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Original Research Article

A low frequency hybrid harvester with ring magnets

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ABSTRACT

Although many hybrid EH devices had been investigated by researchers, their performances at different operating resonance frequencies were not reported. Radial magnetic field was reported as the most efficient architecture to use in electromagnetic energy conversion, this was utilized in the design of a low frequency and efficient hybrid harvester comprising piezoelectric (PZT) and electromagnetic generators. FE simulation was used to obtain the magnetic field, design the coil and locate its position relative to the magnets. The electromagnetic generator consists of ring magnets which act as proof mass, with a hanging coil inside. The harvester was tested at frequency range of (34–40) Hz, produced maximum power of (710) μW. The maximum normalized power density and maximum efficiency of the harvester are (2.272) mW/cm^3/g^2 and (30.1%) respectively, at frequency of 36 Hz and induced acceleration of (0.25) g. The new hybrid harvester has a higher normalized power density compared with others.

Introduction

Piezoelectric and electromagnetic transducers are considered best suited to recover energy from mechanical vibrations [1]. The systems are used separately, but the combination of the two features multi functionality, and produces a hybrid generator. In the PZT generator, the proof mass may be used as part of an electromagnetic generator in addition to its function in tuning the frequency and enlarging the amplitude while the material of the suspending structure of an electromagnetic generator may be PZT, thus making additional use of it in producing power [2]. A vibration based generator produces maximum power at its resonant frequency which should match the ambient vibration frequency. Increasing the operation frequency range may be achieved through tuning or increasing the band width.

Wischke et al. [3] presented a double-side suspended hybrid generator with two magnets fixed at the middle of a PZT beam, to obtain more power from the magnets vertical movement, and conductors. The experimental tests covered different arrangements of magnets, inductors, and different interconnections of the bimorph layers with the conductors. The PZT and the electromagnetic generators produced (300) μW and (120) μW respectively, at resonant frequency of (753) Hz and acceleration of (10) m/s^2.

Khaligh et al. [4] built a mathematical model of the output power for a piezoelectric-electromagnetic hybrid power generation system by using an equivalent spring-mass-damping second-order vibration model, feasible to harvest energy from normal range of human activities for powering wearable electronic devices. The proposed design consists of a vibrating square disc connected to four PZT springs; the disc has a central hole with a copper coil placed inside and two permanent magnets fixed on top on opposite sides. Output powers of (37) mW and (6) mW for the electromagnetic and piezoelectric conversion parts respectively were expected from the proposed structure.

Karami and Inman [5] considered three coupling systems in building a unified mathematical model of a piezoelectric-electromagnetic hybrid harvester; the cantilever mechanical vibration system, the piezoelectric energy generator and the electromagnetic energy generator. Variations in excitation frequency and damping ratio effects were considered and a unified approximation method for a linear, softly nonlinear and bi-stable nonlinear energy harvester was established. Linear, nonlinear mono-stable and bi-stable hybrid energy harvesters were investigated as a case studies and the approximation method was found accurate.

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Challa et al. [6] presented a hybrid harvester consists of PZT and electromagnetic parts. To maximize the efficiency, the electrical damping induced by the energy harvesting mechanism was matched to the mechanical damping in the system by altering the effective magnetic field density through altering the relative displacement between the coil and the magnet. A maximum power of (332) μW at resonance frequency of (21.6) Hz was obtained and a power density of (9.5) μW/cm^3 was reported. A theoretical model was developed which agreed closely with the experimental results. Another device in the d_{33} mode was also tested, maximum power of (182) μW and power density of (3.2) μW/cm^3 were reported for the second device.

Yang et al. [7] reported a hybrid generator consists of a multi-layer piezoelectric cantilever, permanent magnets, and a substrate of two-layer coils. Different number of magnets and magnets locations were explored. The device produced maximum output power and voltage of (176) μW and (0.84) V respectively from the PZT part, and (0.19) μW, (0.78) mV for maximum output power and voltage respectively from the coils, under acceleration of (2.5)*g* and frequency of (310) Hz. Power densities of (790 and 0.85) μW/cm^3 were derived for the piezoelectric and electromagnetic sides respectively.

Beker et al. [8] proposed a hybrid harvester design for keyboards applications; it constitutes a PZT cantilever with a magnet proof mass and a planar coil. The dome structure under the keyboard was modified to support energy harvesting. A frequency-up-conversion technique was used in the design and a total power of (19.76) μW was expected. Wacharasindhu and Kwon [9] developed a micro-generator based on the piezoelectric and electromagnetic principles, and the mechanical energy from finger keystrokes. Maximum harvested powers of (40.8) μW with a (3) MΩ load from piezoelectric conversion and (1.15) μW with a (35) Ω load from electromagnetic conversion were obtained. An array build up possibility was claimed.

Shan et al. [10] presented a hybrid harvester comprising PZT bimorph and a magnetic levitation system consists of two outer disc magnets, fitted at the ends of a hollow cylindrical casing with a center magnet in between. The outer magnets repelled the center magnet. A spiral coil was wound around the casing at the center magnet level. The magnets, casing and the coil acted as a proof mass for the bimorph. At input acceleration of (5) m/s^2, the electromagnetic part produced maximum power of (8.46) mW at a frequency of 9 Hz whereas the PZT part produced maximum power of (19.9) m W at resonance frequency of (16) Hz.

Shan et al. [11] reported a new mathematical model for a piezoelectric electromagnetic hybrid energy harvester comprises two vibrating square magnets with a stationary coil in between. The experiments produced a peak output power of (4.25) mW for the hybrid harvester; it represented an increase of (13.3%) over the single piezoelectric harvester. Experiments results verified the numerical analysis. Values of efficiencies, induced acceleration and power densities were not reported.

A multimodal hybrid harvester was presented by Tadesse et al. [12]; the device consists of six piezoelectric plates bonded on both sides of a trapezoidal cantilever at maximum stress locations. Trapezoidal shape produces more uniform strain distribution along the cantilever length. An attached permanent magnet at the tip of the cantilever acted as proof mass in addition of being part of the electromagnetic generator. The harvester was tested at its first and second modes of (20, 300) Hz with induced acceleration of (35)*g*. The prototype produced powers of (0.25) W from the electromagnetic mechanism and (0.25) mW from the piezoelectric mechanism at resonant frequency of (20) Hz. The calculated volumes of the electromagnetic system and the piezoelectric system were (8.3106 and 3.6231) cm^3 respectively. The harvester produced negligible or no power at acceleration below (5)*g* according to the performance curves.

Two degrees of freedom (TDOF) based hybrid harvester was introduced by Wang et al. [13]. A mathematical model based on the second order differential equation of motion and equivalent electrical circuits was derived and used to investigate the effect of the effective electromechanical coupling coefficients (for the PZT and the electromagnetic generators) on the maximal power outputs from various harvester configurations. Two piezoelectric elements bonded symmetrically to a brass clamped beam constitute the PZT generator. The electromagnetic generator consists of a spring, a magnet, and a cylindrical coil. The hybrid harvester was tested with induced acceleration of (0.1)*g*, in a frequency range of (65–95) Hz, produced two peaks and maximum power output (2.16) mW compared with (1.68 and 0.96) mW from the TDOF stand-alone electromagnetic and PZT generators respectively.

A comparison of different electrodynamics transducer architectures using numerical simulations was performed to find the most efficient magnetic field orientation, the study concluded that an opposing magnet architecture which produces radial magnetic field in the gap between the magnets has the highest transduction coefficient [14]. Our previous work [15] took this into consideration and introduced the ring magnet hybrid energy harvester. This paper is a continuation where finite element (FE) was employed in obtaining the ring magnets characteristics and designing a coil for the electromagnetic part of the hybrid harvester accordingly.

Theory

Williams and Yates [16] developed a generic model based on inertial kinetic energy for power calculation of energy harvesters. The model considers a forced vibration lumped mass second order dynamic system. The instantaneous dissipated power (P) within the damper for a sinusoidal vibration signal equals the product of the velocity and the damping force. Eq. (1) was derived and used to compute the maximum output power.

$$P_{emax} = \frac{ma^2}{16\zeta_m \omega_n} \quad (1)$$

where (P_{emax}) is the maximum electrical power that can be extracted from the system, (m) is the vibrating mass, (ζ_m) is the mechanical damping ratio and (ω_n) is the system resonant frequency.

The mechanical damping ratio can be determined using Eq. (2) for logarithmic decay

$$\zeta_m = \frac{\ln\left(\frac{a_1}{a_2}\right)}{2\pi n} \quad (2)$$

where (a_1, a_2 and n) represent the amplitudes of the first cycle, the last cycle and the number of cycles considered respectively.

In energy harvesters, the electrodynamics transduction coefficient (K) or what is sometimes called the coupling coefficient is an important parameter which affects the degree of transformation of mechanical energy to electrical energy. Cheng et al. [17] used the coupling coefficient in rewriting Eq. (1) for electromagnetic generators as

$$P_{emax} = \frac{(ma)^2}{8b} \times \frac{1}{\left(\frac{R_{coil} b}{K^2}\right) + 1} \quad (3)$$

where (b and R_{coil}) are the damping coefficient and the coil resistance of the generator (Ω).

For a coil crossing radial magnetic field, a parameter named coupling strength (γ) was introduced which is given by