Diagonal Mode: A New Mode for Triboelectric Nanogenerators Energy Harvesters

Reem Abd El-Sttar[1], Endy Onsy[1], George S. Maximous[2], Ahmed Zaky[1], Tamer A. Ali[3], Ashraf Seleym[2], and Hassan Mostafa[1,4]

[1]Nanotechnology Engineering Department, University of Science and Technology at Zewail City, October Gardens, Egypt.
[2]Department of Electrical Engineering, British University in Egypt, Cairo, Egypt.
[3]Communications and Information Engineering, University of Science and Technology at Zewail City, Giza, Egypt.
[4]Electronics and Communication Engineering Department, Cairo University, Giza 12613, Egypt.
[**]*Both of Endy Onsy and Reem Abd El-Sttar have contributed equally to this work.*

***Abstract*—Triboelectric nanogenerators (TENGs) have shown a great potential for harvesting low frequency mechanical energy. It is thus considered a suitable energy source for both self-powered applications and bulk energy harvesting. In this work, a new diagonal motion mode is studied intensively in attached electrode regime and simulated using COMSOL MULTIPHYSICS. The Diagonal motion mode offers a new degree of freedom represented in the angle of motion allowing for further energy optimization. A complete analytical model of the proposed TENG model has been derived. In addition, a comparison between the analytical model and the COMSOL simulation results has been done. The maximum error between the results is equal to 5.3% and the minimum error is equal to 0.88%. The accuracy of the analytical model was a motivation for constructing a Verilog-A model to study the device under different loading conditions. A case of simple resistive load is considered, the results show that the open circuit voltage, VOC, is equal to 5 V while the short circuit charge, Q_{SC}, is equal to 45 pC. The short circuit current is equal to 193 pA at theta of 0. Also, the peak power is equal to 50 pW for a load resistance of 110 GΩ.**

***Index Terms*—Diagonal TENGS, Triboelctric, nanogenerators, COMSOL, Energy Harvesting, Verilog-A**

I. Introduction

Since the worldwide energy demand is growing rapidly, searching for a new source of renewable energy has become a necessity. Mechanical energy can be harvested , due to its abundance, by many emerging technologies such as: piezoelectricity, electromagnetic and triboelectrification. Basically, nanogenerators are developed by using triboelectricity and piezoelectricity [1]. Moreover,one of the most promising technologies are the triboelectric nanogenerators (TENGs) that combine triboelectrification with electrostatic induction [2, 3]

TENGS can scavenge various forms of mechanical energy such as human motion, flowing water and wind while offering a variety of advantages such as low cost, high output power, high efficiency and easy fabrication [3, 4].

There are three TENG types which are attached electrode, single electrode and freestanding, with each type having two basic modes: Contact mode and sliding mode. Each type has a certain structure and triggering order, but for the materials, they can be chosen specifically to optimize the outputs.

Throughout this study, a new diagonal mode attached electrode TENG is introduced in section II, starting from its mechanism, followed by the COMSOL simulation , the complete derivation of the analytical model, and the Verilog-A model. The results of the model are discussed in details in section III. Finally, the conclusion and future work are drawn in section IV.

II. Proposed Diagonal Model

The diagonal mode has been proposed before but with a semi-analytical model based on curve fitting [5]. In this mode the TENG moves with an angle called (theta) offering a new degree of freedom instead of moving in a vertical or horizontal direction, with the angle varying between 0 and 90 degrees. Figure 1 shows the complete setup of the diagonal mode dielectric to dielectric.

$$V = -\left|Q\right|/C(x) + V_{oc}(x) \tag{1}$$

Equation (1), known as (*V-Q-x*) relation, is the fundamental governing equation of any TENG structure. To fully characterize a particular TENG structure operating in a given mode, both $V_{oc}(x)$ and $C(x)$ need to be known explicitly and substituted directly in (1).

A. COMSOL Model

The FEM calculations under both short-circuit (SC) condition and open-circuit (OC) condition of the proposed structure were carried out using COMSOL-Multiphysics 5.3 software. This was done by setting the terminal condition to be $Q_0 = 0$ for OC and $V_0 = 0$ for SC. The structure is surrounded by air insulation, which is applicable in a real life, to get better results in comparison with both Contact and sliding mode of the attached electrode TENG [3]. The parameters used in this simulation are listed in Table 1 but they can be changed according to the application.

B. Analytical Model

The attached electrode diagonal mode with air insulation is equivalent to four capacitors connected in parallel as shown in Fig.1. One capacitor between the upper and bottom electrodes,

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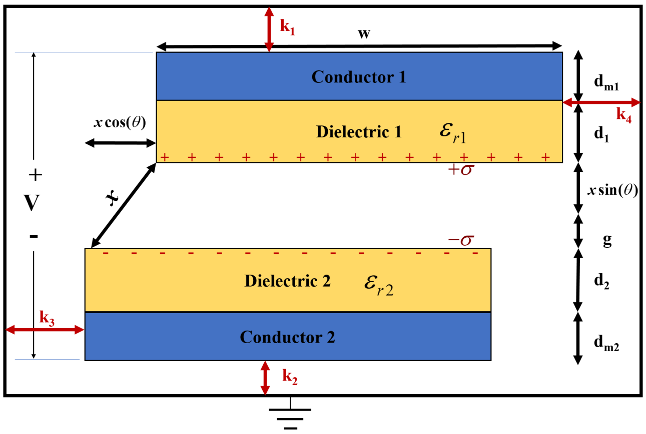

Fig. 1. Device structure of the proposed TENG model. The figure is not to scale, as metal electrodes are much thinner than dielectrics.

one between the upper electrode and the right wall, one between the upper electrode and the left wall and one between the upper electrode and the upper wall. Thus, the total charge is given by:

$$Q_{SC} = Q_{SC_1} + Q_{SC_2} + Q_{SC_3} + Q_{SC_4} \tag{2}$$

And according to the TENG governing equation shown in equation (1) $Q_{SC} = V_{OC} \times C$, so:

$$Q_{SC} = V_{OC_1}C_1 + V_{OC_2}C_2 + V_{OC_3}C_3 + V_{OC_4}C_4 \tag{3}$$

V_{OC} of each capacitor can be derived by thoroughly understanding the charge distribution. At the non-overlapped region of the structure, the dielectric induces an equal and opposite charge on the conductor. The charge of the overlapped region is determined by OC conditions.

Assume the charge at the non-overlapped region of the top and bottom conductors are given by A and B respectively, then to satisfy OC condition:

$$\sum Q_{top} = -\sigma x\cos(\theta)l + A(w - x\cos(\theta))l = 0 \tag{4}$$

TABLE I
PARAMETER SET USED THROUGHOUT COMSOL SIMULATION.

Parameter	Value
Device width and length w, l	1 mm
Diagonal distance x	100 μm
Thickness of the dielectrics d_1, d_2	25 μm
Thickness of the metal electrodes d_m	1 μm
Relative dielectric constants ε_{r1}, ε_{r2}	2, 4
Air insulation distances $k_{1,2,3,4}$	1 μm
Surface charge density σ	100 μC
Average angular velocity ω	1 ms^{-1}
Maximum diagonal angle $\theta_{\max}$	90°

$$\sum Q_{bottom} = \sigma x\cos(\theta)l + B(w - x\cos(\theta))l = 0 \tag{5}$$

Therefore, A and B equal:

$$A = \frac{\sigma x\cos(\theta)}{(w - x\cos(\theta))}, B = \frac{-\sigma x\cos(\theta)}{(w - x\cos(\theta))} \tag{6}$$

For the first capacitor between the two conductors, the electric field is in the z-direction and is found by applying Gauss's law in each of the five regions; the top conductor E_1, first dielectric E_2, the air gap E_3, the second dielectric E_4 and the second conductor E_5 respectively:

$$\oint E \cdot dA = \frac{Q_{enc}}{\varepsilon} \tag{7}$$

First, We find E_1 which is the electric field inside the top conductor:

$$-E_1(w - x\cos(\theta))l = \frac{A(w - x\cos(\theta))l}{\varepsilon_0} \tag{8}$$

Hence E_1 equals to:

$$E_1 = \frac{-A}{\varepsilon_0} = \frac{-\sigma x\cos(\theta)}{\varepsilon_0(w - x\cos(\theta))} \tag{9}$$

Similarly, E_2, E_3, E_4, E_5 can be found as follows:

$$-E_2(w - x\cos(\theta))l = \frac{A(w - x\cos(\theta))l}{\varepsilon_0\varepsilon_{r1}} \tag{10}$$

$$-E_3(w-x\cos(\theta))l = \frac{A(w - x\cos(\theta))l}{\varepsilon_0} + \frac{\sigma(w - x\cos(\theta))l}{\varepsilon_0} \tag{11}$$

$$E_4(w - x\cos(\theta))l = \frac{B(w - x\cos(\theta))l}{\varepsilon_0\varepsilon_{r2}} \tag{12}$$

$$E_5(w - x\cos(\theta))l = \frac{B(w - x\cos(\theta))l}{\varepsilon_0} \tag{13}$$

Thus,

$$E_2 = \frac{-A}{\varepsilon_0\varepsilon_{r1}}, E_3 = -\frac{A}{\varepsilon_0} - \frac{\sigma}{\varepsilon_0} \tag{14}$$

$$E_4 = \frac{B}{\varepsilon_0\varepsilon_{r2}}, E_5 = \frac{B}{\varepsilon_0} \tag{15}$$

V_{OC} is determined using the line integral formula and substituting the values of A and B from equation (6):

$$V_{OC} = -\int_0^{d_{m1}+d_1+g+x\sin(\theta)+d_2+d_{m2}} E \cdot dz \tag{16}$$

$$V_{OC1} = \frac{\sigma x\cos(\theta)}{\varepsilon_0(w - x\cos(\theta))} \times (g + x\sin(\theta) + d_0 + d_{m1} + d_{m2}) + \frac{\sigma(g + x\sin(\theta))}{\varepsilon_0} \tag{17}$$

With d_0 defined as the dielectric equivalent thickness given by $d_0 = d_1/\varepsilon_{r1} + d_2/\varepsilon_{r2}$.

Since the overlapping part of the structure is the most dominating part for the capacitance, the capacitance is given by:

$$C_1 = \frac{\varepsilon_0(w - x\cos(\theta))l}{(g + x\sin(\theta) + d_0 + d_{m1} + d_{m2})} \quad (18)$$

For the capacitor between the top electrode and the right wall, the electric field is in the horizontal direction (x-direction) and is found by applying Gauss's law:

$$E_6 d_{m1} l = \frac{-\sigma d_{m1} l}{\varepsilon_0} \rightarrow E_6 = \frac{-\sigma}{\varepsilon_0} \quad (19)$$

$$V_{OC2} = -\int_{k_3 + x\cos(\theta) + w + k_4}^{k_3 + x\cos(\theta) + w} E_6 dx^{'} = \frac{-\sigma}{\varepsilon_0} k_4 \quad (20)$$

And the capacitance given by:

$$C_2 = \frac{\varepsilon_0 d_{m1} l}{k_4} \quad (21)$$

For the third capacitor between the top electrode and the left wall, the electric field (in the x-direction) is found by applying Gauss's law:

$$-E_7 d_{m1} l = \frac{A d_{m1} l}{\varepsilon_0} \rightarrow E_7 = \frac{-A}{\varepsilon_0} \quad (22)$$

$$\begin{aligned} V_{OC3} &= -\int_{0}^{k_3 + x\cos(\theta)} E_7 dx^{'} \\ &= \frac{\sigma x\cos(\theta)}{\varepsilon_0(w - x\cos(\theta))}(k_3 + x\cos(\theta)) \end{aligned} \quad (23)$$

And the capacitance is given by:

$$C_3 = \frac{\varepsilon_0 d_{m1} l}{(k_3 + x\cos(\theta))} \quad (24)$$

For the fourth capacitor between the top electrode and upper wall, by applying gausss law under OC condition:

$$E_8 w l = \frac{Q_{enclosed}}{\varepsilon_0} = 0 \rightarrow E_8 = 0 \quad (25)$$

Then, $V_{OC4} = 0$ and the capacitance is found to be:

$$C_4 = \frac{\varepsilon_0 w l}{k_1} \quad (26)$$

Using equations (17, 18, 20, 21, 23, 24, 25), Q_{SC} is found to be:

$$\begin{aligned} Q_{SC} = \sigma l x\cos(\theta) &+ \frac{\sigma l(g + x\sin(\theta))(w - x\cos(\theta))}{(g + x\sin(\theta) + d_0 + d_{m1} + d_{m2})} \\ &- \sigma d_{m1} l + \frac{\sigma d_{m1} l x\cos(\theta)}{(w - x\cos(\theta))} \end{aligned} \quad (27)$$

And the total capacitance of the structure is the equivalent of four parallel capacitors as mentioned earlier:

$$\begin{aligned} C_{total} = &\frac{\varepsilon_0(w - x\cos(\theta))l}{(g + x\sin(\theta) + d_0 + d_{m1} + d_{m2})} \\ &+ \frac{\varepsilon_0 d_{m1} l}{k_4} + \frac{\varepsilon_0 d_{m1} l}{(k_3 + x\cos(\theta))} + \frac{\varepsilon_0 w l}{k_1} \end{aligned} \quad (28)$$

And finally V_{OC} can be found as: $V_{OC} = Q_{SC}/C_{total}$. By substituting with QSC shown in equation (27) and C_{total} shown in equation (28) in equation (1), the closed form (*V-Q-x*) relation can be determined.

C. Verilog-A Model

Generally, any TENG structure can be modeled as a lumped element model made up of serial combination between time varying voltage source represented by $V_{OC}(t)$, and time varying capacitor represented by $C(t)$ [6]. Regarding the diagonal mode, the upper part -consisting of the upper electrode attached to the upper dielectric- moves in a rotational motion that can be expressed by the equation,$\theta = \omega t$, In which ω is the angular velocity and t is the time.

$$V = R\frac{d}{dt}Q(\theta(t)) = -\frac{1}{C(\theta(t))} \times Q(\theta(t)) + V_{OC}(\theta(t)) \quad (29)$$

Where *R* is the equivalent resistance as seen at the TENG terminals. However, if more complex loads such active elements are connected, determining the (V-Q-X) relationship requires substituting the previous equation by more complicated ones (e.g. integral or integro-differential equations) whose solving analytically is an arduous task and time-consuming if operated by any of the FEM simulation tools. Therefore, a Verilog-A model for the diagonal mode attached electrode TENG is presented as in [7] to make it easier to incorporate the TENG structure with various complex loads for different applications using different circuit simulation tools (e.g., Cadence Virtuoso).

III. Results and Discussions

Scrutinizing the results of the analytical model and the COMSOL simulation, a comparison between them was needed to demonstrate a well established verified model. The results of COMSOL simulation showing V_{oc}, Q_{sc} and capacitance along with analytical model is depicted in Fig.2 (a), (b) and (c) respectively. Clearly, both the open circuit voltage and the short circuit charge show, almost, the same behavior as Fig. 2(a),(b) depicts. Both variables show a 2nd order filter response showing a maximum value of $\approx$ 5 V and $\approx$ 45 pC for V_{OC} and Q_{SC} respectively at theta = 90°. The capacitance between the two electrodes is almost fixed with small variations around a value of $\approx$ 9.2 pF.

V_{oc}, Q_{sc} and C exhibit an average error of 5.3%, 4.3% and 0.88% respectively, between the FEM - results and analytical model results, which can be justified by the limitations in FEM simulation such as that: COMSOL doesn't include physics for

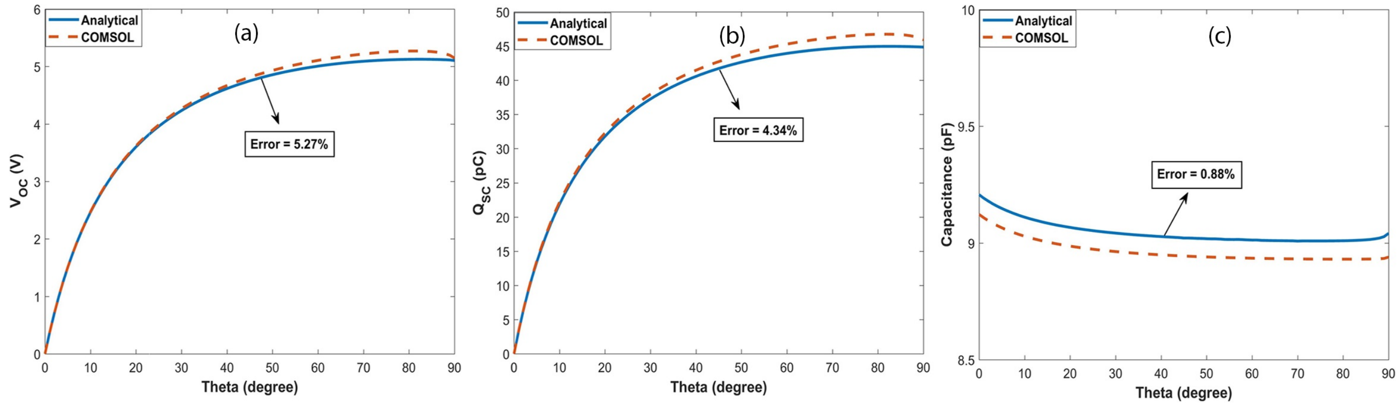

Fig. 2. COMSOL simulation results along with a comparison with analytical model: (a). Open circuit voltage $V_{oc}(\theta)$, (b). Short circuit charges $Q_{sc}(\theta)$, (c). Total Capacitance of the device.

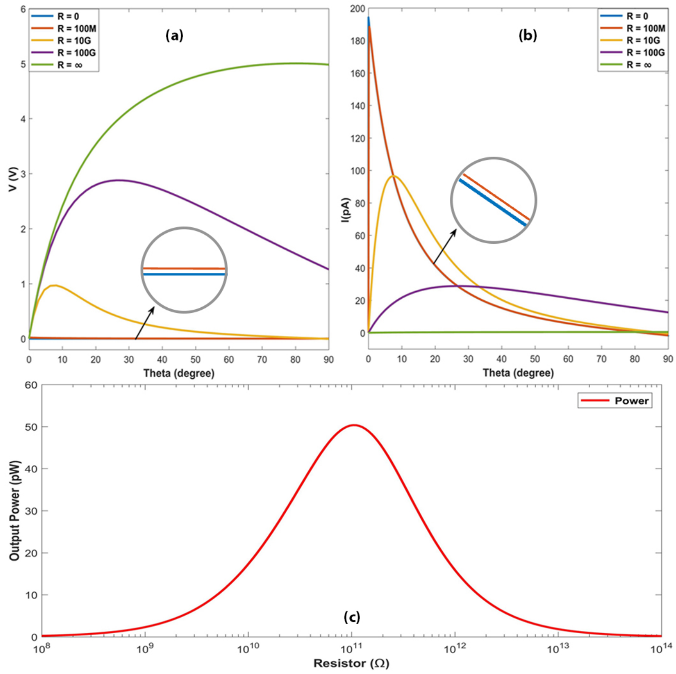

Fig. 3. Verilog-A model of the proposed harvester: (a) $I(\theta)$ vs angle θ at different resistor values. (b) $V(\theta)$ vs angle θ at different resistor values. (c) Average delivered power to the load resistor.

triboelectric effect so an additional air layer is added between the tribo-pairs to enable the simulation.

The accuracy of the developed analytical model was a motivation for constructing a Verilog-A model to investigate the characteristics of the harvester under different loading conditions. A case of simple resistive load is investigated in Fig. 3. The impact of the angle on the I and V is depicted in Fig. 3 (a) and (b) at different resistance values. The same parameters in Table I are used. The results show I_{sc} at $R = 0$, equals to $\approx 193\ pA$, and a V_{oc} at $R = \infty$, equals to $\approx 5\ V$. A peak power of 50 mW is observed at $R \approx 110\text{G}\ \Omega$.

IV. Conclusion

Throughout this study, the first fully analytical model of the diagonal mode , a novel mode, of TENG has been thoroughly derived. The diagonal mode has been studied analytically by MATLAB and practically by COMSOL and Verilog-A. The results show that the maximum open circuit equals 5 V, and the short circuit charge equals 193 pA, and that the peak power when the load applied is 110 G, equals 50 mW. Also, the error between the analytical results and the practical results is less than 6%, which is considered a very promising results compared to contact and sliding mode and other configurations presented in the literature.

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