Energy Conversion and Management 153 (2017) 1–11

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Design and experiment of hybridized electromagnetic-triboelectric energy harvester using Halbach magnet array from handshaking vibration

M. Salauddin, M.S. Rasel, J.W. Kim, Jae Y. Park*

Department of Electronic Engineering, Kwangwoon University, 447-1 Wolgye-dong, Nowon-gu, Seoul 139-701, Republic of Korea

ARTICLE INFO

Keywords:
Handshaking vibration
Halbach magnet array
Hybrid energy harvester
Electromagnetic
Triboelectric

ABSTRACT

We have proposed a new design of hybridized electromagnetic-triboelectric energy harvester using Halbach magnet array from handshaking vibration and validated it theoretically and experimentally. The Halbach array helps to enhance the magnetic flux density and reduce the overall volume as well as generate high power at low frequency. In particular, the proposed dual Halbach array allows the concentrated magnetic flux lines to interact with the same coil in a way where maximum flux linkage occurs. To obtain much higher power generation in low amplitude and low frequency vibrations, the proposed harvester was comprised of a Halbach magnet array, sandpaper passed microstructure PDMS, TENG, and magnetic springs. A prototype of the hybridized energy harvester has been fabricated and tested both using a vibration exciter test and by manual handshaking. Under vibration exciter test, the fabricated prototype of hybridized harvester delivered a high output current and power of 2.9 mA and 11.75 mW, respectively, corresponding to a volume power density of 381 W/m^3 under a loading resistance of 1.39 kΩ at 5 Hz resonant frequency and 0.5 g acceleration. It is also capable of delivering output current and power of 2.85 mA and 8.1 mW, respectively, by handshaking vibration. The fabricated hybridized harvester exhibited much higher power density than the recently reported similar works. Our proposed work takes a significant step toward hybrid energy harvesting from human-body-induced motions such as handshaking, walking, running and its potential applications in self powered portable electronics.

1. Introduction

Eliciting energy from mechanical vibration has pulled much concentration during the last few years, by reason of its capability in nature, and unlimited lifetime. Although various vibration sources, such as water and wind flow, rotary motion, and human and machine motion generate vibrations of different frequencies and amplitudes, maximum vibrations are of low frequencies and big amplitudes, with a variety of rotational movements in various directions. Generally used skills for energy harvesting from mechanical vibrations are electromagnetic [1–4], electrostatic [5], piezoelectric [6–8], and triboelectric [9–11] mechanisms, among which electromagnetic and triboelectric generators are the two most suitable approaches. The electromagnetic generator can also work from the relative movement between magnet and coil. Also, the use of a Halbach magnet array in an electromagnetic energy harvester, instead of a single magnet, increases the magnetic flux density, which in turn partially addresses the power generation issues at low frequencies [12,13]. The electrostatic mechanism is based on repeated charge pumping with variable capacitors, while the piezoelectric mechanism is based on the reconfiguration of unbalanced dipole moments. Recently, the triboelectric nanogenerator (TENG) has been highlighted, because of its high power and low fabrication cost. The TENG can scavenge the mechanical energy from the contact/separation between two triboelectric materials. Despite the continuous improvement of small-scale mechanical energy harvesters, the level of output energy still needs to be improved to meet the requirements of commercial electronic systems, and to further expand their fields of application. By combining two types of mechanical energy scavenging cells, more electricity can be turned out from one mechanical movement, which may convene the power desires of a number of portable electronic devices. A hybrid mechanical energy scavenging process may increase the overall output power [14–16]. Zhang et al. proposed a contact-separation mode hybrid energy harvester with implanted planar coil, which is proper to generate strong instantaneous power [17]. Wu et al. introduced a single electrode based hybrid energy harvester, and analyzed the advantages in charging performance [18], while Han et al. proposed a small size magnetic assisted hybrid energy harvester that could be applied as a self-powered tilt-sensing system [19].

In this work, a hybridized electromagnetic-triboelectric energy

* Corresponding author.
E-mail address: jaepark@kw.ac.kr (J.Y. Park).

http://dx.doi.org/10.1016/j.enconman.2017.09.057
Received 17 July 2017; Received in revised form 12 September 2017; Accepted 20 September 2017

harvester is newly proposed, designed, and developed using a dual Halbach magnets array excited by human hand motion. A Halbach array is an order of magnets that raises the magnetic strength on one hand of the array, while minimizing the magnetic field to nearly zero on the other side of the array (see details Fig. S1 in supporting information). The proposed hybrid EMG and TENG can deliver an output power much higher than that of the individual energy-harvesting units, due to the combined operation of EMG and TENG mechanisms under the same mechanical movement. Section 3 discusses the modeling, design, and the fabrication method of a prototype hybridized energy harvester. Section 4 analyzes and discusses the experimental results and the realistic performance of the fabricated harvester prototype based on the proposed system architecture. Finally, Section 5 concludes the paper.

2. Motivation of hybrid energy harvester for handshaking vibration

Self-sufficient process uses are normally limited by the power issue operational lifetime, such as when battery replacement is complicated, or costly. The device capability and lifespan is usually determined by making a compromise between battery size and battery life. An additional concern is the environmental issue of battery disposal. Worldwide, millions of batteries are discarded and dumped in sanitary landfills, where heavy metals can result in groundwater contamination. Consequently, solutions that reduce or keep away from battery disposal will definitely supply an environmental benefit. As society searches for different energy sources for power generation, energy harvesting research has gained significance. A few efforts have been made to scavenge energy from fundamental human behaviors, for example limb movement, running, finger shaking, and walking [20–24]. While most of these devices are wearable on different places of the human body, they are quite uncomfortable. In this case, we intend to design a hybrid electromagnetic and triboelectric energy harvester to be applied for powering or recharging the batteries of portable smart devices from hand-shaking vibration. A hybrid EMG and TENG can deliver an output power much higher than that of the individual energy-harvesting units, due to the combined operation of EMG and TENG mechanisms [15]. We have observed the basic human activities e.g., walking, running, jumping, exercising etc. However, people only perform these activities occasionally and/or sporadically since most of their time is spent on their regular working tasks. Moreover, any vibration energy harvester performs better in harmonic excitation rather than random excitation. Most of the human activities such as running, jumping, exercising etc. cannot produce harmonic excitation; it produces random excitation in different directions. Mia et al. [25] reported the characteristics of handshaking vibration, showing that the vibration is nearly harmonic with low frequency (2.5 ~ 6 Hz) and high amplitude (15 ~ 20 ms^{-2} peak acceleration). In order to address the challenge of harvesting energy from the vibration of frequency below 6 Hz, a handshaking vibration driven hybrid electromagnetic and triboelectric energy harvester architecture has newly been designed. Fig. 1 shows the reasonable design in this work, in which the electromagnetic generator (EMG) and triboelectric generator (TENG) are integrated in a suspended structure by magnetic springs as a hybrid cell.

3. Modeling and design of electromagnetic and triboelctric harvester

3.1. Analytical modeling of EMG and TENG

We have proposed of hybrid energy harvester model reports in plan movement and we avoid the acceleration due to gravity g. The motion equation from Newton's second law is given by [26]

$$m\ddot{x} + c_t(\dot{x}-\dot{z}) + k(x-z) + k_n(x-z)^3 = 0 \quad (1)$$

where, m is the moving mass of both dual halbach array frame, c_t is the

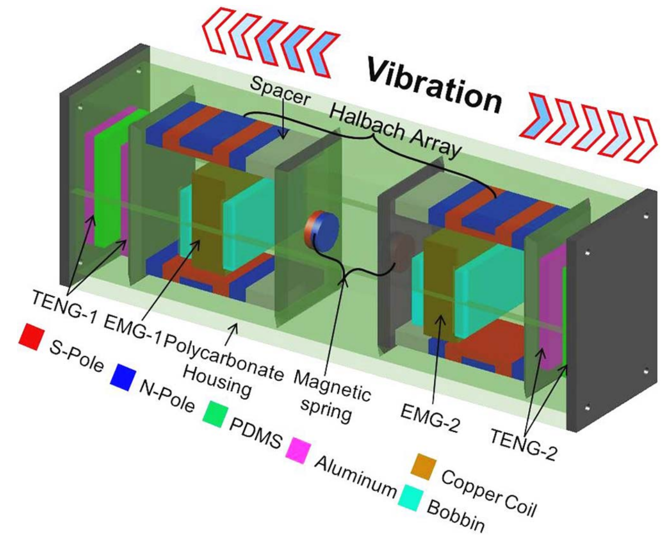

Fig. 1. Schematic structure of handshaking vibration driven hybrid energy harvester using halbach magnet array.

total damping coefficient equal to the sum of mechanical and electrical damping, k and k_n is the linear and nonlinear spring constant, x is the displacement amplitude of the both dual Halbach array structure, and z is the rectangular housing displacement amplitude. The electrical damping coefficient is $c_e = \frac{(NBl)^2}{R_L + R_C}$, where R_L the load resistance is and R_C is the coil resistance.

Repulsive magnetic force of the spring magnet is [27]

$$F_s = \frac{\mu_0 Q_1 Q_2}{4\pi d_1^2} \quad (2)$$

where μ_0 is the magnetic permeability of free space, d_1 is the separation distance between the front-facing spring magnets, and Q_1 and Q_2 are the magnetic-field intensities of the spring magnets that are attached to the both Halbach-array structure. At this point, $Q_1 = Q_2 = H_c A$, H_c the coercive force and the pole surface area $A = \pi r^2$ of the corresponding spring magnet.

When the force is applied directly to the Halbach array mass, the equation of motion of the hybrid structure is given by

$$\ddot{x} + 2\xi\dot{x} + \omega_1^2 x + \frac{k_n}{m}x^3 = \frac{F_1 \cos\omega t}{m} \quad (3)$$

When y= x−z, the modify equation (1) and equation (3) can be written in conditions of displacement between both dual Halbach array frame and the harvester housing as follows

$$\ddot{y} + 2\xi\omega_1 m\dot{y} + \omega_1^2 y + \frac{k_n}{m}y^3 = F_1 cos\omega t \quad (4)$$

where, damping ratio $\xi = \frac{c_t}{2\omega_1 m}$, resonant frequency $\omega_1 = 2\pi f_0 = \sqrt{\frac{k}{m}}$, and the excitation force $F_1 = \omega^2 Y_0$. The modified frequency response by solving equation (4) is

$$\left(\frac{3k_n}{8m\omega_1}\right)^2\alpha^6 + \left\{\frac{3}{4}\frac{k_n}{m}\left(1-\frac{\omega}{\omega_1}\right)\right\}\alpha^4 + \{(\omega-\omega_1)^2 + (\xi\omega_1)^2\}\alpha^2 - \left(\frac{F_1}{2\omega_1}\right)^2 = 0 \quad (5)$$

The full derivation can be found in Ref. [26]. Eq. (5) gives the frequency response amplitude for the relative displacement amplitude (α) of the moving magnet attached to the both dual halbach array structure against the excitation frequency (ω), where the relative displacement is $y = \alpha cos(\omega t - \varnothing)$ and the predicted relative velocity is $\dot{y} = -\alpha\omega sin(\omega t - \varnothing)$.

For EMG, the e.m.f (electromotive force) voltage induced in the coil is [3]