Nano Energy 23 (2016) 50–59

Contents lists available at ScienceDirect

Nano Energy

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

Hybrid energy harvester with simultaneous triboelectric and electromagnetic generation from an embedded floating oscillator in a single package

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ARTICLE INFO

Article history:
Received 20 January 2016
Received in revised form
24 February 2016
Accepted 1 March 2016
Available online 11 March 2016

Keywords:
Energy harvesting
Triboelectric nanogenerator
Electromagnetic induced generator
Hybridization
Packaging
Circuit

ABSTRACT

Hybridization of two energy harvesters with different mechanisms in one device is a fascinating idea, but a rational design of a hybrid energy harvester for practical applications is challenging. In this work, a floating oscillator-embedded triboelectric-electromagnetic (FO-TEEM) generator is proposed. A triboelectric nanogenerator (TENG) component and an electromagnetic generator (EMG) component independently but simultaneously produce power using the shared floating oscillator. This floating oscillator-based configuration enables versatile energy harvesting capability, excellent size scalability, self-packaged structure, and operation at frequencies in the sub-10 Hz range. Under sinusoidal vibrations with 7.5 Hz frequency, the TENG and the EMG components produced normalized output power of 130 W/kg m^3 and 128 W/kg m^3, respectively. The charging characteristics were analyzed to design an effective operation scenario. From experimental results, it was found that the TENG component provides consistent charging characteristics, while the EMG component provides fast charging speed. The hybrid device provides both advantages. Using stored electrical energy collected from the FO-TEEM generator, commercial products were successfully powered including an LED lamp, a portable fan, wireless illuminance sensor system, and charging of a smart phone.

1. Introduction

With recent advances in electronics, both the size and required operating power of wearable and portable devices, implantable devices, and wireless sensor networks (WSN) have been scaled down intensively. These small-scale wireless systems are usually powered by a battery, but there is increasing demand for an alternative power source because of an inevitable recharging process and limited lifetime of the battery. Harvesting small-scale energy from wasted ambient sources has become an attractive approach for a sustainable, reliable, and cost-effective system [1]. Numerous energy harvesters have been developed using various kinds of energy sources and mechanisms. In particular, mechanical energy harvesters have attracted special interest because of the abundance of sources of vibrations in the immediate environment, including machinery operation, roads, bridges, airflow, water waves, and human motions.

Traditional mechanisms that have been exploited in mechanical energy harvesters include the piezoelectric [2–5], the electrostatic [6,7], and the electromagnetic mechanisms [8–11]. The piezoelectric mechanism is based on the reconfiguration of asymmetric dipole moments, while the electrostatic mechanism is based on repeated charge pumping with variable capacitors. The electromagnetic mechanism is based on the current induced by Lenz's law. More recently, the triboelectric nanogenerator (TENG) has been highlighted due to its high output power and low fabrication cost [12–24]. In the TENG, strong static charges are formed by a contact electrification process, and the static triboelectric charges induce mobile charges of opposite polarity at metal electrodes. When mechanical actuation pulls the triboelectric layer in or out, current is generated between the electrodes to rebalance the mobile counter charges.

Despite the continuous development 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. One promising approach has been to design a hybrid energy harvester that combines two energy harvesting mechanisms within a single device [25–31]. For instance, Hu et al. introduced a hybridized energy harvester based on single-directional floating

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http://dx.doi.org/10.1016/j.nanoen.2016.03.004

structure, and energy-generating vibration isolator was successfully demonstrated [26]. Han et al. introduced small-size magnetic-assisted hybrid energy harvester, which can be applied as self-powered tilt sensing system [27]. Zhang et al. proposed contact-separation mode hybrid energy harvester with embedded planar coil, which is suitable to generate strong instantaneous power [28]. Wu et al. presented single-electrode mode hybrid energy harvester and analyzed advantages in charging performance [29].

Despite the attractiveness of the concept, implementing a practical hybrid energy harvester design that is more efficient than just adding or stacking parallel components is challenging. Two prerequisite conditions need to be resolved to construct a practical hybrid energy harvester. First, the performance of the system components should not be altered by the hybridization. To accomplish this, the two mechanisms should be systematically cooperative without any destructive interaction. Second, the conversion efficiency normalized by the total mass of the hybrid generator needs to be greater than the simple arithmetic sum of the individual harvesters. The hybrid device inevitably involves an increase in mass compared to a single-type device, and there should be a benefit in the normalized output energy as well as the absolute output energy. Simply stacking two generators may increase the output power but that does not mean there has been an increase in efficiency. In this regard, a portion of the mass of the system should contribute to both generation mechanisms. Considering the operating requirements and recent application demands, it is timely to design a practical hybrid energy harvester.

In this work, a floating oscillator-embedded triboelectric-electromagnetic (FO-TEEM) generator is proposed as a hybrid energy harvester platform. The FO-TEEM generator simultaneously utilizes both the mechanisms of a TENG and an electromagnetic generator (EMG). Input mechanical energy is first converted into the repeating oscillations of the floating oscillator, and the repeating oscillations activate sliding electrification at the sidewall as well as provoking time-varying magnetic flux inside the tube. The oscillator-based operation of the FO-TEEM generator offers high versatility to various kinds of mechanical excitations such as an incident impulse and sinusoidal vibrations. In addition, the bidirectional magnetic repulsion configuration results in wide operating frequency in sub-10 Hz range, which is commonly existed in human body motion and usual ambient. Because the structure is based on case-encapsulated oscillator with magnets at both ends, the FO-TEEM generator is naturally self-packaged, so undesired environmental factors comes from humidity and debris can be blocked.

2. Experimental methods

2.1. Fabrication of the oscillator

In this work, a sugar handicraft was used to fabricate the porous PDMS sponge in a specific shape [32,33]. First, a circular tube with an inner diameter of 13 mm and a height of 30 mm was prepared. Then a magnetic rod with a diameter of 7 mm and a height of 30 mm was placed in the center of the tube. The empty space between the tube and the core magnetic rod was filled by wet xylose sugar. After natural drying for 3 days in air, the sugar layer was hardened and maintained its original circular shape even after the removal of the tube. The bottom part of the sugar-coated magnetic rod was then dipped into the polydimethylsiloxane (PDMS) solution (Sylgard 184). After 3 h, the PDMS solution filled the airgaps between the sugar particles by capillary force. The PDMS-filled rod was then baked in an oven (110 °C, 20 min) to solidify the PDMS layer. The solid PDMS-filled rod was subsequently dipped into water and sonicated for 1 h. After the sonication, the sugar layer was selectively removed and only the PDMS layer remained. The PDMS-coated magnetic rod was then dipped into a polytetrafluoroethylene (PTFE) solution (solvent: FC-40) and dried on hot-plate (110 °C, 24 h). During this process, the PTFE solution was smeared into the porous sponge with good step coverage. At this stage, the PTFE-coated PDMS sponge with the core magnetic rod was completely fabricated, and could be used as the floating oscillator of the FO-TEEM generator.

2.2. Al nano-grass formation

An Al nano-grass structure was formed using a water-assisted oxidation process [34]. First, two Al electrodes were separated from the case and subsequently cleaned by acetone, methanol, and isopropyl alcohol. The cleaned Al electrodes were dipped into water of 90 °C for 30 min. During this process, the nano-grass structure is chemically formed on the surface of the Al electrodes. Then the processed electrodes were dried in air and reassembled into the FO-TEEM generator for further experiments.

2.3. Electrical measurement apparatus

A function generator (33120, HP) first generated an electric signal and sent it to an electrodynamic shaker (LW-140-110, Labworks). The head of the electrodynamic shaker operates according to the signal shape and frequency provided by the function generator. The shaker produces an impulse train movement when the function generator sends a ramp wave signal, and the shaker produces a sinusoidal vibration movement when the function generator sends a sine wave signal. The corresponding output voltage and current from the devices were measured by electrometer (Keithley 6514).

3. Results and discussion

3.1. Device structure

Fig. 1a depicts the structure of the TENG component, the EMG component, and the FO-TEEM generator. The FO-TEEM generator consists of a circular hollow tube and a cylinder-shaped oscillator embedded inside the tube (Fig. 1b). The oscillator is floating inside the tube by the bidirectional magnetic repulsive forces. The frame of the tube is made of polyethylene (PE). The top and bottom ends of the tube are blocked by permanent magnets (NdFeB). The magnets have a hole in their center in order to make an air tunnel to prevent undesired air damping (Fig. 1c). The air hole can be replaced by a porous membrane to protect the hybrid generator from air-born dust and moisture when it is operated in an open air environment. At the two ends of the tube, the inner sidewall is partially covered by two Al electrodes. The two electrodes for the TENG component are electrically connected to the outside via small feedthrough holes in the tube sidewall. The Al electrodes are designed to be a C-shape to prevent an undesired eddy effect (Fig. 1c). The surface of the Al is modified to have a nano-grass structure to increase its effective surface area, which results in higher triboelectric charge density (Fig. 1d). Along the top and bottom ends of the outer wall of the tube, two coil spools wound with 1000 times each are formed. The coil spools are electrically connected to induce constructive electricity.

The floating oscillator is composed of a core magnetic rod and a polydimethylsiloxane (PDMS) sponge surrounding the rod. In addition, the outer surface of the porous PDMS sponge is coated with a polytetrafluoroethylene (PTFE) layer (Fig. 1e–f). The detailed fabrication procedure of the floating oscillator is described in the