stand-alone electromagnetic transducer is given by expression Eq. (13).

$$P_{EM}=\frac{m\omega^3\zeta_{EM}Y^2}{4(\zeta_M+\zeta_{EM})^2} \tag{13}$$

where m is the quality of the electromagnetic generator, Y is the amplitude of the vibration source, ω is the resonant frequency of the system. Maximum power is delivered to electrical domain when the mechanical damping factor ζ_M should be equal to the electromagnetic damping factor ζ_{EM}. In this case, expression Eq. (13) could be simplified as

$$P_{EM\_MAX}=\frac{m\omega^3Y^2}{16\zeta_{EM}} \tag{14}$$

Not all the power from expression Eq. (14) will actually be delivered into the load. In the case of electromagnetic transduction, some of the power is lost within the coil because of the existence of the coil's resistance. The actual power delivered into the load is a function of the coil resistance and load resistance, which could be up to the maximum when the load resistance R_L should be equal to the coil resistance R_{coil}.

$$P_{EM\_LOAD}=\frac{m\omega^3Y^2}{16\zeta_{EM}}\left(\frac{R_{load}}{R_{load}+R_{coil}}\right) \tag{15}$$