Bennet's doubler working as a power booster for triboelectric nano-generators

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In this Letter, the authors introduce for the first time how a Bennet's doubler conditioning circuit will boost the extracted energy from an electrostatic kinetic energy harvester based on triboelectricity. With zero initial bias on all capacitors, after 1000 charging cycles, the harvested power is amplified by more than 2 orders of magnitude by the Bennet's doubler in comparison to a half-wave diode bridge. The harvested energy derived from a 3×3 cm^2 device made of polymer PFA and aluminium is at least 4.6 µJ per tap with the Bennet's doubler conditioning circuit, and only 30 nJ per tap with the half-wave bridge.

Introduction: As the need for new miniature sources of ambient energy increase, the development of electrostatic kinetic energy harvester (e-KEH) is under research for more than one decade. With e-KEH, the energy of mechanical vibrations is converted into electrical energy by varying the capacitance of an electromechanical transducer [1]. An initial bias is required that can be provided by an external voltage source [2], an electret layer [3, 4] or successive triboelectric contacts [5]. With triboelectric e-KEH, which is often named tribo-electric nano-generator (TENG), the initial charging is based on charge transfer between materials covering the electrodes with different electronegativity condition.

Compared to electret-based e-KEHs, tribo-based e-KEHs do not carry a pre-imposed charge with them. The electrical bias depends on the applied force, the coefficient of friction, the surface energy, the ambient humidity and the electron affinity of the contacting materials [6, 7]. Therefore, the level of triboelectric charging is mainly random and it is very difficult to reach the theoretical maximum charge density on the material surface, as with corona-charged electret [8]. Consequently, tribo-based e-KEHs usually produce less energy per cycle compared to electret-based e-KEH. Thus, it is important to have a conditioning circuit that has the ability to self-increase the charge on the transducer's terminals during its operation like the Bennet's doubler [9]. In recent years, the attractiveness of the Bennet's doubler and related circuits for e-KEH is increasing [10–13]. To our knowledge, this Letter is the first application of a Bennet's doubler to triboelectric e-KEH/TENG.

Measurement setup: The experimental setup is made of three main parts: (i) the tribo-based e-KEH, (ii) a force sensor that is attached to a magnetic shaker and (iii) the conditioning circuit. The e-KEH is a parallel plate variable capacitor, which is made of two aluminium electrodes with an area of 3×3 cm^2. A layer of perfluoroalkoxy polymer, provided by GoodFellow [14] with a thickness of 50 µm and a relative permittivity of 2.1, covers the bottom electrode that is anchored. The top electrode is attached to the force sensor, which in turn is attached to a magnetic shaker. The shaker provides a vertical sinusoidal motion of the top electrode with a frequency of 5 Hz and a normal maximum contact-force of 0.3 ± 0.05 N on the transducer during the contact. This allows both the transducer's capacitance variation and the triboelectric charge induction needed to produce electrical power.

We have tested the tribo e-KEH with a classical half-wave diode bridge and compared the results with a Bennet's doubler. Both circuits (Fig. 1) store the electrical energy in a reservoir capacitance C_{res}. Each diode is a series connection of two diodes with a breakdown voltage of 200 V and a typical reverse saturation current of 1 nA. Since the high-impedance follower (OPA445AP) in Fig. 1 has a limited span, much lower than the expected output voltage V_{res} across the C_{res}, C_{res} is set as a series combination of $C_{res1} = 100$ nF and $C_{res2} = 10$ nF working as a capacitance divider. The voltage source $V_b = 25$ V is used to increase the positive saturation voltage of the follower. V_{res} is defined by the following formula:

$$V_{res} = k_1(k_2 V_{out} + V_b) \qquad (1)$$

where $k_1 = 1 + C_{res1}/C_{res2}$, $k_2 = 1 + R_2/R_1$ and $R_1 = R_2 = 1$ kΩ. Therefore, the theoretical maximum V_{res} value that can be measured is 605 V. A and B are connected to the top and bottom electrodes of the triboelectric harvester, respectively.

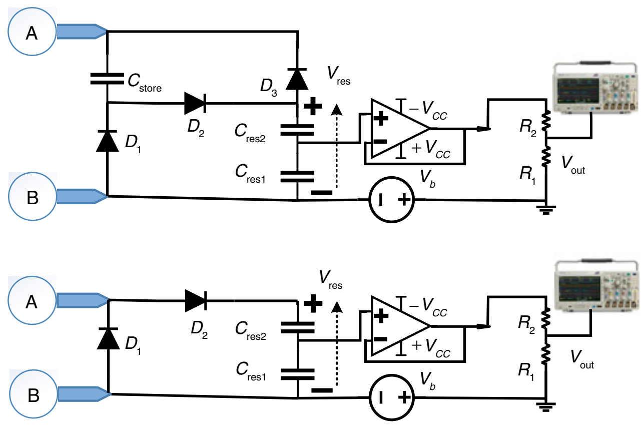

Fig. 1 *Conditioning circuits used for triboelectric e-KEH*

a Bennet's doubler
b Half-wave bridge. $C_{res1} = 100$ nF, $C_{res2} = 10$ nF, $\pm V_{cc} = \pm 30$ V, $R_1 = R_2 = 1$ kΩ, $V_b = 25$ V, $C_{store} = 100$ nF

Experimental results and discussion: The maximum and minimum values of the variable capacitor are measured as $C_{max} = 78$ pF and $C_{min} = 26$ pF with the technique introduced in [15]. Fig. 2 shows the measured evolution of V_{res} as a function of the number of taps. It shows a saturation around 500 V, even with the Bennet's doubler circuit that is supposed to show an exponential increase of V_{res} [10]. The maximum value of V_{res} with the Bennet circuit is more than ten times larger than with the half-wave bridge; and the total stored energy is 1.2 mJ and 10 µJ, respectively.

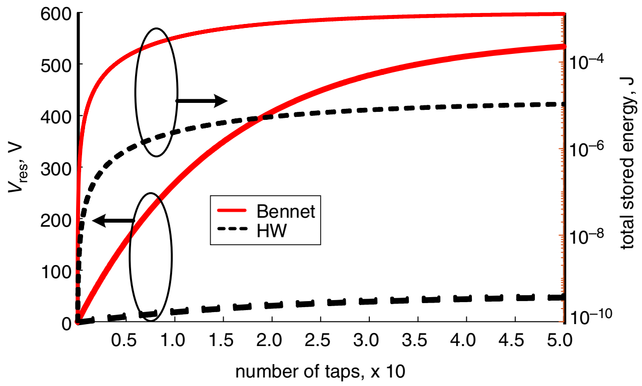

Fig. 2 *Measurements of voltage and total stored energy in C_{res} for HW rectifier and Bennet's doubler*

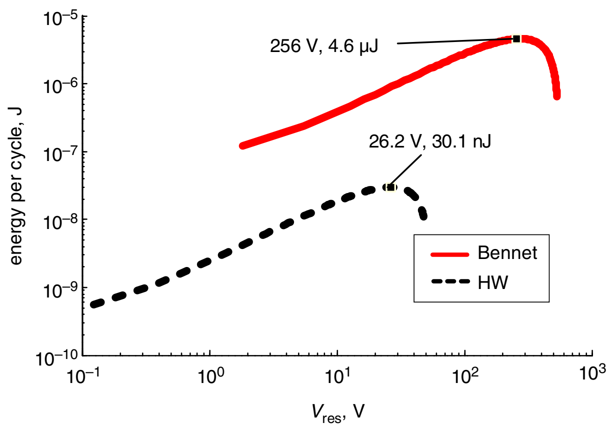

Fig. 3 *Converted energy per tap as function of voltage across reservoir capacitance with Bennet doubler and half-wave rectifier*

Fig. 3 shows the converted energy per cycle as a function of the voltage across C_{res}. The highest energy per tap obtained with the half-wave bridge is 30 nJ, which increases to 4.6 µJ with the Bennet circuit. Thus, the harvested power is improved by more than 2 orders of magnitude. The self-charging ability introduced by the Bennet's doubler is the reason for such improved performance over the half-wave circuit. The maximum harvested energy for the Bennet's doubler is obtained for a bias of 256 V, compared to 26 V for the half-wave circuit.

Fig. 4 depicts the harvested power for the two conditioning circuits. The maximum power occurs around 200 s for both, which is 23 µW for the Bennet's doubler and only 138 nW for the half-wave bridge.

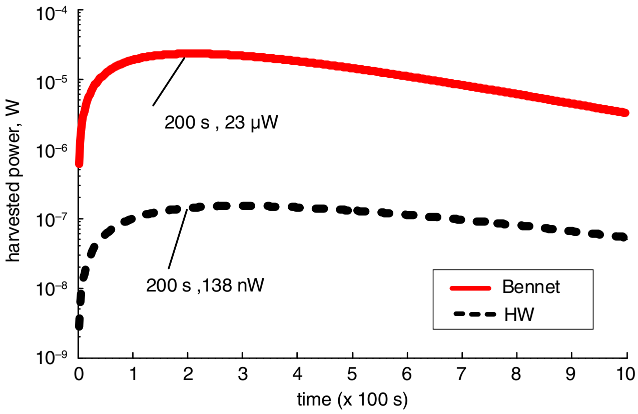

Fig. 4 *Harvested power at 5 Hz for Bennet's doubler and half-wave rectifier*

Conclusion: The exceptional performance of Bennet's doubler conditioning circuit with triboelectric e-KEHs is due to the self-increase of the triboelectric charge generated at each contact. It makes it possible to reach a bias voltage up to 550 V across the capacitive transducer, much higher than the 48 V that the half-wave bridge can provide. The maximum extracted energy per cycle with the Bennet's doubler is 4.6 µJ, compared to 30 nJ for the half-wave circuit. This limitation at 4.6 µJ/per tap is attributed to the relatively high reverse current of the HV diodes.

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One or more of the Figures in this Letter are available in colour online.

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