Assembling and Characterizing a Simple Tapping-Actuated Triboelectric Nanogenerator as a Pedagogical Tool for Introductory Electronic Circuits

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Acknowledgments

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CONTENTS

1. INTRODUCTION

Contact electrification (CE) was observed by Thales of Miletus around 600 b.c, where an amber rod rubbed with wool was found to attract small objects or even generate an electric spark [1]. This phenomenon is now known as the triboelectric effect, or triboelectrification, where a material becomes electrically charged thanks to the friction produced between two materials. The sign of the charges on each material depends on the relative polarity [2]. In other words, this is the principal cause of the daily electrostatic shocks produced by the accumulation of charges because of friction [3] [4]. Based on this physics effect, Li Wang and co-workers developed a Triboelectric Nanogenerator (TENG) in 2012, as a device capable of harvesting a small magnitude of mechanical energy. Since then, TENGs have been studied as an opportunity to expand the nano and macro energy levels. The functionality of the existing electronics explores a new method to obtain energy that provides efficiency, stability, power, and low cost [5]. As a result of this, new TENG designs have been reported by optimizing their geometry and materials for a variety of applications (Figure 1.1a). Broadly, these applications include self-powered sensors/systems [6], micro/nano power sources [7], and blue energy [8]. This has created a research topic full of diversity and innovation from various perspectives.

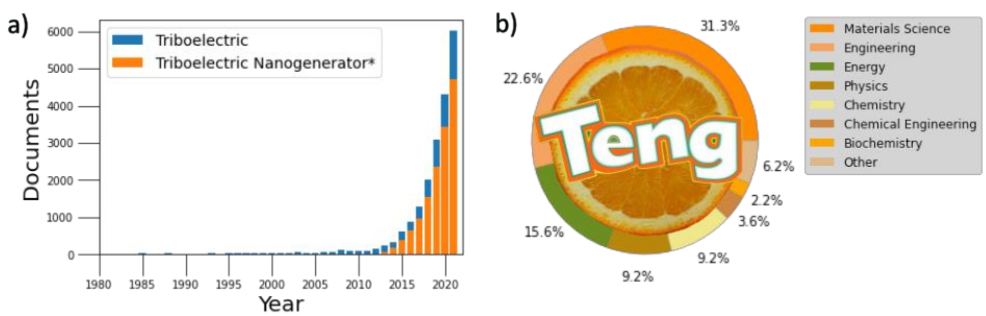

Figure 1.1. a) Document publication statistics by year for triboelectric nanogenerators from 1980 to 2022, b) Data from Figure 1.1a grouped according to document fields.

However, due to the multidisciplinary nature of these devices and applications (Figure 1.1b), the reported literature often has terminology, measurement techniques, and basic electronic knowledge foreign to researchers and students new to TENGs. For this reason, this article follows an Inquiry-Based Learning approach, to teach and familiarize students who have minimal or no experience with the triboelectric effect and electrical circuits (*i.e.*, technical terms, measurements, and interpretation of results). Herein, a team of researchers in Canada (Chemistry), China (Materials Science), and Colombia (Biomedical Engineering) has come together to share their experience with the next generation of TENG enthusiasts on how to fabricate a TENG based on *P*aper and packing *T*ape by performing several standard TENG measurements using an oscilloscope with LEDs, resistors, and capacitors.

2. OBJECTIVES

General

Develop an academic article as a pedagogical tool for new researchers in the field of TriboElectric NanoGenerators (TENG).

Specific objectives

- To detail the basic terminology in terms of measurements and elementary concepts necessary for the interpretation of TENG literature.
- To develop and replicate the Paper TENG proposed by the Materials Research Science and Engineering Center University of Wisconsin-Madison (MRSEC).
- To develop the characterization of the output produced by TENG, to provide a learning and analysis guide for students.

3. THEORETICAL BACKGROUND

Herein the concepts and terminology that were used for the development of the article are defined. It describes the electrical measurements necessary for the characterization of the TENG output, as well as the explanation of the work function of the measuring devices such as the oscilloscope.

3.1 Triboelectric Nanogenerator (TENG)

The first Triboelectric Nanogenerator (TENG) was created by Wang's groups in 2012, with the principal objective of harvesting mechanical energy [4]. These devices are two triboelectric materials attached to a pair of electrodes. The charges produced by the physical contact between the materials create a potential difference between the two surfaces, allowing the electrons to flow between the electrodes by electrostatic induction [9]. TENGs can be classified into four basic operation modes:

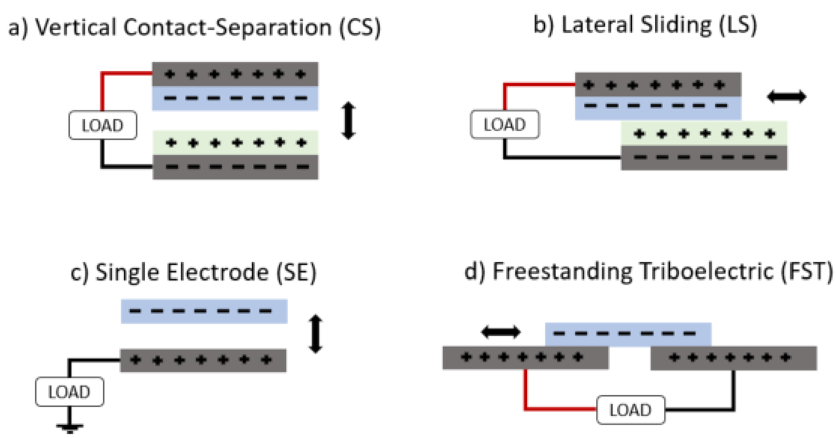

Figure 3.1. Triboelectric Nanogenerators Operation Modes.

Vertical Contact-Separation Mode

Two dielectric materials face each other (Figure 3.1a) and the vertical contact between them creates oppositely charged surfaces. If the two electrodes are electrically connected with a load, the electrons will flow from one to the other, creating a potential difference to balance the electrostatic field. Once the charges are in equilibrium, the potential difference disappears, and the electrons flow back in the opposite direction [4][10].

Lateral Sliding Mode

The working principle is the same as the Vertical Contact Separation. In this case, the dielectric materials are in contact because of the sliding motion (Figure 3.1b), which induces a lateral polarization that drives the electrons from top to bottom to balance the electric field [4] [11].

Single-Electrode Mode

In some cases, one of the triboelectric materials cannot be electrically connected. For this case, the single electrode mode corresponds to a grounded electrode on the bottom part of the TENG (Figure 3.1c). This configuration can be used in the contact-separation mode and the contact-sliding mode [8] [10].

Freestanding Triboelectric-Layer Mode

This configuration corresponds to a symmetric electrode pair underneath a dielectric layer (Figure 3.1d), where the distance between the two electrodes has the same size as the moving object. In this operation mode, the electrons will flow when the object approach or depart from the electrodes, which creates the asymmetric charge distribution [4] [8].

3.2 Triboelectric Series

Almost any material can be used for the fabrication of a TENG. However, the affinity of the material to gain or lose electrons will depend on its polarity [12]. Figure 3.2 shows the triboelectric series published in 1757, where the materials are organized from top to bottom from the most negative to the less one [13]. Additionally, the materials in the triboelectric series can be modified by physical techniques for enhancing the contact area and facility triboelectrification. The contact materials can be made of composites or being chemically modified [14].

	Polyformaldehyde 1.3-1.4	(continued)	
	Etylcellulose	Polyester (Dacron)	
	Polyamide 11	Polyisobutylene	
Positive	Polyamide 6-6	Polyuretane flexible sponge	
	Melanime formol	Polyethylene Terephthalate	
	Wool, knitted	Polyvinyl butyral	
	Silk, woven	Polychlorobutadiene	
	Aluminum	Natural rubber	
	paper	Polyacrilonitrile	
	Cotton, woven	Acrylonitrile-vinyl chloride	
	Steel	Polybisphenol carbonate	
	Wood	Polychloroether	
	Hard rubber	Polyvinylidine chloride (Saran)	
	Nickel, copper	Polystyrene	
	Sulfur	Polyethylene	
	Brass, silver	Polypropylene	
	Acetate, Rayon	Polyimide (Kapton)	Negative
	Polymethyl methacrylate (Lucite)	Polyvinyl Chloride (PVC)	
	Polyvinyl alcohol	Polydimethylsiloxane (PDMS)	
	(continued)	Polytetrafluoroethylene (Teflon)	

Figure 3.2. First section of the first reported triboelectric series.

3.3 Open Circuit and Short Circuit

Two important electrical configurations are used to explain and characterize the output of a TENG [15]. The open circuit corresponds to the circuit in Figure 3.3a, where the resistance value between the two terminals of the TENG is ideally infinite and the current flow between them is close to zero. This configuration allows one to measure the voltage using devices such as voltmeters or oscilloscopes [16]. On the other hand, a short circuit corresponds to a configuration that makes the resistance close to zero and measures the current by using an ammeter as shown in Figure 3.3b. These types of circuits are useful for characterizing the maximum voltage and current that can be produced by an electrical system.

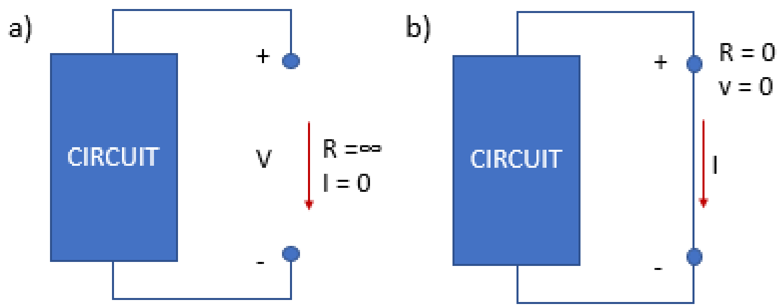

Figure 3.3. Open circuit and short circuit.

3.4 Series and Parallel Configuration

Circuit theory described the concepts of parallel and series circuits to measure the voltage and current of an electrical element. In the series configuration, the elements are connected one after the other, creating a single closed way for the current (Figure 3.4a) [15]. For the parallel configuration, all the input connectors match each other, as do the output terminals. This means the current does not stop flowing to the other elements (Figure 3.4b). Devices such as oscilloscopes or multimeters are used to measure in parallel to get the voltage (V) between two points. On the other hand, for ammeters to measure current (I), they must be placed in series since the current must pass through an internal coil that creates the displayed current value [16].

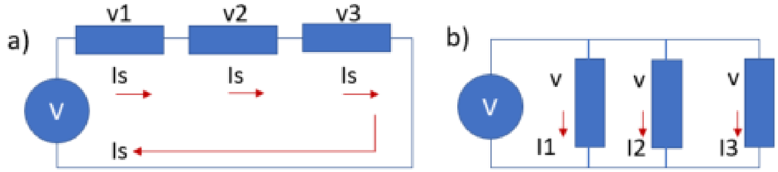

Figure 3.4. Series and parallel configuration

3.5 Resistive Loads

A resistive load (R) is a circuit that contains only resistors that consume active power. The voltage and current of the resistive loads are perfectly in phase, which means they reach their peak value at the same time, making it easy to characterize these systems with equations such as Ohm's law (1). After obtaining the current and voltage parameters the power and energy provided and consumed by the system can be calculated with (2) and (3) [17] [18].

$$I = V/R \ (1)$$
$$P = V \times I \ (2)$$
$$E = P \times t \ (3)$$

3.6 Diode Bridge Rectifier

There exists two main types of current, direct current (DC) and alternate current (AC). DC is characterized by having a voltage value constant, in other words, it could be negative or positive. On the other hand, the alternate current, changes the polarity of its voltage, reaching from negative to positive maximums. Due to most electronic devices and applications functioning with DC, circuits such as diode bridge rectifiers are used to convert AC into DC. These circuits are designed with four diodes (Figure 3.5) that allow the current to flow in one direction [15][17].

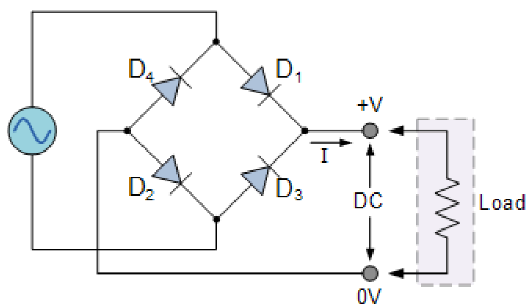

Figure 3.5. Schematic circuit for a diode bridge rectifier.

3.7 Oscilloscope

The term oscilloscope refers to the name of an electronic measurement device, where the instrument displays electrical signals over time (Figure 3.6). These signals are represented in graphs where the amplitude is defined by the vertical axis and the time by the horizontal axis. These devices are designed to stop the data acquisition to be saved and exported [19].

Figure 3.6. Oscilloscope used for measuring the experimental output.

4. METHODOLOGY

The article was divided according to two main sections (Figure 4.1). The first corresponds to the construction process of a triboelectric nanogenerator based on paper and packing tape. This was a replicating procedure, of a TENG reported by the Materials Research Science and Engineering Center. The second stage follows a series of electrical measurements for the characterization of the TENG output, with the objective of using inquiry-based learning, as a teaching method for the paper audience.

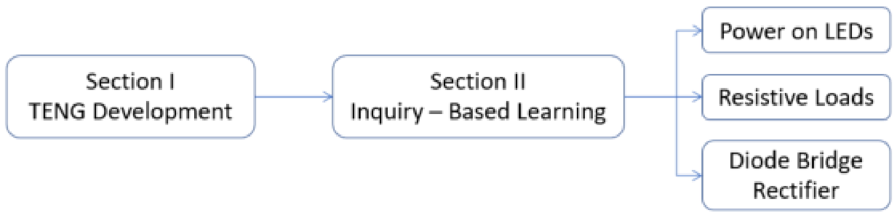

Figure 4.1. Methodology diagram of the academic paper stages

4.1 Paper – Packing Tape TENG

To assemble the paper TENG, the procedure from the Triboelectric Nanogenerator developed by MSERC Laboratory was replicated [20]. Two pieces of paper (6 $\times$ 10 cm) and two pieces of Aluminum foil (4.5 $\times$ 7 cm) were cut, as shown in Figure 4.2a. The aluminum (Al) foil (dull side up) was placed on top of the paper, followed by a stripped and splayed (5 cm) copper wire. The assembly was attached to the paper with packing tape (6 cm $\times$ 10 cm) (Figure 4.2b). This process was repeated twice, to obtain two surfaces with the same layer composition in the order of paper, aluminum foil, copper wire, and packing tape. Finally, both pieces (Al foil up) were hinged at both 6 cm sides to complete the TENG device (Figure 4.2c).

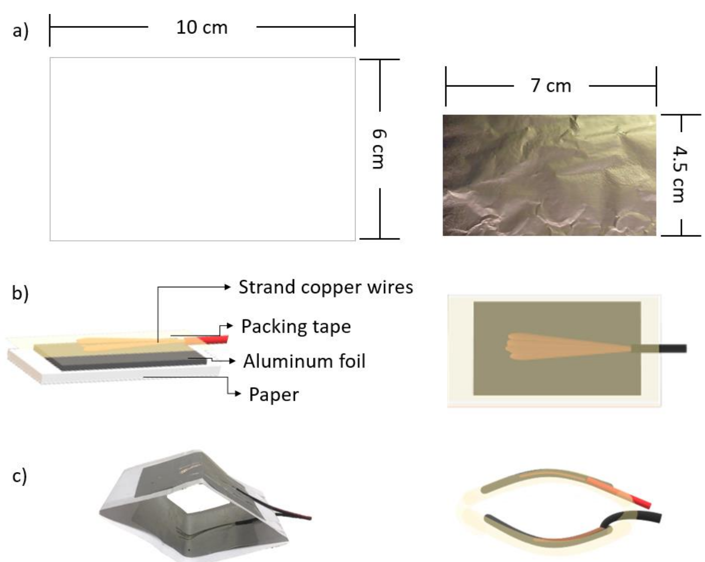

Figure 4.2. Step-by-step paper TENG development procedure.

4.2 Electrical Measurements – TENG Output Characterization

The first experiment was to power a green LED attached to the TENG terminals, with the objective of understanding the AC signal produced. Subsequently, two LEDs were attached in series and parallel with different variations in the LED polarity (Figure 4.3a). The third experiment is the load resistance circuit (Figure 4.3b), where different values of resistors (0.001 MΩ, 0.01 MΩ, 1 MΩ, 10 MΩ, 100 MΩ) were placed to analyze the power provided by the system. Finally, the last experiment wired (Figure 4.3c) was the diode bridge rectifier, converting the AC into DC to charge three capacitor values (1 µF, 4.7 µF, 22 µF). In the circuit diagrams, the TENG is represented as a sinusoidal AC source in series with a variable capacitor (blue boxes). This is because the configuration and mode of operation of the TENG are modelled as a variable capacitor.

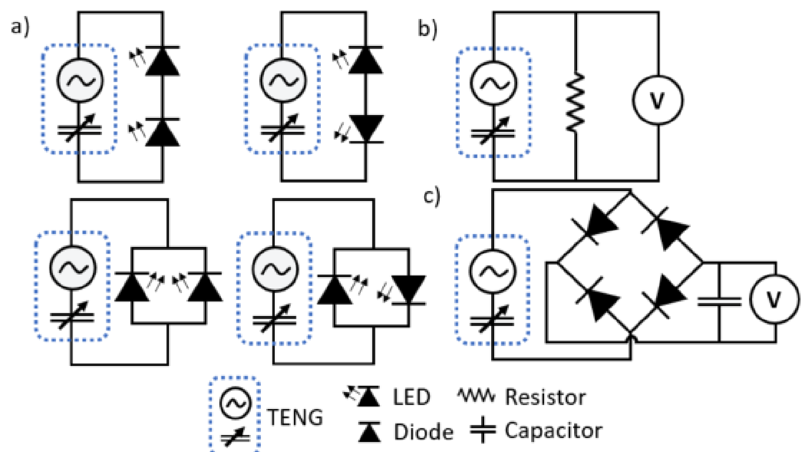

Figure 4.3. Series of experiments developed for the paper TENG output characterization, a) Series and parallel configurations for LEDs with polarity variations, b) Resistive loads circuit, c) Diode bridge rectifier for capacitor charging.

5. RESULTS AND DISCUSSION

This section describes the results and discussion obtained from the series of measurements developed for the second stage of the academic paper.

5.1 Power On LEDs

To explore the type of signal produced by the triboelectric nanogenerators, it was attached a light emitting diode (LED) between the TENG terminal. The AC nature of the TENG output and the mechanical energy applied generates a flashing effect on the LED. Figure 5.1 shows the signal obtained for each step of the tapping motion, where the flashing is produced in one of the peaks of the voltage signal. If the LED polarity was inverted, the light will be observed during the negative peak of the signal instead of the positive as is shown in the figure.

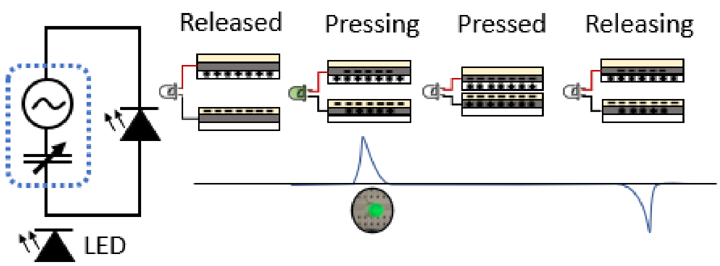

Figure 5.1 Diagram of the AC signal produced by a TENG represented by a powering LED experiment.

The signal produced can be used according to the desired application. For example, Figure 5.2a shows a series circuit with two LEDs, where, because of the voltage drop one LED shines brighter than the other. When more LEDs are connected in this type of configuration, the voltage produced by the TENG will be less for each subsequent element, where eventually, the minimum voltage required to turn on the LEDs will not be met (note that the minimum threshold also differs according to the color and the type of LED used). In addition, a modification in the circuit can probe how the elements of a series circuit have the same current. The output of the circuit in Figure 5.2b shows how once the LED has an inverted polarity, it interrupts the electron flow making the LEDs stay off because there is no current flow. On the other hand, for the parallel configuration, the LEDs are illuminated simultaneously with the same intensity when they are connected with the same polarity as shown in Figure 5.2c. For the modification of this circuit, the polarity inversion is shown in Figure 5.2d, where the LEDs flash intermittently according to the sign of the signal. This configuration makes it possible to take advantage of the full AC signal, making use of both cycles (positive and negative).

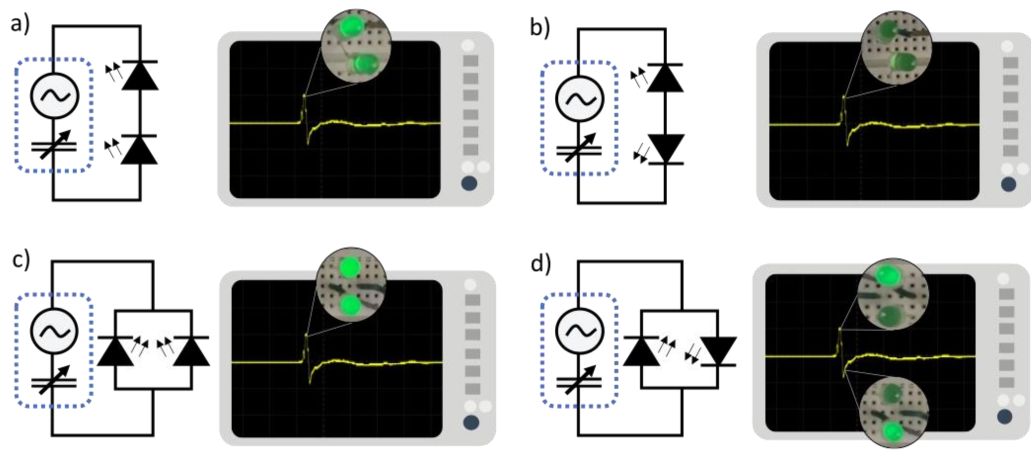

Figure 5.2 Series and parallel configuration with LEDs, a) series configuration, b) series configuration with inverted polarity in one of the LEDs, c) parallel configuration, d) parallel configuration with inverted polarity in one of the LEDs.

5.2 Resistive Load

A resistive load was used to characterize the power with equation (2) and energy with equation (3). First, the current was calculated with equation (1), where R corresponds to: 0.001 MΩ, 0.01 MΩ, 1 MΩ, or 10 MΩ, and V corresponds to the average voltage of the positive peaks. Figures 5.3 show the relationship between voltage, current, power, and energy *vs.* resistive load. In Figure 5.3a, the output voltage and current are proportional and inversely proportional to the resistive load value according to Ohm's law. Furthermore, in Figure 5.3b, the power curves show the device's resistance according to the maximum peak obtained with equation (3). Appendix 1 gives the results obtained by the groups from Canada, Colombia, and China using a Python code designed for processing the data. The template of the code developed is also available in Appendix 2.

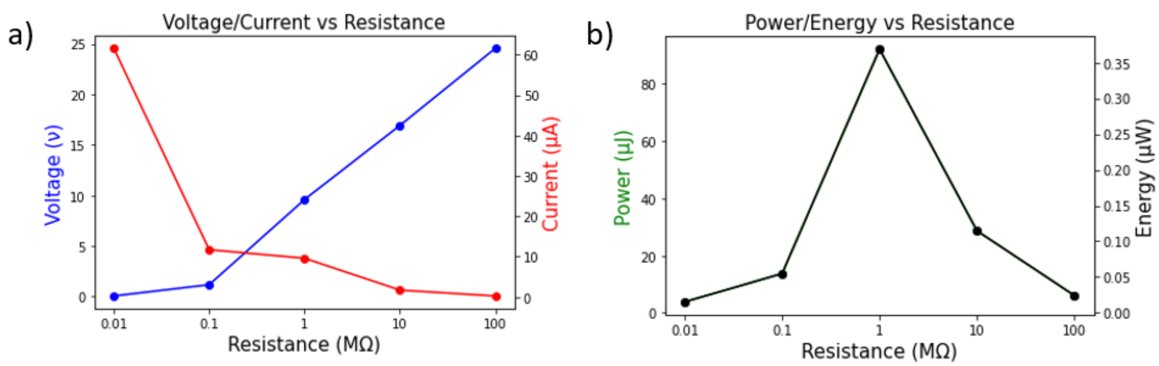

Figure 5.3. Voltage output and power relation in resistance load circuits.

5.3 Diode Bridge Rectifier for a Capacitive Charge

To comprehend and evaluate the charge capacity produced by the TENG, which can be stored with different capacitance values. The charging graphs for 1, 4.7, and 22 μF capacitors are shown in Figure 5.4, where the high, intermediate, and low slopes are related to each capacitor value, respectively. The maximum values in this plot correspond to the saturation point of the voltage that can be stored in the capacitors. To improve the effective surface charge density in TENGs the circuits for power low-consumption electronics and the Internet of Things (IoT), are examples of TENG applications that highlight the importance of the diode bridge rectifier circuits.

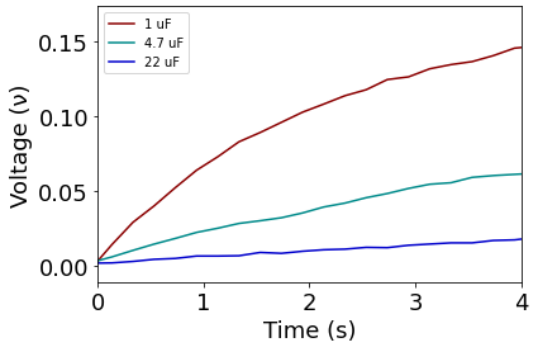

Figure 5.4. Capacitive charging graph.

6. FUTURE WORK

The inspiration for the development of this paper was to give students a friendly and educative introduction to the TENG world. The designs and measurements described in Section I and the paper–packing tape TENG output characterization in Section II provide helpful explanations to understand the engineering and electrical circuit background used in TENG research. For this reason, the Canadian group will integrate this as a detailed exercise for physics students to replicate in their introductory Electricity and Magnetism course. In the same way, the Colombian group will include this lab exercise for biomedical engineering students. This will generate a pedagogical environment where students can discuss the characteristics that can improve and modify TENG output for different applications, such as biosensors, harvesting circuits, etc. Our long-term goal is to design a TENG-based boot camp for graduate students, where they will develop the fundamental skills required to immerse themselves in triboelectric nanogenerator research. At the same time, this will encourage students to study these devices at an advanced level to contribute and innovate in this growing field.

7. CONCLUSIONS

With the development of this academic paper, it was possible to demonstrate the construction and electrical characterization of a paper and tape TENG suitable for those wishing to get started in the field of TENGs and to be introduced to the associated terminology and concepts. The simplicity of the paper TENG assembly, its safety and accessibility, combined with the detailed instructions and data template provided here, will lay the groundwork for students to perform this type of experiment successfully. In this way, students will learn the concepts of LED powering, capacitor charging, oscilloscope handling, grounding, and other concepts associated with basic circuitry and device characterization. In addition, this academic platform presents the basic knowledge necessary to understand the electronics, experimental design and data management presented in the reported literature for TENG output characterization.

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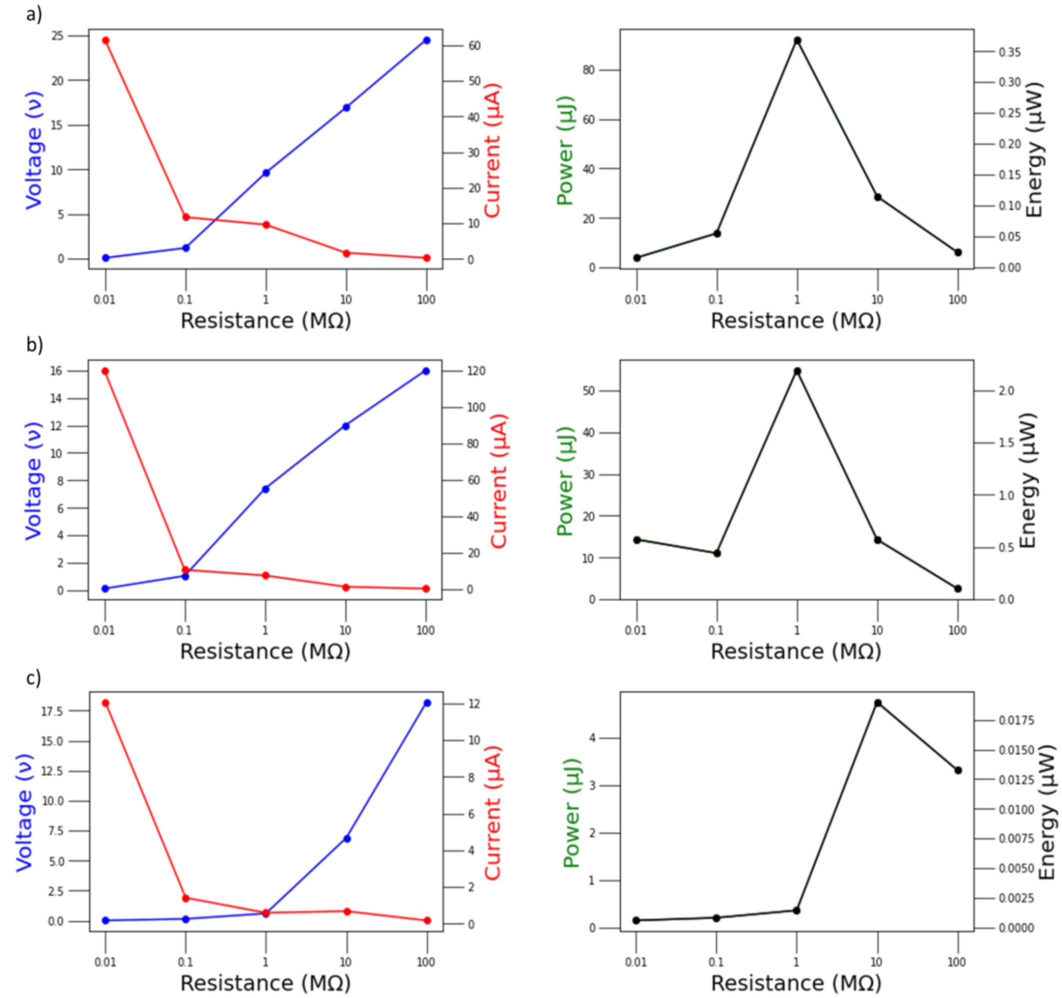
APPENDIXES

Appendix 1: Results from Canada, China, and Colombia Labs



Results obtained by the multidisciplinary group for the resistor load experiment. a) Data obtained by the Canadian group, b) Corresponds to the data obtained by the Colombian group, c) Corresponds to the data obtained in the Chinese group.

Appendix 2: Python Code

```
# Import libraries
from pandas import read_csv
from statistics import mean
import matplotlib.pyplot as plt
from scipy.signal import find_peaks
import numpy as np
# Reading csv file
dataset = read_csv('Resistance.csv',delimiter=',')
res=[0.01,0.1,1,10,100]
values = range(len(res))
########################################
x0 = dataset['TimeR0']
x1 = dataset['TimeR1']
x2 = dataset['TimeR2']
x3 = dataset['TimeR3']
x4 = dataset['TimeR4']
y0 = dataset['R0']
y1 = dataset['R1']
y2 = dataset['R2']
y3 = dataset['R3']
y4 = dataset['R4']

peaks0, _ = find_peaks(y0, height=max(y0)/2) #Function to find the
positive peaks
peaks1, _ = find_peaks(y1, height=max(y1)/2)
peaks2, _ = find_peaks(y2, height=max(y2)/2)
peaks3, _ = find_peaks(y3, height=max(y3)/2)
peaks4, _ = find_peaks(y4, height=max(y4)/2)
peaksn0, _ = find_peaks(-y0, height=-min(y0)/2) #Function to find the
negative peaks
peaksn1, _ = find_peaks(-y1, height=-min(y1)/2)
peaksn2, _ = find_peaks(-y2, height=-min(y2)/2)
peaksn3, _ = find_peaks(-y3, height=-min(y3)/2)
peaksn4, _ = find_peaks(-y4, height=-min(y4)/2)
fig, axs = plt.subplots(3,2)
axs[0,0].plot(x0,y0)
axs[0,0].plot(x0[peaks0], y0[peaks0], "x")
axs[0,0].plot(x0[peaksn0], y0[peaksn0], "x")
axs[0,0].set_title('0.01MΩ')
axs[0,1].plot(x1,y1)
axs[0,1].plot(x1[peaks1], y1[peaks1], "x")
axs[0,1].plot(x1[peaksn1], y1[peaksn1], "x")
axs[0,1].set_title('0.1MΩ')
axs[1,0].plot(x2,y2)
axs[1,0].plot(x2[peaks2], y2[peaks2], "x")
axs[1,0].plot(x2[peaksn2], y2[peaksn2], "x")
axs[1,0].set_title('1MΩ')
axs[1,1].plot(x3,y3)
axs[1,1].plot(x3[peaks3], y3[peaks3], "x")
axs[1,1].plot(x3[peaksn3], y3[peaksn3], "x")
axs[1,1].set_title('10MΩ')
axs[2,0].plot(x4,y4)
axs[2,0].plot(x4[peaks4], y4[peaks4], "x")
```

```
axs[2,0].plot(x4[peaksn4], y4[peaksn4], "x")
axs[2,0].set_title('100MΩ')
fig.tight_layout()
volt0 = mean(y0[peaks0])
volt1 = mean(y1[peaks1])
volt2 = mean(y2[peaks2])
volt3 = mean(y3[peaks3])
volt4 = mean(y4[peaks4])
volt =[volt0,volt1,volt2,volt3,volt4]
####################################
current                              =                             [
volt[0]/0.001,volt[1]/0.1,volt[2]/1,volt[3]/10,volt[4]/100]
fig, ax1 = plt.subplots()
ax2 = ax1.twinx()
ax1.plot(values,volt,marker="o", color ='b')
ax2.plot(values,current,marker="o", color ='r')
ax1.set_xlabel("Resistance (MΩ)", fontsize = 15)
ax1.set_ylabel("Voltage (ν)", color ='b', fontsize = 15)
ax2.set_ylabel("Current (µA)",color ='r', fontsize = 15)
plt.title("Voltage/Current vs Resistance", size=15)
plt.xticks(values,res)
plt.show()
###############################
pow                                =                               [
volt[0]*current[0],volt[1]*current[1],volt[2]*current[2],volt[3]*cu
rrent[3],volt[4]*current[4]]
ener=
[pow[0]*0.004,pow[1]*0.004,pow[2]*0.004,pow[3]*0.004,pow[4]*0.004]
fig, ax3 = plt.subplots()
ax4 = ax3.twinx()
ax3.plot(values,pow,marker="o", color ='g')
ax4.plot(values,ener,marker="o", color ='k')
ax3.set_xlabel("Resistance (MΩ)", fontsize = 15)
ax3.set_ylabel("Power (µJ)", color ='g', fontsize = 15)
ax4.set_ylabel("Energy (µW)",color ='k', fontsize = 15)
plt.title("Power/Energy vs Resistance", size=15)
plt.xticks(values,res)
plt.show()
```