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A CONDITIONING SYSTEM FOR HIGH-VOLTAGE ELECTROSTATIC/TRIBOELECTRIC ENERGY HARVESTERS USING BENNET DOUBLER AND SELF-ACTUATED HYSTERESIS SWITCH

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ABSTRACT

Electrostatic kinetic energy harvester and more particularly triboelectric nanogenerators (TENG) can generate very high output AC voltages of several hundred volts. In addition, the losses due to the energy transfer between the typically small inner capacitance of the generators and a necessary large reservoir capacitance for collecting the harvested energy, severely limits the energy storage efficiency. In this paper, we propose a 2-stage conditioning system that efficiently manages the high-voltages of a TENG without any external active control. It includes, as the 1st stage, an unstable charge pump (a Bennet doubler) for the signal rectification and, as the 2nd stage, a novel self-actuated electrostatic switch having a narrow hysteresis followed by a DC-DC Buck converter. With this system, the converted energy is improved by 24 times compared to a classical full-wave diode bridge, while the output voltage remains below 20 V and then is compatible with commercial regulators.

KEYWORDS

Triboelectric nanogenerator, energy harvesting, Bennet doubler, high-voltage conditioning circuit.

INTRODUCTION

With the development of the flexible electronics, wireless sensing nodes and smart medical diagnostic devices, there is a raising demand for high-efficiency energy harvesters that can transduce the environmentally existing energy into electricity, including solar, thermal, mechanical or chemical energy. Among the most popular types of kinetic energy harvesters, the electret kinetic energy harvesters [1]-[4] and the triboelectric nanogenerators (TENGs) [5]-[7] share the common basis of electrostatic induction, while TENGs also couple it with the principle of triboelectric charge generation.

TENGs generate a direct high output voltage (>100V). How to manage such a high voltage and to store it efficiently is still underdeveloped. The most common and simplest method is to use a full-wave rectifier to charge a capacitor or a chemical battery (while using a half-wave rectifier have been proven more efficient most of the time [8]). However this leads to a huge energy loss during the energy transferring from a small capacitor (the inner capacitance of the TENG) to a large capacitor (the storage capacitance), and the difference can be of several magnitudes orders. Using a two-stage conditioning circuit is a potential solution to eliminate the transferring loss [9]. This circuit included (i) as the 1st stage, a full-wave rectifier to charge, at a high voltage, a small capacitor that matched with the inner capacitance of the TENGs, and (ii) as the 2nd

stage, a transformer that transfers the harvested energy to a large reservoir capacitance. However, the control of the energy transfer was realized with an electronic switch, which increased significantly the energy consumption of the system. We have recently proposed to replace this electronic switch with an automatic electrostatic one in order to eliminate the consumption of the control electronics, and to replace the full-wave rectifier with a half-wave one [10]. It obviously improved the charging efficiency but can still be optimized.

In this paper, we propose to use an *unstable charge pump (a Bennet doubler)* in combination with a self-actuated electrostatic switch having a *narrow hysteresis* to increase dramatically the energy conversion. Although the previously used half-wave rectifier can increase the saturated voltage to several times higher than the full-wave, it still has a saturated voltage, which limits the maximum harvested energy per cycle. The Bennet doubler [8][11] is an unstable charge pump allowing the voltage across the capacitor to increase exponentially across the transducer, leading to a much higher output power of TENGs or any other kind of electrostatic kinetic energy harvesters. Furthermore, the proposed electrostatic switch has a narrow hysteresis that keeps the capacitor voltage always at a high level: it reduces drastically the wasted time needed to re-charge the buffer capacitor after each actuation.

METHODS AND RESULTS

Descriptions of The Conditioning System

The schematic of the system is shown in Fig. 1a. The 1st stage includes a 6x6 cm² TENG fabricated using macro-shaped conductive polyurethane foam, polytetrafluoroethylene (PTFE) and aluminum electrodes [6]. The device was excited at 5 Hz with a peak force of 10 N. The TENG generates an open-circuit voltage with a peak value higher than 100 V and a short-circuit current with a peak of about 3 μ A. A Bennet doubler circuit increases the voltage across a 5 nF buffer capacitor C_{buf} until several hundred of volts (Fig. 1c).

The 2nd stage contains an electrostatic switch. The switch is self-activated when the voltage across C_{buf} reaches 450 V. The switch is OFF again when this voltage drops to 250 V: thus there is a relatively narrow hysteresis (Fig. 1c). Another part of this 2nd stage is a DC/DC buck converter combining a 100 mH inductor, a diode and a 22 μ F storage capacitor C_{store} . The voltage across C_{store} increases step-by-step with a frequency synchronized with the switch (Fig. 1d). The voltage across C_{store} has to be comprised between 5 and 20 V, so it can be regulated to 1.8 or 3.3 V using the commercial regulator LTC3588-1 (Fig. 1e).

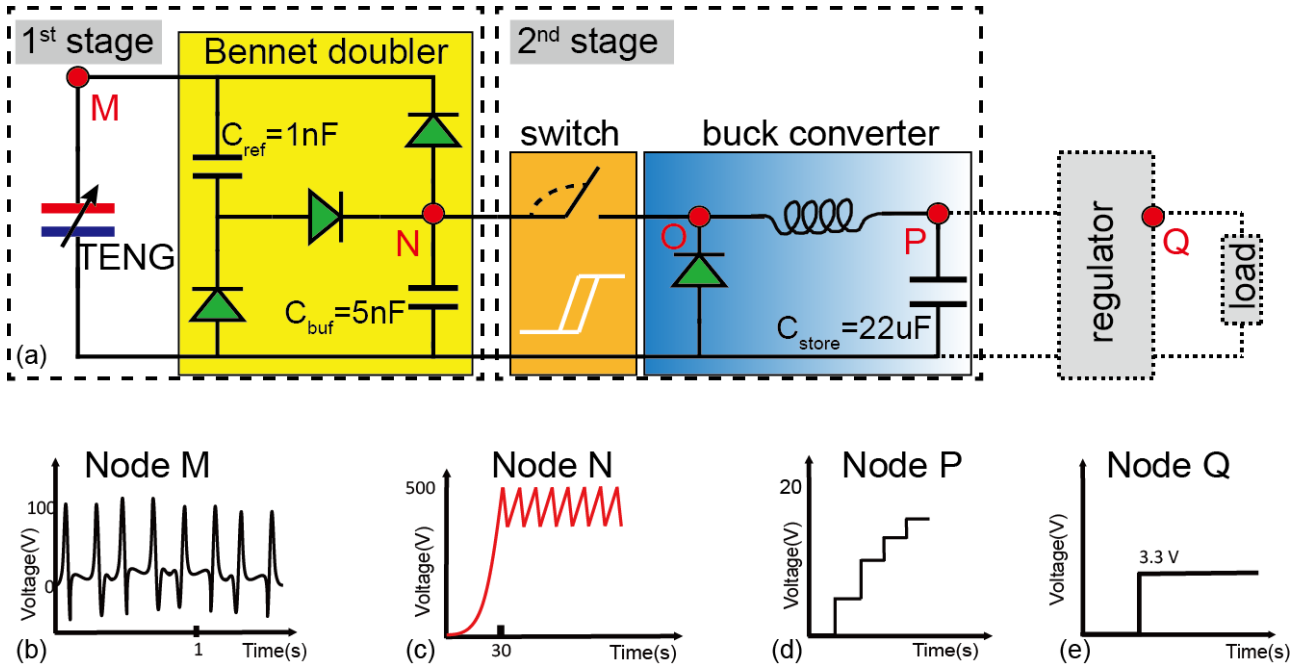


Figure 1: Schematic view and signal shapes of the 2-stage conditioning circuit with Bennet doubler, automatic switch and DC-DC buck converter. (a) Schematic of the circuit; (b) Output of the TENG; (c) Output of the Bennet doubler; (d) Output of the storage capacitor; (e) Output of the regulator.

The switch is made of a steel wire connected to the high-voltage end of the buffer capacitor (Node N), and a counter aluminum electrode plate connected to the input of the buck (Node O) [12]. When in the ON state, a micro-plasma is created between the electrodes so that a current can flow between them before having a physical contact [13]. The narrow hysteresis is obtained by sharpening the tip of the steel wire to maximize the electric field (Fig. 2). The air around the sharp tip is ionized due to the high electric field generated by the high voltage across the buffer capacitor, and a spark can be observed when the switch is ON. When using a full-hysteresis switch [10], the buffer capacitor has to be recharged to the ON voltage from zero. In contrast, in this work the buffer capacitor can be recharged starting from a high voltage, which saves the charging time and thus improves the conversion efficiency.

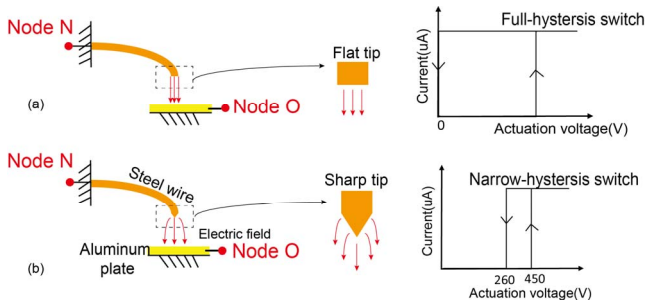


Figure 2: The schematics of the switch with full-hysteresis (a) and narrow-hysteresis (b).

Experimental Results

The voltages across C_{buf} and C_{store} are shown in Fig. 3. During the starting time (0-20s), the voltage across C_{buf} is exponentially increasing until the switch reaches the ON voltage of 450 V. This kind of exponential increase is different with the voltage curves using half-wave [10] or

full-wave [6] rectifiers, which stop at a saturated value. The switch is thus oscillating between 400-450 (peak value) and 200-250V (valley value).

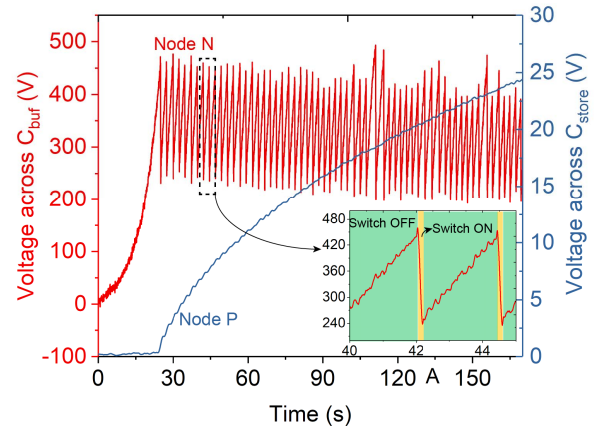


Figure 3: The voltages across the buffer capacitor (C_{buf}) and storage capacitor (C_{store}).

When the switch is OFF, the energy is stored in C_{buf} . When the switch becomes ON, the energy in C_{buf} is transferred to C_{store} through the Buck converter. The switch OFF duration is ~ 2.3 s and the ON duration is ~ 0.2 s, indicating a switching frequency of 4Hz. There is a small peak-voltage drop with time going on, which may be caused by the electrical measurement errors. Voltage across C_{store} stays at zero during the starting period, and increases step by step synchronized with the switch turning ON and OFF. The voltage across C_{store} approaches to 23.5 V within 170 s. The totally stored energy in the buffer capacitor ($C_{buf} = 5$ nF) is calculated based on the formula:

$$E_{res}^{total} = \frac{1}{2} C_{buf} V_{buf}^2 \quad (1)$$

It can be observed that 380 μJ of converted energy is transferred per 2.5s to C_{store} through the Buck, corresponding to 152 μW of average brut power. However, not all of the energy is stored in C_{store} as some of it is consumed by or leaked through the switch and other components. The efficiency of this transfer is around 30%, so that C_{store} receives at average 48 μW , which corresponds to 9.6 μJ per cycle of external excitation, as the excitation frequency is 5 Hz.

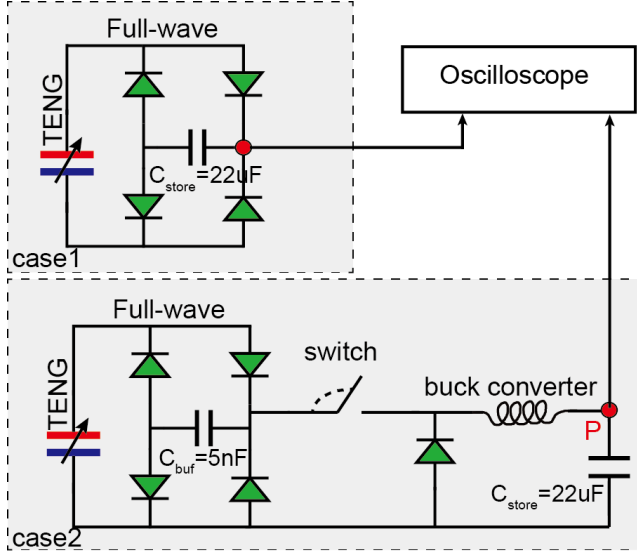


Figure 4: The electrical setups for case 1 and case 2.

In order to compare the efficiency improvement of this conditioning system with the classical ones, we also did experiments using a 1-stage system with a full-wave rectifier (case 1) and a 2-stage system with a full-wave rectifier plus a full-hysteresis switch (case 2, [10]). One can also note that in this work the ON voltage of the switch is higher than that of case 2. The electrical setups for case 1 and 2 are shown in Fig. 4. The voltage across the storage capacitor was observed through a high-impedance follower. The curves of the voltage across C_{store} using the three different conditioning circuits are shown in Fig. 5. Within 100 s, the voltage across C_{store} increases to 17.1 V using the proposed 2-stage conditioning circuit with a Bennet doubler, while the voltage is 3.0 V and 6.4 V using the conditioning system of case 1 and case 2. The charging speed is obviously much faster with the application of the proposed circuit, although a longer starting time is needed. In case 2, in addition to a full-hysteresis [10], we could also observed a lower switch ON voltage ($\sim 150\text{V}$), which makes the charging efficiency better than case 1 but worse than current work.

The energy per cycle in the storage capacitor C_{store} is calculated based on the following formula:

$$\Delta E_{store} = E_{store,i+1}^{total} - E_{store,i}^{total} \quad (2)$$

where i is the index of the operation cycles. It can be obtained from Fig. 6 that within 100s, the energy per cycle is 0.4 $\mu\text{J}/\text{cycle}$ under case 1, 1.25 $\mu\text{J}/\text{cycle}$ under case 2 and 9.6 $\mu\text{J}/\text{cycle}$ under this work. This means that the available

electrical energy per cycle coming from the mechanical domain using the proposed method is 24 times higher than in case 1 and 7.7 times higher than in case 2.

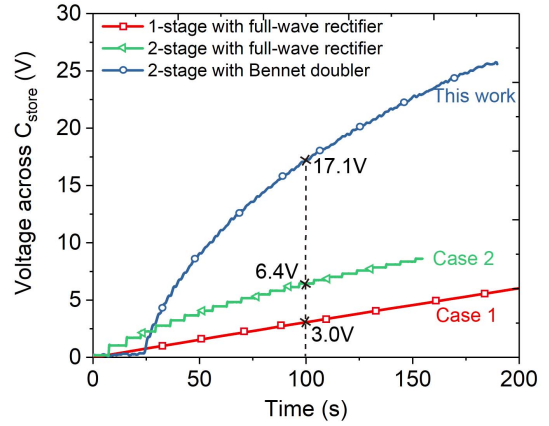


Figure 5: The comparison of the voltage across the storage capacitor (C_{store}) for the three cases.

The proposed implementation of the DC-DC converter offers an efficient energy transfer from a high-voltage and high-impedance output toward low voltage reservoir, with the use of the self-controlled mechanical switch. The energy transfer efficiency of this new conditioning system is $\sim 31.6\%$, and the net average power available for the load is 48 μW on 17 V. There is a large room for the efficiency improvement, through an optimization of the mechanical switch and of the buck converter.

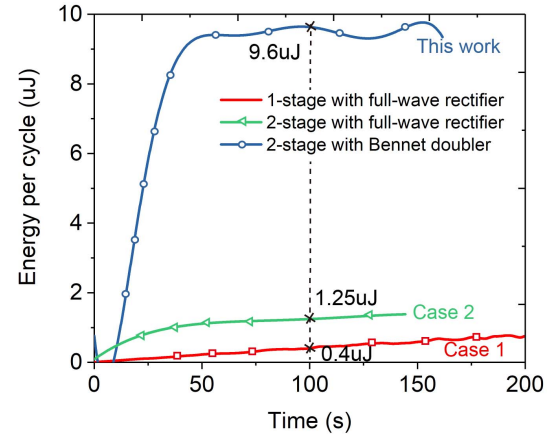


Figure 6: The comparison of the energy per cycle in the storage capacitor (C_{store}) for the three cases.

CONCLUSIONS

In summary, we propose a 2-stage conditioning system that can efficiently manage the high voltage generated by the triboelectric nanogenerators. The core of the system is to firstly match the inner capacitance of the TENGs using a small-capacitance buffer capacitor for temporary energy harvesting and then to transfer the energy to a high-capacitance reservoir. A Bennet doubler is implemented to rectify the TENGs-generated AC voltage and to charge a buffer capacitor. A narrow-hysteresis switch is designed to control the energy transfer from the buffer to the storage capacitors. The realization of the narrow-hysteresis is

based on the tip discharge and electrostatic pull-in. Using this proposed method, the charging efficiency can be improved by more than 24 times compared to the classical full-wave rectifiers in the view of energy per cycle. The energy transfer efficiency can still be improved if we can control the switch more precisely, for example using the MEMS (microelectromechanical system) technologies to fabricate the switch. We aim to further optimize the circuit to reduce the energy loss and leakage of the components to realize a practically-applied, self-sustained, high-efficiency conditioning circuit for not only triboelectric nanogenerators but also for any kind of electrostatic kinetic energy harvesters.

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