LAUTECH Journal of Engineering and Technology 18 (4) 2024: 34-40

10.36108/lauiet/4202.81.0440

Simulation Study of the Output Characteristics of Freestanding Triboelectric Nanogenerators with Interdigitated Electrodes for Self-Powered Sensing Application

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Article Info

Article history:

Received: Oct. 16, 2024
Revised: Nov. 15, 2024
Accepted: Nov. 16, 2024

Keywords:

Mechanical energy,
Nanogenerator,
Triboelectric,
Electrodes.

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ABSTRACT

Diverse forms of mechanical energy are available in environmental routine activities. These energy forms can be harvested, measured and converted to produce electricity at nanogenerator (NG) and micro-scale levels based on the phenomenon of triboelectrification. These motivate this work to develop a self-powered sensing device to detect and monitor static and dynamic processes associated with mechanical activities. The aim is to study the output characteristics of a freestanding mode triboelectric nanogenerator (TENG) with multiple units of metal and dielectric electrodes. The integrated modeling environment of COMSOL Multiphysics software was employed for the simulation study of the proposed TENG. The system output responses considered for analysis include open circuit electric potential and short circuit surface charge density. For the open circuit, the electric potential was achieved at the maximum value of 10000V, while for short circuit surface charge density, the electric potential was achieved at a maximum value of 27 Cm-2. The results of the study revealed that the input parameter of contact displacement of electrodes is proportional to the output electrical potential of the system. Hence, the efficiency of TENG can be deployed for energy harvesting and sensing of mechanical variables.

INTRODUCTION

The trend in the design and development of electronic sensing and Nano-energy harvesting devices has been to achieve system miniaturization and self-generation of energy (Linjie *et al.*, 2022). Miniaturized electronic systems operate at a very low power consumption rate, enabling the possibility of harvesting energy to power the devices from their operating environment. The applications of these types of devices include the development of ultrasensitive physicochemical sensors, remote and mobile environmental sensors, as well as implantable and wearable biomedical sensors. These are the evolving areas of application of nanotechnology and nanomaterials (Wang *et al.*, 2016: Zhiyi *et al.*, 2020). An emerging nanotechnology application is the development of nanogenerators (NGs) for building self-powered systems-based active sensors. Nanogenerators are designed from the physics of electrostatics. The justification for the development of these self-powered sensing and energy-harvesting devices is premised on availability, efficiency and stability. The factor of availability indicates that the type of energy to be converted or harvested depends on the operating environment of the nanogenerator. The stability factor guarantees the long-term operation of the Nano-energy system. While the efficiency factor deals with the effectiveness of the energy conversion or harvesting process of the technology (Wang, 2020: Junpeng *et al.*, 2021).

The development of triboelectric nanogenerators (TENG) is based on the frictional contact and interaction between two dissimilar materials to produce high-voltage static electricity from ambient mechanical energy. Conceptually, when two materials have frictional interaction, chemical bonding between some atoms on the surfaces results. However, this causes the transfer of charges between interacting surfaces to bring their electrochemical potential into equilibrium. The transferred charges can be electrons or may be ions or molecules. After separation, some of the bonded atoms may retain extra electrons, and others donate their electrons to produce triboelectric charges on their surfaces (Mule *et al,* 2019: Jiang *et al.*, 2021).

The materials that tend to capture transferred charges and keep them for a sustained period to accumulate electrostatic charges on their surfaces are said to have a strong triboelectric effect (Nannan *et al.*, 2023). Therefore, this work aimed to study the output characteristics of a freestanding mode triboelectric nanogenerator with multiple units of electrodes.

REVIEW OF RELATED WORKS

This section deduced the review of related works of the effectiveness of triboelectric nanogenerators (TENG). Vivekananthan *et al* (2020) proposed implantable TENGs using polyvinylidene fluoride (PVDF) based nanogenerators. The work channeled toward the modalities for designing TENGs in different operating modes, and micro-structured electrode surface fabrication to enhance output responses for portable-wearable power source applications. PVDF is a polymer material that stands for ferroelectric polymer polyvinylidene fluoride employed for implantable biosensing devices due to its property of biocompatibility. It can be used to monitor fluid flow, sound and thermal fluctuations. In micro-structured layer TENG designs, performance has been enhanced by the optimization of dielectric-to-electrode structural parameters, displacement gap and load characteristics.

Lijun *et al* (2020) worked on flexible PVDF-based piezoelectric nanogenerators. Flexible PVDF-based piezoelectric nanogenerators represent a typical alternative to green energy and promising for powering next-generation flexible and wearable electronics replacing the conventional chemical battery. With the extensive application of smart and flexible wearable devices in the fields of medical monitoring, human-machine interaction and artificial intelligence, energy supply and consumption are still the most critical limiting factors in the development of flexible electronics. Therefore, it is highly desirable to develop a new family of flexible self-powered intelligent electronics.

Emmanuel (2022) developed a wearable electronics-based human-machine interaction system for harvesting biomechanical energy produced by human skin. These technologies have been employed to develop ultra-low-power electronic devices and self-powered biomedical devices. These have been achieved by using fine spring as the conductive core and polydimethylsiloxane as the cladding layer as well as, using polypyrole as electrode material, a flexible interlaced micro-fibrous mesh fabric.

Nurmakanov *et al* (2021) developed autonomous self-powered active sensors, and power units, based on Internet of Things (IoT) devices. This is another remarkable outcome of the application of micro-patterns and nano-patterns structured triboelectric nanogenerators. Contact-separation mode TENG system was developed to transform the mechanical energy of vibrating pipes into electrical control signals for monitoring the structural health and safety of marine pipes. The energy of ocean waves has been harnessed and transformed by dielectric-metal contact separation mode TENG for the generation of electricity.

Quang *et al* (2023) worked on a self-powered sensor based on a liquid-solid triboelectric nanogenerator (L-S TENG). Self-powered sensors have emerged as a promising solution to this challenge, offering a range of benefits such as low cost, high stability, and environmental friendliness. One of the most promising self-powered sensor technologies is L-S TENG. This technology works by harnessing the mechanical energy generated by external stimuli such as pressure, touch, or vibration, and converting it into electrical energy that can be used to power sensors and other electronic devices. Therefore, self-powered based on L-S TENG, which provides numerous benefits such as rapidly responding, portability, cost-effectiveness, and miniaturization, is critical for increasing living standards and optimizing industrial processes.

Most of the recent work in the literature was limited to how the implementation of self-powered sensor-based nanogenerators has brought great progress in reducing power consumption at high energy conversion efficiency. Also, no account was reported on interdigitated electrodes for self-powered sensors, supplying electrical energy for electronic devices with power consumption to avoid the use of harmful chemical batteries. Therefore, this paper is highly desired to analyze in real-time the output characteristics of a freestanding mode triboelectric nanogenerator with multiple units of electrodes.

METHODOLOGY

This section demonstrated the materials and methods used for the work. The materials used for the modeling of the TENG device include air as the infinite domain, copper for the metal electrodes and fluorinated ethylene propylene (FEP) as dielectric electrode materials. The FEP has the desired properties of easy formation, low friction and non-reactivity, as well as a relative permittivity value of 2.1 (Fm^{-1}). The integrated modeling environment of COMSOL Multiphysics software was employed for the simulation study of the proposed TENG. The proposed system was modeled in 2D space. Multiple units of metal and dielectric electrodes with even separating distances were used. Eight metal electrode units were employed as stationary bottom electrodes while four dielectric units were employed as top moveable electrodes. The whole model structure was surrounded by air space and the infinity domain was chosen as the reference point. A parametric sweep through a range of values defined for the electrode's contact displacement was implemented for the stationary study of the output characteristics of the proposed TENG device. The workflow for the adopted methodology is depicted in Figure 1.

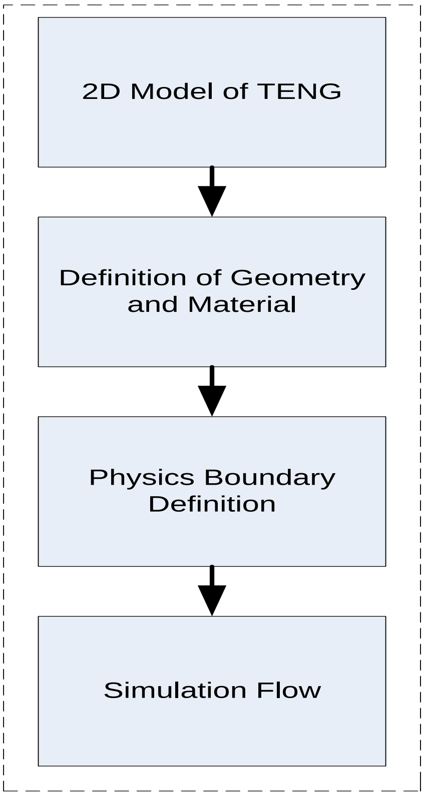

Figure 1. The workflow modeling of TENG

For geometric objects defined for the system modeling, copper was employed as a bottom metal electrode, FEP was used as the top dielectric material, and the air domain as surrounding layers representing the infinite domain.

The layout of the proposed interdigitated freestanding TENG device is shown in Figure 2. The strength of the electric field is proportional to the induced charge density in the metal electrode. The potential difference is determined by the separation displacement and electric field strength. At the same time, the separation process also creates an energy barrier between the two surfaces that prevents the reverse flow of electrons.

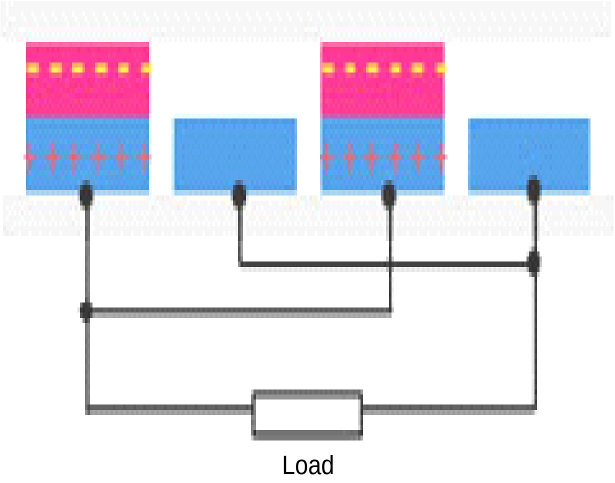

Figure 2. The model layout of the TENG device

MATHEMATICAL FORMULATION

As a simplification assumption, let z be a critical tunneling displacement threshold, and electrons can flow freely between two surfaces below the threshold. Tunneling is prevented above the threshold. Therefore, for a parallel metal electrodes model, at the displacement threshold z, the dielectric surface charge σ induces σ_1 on the top metal and σ_2 on the bottom metal (Mule *et al.*, 2019: Wang *et al.*, 2020). This relationship is expressed as:

$$\sigma + \sigma_1 + \sigma_2 = 0 \tag{1}$$

Due to the inherent electric field σ_1/ε_0, the vacuum energy level between the metal and the dielectric surface changes by ΔE_{vcc}:

$$\Delta E_{vcc} = \sigma_1 ze/\varepsilon_0 \tag{2}$$

Assuming, the surface density of states is Ns(E) and the range of filled surface states is ΔEs, at equilibrium condition. Hence, the dielectric surface charge σ is given as:

$$\sigma = -e\int_{E_0}^{E_0+\Delta Es} Ns(E)dE$$

(3)

The average surface density of states is given as:

$$AveNs(E) = \frac{\int_{E_0}^{E_0+\Delta Es} Ns(E)\,dE}{\Delta Es}$$

(4)

$$\Delta Es = \frac{-\sigma}{AveNs(E)e}$$

(5)

It is noted that under the parallel-electrode surface assumption, the bias potential, V between two metal electrodes can be written using the Poisson equation

$$V = \frac{\sigma_1}{\varepsilon_0}z - \frac{\sigma_2}{\varepsilon\varepsilon_0}t$$

(6)

From Equations (1), (5) and (6), the surface charge density on the dielectric surface σ can be expressed as:

$$\sigma = \frac{V + \frac{(W-E_0)}{e}(1+t/\varepsilon z)}{t/\varepsilon\varepsilon_0 + \frac{1}{AveNs(E)e^2}(1+t/\varepsilon z)}$$

(7)

This expression quantitatively describes contact electrification via an externally applied electric field.

where, ΔE_{vcc} is the change in vacuum energy (J)
e is the elementary charge (C)

Ns(E) is the surface density (Cm^{-2})

ΔEs is the filled surface density (Cm^{-2})

Ave is the average surface density (Kgm^{-3})

σ is the dielectric surface charge (Cm^{-2})

V is the surface electric potential distribution (V)

N_S is the surface density (Kgm^{-2})

ε_0 is the relative permittivity of a free space (Fm^{-1})

t is the time taken (sec)

The physics of electrostatics which governs the triboelectricity output characteristics of electric potential and surface charged density was defined for the model simulation. The electric or electrostatic potential is defined as the amount of energy needed to transfer a unit of electric charge from a reference point to a specific point in an electric field (Ojo *et al.*, 2024: Ojo *et al.*, 2023). The floating potential, V was initialized to zero and defined as boundary conditions at the outer boundaries of the top and bottom electrodes. The surface charge density was initialized as a boundary condition at the inner boundaries of the TENG electrodes taking into cognizance the need for charge balance and symmetry of geometries (Chen *et al.*, 2018: Zhang *et al.*, 2020).

RESULTS AND DISCUSSIONS

This section evaluates the performance analysis of the TENG simulation model TENG. From the results of the model analysis, a range of -6V to 6V electric potential distribution for a displacement value of 0.0 m between the top dielectric units and bottom metal electrodes was obtained as presented in Figure in 3. Thus, the electric potential difference separated by 0.0 m indicated that the dielectric field existing between them is neglected. Also, for specific displacement values of -0.0535m and 0.0535m, the electric potential distribution ranges from -25kV to 5kV and -60kV to 10kV respectively. Thus, these were presented in Figure 4 and Figure 5 respectively.

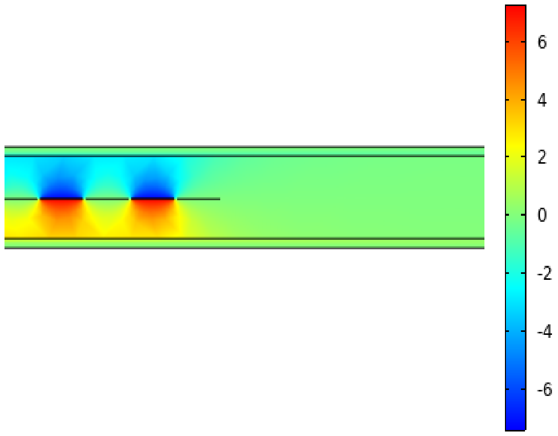

Figure 3. Surface electric potential distribution (V) ranges from -6V to 6V at 0.0m separation distance.

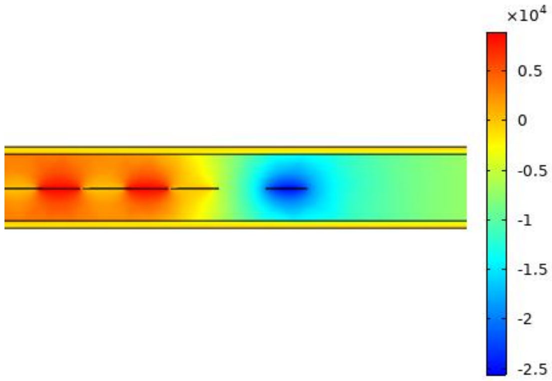

Figure 4. Surface electric potential distribution (V) ranges from -25kV to 5kV at -0.0535m separation distance

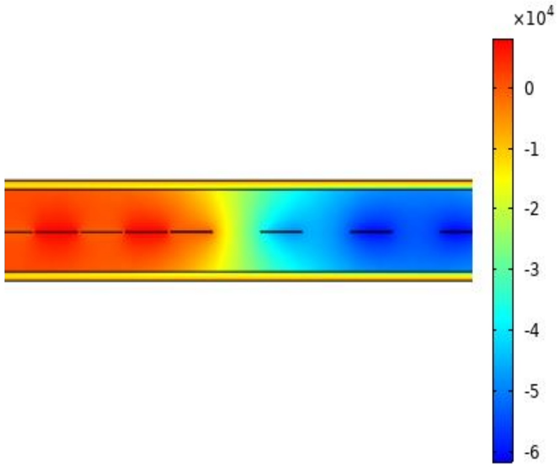

Figure 5. Surface electric potential distribution (V) ranges from -60kV to 10kV at 0.0535m separation distance

Furthermore, the simulation study analyzed the output characteristics of the proposed TENG in terms of open circuit voltage potential (V) and short circuit surface charge density (Cm^{-2}). Surface charge density is the quantity of accumulated charges at the surface of the electrodes in 2D space. As shown in Figure 6, a maximum value of 10000V electric potential was achieved in the simulated TENG device. Also, the results obtained for the open circuit surface charge density is shown in Figure 7, at a maximum value of 27 Cm^{-2}.

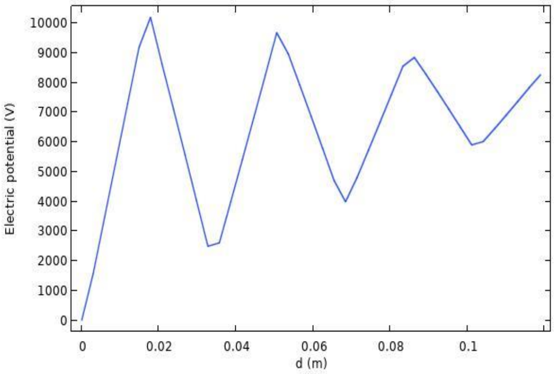

Figure 6. A plot of open circuit voltage potential against electrode displacement

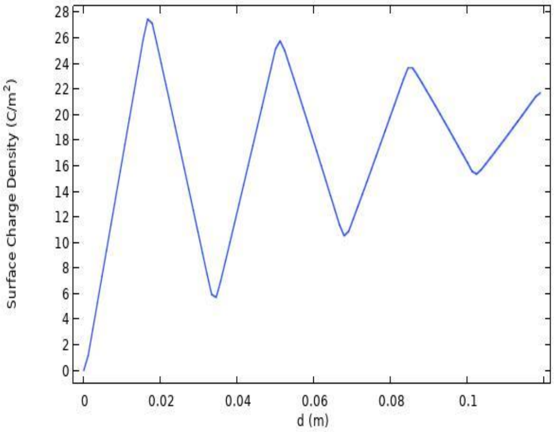

Figure 7. Plot of short circuit charge transfer of TENG structure

Hence, the significance of these results is that contact displacement is a major design parameter as it is the input to the system. As shown in the results, the input parameter is linearly proportional to the output response of the TENG device because as the value of the contact displacement changes, the electric potential which is the system output response changes simultaneously. Therefore, an efficient TENG design allows for optimal values of contact displacement, so that optimal values of electrical output responses can be realized.

CONCLUSION

In conclusion, a simulation study of a freestanding mode triboelectric generator with multiple units of electrodes was conducted. The system output responses considered for analysis include open circuit electric potential and short circuit surface charge density. Multiple units of electrodes in the form of interdigital electrode arrangement were employed to enhance the output response of the system. As the contact displacement between the multiple units of dielectric and copper electrodes was increased, the values of the output electrical parameters increased in turn.

Consequentially, a triboelectric nanogenerator device would be suitable for energy harvesting and sensing of mechanical variables. In the future, researchers can integrate machine learning for more accuracy and efficiency instead of self-powered sensing applications.

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