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• **LETTER** •

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A power manager system with 78% efficiency for high-voltage triboelectric nanogenerators

Lichuan LUO[1,2], Dechun BAO[1], Wuqi YU[1], Zhaohua ZHANG[2*] & Tianling REN[2*]

[1] *Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing* 100083*, China;*
[2] *Institute of Microelectronics & Tsinghua National Laboratory for Information Science and Technology* (*TNLIST*)*, Tsinghua University, Beijing* 100084*, China*

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Dear editor,

The Internet of Things (IoT) refers to a growing trend to create relatively simple devices that interconnect and share data independent of computers or human intervention [1]. In these applications, a continuous power supply system is necessary. There are many research studies that focus on environmental energy for self-powered portable electronics, which can minimize battery consumption and extend cell life. This is the field of nanoenergy, which is power for the sustainable, maintenance-free, and self-powered operation of nanosystems [2]. Recently, Professor Wang invented the triboelectric nanogenerator (TENG), which is used to convert mechanical energy into electricity by a conbination of triboelectrification and electrostatic induction [3]. A TENG in a circuit forms a very high resistance, as materials with strong triboelectrification effects are more like insulators. A power-switching circuit was designed to collect energy to power a sensor, microcontroller, or wireless transducer [4]. The integrated circuit (IC) is an ideal solution to supply high efficiency and a seamless connection between a collector of energy and a battery. In this paper, a novel power manager is introduced to provide low current and high voltage with high efficiency to store power. This makes nanoenergy power sources available and stable [5].

The modes of the TENG include a vertical contact-separation mode, in-plane sliding mode, and single-electrode mode [6]. The actual TENG has a bottom stator and a top rotor. On the rotor board there is a radial array of copper gratings, each of which has a length of 7.2 cm and a central angle of 9°. The output voltage and the current of the TENG were tested as shown in Figure 1 (c) and (d). The average of voltage $V_{\rm in}$ is approximately 240 V, and the maximum value is approximately 400 V. The average of current $I_{\rm in}$ is approximately 1.17 mA, and the maximum current can be 2 mA, which cannot directly access the backend.

In this paper, the backend is directly integrated with the TENG through an LTC3330 chip. This chip can solve the problem of huge energy loss. The LTC3330 module contains an energy-harvesting bridge shunt, energy-harvesting buck, prioritizer, status outputs, sleep comparator, buck boost, pin-strapped configurability, low dropout (LDO) regulator, and super capacitor balance. The full-wave energy bridge rectifier can directly turn alternating current AC energy-harvesting sources to the direct current DC. An energy-gap reference signal is used to prioritize between the battery and environmental energy. When environmental energy is available and the voltage is higher

* Corresponding author (email: imezzh@hotmail.com, RenTL@tsinghua.edu.cn)
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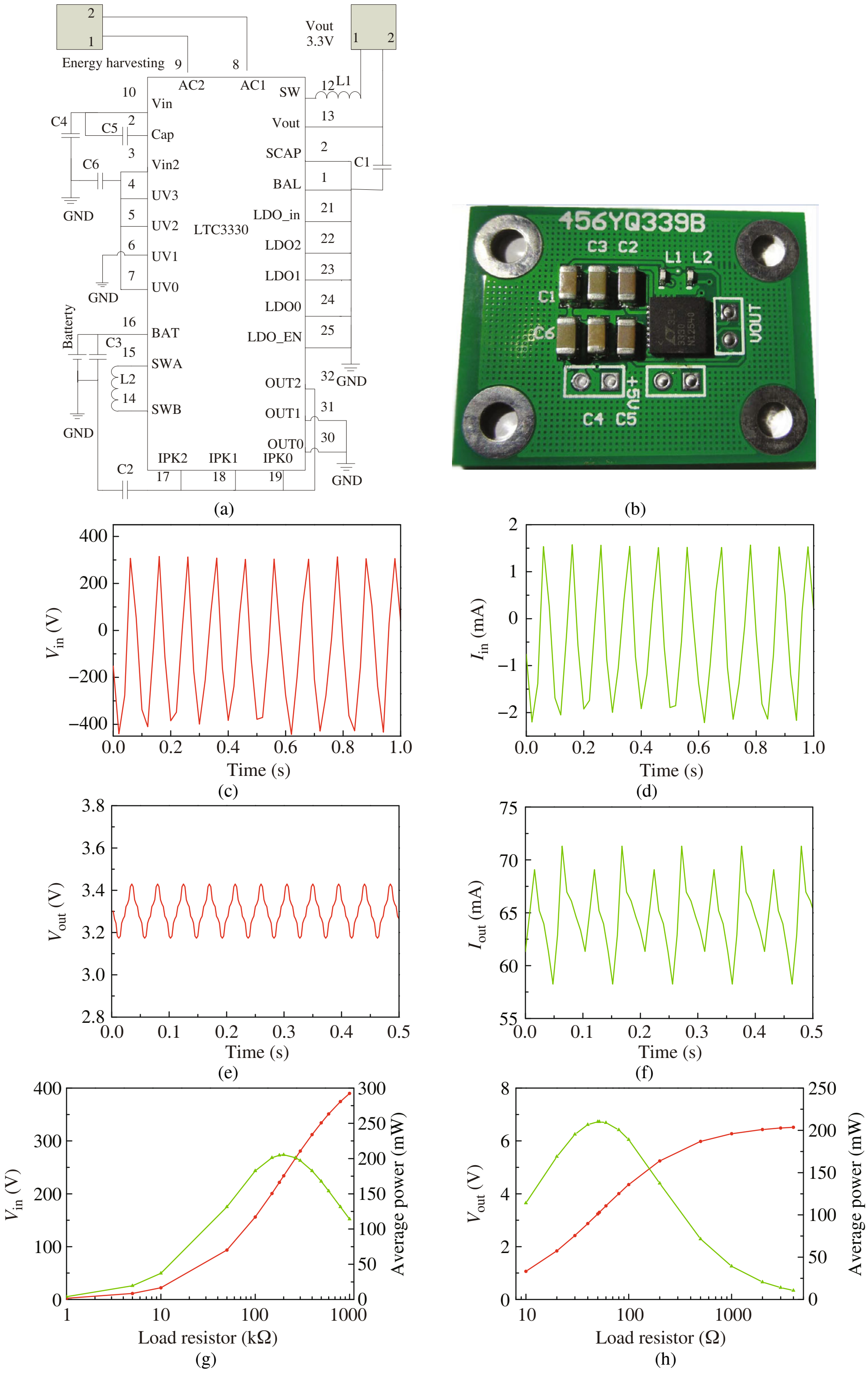

Figure 1 (Color online) Optical photo of energy-harvesting system sample and test results. (a) The actual design circuit; (b) PCB sample of the system; (c) output voltage of the actual TENG; (d) output current of the actual TENG; (e) actual output voltage of power manager; (f) actual output current of power manager; (g) output voltage and average power of the TENG with different load resistors; (h) output voltage and average power of power manager system with different load resistors.

than the output voltage, the buck control module is woken up through energy harvesting. The synchronous buck converter is an ultralow quiescent current power supply tailored to energy-harvesting applications. It can also bleed off any excess input power via an internal protective shunt regulator. The voltage is then stepped-down and output with high efficiency by the module of the switch node. When no environmental energy is available, the output will prioritize choose the battery to power, through the module of the buck-boost to control. When the pin-strapped configurability was set at 0 or 1, the output range could be set from 1.8 V to 5 V depending on the application.

According to the characteristics of the LTC3330 and the TENG, an entire system circuit was designed as shown in Figure 1(a). Capacitor C_4 serves as an energy reservoir and input supply for the buck regulator. Capacitor C_5 between Cap and $V_{\rm in}$ serves as an internal rail referenced to $V_{\rm in}$ to serve as a gate drive for the buck positive channel metal oxide semiconductor (PMOS) switch. With pins UV_3 to UV_0, pin UVLO selects bits for the buck-switching regulator. The falling threshlod of UVLO must be greater than the selected $V_{\rm out}$ regulation level. Pin UV_1 connects to GND, and the others connect to VDD. Pin BAT serves as the battery input to the buck-boost switching regulator. Pins SWB and SWA connect to each other through the external inductor of the buck-boost switching regulator. Pin SW switches the node for the buck-switching regulator that connects an inductor between the node and $V_{\rm out}$. For special applications, the rest of the nodes will connect to GND, and the power is output from $V_{\rm out}$. Furthermore, in order to test and verify the performance and efficiency of the power manager system, a printed circuit board (PCB) was designed and fabricated as shown in the Figure 1(b). The voltage and current test results for the entire system circuit are shown in Figure 1 (e) and (f). The average output voltage is approximately 3.3 V, and the average current is approximately 64 mA.

The circuit PCB samples were tested with different load resistors to verify the performance and efficiency of the power manager system. The test results are shown in Figure 1 (g) and (h). In Figures 1(g), as the load resistor increases, the output voltage of the TENG increases as well. When the load is approximately 230 kΩ, the maximum output power of the TENG is approximately 273 mW at a of approximately voltage 234 V. For the power manager system in Figure 1(h), when the load is approximately 50 Ω, the maximum output power is approximately 213 mW at an output voltage of approximately 3.3 V. The efficiency of the power manager system is approximately 78%, as shown in (1):

$$\eta = \frac{P_{\rm out}}{P_{\rm in}} = \frac{V_{\rm out}\cdot I_{\rm out}}{V_{\rm in}\cdot I_{\rm in}} = 78\%. \qquad (1)$$

This letter is the first time to design an integral power manager system for the TENG. The output voltage of the TENG is high at approximately 100 V to 400 V, and the output current is small at approximately 1.17 mA. This is not sufficient for the direct integration of the TENG with Li-ion batteries. A power manager system with a high-voltage buck regulator for the TENG is introduced in this manuscript. The LTC3330 chip can transform the output signal of the TENG into a signal that will fit most applications. The system circuit is designed and verified through a PCB experiment. The circuit can achieve an efficiency of 78% for a high-voltage TENG. The power of the TENG drives certain small electronics that could be widely used as environmental sensors and wearable personal electronics [7,8].

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