Bennet's charge doubler boosting triboelectric kinetic energy harvesters

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Abstract We present for the first time how a Bennet's doubler conditioning circuit can boost the electrical energy extracted from an electrostatic Kinetic Energy Harvester (e-KEH) based on triboelectricity, commonly called Tribo-Electric Nano-Generator (TENG). After 1000 charging cycles, the harvested power is increased by more than 2 orders of magnitude with the Bennet doubler compared to a half-wave diode bridge. The maximum energy extracted by a 3×3 cm² device made of PFA and aluminum is no less than 4.6 μJ per tap through the Bennet’s doubler circuit.

1. Introduction
Electrostatic Kinetic Energy Harvesters (e-KEHs), along with piezoelectric and electromagnetic ones, have been under extensive research in the recent years as a new source of energy [1],[2],[3]. E-KEHs convert power from mechanical vibrations into electrical power by varying the capacitance of an electromechanical transducer. For the energy conversion, the capacitive transducer needs an electrical charge that can be obtained by successive triboelectric contacts. Triboelectric charging of the capacitance’s electrodes is based on the principle of charge transfer between two contacting surfaces due to the difference in the electronegativity of the materials they are made of [4]. Various applications are introduced for triboelectric KEH such as powering implantable medical devices[5], powering of sensors [6], energy scavenging from water motion[7] or human daily activities[8].

Compared to electret-based e-KEHs, triboelectric e-KEHs do not carry a pre-imposed charge with them. Therefore, the bias of the capacitive transducer comes from repeated tapping or sliding motions of its electrodes. Since triboelectric charging is not uniform on the surface, it is very difficult to reach the theoretical maximum charge density on the material. Thus, tribo-based e-KEHs usually produce less energy per cycle in comparison with electret-based harvesters. Hence, it is important to have a conditioning circuit that has the ability to increase the charge on the transducer’s terminals during its operation like the Bennet's doubler family[9] [9],[10] to boost the harvested power. Several instances of application of the Bennet’s doubler in energy harvesting applications have been reported previously that emphasize the importance of this circuit configuration as a conditioning circuit for energy conversion purposes[11].

2. Test and Measurement Setup
Figure 1 displays the setup used to actuate the capacitive harvester. The variable capacitance is composed of two electrodes in aluminium and a dielectric layer made of Polymer-PFA
(Perfluoroalkoxy) covering one of the electrodes. The PFA is provided by GoodFellow [12] and has a thickness of 50µm, a relative permittivity of 2.1 and a melting point of 315°C.

2.1. sample preparation and actuation

To build the variable capacitance, the PFA is cut in squares of 3×3 cm². One polymer piece is attached firmly on the bottom electrode, which is a one-sided aluminum tape with the same dimensions as the polymer. The bottom electrode is glued on the supporting table through a rigid insulator. The top electrode is glued on the force sensor with the same type of rigid insulator.

A magnetic shaker is adjusted to produce a vertical sinusoidal vibration with frequency of \( f = 5 \text{Hz} \) that applies a normal maximum force on the polymer surface in contact mode, measured with a force sensor as 0.3±0.05N. The vertical motion serves two purposes: (i) the variation of the capacitance value of the harvester in order produce electric power, (ii) the application of a pressure contact between the PFA and the aluminum surface that is hard enough to induce triboelectric charges.

2.2. Conditioning circuits

Figure 2 shows two conditioning circuits working with a e-KEH: a Bennet's doubler and a half-wave diode bridge. Both are employed to store electrical energy in a reservoir capacitance \( C_{\text{res}} \). Each diode on the schematic is actually composed of two diodes with a breakdown voltage of 200V and a reverse saturation current of 1 nA. To overcome the limited span of the high-impedance follower used for recording the output signal, \( C_{\text{res}} \) is the series combination of \( C_{\text{res1}} = 100 \text{nF} \) and \( C_{\text{res2}} = 10 \text{nF} \), which works as a capacitance divider. An additional voltage source of \( V_b = 25 \text{V} \) is also employed to extend the output saturation range of the amplifier. The storage voltage \( V_{\text{res}} \) is measured through this capacitive divider and the follower loaded with a resistive divider \( (R_1 = R_2 = 1\text{kΩ}) \). Evolution of \( V_{\text{res}} \) over time with respect to recorded \( V_{\text{out}} \) is defined by the following formula:

\[
V_{\text{res}} = k_1 (k_2 V_{\text{out}} + V_b)
\]  

Where \( k_1 = 1 + \frac{C_{\text{res1}}}{C_{\text{res2}}} \) and \( k_2 = 1 + \frac{R_2}{R_1} \).

**Figure 1.** Setup of the experiments. A magnetic shaker, force sensor and variable capacitor are the basic parts of the tests.

**Figure 2.** Conditioning circuits used for the triboelectric e-KEH. (a) Bennet’s doubler. (b) Half-wave rectifier. \( C_{\text{res1}} = 100 \text{nF}, \ C_{\text{res2}} = 10 \text{nF}, \ \pm V_{cc} = \pm 30, \ R_1 = R_2 = 1\text{kΩ}, \ V_b = 25 \text{V}, \ C_{\text{store}} = 100 \text{nF}. \)
By setting proper values for $k_1$ and $k_2$, large value of $V_{\text{res}}$ can be measured. Since the AOP is powered with +/- 30V, in the following experiments the maximum value of $V_{\text{res}}$ is 605 V. Connecting points A and B in figure 1 and figure 2 indicate the proper connection of the output of the e-KEH to the input of conditioning circuits.

### 3. Experimental results and discussion

To evaluate the capacitance variation of the device, we used the technique introduced in [13] during the oscillation of the top electrode. According to figure 3, extreme values of the transducer variation in one cycle under the applied excitation are $C_{\text{max}}$=78pF and $C_{\text{min}}$=26pF, plus 16pF of parasitic capacitance introduced by the setup. Figure 3 also depicts the magnitude of the contact force between top and bottom electrode during one cycle of oscillation. As we expect, the maximum capacitance occurs at the same time with the maximum of the force.

![Figure 3](image1.png)

**Figure 3.** Measurements of the applied force and capacitance variation of the tribo e-KEH (including a 16 pF parasitic capacitance).

As shown in figure 4, after 5000 taps a saturation occurs with $V_{\text{res}}$, even with the Bennet’s doubler conditioning circuit that is supposed to generate an exponential increase[14]. However, the maximum value of $V_{\text{res}}$ is 533V with the Bennet circuit, to be compared with 48V for the half-wave circuit. Consequently, the total storage energy is 1.2mJ and 10µJ respectively. On the contrary to the experiments in [11], the origin of this saturation for the experiment with the Bennet’s doubler is not due to the spring-softening effect but to the saturation of the operational amplifier at the output.

![Figure 4](image2.png)

**Figure 4** Measurements of the voltage and the total stored energy in $C_{\text{res}}$ for the half-wave (HW) rectifier and the Bennet's doubler.

Figure 5 compares the harvested power for the two conditioning circuits. The maximum power for both circuits occurs around 200 s. Then 23µW are extracted with the Bennet’s doubler and only 138 nW with the half-wave bridge.

![Figure 5](image3.png)

**Figure 5.** Harvested power for the Bennet doubler and half-wave rectifier.

![Figure 6](image4.png)

**Figure 6.** Converted energy per tap as a function of voltage across reservoir capacitance with Bennet doubler and half-wave rectifier.
Figure 6 depicts the converted energy per cycle as a function of stored voltage across $C_{res}$. From this figure, it appears that the highest energy per tap extracted from the e-KEH using the half-wave conditioning circuit is 30 nJ, compared to the 4.6 µJ for the Bennet’s circuit, which shows more than 2 order of magnitude improve in the harvested power. The reason for this much better performance is the self-charging behavior introduced by the Bennet's doubler, which in theory double the charges in the transducer’s terminals during each tap. However, it is also noticeable that the peak harvested energy for the Bennet’s doubler is at $V_{res}$ = 256V while it is 26V for the half-wave circuit.

4. Conclusion:
The much improved performance of the Bennet’s doubler circuit with triboelectric e-KEHs is due to the self-increase of the triboelectric charge generated at each contact. By the Bennet’s circuit, it was possible to reach up to 550 V across the capacitive transducer, much higher than the 48 V provided by half-wave circuit. Using the Bennet’s doubler the maximum obtained energy per cycle of 4.6 µJ is calculated, compared to 30 nJ for the half-wave circuit. The limiting factor that prevents the Bennet’s circuit to reach values above 4.6µJ/per tap is the high reverse current of the HV diodes used in the circuit, while the maximum voltage of 605V is imposed by the monitoring setup.

5. References
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