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SIMPLE TECHNIQUE FOR THE ELECTRICAL CHARACTERIZATION OF TRIBOELECTRIC NANOGENERATORS AND OTHER KINETIC ENERGY HARVESTERS WITH ELECTRET

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ABSTRACT

This study presents a novel approach to characterize and define a simple Spice model for a triboelectric nanogenerator (TENG). It combined the measurement of the built-in surface voltage V_{TE} with the dynamic capacitance variation of the transducer. The proposed approach focuses on the indirect measurement of V_{TE} (which is assumed to be constant) instead of the open-circuit voltage $V_{OC}(t)$. The extraction of V_{TE} is obtained using the saturation voltages of either half-wave or full-wave rectifiers, while the dynamic TENG capacitance is based on the phase-shift measurement in a RC_{TENG} circuit. This approach was validated experimentally with a TENG consisting of two 625 cm² aluminum electrodes, one of which was coated with a 52 μ m PFA tribo-layer.

KEYWORDS

Kinetic energy harvesters, TENG, Characterization, Surface charge density, Electret Layer Built-in voltage.

INTRODUCTION

Triboelectric nanogenerators (TENG) have been considered as promising small-scale mechanical to electrical energy harvesters, since about a decade ago [1]. They convert mechanical energy into electricity through the combined effect of electrostatic induction and the triboelectric effect. A TENG is fundamentally a variable capacitor. Its electrodes are separated by air, and by a triboelectric dielectric material that can semi-permanently trap charges upon contact or rubbing against a conductor, or against another such dielectric. These two processes (separation and contact/rubbing) are driven by an external mechanical excitation. When combined, they result in an electrostatic force working against the mechanical separation of the capacitor plates imposed by this excitation. Mechanical energy is therefore converted into electricity. A proper power management circuit can then supply some useful electronic load with this energy [2].

The electrical circuit model of a TENG is a dipole comprising an ideal variable capacitor in series with either an alternative [3] or a DC voltage source [4]. The two models are equivalent, and the choice of the AC vs. DC source is a matter of convention and preference.

The model featuring an AC voltage source is commonly fitted by measuring the TENG's open-circuit voltage V_{OC} and/or its short-circuit current I_{SC}

over time [3]. This can be challenging to achieve accurately, even with costly equipment. To obtain precise $V_{OC}(t)$ measurements, a dynamic voltage measurement is necessary. The main issue is that this dynamic voltage often has an amplitude of several hundreds of volts. Besides, the typical capacitance of TENGs rarely exceeds a few nanofarads, while mechanical forcing frequencies are of a few hertz. The high voltage measurement must therefore be done with a measurement apparatus with input impedance of the order of a T Ω . Common practices involve using voltage dividers and input impedance measurement tools in the G Ω range, but this can result in significant errors and losses that may profoundly impact results [5].

In this paper, we propose a method for measuring the two electrical parameters of a TENG: its dynamic capacitance variation C_{TENG} and its equivalent DC voltage source V_{TE} (see Fig. 1), namely the built-in or surface voltage of the triboelectric layer. V_{TE} is usually measured with a non-contact electrometer. However, this technique requires the sensing probe to be very close to the charged layer, necessitating separation of the two electrodes: this measurement cannot therefore be carried out when the TENG is active. The method is illustrated on a contact-separation (CS) device. The measurement of $C_{TENG}(t)$ is based on a dynamic phase-shift detection technique. The measurement of V_{TE} is based on two ingredients: (i) the independent measurement of the TENG's extremal capacitance ratio η under the desired mechanical excitation, and (ii) the knowledge of the TENG dynamics when polarized by diode bridge rectifiers, namely the half-wave (HW) and full-wave (FW) rectifiers. These dynamics imply that the saturation voltage on the output capacitors of both rectifiers, that can be measured by standard techniques, is related to η and V_{TE} by a simple expression, which can be inverted to find V_{TE} .

This technique provides a simple and efficient way of characterizing TENGs. It enables measuring the macroscopic parameters that determine the output power of TENGs under any desired mechanical excitations. This ultimately allows for joint device and circuit optimization.



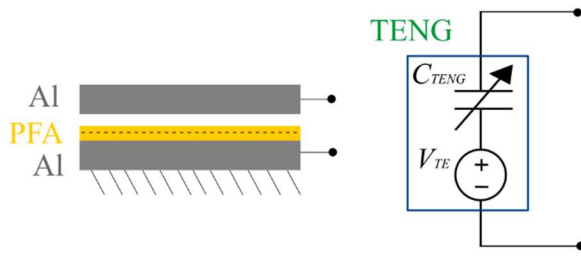


Figure 1: Tested TENG architecture and its general electrical model based on the built-in voltage.

DESCRIPTION OF THE TRANSDUCER ELECTRICAL MODEL

A typical TENG is a capacitive device, in which at least one electrode is covered by a dielectric material capable of trapping electrical charges. This dielectric layer, referred to as an electret, is placed between the electrodes of the variable capacitance. It has the capability to store a charge Q_{TE} on its surface through mechanical contact due to the triboelectric effect. After being pre-charged by contact electrification, any variation in the capacitor resulting from external mechanical forces generates an electric current by electrostatic induction. This current flows through a conditioning circuit, allowing for the conversion of energy from the mechanical to the electrical domain.

The variable capacitance, ranging from $C_{TENGmax}$ to $C_{TENGmin}$, is defined as:

$$C_{TENG} = \frac{\epsilon_{air} S}{\frac{d_{die}}{\epsilon_{die}} + \frac{d_{var}}{2} - \frac{d_{var}}{2} \cos(2\pi ft)} \quad (1)$$

where d_{die} is the thickness of the triboelectric layer, ϵ_{die} its permittivity, σ its surface charge density distribution over the contact area S , which is supposed to be uniform. The variable air gap d_{var} has a permittivity of ϵ_{air} . A sketch of the device is depicted in Figure 2.

The built-in triboelectric voltage V_{TE} is defined as:

$$V_{TE} = \frac{\sigma d_{die}}{\epsilon_{air} \epsilon_{die}} \quad (2)$$

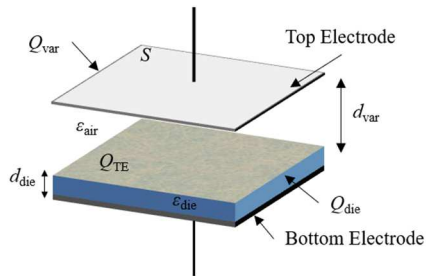


Figure 2: Model of the gap-closing TENG.

Transducer's mechanical design

The TENG has a contact area of up to 625 cm² and can be excited by vertically deflecting it from a few millimeters to a few centimeters. It consists of two aluminum electrodes, one of which is covered with a 25x23 cm² wide PFA sheet that is 52 μm thick, attached with double-sided adhesive conductive tape. A foam layer has been added between the electrodes and the supporting frame to enhance the transducer's reliability (cf. Figure 3).

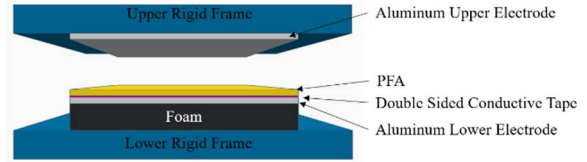


Figure 3: 3D view of the transducer.

TENG CHARACTERIZATION

Dynamic capacitance measurements

To measure $C_{TENG}(t)$, the phase-shift $\Delta\Phi$ between *Signal 1* and *Signal 2* in the RC_{TENG} circuit presented in Figure 4 is measured. *Signal 1* is a sinusoid whose angular frequency ω is several orders of magnitude higher than the mechanical movement of the TENG electrode(s). The dynamic capacitance can subsequently be determined using the phase shift method as described in [6]. With R being chosen as $R=R_{opt}$, $C_{TENG}(t)$ is given by:

$$C_{TENG}(t) = -\frac{\tan[\Delta\phi(t)]}{R_{opt} \omega} \quad (3)$$

R_{opt} is the value of R that minimizes the error on $C_{TENG}(t)$ due to the oscilloscope's limited sampling frequency. This is when the phase shift between the two signals is close to $-\pi/4$, i.e:

$$R_{opt} = \frac{1}{C_{TENG} \omega} \quad (4)$$

where C_{TENG} denotes a first estimate of the average value of $C_{TENG}(t)$.

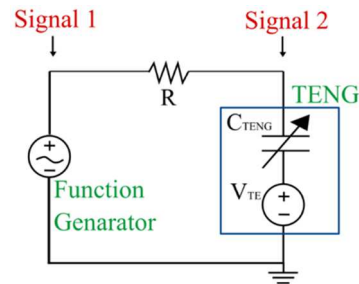


Figure 4: Circuit for $C_{TENG}(t)$ measurement based on signals dynamic phase-shift.



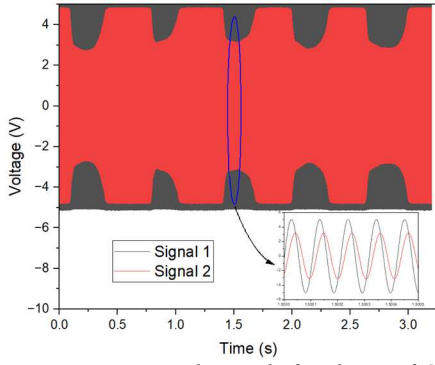


Figure 5: Raw measured signals for the m of $C_{TENG}(t)$.

Signal 1 is a sinusoid at 9.5 kHz, while the TENG is manually operated at approximately 2 Hz. From Equation (4), a first evaluation of $R_{opt} = 10$ k Ω is obtained by statically measuring the maximum capacitance $C_{TENGmax} = 10$ nF with an LCR meter. The evolution of $\Delta\Phi$ is measured by finding the difference between the consecutive zero-crossing times of the two signals (Figure 5). This is done by a Python script that first pre-processes the waveforms and produces a plot the dynamic capacitance of the TENG, as shown in Figure 6. This measurement shows results of $\eta = C_{TENGmax}/C_{TENGmin}$ ratio of $\eta = 6$ nF/420 pF = 14.3.

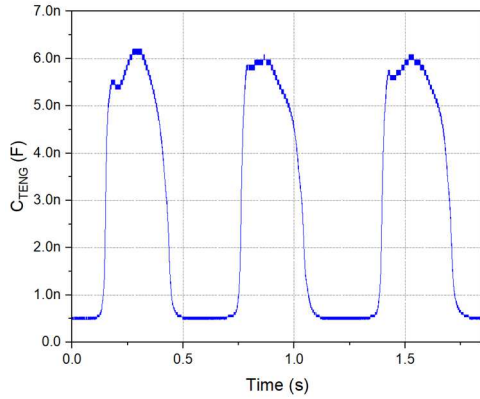


Figure 6: Extracted dynamic evolution of $C_{TENG}(t)$.

Built-in voltage (V_{TE}) characterization

V_{TE} can be determined from the saturation voltage of a half-wave diode bridge (V_{sat-HW}) or full-wave (V_{sat-FW}) diode bridge from the following equations [7]:

$$\begin{cases} V_{TE} = -V_{sat-FW} \frac{(\eta + 1)}{(\eta - 1)} \\ V_{TE} = -V_{sat-HW} \frac{1}{(\eta - 1)} \end{cases} \quad (5)$$

Due to the high capacitance ratio of the tested transducer, the saturation voltage of the diode bridges across C_{rect} is expected to exceed 1 kV, which renders its measurement delicate. Therefore, an external parasitic capacitor $C_{par} = 4$ nF was added in parallel

with the TENG (see Figure 7), reducing its capacitance ratio to $\eta = 2.3$, and hence the expected saturation voltage.

The output voltage V_{rect} is calculated by measuring the charge Q_{rect} of the output capacitor C_{rect} through a Keithley 6514 electrometer that is connected in series with C_{rect} :

$$V_{rect} = \frac{Q_{rect}}{C_{rect}} \quad (6)$$

Figure 8 shows the measurements of V_{rect} of both rectifiers across $C_{rect} = 10$ nF. The saturation voltage of the HW rectifier V_{sat-HW} is 80 V, indicating $V_{TE} = -207$ V. The saturation voltage of the FW rectifier V_{sat-FW} is 260 V, indicating $V_{TE} = -206.3$ V. These measurements are consistent and validate the approach. Thus, this TENG can be modeled by a DC source of $V_{TE} = -206$ V in series with the measured $C_{TENG}(t)$.

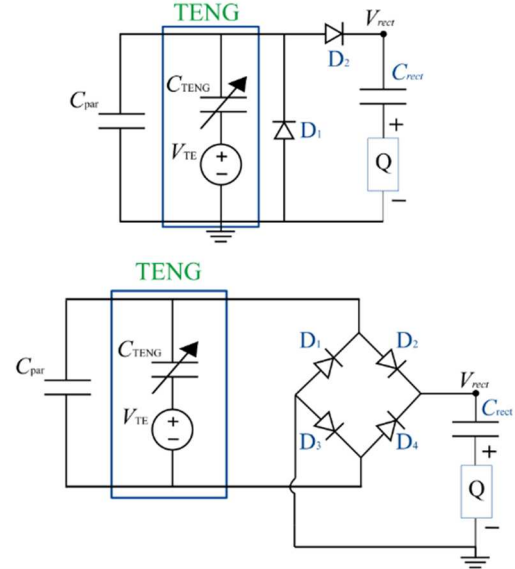


Figure 7: Half-wave (HW) (a) and full-wave (FW) (b) diode bridge rectifiers

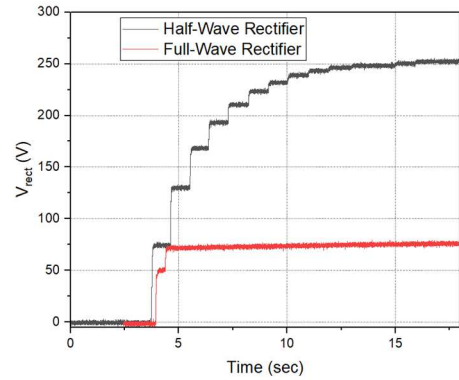


Figure 8: Evolution of the rectified voltages of FW and HW circuits across a 10 nF output capacitor.



CONCLUSION

We have presented a method for electrically characterizing triboelectric nanogenerators (TENG) in order to define a simple lumped-element model, made of the variable capacitance of the TENG $C_{\text{TENG}}(t)$ in series with its built-in voltage V_{TE} , that can be used in a SPICE simulator. The dynamic capacitance $C_{\text{TENG}}(t)$ is determined by measuring the phase-shift in a $RC_{\text{TENG}}(t)$ circuit, and V_{TE} is obtained by measuring the saturation voltages of a full- or half- wave bridge rectifier connected to the TENG. This method has been validated experimentally with a 625-cm² gap-closing TENG made of aluminum and PFA, and excited by a pedestrian. It can be noted that $V_{\text{OC}}(t)$, and so the model with the AC voltage source described in [3], can also be reconstructed from these values.

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