A triboelectric-electromagnetic hybrid generator for wave energy harvesting

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1 Abstract

Wave energy is one of the most promising renewable energy sources in the ocean, which comes with high energy density, water depth independence and 24-hour availability, collecting low-frequency wave energy by triboelectric nanogenerators (TENGs) is still a considerable challenge. In this study, a hybrid wave energy harvester (H-WEH) is proposed. Herein, the H-WEH composes coupled TENG and electromagnetic generator (EMG). This design exhibits better output performance in harvesting wave energy compared with individual components. Moreover, the electricity generation unit makes no direct contact with the water surface, which enhances the durability of the generator. Additionally, the output characteristics of TENG can be complementary to the performance of EMG to achieve satisfactory power production. The device can work in the frequency range of 0.1-1Hz, which provides a simple, reliable, and durable alternative for large-scale and low-frequency wave energy harvesting.

Keywords: Hybrid Wave Energy Harvester, Triboelectric Nanogenerator, Electromagnetic Generator

2 Introduction

Electricity generation provides 18,000 terawatt-hours of energy a year, around 40% of humanity's total energy use[1]. Therefore, developing renewable energy is the one of the top priorities in the future. Utilizing renewable energy to generate electricity is not a new concept. With the boosting requirement for energy, the extensive use of blue ocean energy is an inevitable choice. Seawater covers 71% of the earth's surface, with a total area of approximately

360 million km^2, which contains abundant wave energy[2,3]. According to the researcher's statistics, the wave energy reserves in the oceans worldwide is about 80,000 TWh, which is enough to fulfill the world's total electricity demand[4–7].

Though the cnventional electromagnetic generators (EMG) have been applied in harvesting the wave energy[8,9], they usually don't function well (directly) with low-frequency wave inputs. Triboelectric nanogenerator (TENG) was invented by Wang's group in 2012[10]. The TENG exhibits many advantages including low costs, manufacturing easiness and lightweights. In particular, the TENG is superior to the EMG in harvesting low-frequency mechanical energy[11]. This feature has inspired many researchers to develop triboelectric-electromagnetic hybrid generators to harvest wave energy more efficiently[12,13].

In this work, a triboelectric-nanogenerator hybrid wave energy harvester (H-WEH) has been proposed to harvest wave energy. H-WEH is connected to a floating sphere. Under the excitations of the waves, the floating sphere drives the generator reciprocally, transforming mechanical energy into electrical energy. This structure can largely avoid the risks of water leakage into the power generation unit. What's more, combining two generators (EMG and TENG) increases the output of H-WEH and enhance the practicality of wave energy conversion. After systematical design optimization, this H-WEH can effectively collect wave energy in the frequency range of 0.1 to 1Hz. Besides, one of its applications in charging capacitors is also demonstrated. This work may give rise to new insights in harvesting wave energy.

2 Experimental Section

2.1 Fabrication of mover

The mover, a cylinder with a radius of 3cm and a height of 2cm, was made using photocurable 3D printing technology. Four holes with a radius of 1mm and a depth of 3cm were dug on the bottom of the circular surface to place the bolts. A breakthrough hole with a depth of 2cm and a diameter of 1cm was dug along the axis on the side of the curved surface. A 40mm*20mm*10mm rubidium iron boron magnet is placed inside the mover, and a layer of copper foil with Polytetra fluoroethylene (ptfe) film is attached to the curved side of the mover.

2.2 Fabrication of stator

The stator is a circular structure with an outer diameter of 8cm and an inner diameter of 6.5cm following the same manufacturing process. A copper foil electrode with a width of 1cm and a thickness of 50 μm is affixed to the inner surface of the stator. An 8cm outside diameter and 7cm inside diameter circular arc is used to place the coil (0.02mm wire diameter, 100 in turns). Four fixtures are arranged to fix the stator to the optical plate, and connecting structures are designed to connect the other stators.

2.3 Electrical Measurement

The output signals of H-WEH were measured via a programmable electrometer (Keithley 6514 System Electrometer). The software platform was built based on LabVIEW, which was capable of realizing real-time data acquisition and analyzing the wave simulation system. An adjustable speed motor (US-52) equipped with a reduction gearbox (5GU-5-K MAILI) was conducted to simulate the water wave motion. Finally, for measuring the charging and discharging performance of the H-WEH, a capacitor (4.7μF, 50V) was used.

3 Results and Discussion

3.1 Structural Design and Working Mechanism

The H-WEH is composed by multiple power generation units. As shown in Figure 1a, the power generation unit is connected to a floating sphere that ocsilates under the excitation of waves. The structure of the H-WEH is depicted in **Figure 1(b)**, which mainly consists of two parts: Mover and Stator. The number of mover and stator in H-WEH can be adjusted flexibly according to various working conditions. As can be seen, a contact-sliding mode TENG is established between the outer ring of the actuator and the inner ring of the stator. To enhance the contact electrification effect, 2000 mesh sandpaper was used to grind the PTFE and copper foil before spraying with the hydrophobic coating (Rust Oleum 274232 Never Wet Multi Purpose Kit) to improve H-WEH flexibility under the marine environments. At the same time, the magnet inside the mover and the coil outside the stator constitute an EMG.

Under the excitations of waves, the actuator moves back and forth in the pool of the stator. Based on the coupling effect of triboelectrification and electrostatic induction[14], the working mechanism can be illustrated in five steps in a cycle as shown in **Figure 1(c)**. Due to the electronegativity difference between the nylon and PTFE, positive and negative triboelectric charges are generated on the surfaces of the nylon and PTFE respectively. The charge will not

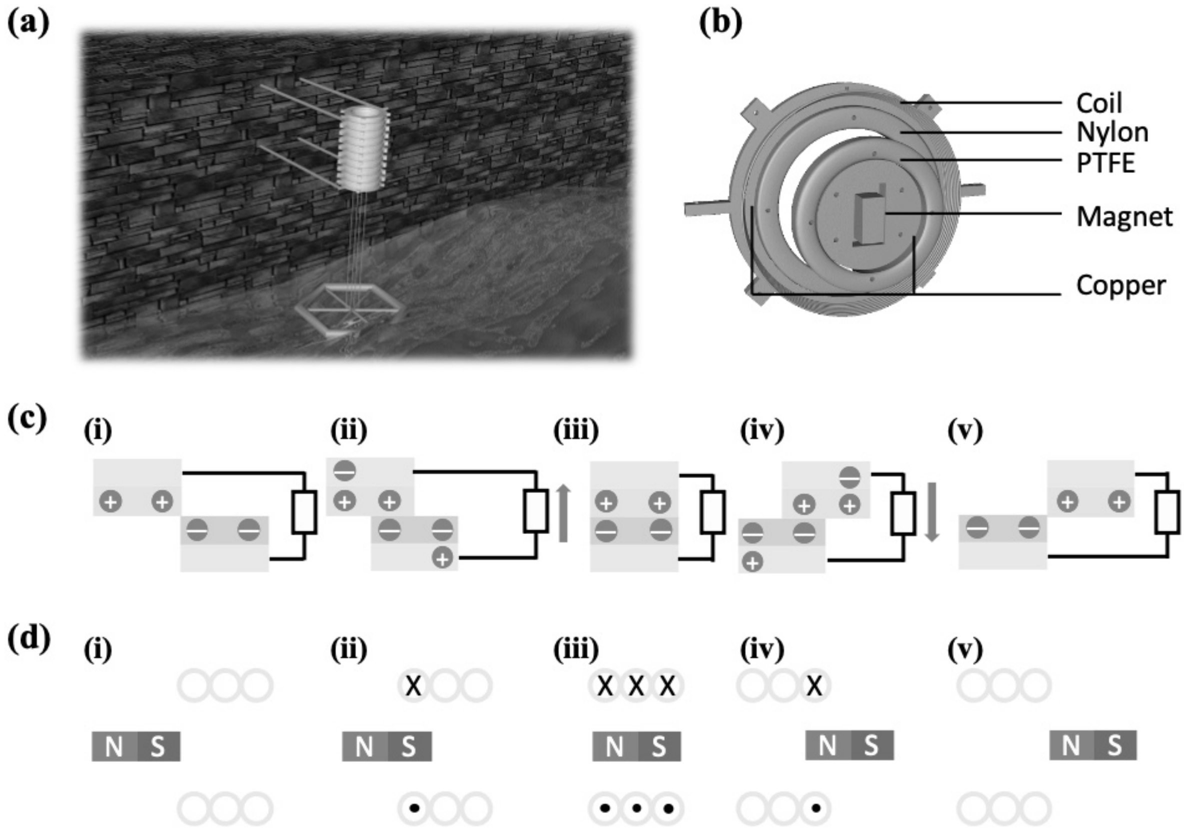

Figure 1. Structural design and working principles of the T-TENG. (a) Schematic diagram of the designed H-WEH consisting of multiple units. (b) Exploded view of the H-WEH's structure. (c) The working principle of the TENG component. (d) The working principle of the EMG component.

leak in one cycle because the triboelectric charge is only distributed on the surface layer of the polymer and the polymer has excellent insulationperformance. In the initial position, Nylon and PTFE carrying equal charges of opposite signs, and there is almost no potential difference between the two electrodes as shown in **Figure 1c(i)**, once the positively charged mover starts to slide to the right, the contact area of the two materials will increase, leading to charge separation. As shown in **Figure 1c(ii)**, due to the insulator nature of the polymer material, as the contact area increases, the excess transferred charge on the electrode flows from the upper electrode to the lower electrode through the external load. As shown in **Figure 1c(iii)**, when the surfaces of the two polymers are completely overlapped, there is no potential difference between the two poles, and no electron transfer occurs. As shown in **Figure 1c(IV)**, the separated charge causes the upper plate to have a higher potential. Driven by the potential difference, electrons will flow from the lower electrode to the upper electrode to offset the

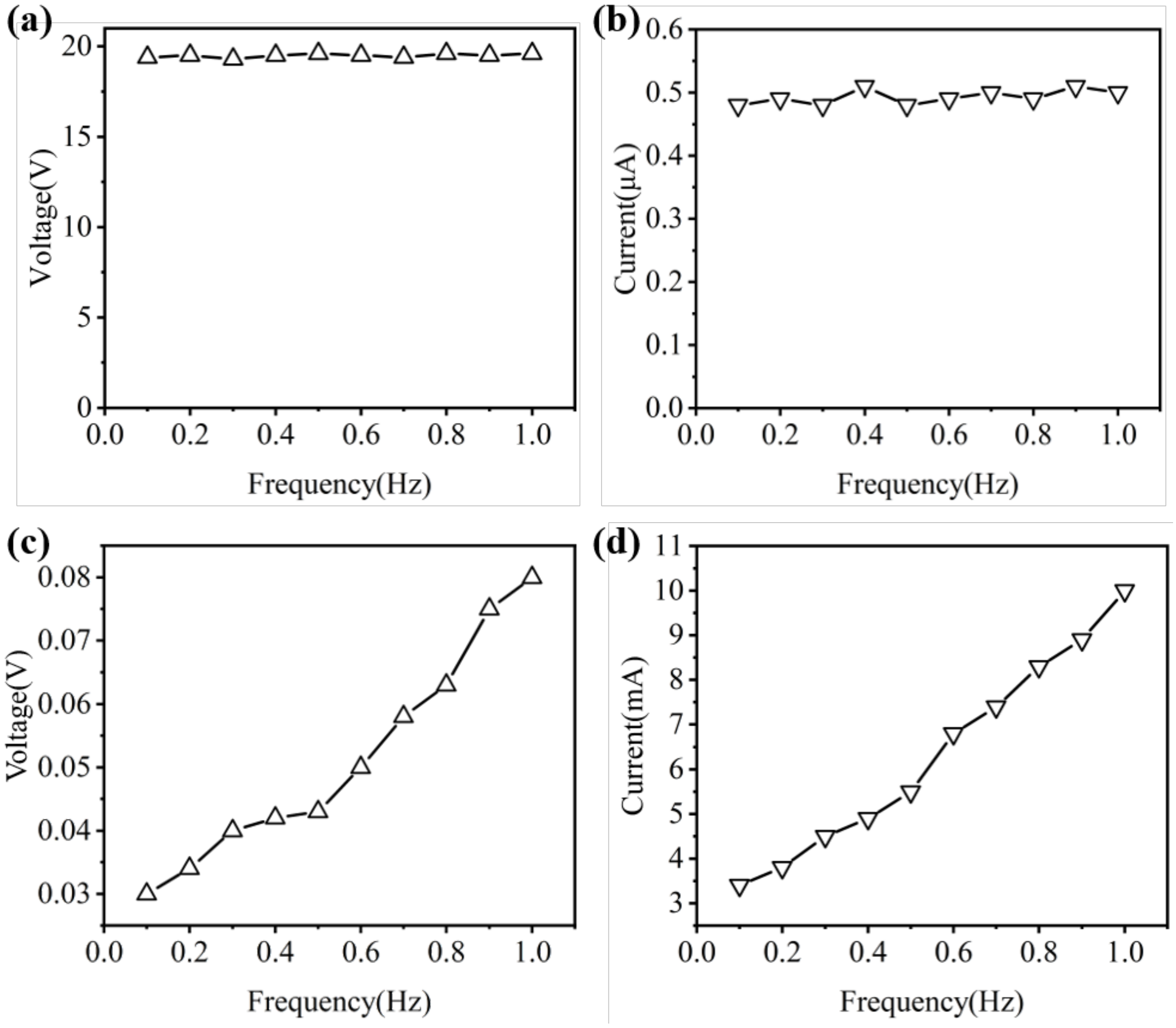

Figure 2. H-WEH output characteristics at different frequencies. (a) The voltage of the TENG component at different frequencies. (b) The Current of the TENG component at different frequencies. (c) The voltage of the EMG component at different frequencies. (d) The current of the EMG component at different frequencies.

potential difference generated by the frictional charge. Finally, the mover moves right to the position shown in **Figure 1c(V)**, the upper and lower plates have the same potential, and there is no electron transfer. Meantime, based on electromagnetic induction, the EMG component can generate alternating current due to the periodic change of the magnetic flux caused by the periodic displacement change between the magnet and the copper coil, as shown in **Figure 1(d).**

3.2 Electrical output performance of the H-WEH

To further study the performance of the H-WEH the stator is fixed on the optical plate and a linear motor is used to exert a forced motion to the mover. The output of the TENG and the EMG was tested under a fixed amplitude of 40mm and various frequencies from 0.1 to 1Hz. As

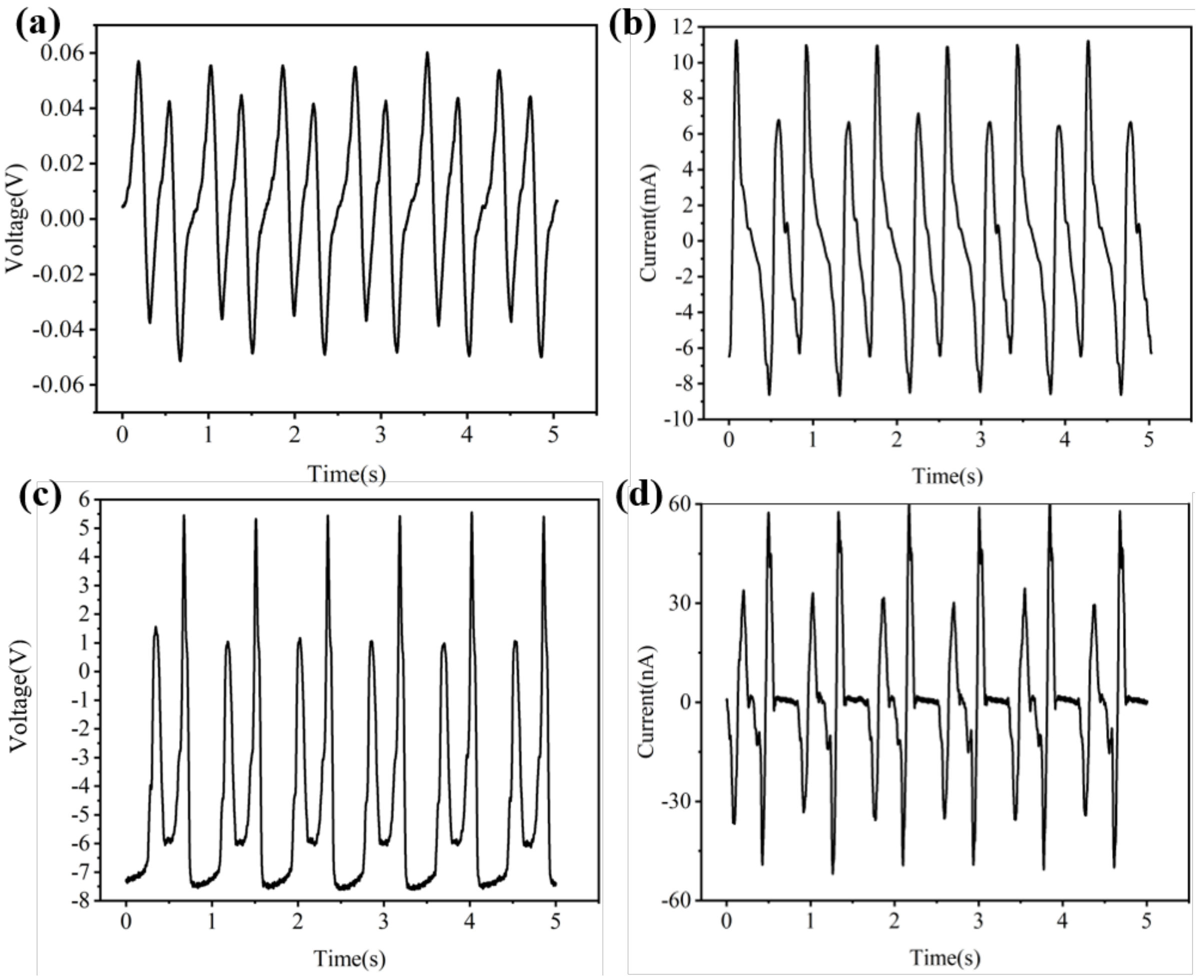

Figure 3. The output characteristics of H-WEH under the excitation of waves with a frequency of 1HZ and a height of 5CM. (a) TENG's voltage curve. (b) TENG's current curve. (c) EMG's voltage curve. (d) EMG's current curve.

shown in **Figure 2a, b,** the voltage and the current of TENG hardly change as the frequency increases. The maximum voltage and the current is 20V and 0.5μA, respectively. As shown in **Figure 2c, d,** the voltage and current of EMG improve with increasing frequency. Under the fixed frequency of 1Hz, the voltage is 0.08V and the current is 10mA. This also reflects that TENG is more stable than EMG under the low-frequency excitation.

3.3 Practical Applications

For the purpose of practical applications, we link the H-WEH with the floating sphere and place it in an experimental water tank. Linear motors are used as the wave maker. Under the excitation of waves with the frequency of 1Hz and the height of 5cm, the output performances of the H-WEH are shown in **Figure 3.** The output of the H-WEH decreased compared with its output under the driving of a linear motor because in the process of energy transfer between the wave

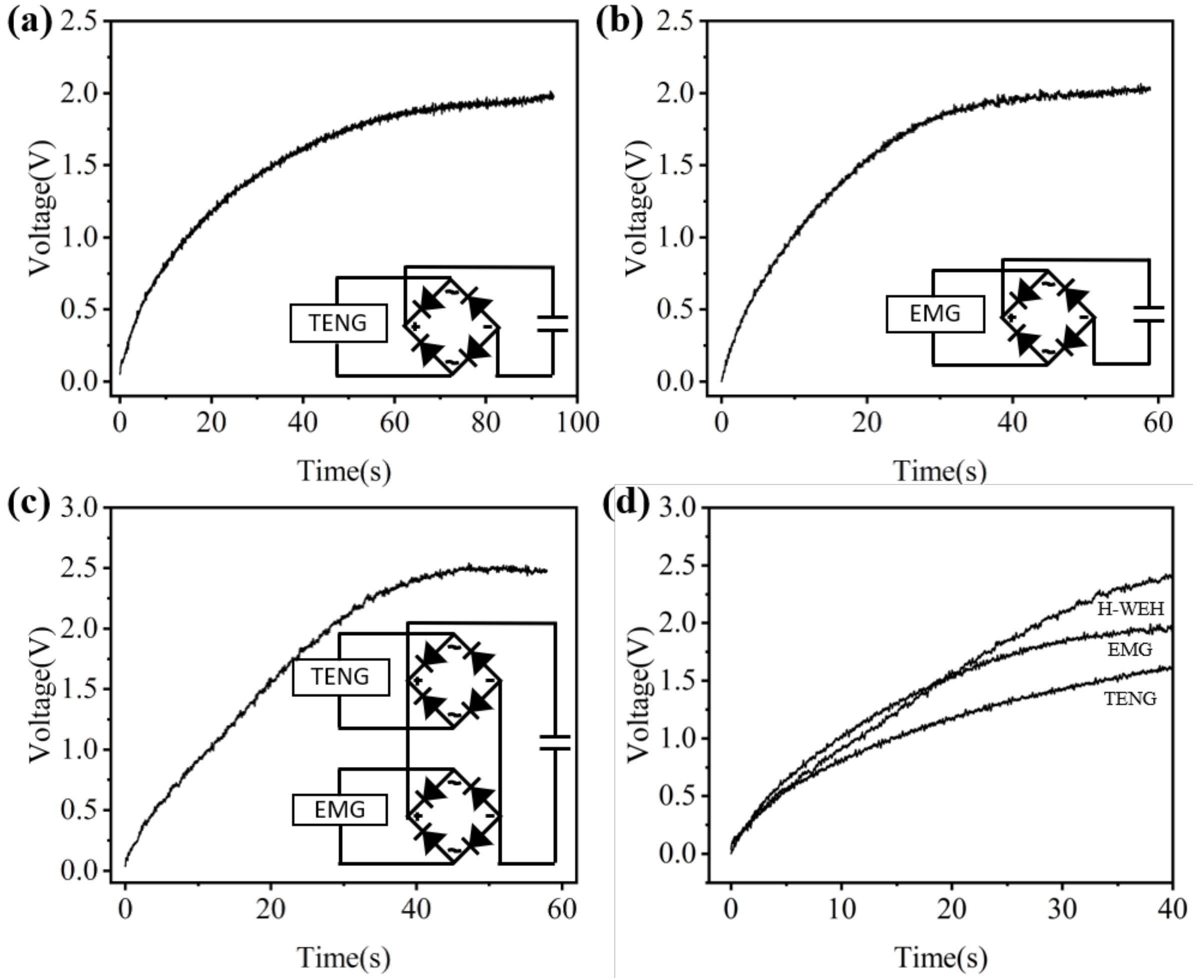

Figure 4. (a) Voltage curves of a capacitor charged by the TENG component. (b) Voltage curves of a capacitor charged by the EMG component. (c) Voltage curves of a capacitor charged by H-WEH. (d) Charging curves of a capacitor using TENG only, EMGs, and the H-WEH.

and the float, part of the energy will be dissipated due to the fluid viscocity .As the power generation unit in the H-WEH makes no direct contact with water, the probability of water leaking into the generator is greatly reduced. A 4.7μF capacitor is connected to the H-WEH and its charging characteristic curve is shown in **Figure 4**. The TENG can charge the capacitor from 0V to 2V in 95 seconds. For the EMG, it only takes 58 seconds. When TENG and EMG charge the capacitor together, the capacitor can be charged from 0V to 2.5V in 51 seconds. As shown in **Figure 4(d)**, the charging capability of the H-WEH was compared with that of the TENG and the EMG when they work independently. Apparently, the EMG has a faster charging speed than that of theTENG at the beginning due to the larger current output. In contrast, the H-WEH has a faster charging speed than the TENG and can charge the capacitor to a higher voltage at the same time.

3 Conclusion

In summary, we have designed a hybrid generator by combining TENG and EMG together to harvest wave energy. Benefiting from the design of the float and the power generation unit, the H-WEH can be used for low-frequency wave energy collection. The power generation performance of H-WEH under different frequencies has been studied systematically. Under the excitation of 1Hz frequency and 5cm wave height, the TENG component can output a voltage of 20V and a current of 0.5μA, while the EMG component can output a voltage of 0.08V and a current of 10mA. For the demonstration, a capacitor was charged successfully through the H-WEH in the water tank, which is superior in maximum charging value and speed compared with individual EMG and TENG components. Because of its small size and easy materials availability, the H-WEH could become a novel way to capture ocean energy.

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