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An 11.9 Volts Paper Based Solar-Teng For Self-Powered Systems

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Abstract – In the face of increasing energy demand and the imperative to shift towards sustainable sources, this study presents a novel approach to continuous electricity generation leveraging a hybrid system. The system integrates a Triboelectric Nanogenerator (TENG) with a conventional solar panel to ensure uninterrupted power supply under varying weather conditions. Operating at 11.9 volts, the TENG harnesses mechanical energy from environmental movements, such as wind or vibrations, while the solar panel taps into solar radiation. The synergy between these two technologies enhances energy output, providing a reliable energy solution for both sunny and rainy days. During sunlight hours, the solar panel predominately generates electricity, supplemented by the TENG to maximize efficiency. Conversely, on cloudy or rainy days when solar irradiance diminishes, the TENG compensates by continuously harvesting mechanical energy, ensuring a consistent power supply. This hybrid system offers a sustainable and versatile solution, suitable for a wide range of applications, including off-grid power generation, wearable electronics, and IoT devices. Through experimental validation and performance analysis, this research underscores the feasibility and efficacy of combining TENG with solar panels to meet the energy needs of diverse environments, regardless of weather conditions.

Keywords – 11.9 Volts, Paper, Based Solar-TENG,Self-Powered Systems.

I. INTRODUCTION

The Triboelectric Nanogenerator (TENG) originated in 2012 through the pioneering efforts of the Wang research group. Their innovative work aimed to harness the abundant yet often overlooked mechanical energy present in everyday experiences, as documented by Fan et al. (2012). This milestone was achieved by adeptly combining the principles of triboelectrification/contact electrification and electrostatic induction. The initial TENG device, characterized by a contact-separation configuration that remains foundational to contemporary designs, featured a composite of polyester (PET) film and Kapton film, with back electrodes as presented by Wu et al. (2018).

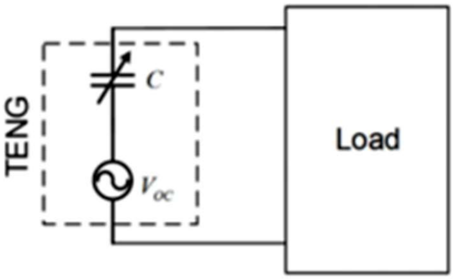

Fig 2: The equivalent electrical circuit model of TENG (Yue et al, 2016)

The concept of energy harvesting plays a pivotal role in advancing portable power solutions and electronics capable of operating independently of traditional power sources. This technology holds particular significance for a wide range of applications, including wearables, implantable devices, monitoring networks, and robotics, as highlighted by Won et al. (2020). The energy generated by these harvesters can be effectively stored in rechargeable batteries or supercapacitors, ensuring a readily available energy supply to operate the electronics as needed.

The Triboelectric Nanogenerator (TENG) represents an innovative and highly promising energy-harvesting technology that has garnered significant attention across a wide range of applications. These applications range from self-powered sensing to implantable medical devices, and even the harnessing of blue energy, as highlighted by Babarit et al. (2012). The device demonstrates the capability to produce AC output through variations in the contact status between the two films, particularly during cyclic pressing or bending motions. Initially, the operational concept was presented qualitatively.

The mechanism of operation of TENGs was traced back to Maxwell's displacement current (Wang L et al, 2017) which is defined as

$$J_D = \frac{\partial D}{\partial t} = \in \frac{\partial E}{\partial t} + \frac{\partial Ps}{\partial t} \qquad - \quad - \quad - \quad - \quad - \quad - \quad - \quad - \; 1$$

Where D is the Electric displacement and E is the electric field , P is the polarization and J is the current density.

The corresponding displacement current can be calculated as

$$J_D = \frac{\partial D_z}{\partial t} = \frac{\partial \sigma_{tz}(z,t)}{\partial t} \qquad - \quad - \quad - \quad - \quad - \quad - \quad - \quad - \; 2$$

TENGs operate based on a principle that merges the triboelectric effect with electrostatic induction. As the advantages of TENGs become increasingly evident, their adoption is growing. TENGs offer benefits such as low fabrication cost, high energy-conversion efficiency, ease of production, lightweight nature, and environmentally friendly characteristics, as detailed by (Fan et al. 2012).

While TENGs typically generate a high output voltage, their limited output current under normal conditions restricts their applicability and sustainability. To address this limitation, researchers have explored integrating TENGs with other energy-harvesting mechanisms to create hybrid energy-harvesting systems capable of capturing energy from various sources in the surrounding environment, as investigated by (Yang and Wang 2015). One such integration involves photovoltaic panels.

Rooftop photovoltaic (PV) panels, though efficient and cost-effective, stop generating power during rainy periods. To tackle this issue, an innovative approach is needed to create a solar cell that works in all weather conditions, utilizing both sunlight and raindrops. This is where the combination of solar cells with Triboelectric Nanogenerators (TENGs) becomes crucial, ensuring effective energy harvesting even without sunlight, thus enabling sustainable energy generation. This hybrid device has the potential to provide electricity for households, industries, and buildings. The core concept is to develop a device that captures kinetic energy from raindrop motion across solar panels without compromising the solar cell's performance under sunny conditions, as proposed by (Suryati et al, 2019).

II. A REVIEW OF RELEVANT LITERATURE

In the year 2016, a revolutionary hybrid nanogenerator that integrates a solar cell and a Triboelectric Nanogenerator (TENG), allowing for the simultaneous harvesting of wind and solar energy was introduced by (Wang et al., 2016) . This innovative system included three Si-based solar cells mounted on top of a TENG, which consisted of Kapton/Cu/fluorinated ethylene propylene (FEP) vibration films in the middle. Furthermore, two Cu electrodes were attached to the top and bottom of an acrylic substrate.

Zi et al., (2016) conducted a study that systematically compared the output performance of Electromagnetic Generators (EMGs) and Triboelectric Nanogenerators (TENGs) under low-frequency motions. The results showed that the power density of EMGs was proportional to the square root of the frequency, whereas that of TENGs was directly proportional to the frequency itself. As a result, within the low-frequency range, TENGs outperformed EMGs in terms of output power.

Yu et al. (2021) presented a simple yet effective method for manufacturing Triboelectric Nanogenerators (TENGs) that maintain stability even under deformation, marking a significant advancement in TENG technology. Their approach involved spin-coating silver nanowires (AgNWs) onto a pre-stretched Polydimethylsiloxane (PDMS) surface to create a flexible electrode. This innovative technique resulted in a stretchable TENG capable of impressive performance, achieving an output voltage of 50V and an output current of 20µA under an 80% stretching condition.

Additionally, researchers have developed hybrid TENGs by integrating an economical dye-sensitized solar cell (DSSC) into the design. Wen et al. (2016) introduced a comprehensive textile-based energy-harvesting system by combining fabric-based TENGs, fiber-shaped DSSCs (F-DSSCs), and fiber-shaped supercapacitors.

Due to its abundant availability, solar photovoltaic (PV) energy is regarded as the most promising renewable power source. However, it faces challenges such as weather-related intermittency, low efficiency, and high initial costs. The development of hybrid solar and Triboelectric Nanogenerator (TENG) systems has emerged as a highly promising sustainable energy source that operates effectively in both rainy and sunny conditions. The rapid progress in energy harvesting using nanogenerators has opened up the possibility of powering electronic devices using wasted mechanical energy from the environment. Numerous research efforts have been dedicated to TENGs, with ongoing work focused on enhancing output power and increasing the duty cycle of TENG-based devices.

The literature review indicated that standalone TENGs typically yield high voltage outputs but lower current outputs, which may limit their potential applications. Additionally, all TENGs exhibit similar output characteristics, as confirmed by (Chen et al., 2017). Therefore, hybrid energy harvesters incorporating TENGs offer a promising method to efficiently utilize environmental conditions for energy generation. These hybrid systems, by integrating two or more operational mechanisms, can generate higher currents through the harvesting of various forms of available energy, thereby meeting the requirements of distributed energy units (Ryan et al., 2022). This insight guided the goal of this research, which aims to develop an improved TENG that integrates with solar cells to perform effectively in diverse environmental conditions.

III. MATERIALS AND METHOD

Integrating solar cells and TENGs to produce electricity involves a series of systematic steps. Initially, it requires an assessment of the specific energy requirements for the application, which then determines the system's size and capacity.

The materials chosen for the TENG must possess adequate electrical conductivity to facilitate charge transfer between the surfaces during contact and separation. The mechanical properties of the TENG materials can impact its durability and efficiency. For example, cardboard paper offers high tensile strength, while plastic materials provide high elasticity. These properties can enhance the TENG's durability and ensure it can withstand repeated mechanical stress. Additionally, aluminum foil was incorporated in the fabrication process to improve the TENG's electrical conductivity.

When selecting solar panels for the system, factors such as efficiency, durability, and cost were considered. The size and capacity of the required system also influenced the choice of solar panel.

The following materials were used in the experimental setup

a) Cardboard Paper
b) Aluminum foil
c) Teflon Tape
d) Conductor Wire (1mm flex)
e) Stapling pin

To fulfill the objectives of this research, a standard TENG system was devised and analyzed to determine its operational principles and modes. The outcomes of this analysis were utilized to assess the enhancements realized in the proposed hybrid system.

The designed TENG comprises several layers, including a conductive layer, a dielectric layer, and a triboelectric layer, as illustrated in figures 1a and 1b. The conductive layer was constructed from aluminum foil, while the dielectric layer was composed of plastic. Additionally, the triboelectric layer consisted of cardboard paper with distinct triboelectric properties. These layers were measured, cut, stacked, and affixed with adhesive. The TENG's electrodes were designed using thin conducting wires and aluminum foils to collect the electrical charge generated during the contact and separation of the layers. To shield the TENG from environmental factors such as moisture and dust, the entire design was encased in a protective layer of plastic. The shape and configuration of the TENG are also crucial factors influencing its performance, with different designs exhibiting varying levels of effectiveness based on the intended application.

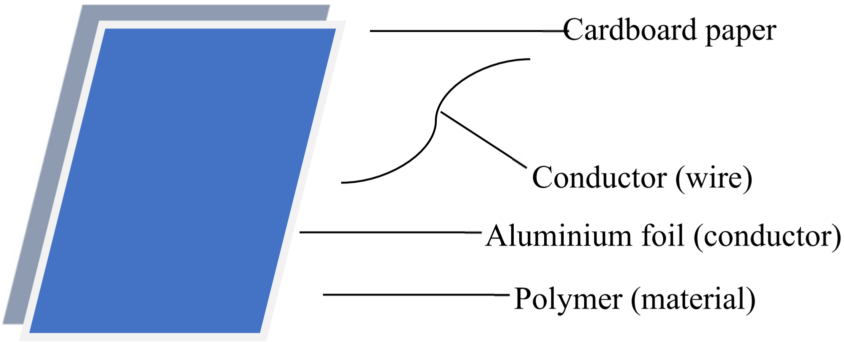

Fig 1a: Top layer of the TENG design

The diagram in Fig 3b shows the components of the bottom layer of the TENG design.

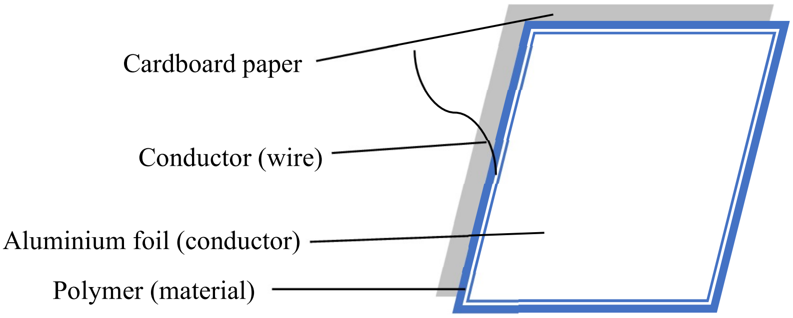

Fig 1b: Bottom layer of TENG design

When considering surfaces with opposite charges and a variable gap distance between them, it is similar to visualizing a capacitor with varying capacitance. This perspective offers a more intuitive representation of the TENG, using the capacitor model, with the current expressed as:

$$I = \frac{\partial Q}{\partial t} = A\frac{\partial \sigma_{tz}}{\partial t} \quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad - \qquad 3$$

The result aligns with Equation 3 and confirms that Maxwell's displacement current is fundamental to the capacitive model. The resultant output voltage of the TENG can be articulated as follows:

$$V = \frac{1}{C(z)}\, x\, Q + V_{oc}(z) \quad - \quad - \quad - \quad - \quad - \qquad - \quad - \qquad 4$$

In the Solar-TENG system, a power converter played a crucial role in converting the DC voltage produced by the TENG module into AC voltage suitable for powering electrical devices. Additionally, power converters regulated the voltage and current output of the modules to ensure the system operated at peak efficiency. Figure 2 illustrates the circuit diagram of the power converter utilized in this study.

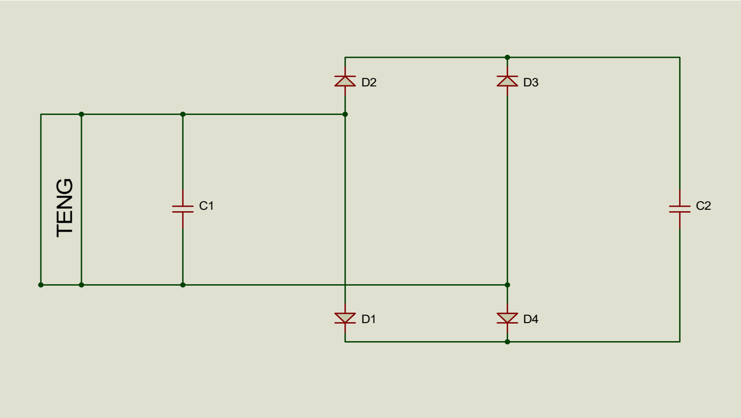

Fig 2: TENG AC-DC converter

a. Experimental setup

The experiment utilized a TENG with known dimensions, measuring the output current and voltage across three different frequencies of layer movement (contact frequency). The contact frequency, output voltage, current, and short circuit current were observed and measured. The TENG system assembly included a solar cell module, a TENG module, a power management unit, and an energy storage unit, as illustrated in Figure 3.

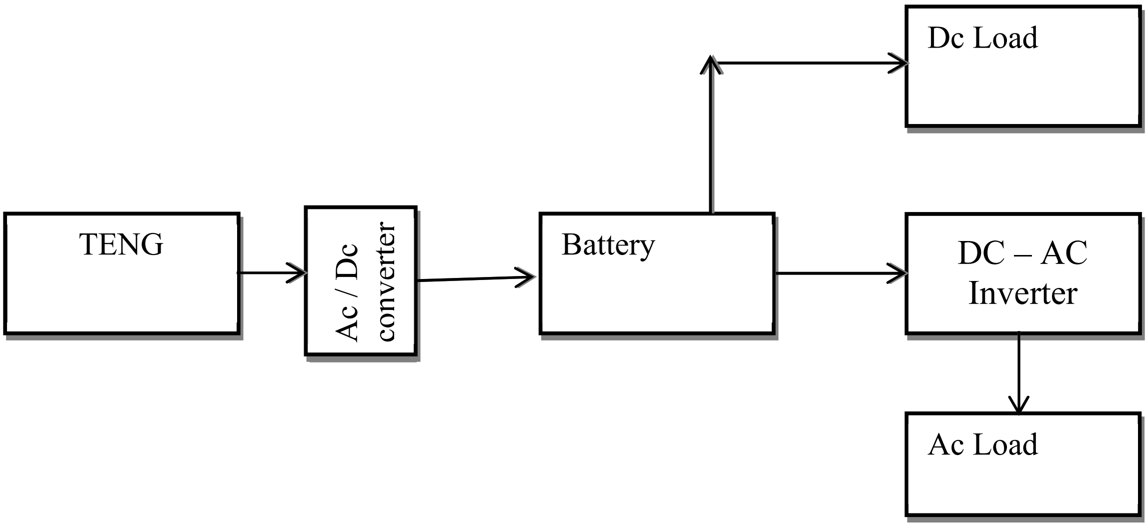

Fig 3: TENG Model

7Fig. 4 shows the experimental setup for hybridized PV and TENG. The solar panel used is a 40watts, 7v PV panel connected in parallel with a TENG to a 3.2V battery. While the TENG length and width od the TENG was varied, its thickness was kept constant at 1.5mm. The solar panel parameters also remained constant .

Fig 4. An Experimental setup for a hybridized PV and TENG. Size: 435x356x25

IV. RESULTS AND DISCUSSION

In this study, the parallel-plate capacitor model was employed to investigate how the resistance relates to the output performance of TENGs across different size configurations. The impact of various dimensions on output performance was experimentally analyzed using this model, revealing certain output characteristics of TENGs.

During testing, the developed TENG underwent repetitive mechanical compression through tapping its top plate with a finger. This tapping action occurred at frequencies of 2Hz, 4Hz, and 6Hz, generating a continuous dynamic sinusoidal motion. The controlled displacement levels ranged from 0 to +10 mm. Furthermore, the TENG was connected to an oscilloscope to visualize the waveforms.Table 1 shows the voltage and current output for the TENG during the mechanical compression. The voltage and current output were measured under three different tapping frequencies of 2Hz, 4Hz, and 6Hz.

The following materials were used for TENG experiments.

1. Cardboard paper (400 x 350 x 1.5mm)
2. Aluminum foil
3. Teflon tape
4. Conductor

Figure 5: picture of the design

Table 1 :Results and readings from Experiment 9 setup

Frequency (Hz)	2Hz	4Hz	6Hz
Voltage (v)	4.27v	5.86v	11.42v
Current (A)	0.032mA	0.049mA	0.071mA
Short circuit current isc (A)	0.031mA	0.038mA	0.043mA
Teng size (mm) L x W x T	400 x 350 x 1.5mm		

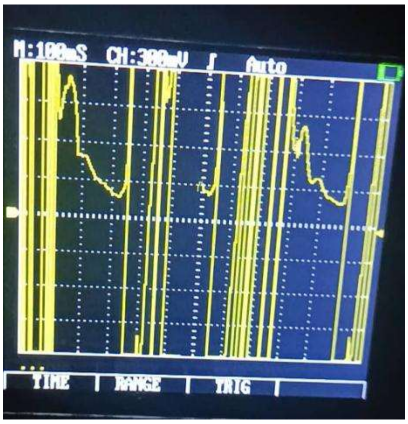

Figure 4.9a: The flow of the TENG output Voltage with time at 2Hz

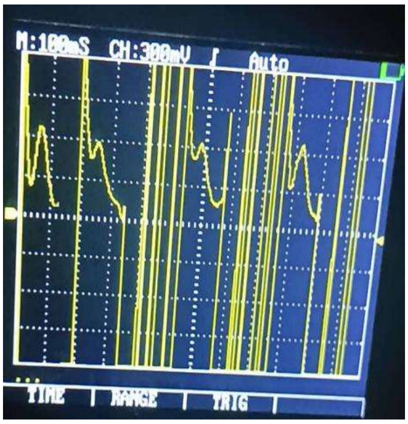

Figure 4.9b: The flow of the TENG output Voltage with time at 4 Hz

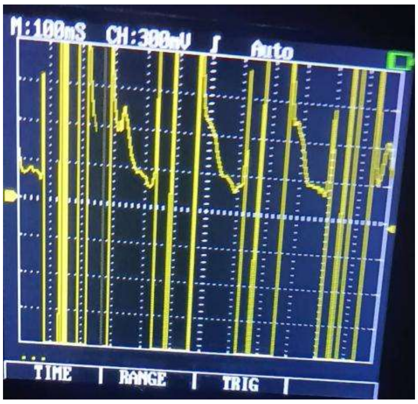

Figure 4.9c: The flow of the TENG output Voltage with time at 6Hz

These experimental setups also enabled the observation of how surface area affects TENG output, with the thickness maintained constant at 1.5mm. The findings revealed that a larger surface area with a thinner layer thickness yielded superior output.

Furthermore, it was noted that higher tapping frequencies enhanced the output voltage across the various size configurations of the TENG.

Lastly, a solar panel and TENG were combined and operated as a unified unit to generate electricity. The output voltage and current of this integrated system were examined under sunny, rainy, and cloudy weather conditions, and the outcomes are detailed in Table 2.

Table 2: The output performance for an assembled solar TENG system.

S/N	**Date d/m/y**	**Time**	**LUX**	**PV1 voltage**	**PV1 current**	**PV2 TENG voltage**	**PV2 current**	**TENG**	**Remark**	**% improvement in V**
1.	3/06/23	1:30pm	46400 lx	2.4V	1.7A	2.4V	1.7A		Cloudy	0%
2.	3/06/23	1:40pm	46900 lx	2.4V	1.7A	2.4V	1.7A		Cloudy	0%
3.	3/06/23	1:50pm	38100 lx	1.8V	1.5A	1.8V	1.5A		Cloudy	0%
4.	3/06/23	2:00pm	33400 lx	1.6V	1.2A	2.3V	1.2A	0.021uA	Raining	43.7%
5.	3/06/23	2:10pm	36300 lx	1.8V	1.2A	2.4V	1.2A	0.033uA	Raining	33%
6.	3/06/23	2:20pm	44500 lx	1.9V	1.6A	2.8V	1.6A	0.098uA	Raining	47.3%
7.	3/06/23	2:30pm	42500 lx	1.5V	1.3A	2.6V	1.3A	0.006uA	Raining	41.2%
8.	3/06/23	2:40pm	45100 lx	2.0V	1.8A	3.1V	1.8A	0.005uA	Raining	55.0%
9.	3/06/23	2:50pm	44500 lx	1.9V	1.7A	2.7V	1.7A	0.039uA	Raining	42%
10.	3/06/23	3:00pm	11700lx	1.2V	0.7A	1.9V	0.7A	0.041uA	Raining	58% 2.8%
11.	3/06/23	3:10pm	21100 lx	1.4V	0.8A	2.2V	0.8A	0.043uA	Raining	57% 5.0%

In cloudy weather, the output current and voltage of the solar-TENG system, represented by Pv2, closely resembled those of the solar panel alone, denoted by Pv1. This similarity is depicted between 1:30 pm and 2:00 pm in Figure 7.

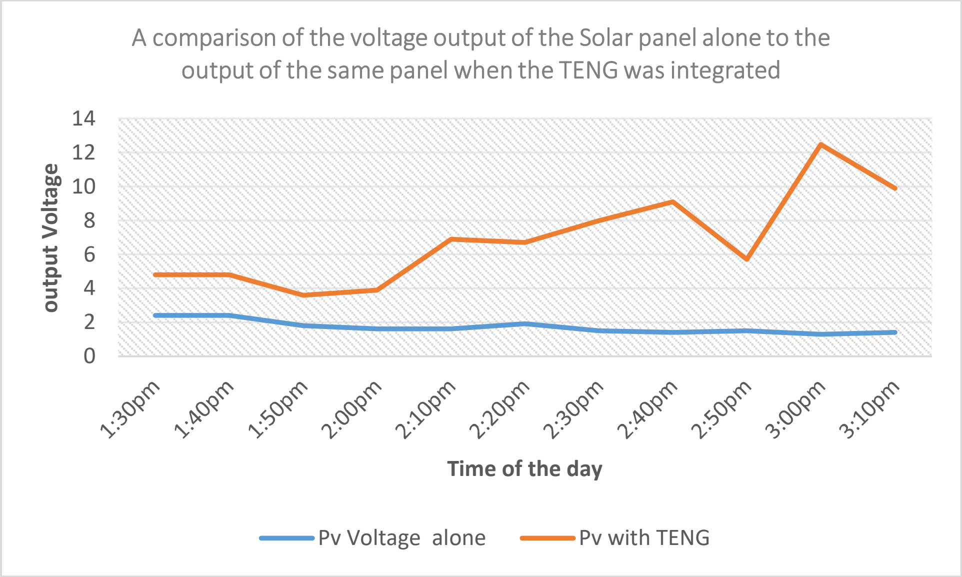

Fig 7: The output voltage of a stand-alone solar PV compared to a solar TENG system

This is because the TENG component of the system was inactive during cloudy weather, as indicated in Table 2. However, during rainy weather, the PV2 outputs of the hybrid system, as detailed in Table 2, saw a significant increase, with the current rising by up to 53% and the voltage by 43.75% from their initial values. This surge occurred because the TENG became operational due to the motion of raindrops, which mechanically compressed the TENG. As a result, the impact of the raindrops generated electricity, supplementing the energy already produced by the solar panel. The same trend was observed for the current output of the combined solar-TENG system.

In summary, the experiment involved operating the solar-TENG system with TENGs of varying dimensions and tapping frequencies (the rate at which the contacting surfaces are separated and brought into contact). The following findings were observed:

The TENG systems demonstrated the capability to generate both current and voltage, with output largely dependent on the TENG design, the materials used in the layers, and environmental conditions. Voltage outputs ranged from millivolts to several volts, while currents ranged from microamps to milliamps.

Increasing the excitation frequency resulted in higher output voltage and current for each experimental setup. Additionally, larger cross-sectional surface areas of the TENGs led to higher voltages, while the current remained relatively constant at approximately 0.054, even as the cross-sectional area increased significantly.

Furthermore, the TENG was able to drive a commercial LED instantaneously, albeit in a discontinuous manner. The tapping frequency played a crucial role in the experiment, impacting the efficiency of energy harvesting. The optimal tapping frequency can vary depending on the materials used in the TENG and its intended application. Some TENG designs are tailored for low-frequency, slow-motion interactions (such as human motion), while others are designed for higher-frequency vibrations (such as wind-induced vibrations).

Conventional TENGs often have high internal resistance inherent in their design, leading to high output voltages in the hundreds of volts range. However, they produce low currents typically in the nano/microampere range. This high impedance characteristic makes them unsuitable for various circuits and charging systems.

TENGs are influenced by various environmental factors, including temperature and humidity, with humidity being the most significant factor. In a humid air environment, when a solid object is present, water adsorption occurs. This adsorption process enhances the electrical conductivity of the object's surface, thereby increasing electrostatic leakage and accelerating the rate of electrostatic charge dissipation. As a result, the accumulation of electrostatic charge is greatly limited. Consequently, higher humidity levels lead to lower output power from the TENG.

On the other hand, temperature has a relatively minimal impact on static electricity. Warm air tends to be more humid, making it less prone to static electricity generation. In contrast, cold air is drier and favors static electricity accumulation. Therefore, low temperatures are more conducive to static electricity generation. Consequently, the output power of the TENG may vary under different conditions and times. For instance, on rainy days with high humidity, the output power of the TENG tends to decrease. Furthermore, daytime humidity levels are typically lower than nighttime, resulting in higher TENG output power during the day.

In order to maintain consistency within the experimental environment, the indoor temperature and humidity are carefully regulated using an air conditioner prior to each experiment. This ensures that all experiments are conducted at a temperature of 20 °C and a humidity level of approximately 50%.

V. CONCLUSION

In this research endeavour, we have also delved into various theoretical simulation approaches for assessing the electrical performance of Triboelectric Nanogenerators (TENGs).

The theoretical and practical methodologies outlined in this research have the potential to serve as guiding principles for experimental work on Triboelectric Nanogenerators (TENGs) and facilitate device optimization within commercial manufacturing

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