**Design and Fabrication of a Spiral Single Electrode Triboelectric Nanogenerator for Harvesting Energy from Environmental Random Motions**

**Abstract**

In this paper, a spiral single electrode triboelectric nanogenerator has been designed and constructed. This simple and special design is such that it can simultaneously turn rotary mechanical and reciprocating energies into electrical energy. In most nanogenerators with different structures, the maximum output power is obtained only in one direction or a certain path, and as soon as the predicted way of motion or path changes, the output power decreases dramatically; but, constructed Nanogenerator is completely independent of the path and direction of motion, and it can be used to harvest energy from unpredictable and random movements. Due to this capability, this structure in small scales can be used in order to harvest energy from the motion of sea waves and the movement of the axis of industrial devices, and in larger scales it can be employed in wind turbines moving at variable speeds and in different directions. In this Nanogenizer, the contact is performed by scanning onto the electrode. To investigate the effect of the number of rounds, other parameters including thickness of the electrodes, the distance between the electrodes and the scanning frequency are considered to be 25μm, 1.5mm, and 2Hz respectively. The number of rounds used is 4, 8, 16, and 20 rounds. At low frequencies, the Nanogenizer has the ability to generate a power of 1.21 mW / m2, which will increase with increasing frequency of oscillations.

**Keywords**: Nanogenetator, Triboelectric, Spiral electrode, Energy harvesting, sliding.

**1- Introduction**

Nowadays, given the limited resources of fossil fuels, the high energy consumption around the world, and the pollution of the earth's atmosphere, the use of clean and renewable energies has attracted great interest. On the other hand, the human need for wireless systems and the lack of access to them, and the limitation of the use of constant power supplies in advanced sensors and circuits have increased the requirement for simultaneous use of renewable and portable sources for applications such as construction of charger and power supplies in small size, and the use of them in wireless systems, and in larger sizes, such as power generation for homes, buildings and industrial. One of the easiest ways to achieve this goal is to employ the inherent characteristics of materials to convert the mechanical energy from environmental degradation of movements to electrical charge and use it to charge Self-Power power supplies. [1] In many studies, piezoelectric Nanogenerators have been used to convert kinetic energy to electrical energy using the properties of pizzo materials, which the basis of their operation, is applying external force and hence the orientation of bipolar. [1, 2] However, energy transfer is carried out as a result of electrostatic charges produced on the surface of two dissimilar materials during contact and separation. In this case, due to the difference in the electron affinity of the two contacting materials, electrostatic charges are transmitted and create an electrical potential and thus produce a flow in the external charge. Accordingly, triboelectric Nanogenerators are designed and constructed to convert kinetic energy to electric energy by using triboelectric materials with maximum difference in electron affinity. The nanogenerators were introduced for the first time by Z.L.Wang [3].

The most primary type of type of triboelectric Nanogenerator was the type with vertical contact separation. It is made up of two dissimilar dielectric layers with two electrodes at the top and bottom. The contact between the two dielectric layers by the external force causes the electrical charges to be transmitted at the contact point, and when the two triboelectric layers are separated, a voltage drop occurs between the two electrodes. At this time, if two electrodes are connected with an electric charge, free electrons flow from one electrodes to another electrodes to create a mutual potential and equilibrium of the electrostatic field. When the contact between the two layers is established, the potential generated by triboelectric charges is neutralized and the direction of flow is reversed [4, 5]. In Lateral sliding triboelectric type nanogenerators, when two triboelectric layers move over each other, electric charges are also transmitted between two surfaces and a horizontal polarization is created in the direction of abrasion, which is balanced by flowing in external charge of the electrostatic field created by electric charges. The alternating and limiting sliding motion produces an alternating output that can be rotational like a cylindrical rotation or disc rotation [6]. The construction of a triboelectric nanogenerator with only one layer and one electrode in contact with an appropriate environment is also possible, in which the electrode layer coincides with the role of the triboelectric layer and the electrode. This structure was first introduced in 2013 [7]. In this type of nanogenerator, one side, which is electrodes or dielectrics, can be connected to the moving environment, while the other side is fixed. Charge transmission is carried out by considering proper materials. The single-electrode nanogenerator can also be made in both vertical and slip contacts. In the vertical type, electric current is generated alternately in external charge by the separation and reconnection of electrode and triboelectric layer [8].

In this paper, the construction of a single-electrode sliding type triboelectric nanogenerator is presented. In similar triboelectric single-electrode nanogenerators [6-8], the path of layers’ motion on each other is only reciprocal and in a specific path, which causes a limitation in the use and dependence of the nanogenerator and its output power to the path of motion. But, in the structure presented in this paper, it is possible for layers to move on each other feely in all directions and the output power of the nanogenerator is independent of the motion direction. This structure can be used to harvest energy from unpredictable and random movements, such as shaking devices and random displacements. In small scales, this structure can be used to harvest energy from the motion of the sea waves and the movement of the axis of industrial machines, and in larger scales, it can be employed in wind turbines that move at variable speeds and in different directions.

**2. an Analytic Study on the Performance of a Single-Electrode triboelectric nanogenerator**

The principles of the performance of the triboelectric nanogenerators are based on the transfer of electrostatic charge between the two surfaces in contact and induction of equivalent charges in the outlet electrodes and, consequently, the electrical current in the outlet charge. Every triboelectric structure consists of two materials that are in contact. The distance between the two triboelectric layers changes due to the application of mechanical force. After two layers are contacted, opposite charges are created on each surface (triboelectric charges) which are transmitted to the outlet charge only through two metal electrodes. If Q is the charges transferred from one electrode to the other electrode, the charges on an electrode would be +Q and the charges on the other electrode would be –Q [5-7], accordingly, a potential difference is created between the two metal electrodes that has two parts. The first part is due to polarized triboelectric charges, which is represented by VOC (x) and is a function of the distance x, and the second part is the voltage due to the displaced Q charges. If we assume that there is no tribolectric load in this structure, this structure will be a conventional capacitor. Therefore, these transmitted charges produce the -Q/C(x) voltage, which is capacitance, C, between the two electrode. Then, the total voltage between the two electrodes is as follows [10].

In the above equation, the term of VOC (x), has the positive sign and the Q/C (x) part appears with a negative sign, meaning that when two surfaces are at the lowest distance, VOC (x) has the maximum value and Q/C (x ) has the minimum amount and vice versa. Also, when the two surfaces are placed at a certain distance from each other, and the VOC (x) and Q / C (x) values become equal, the output voltage will be zero.

If an external charge is applied to the electrodes, the abovementioned potential difference leads to conduction of electric charges from one electrode to another. In the short-circuit situation, the above equation will be as follows: [10]

A typical capacitor consists of two conductive layers (plates) and one dielectric in between. The voltage difference applied between these plates creates an electric field between them. This electric field not only exists directly between the plates, but also an electric field will be created between the edges, which is called the edge effect, and the capacitor created from this electric field is called “fringing effect capacitance” or “Fringing field capacitance”. Due to edge effects, the capacitance of the parallel plate is greater than the capacity calculated by the formula. Edge effects occur when the electric field extends the surface of the overlap. Since in the proposed structure, other capacitors are also effective in addition to fringing effect capacitance, the following equation is used to calculate the proposed structure: [12]

**3. Experimental results of constructed single-electrode nanogenerator**

Figure 1 (a) shows the schematic and general structure of the constructed single-electrode nanogenerator where spiral electrodes are located on a 1.6mm layer of phenolic fiber. On the spiral electrodes, a layer of 200μm of Polyvinyl chloride (PVC) is located, all of which forms the fixed part of the nanogenerator. On these layers, a layer of Polyurethane with a thickness of 3cm will reciprocally erode on the PVC layer with a constant frequency of 2Hz. In all samples, the length and width of all three layers of Polyurethane, PVC, and phenolic fiber are equal and proportional to the number of spiral electrodes’ rounds. In this paper, the number of rounds, 4, 8, 16, 20 was studied; the length and width of the layers were 2, 3, 4, 6, and 10 cm2, respectively. The thickness, width and distance between the electrodes are fixed in all cases, and are 32μm, 0.25mm and 1.5mm, respectively. Here, like other single-electrode nanogenerators, the copper electrode also plays the role of both triboelectric layer and the electrode.

In order to construct this nanogenerator, first, a mask is constructed proportional to the number of rounds, and using FeCl3 acid (iron (III) chloride) accompanied with the process of etching, electrodes with a different number of rounds are formed on the phenolic fiber. Then, a PVC layer is placed on the electrode and fixed on it. Finally, a Polyurethane layer is placed on the fixed part of the nanogenerator in order to abrasion.

 Similar to that of other single-electrode Triboelectric nanogenerators, the basis of this nanogenerator function is based on the displacement of charges between the Polyurethane layer, PVC and copper; here, the injection of the charge by copper electrodes into the Polyurethane layer is performed and the Polyurethane is converted to negative ion and copper will become a positive ion.

Fig. 1 (b) shows the structure of the constructed nanogenerator’s electrodes. Despite other structures such as the shoulder structure that needs reciprocal motion to be in certain path to have maximum power, the spiral electrodes add the advantage of having a maximum power at 360 degrees to this structure. Another advantage of the built-in structure is the motion type of the moving part, which rotary motion can be used instead of reciprocating motion. These advantages make it possible to take advantage of the built-in structure for a variety of applications, which, in addition to having the proper output power, will allow simultaneous use in various designs and hybrid designs.

The obvious feature of presented nanogenerator is its use in random and unpredictable motions of devices; because, the weakness of all existing nanogenerators with different technologies, is having the maximum efficiency in one direction or a certain path, and as soon as the change occurs in the method or path of the predicted motion, the output power is strongly affected. But the nanogenerator developed in this paper has the least dependence on the path and direction of motion of the layers on each other. Fig. 1 (c) shows the device made to test the nanogenerator. This device provides the possibility of measuring by constant frequencies, force and erosion constant speed. Fig. 1(d) shows the topography of the phenolic layer which electrodes formed on it, taken by the Atomic Force Microscope (AFM). The main advantage of the use of AFM is measuring in various dimensions with very high resolution and providing three-dimensional data in numerical manner. As can be seen in Fig. 1(d), the average ups and downs in surface of the phenolic layer are 204.4nm, which indicates the almost uniform surface of the electrodes formed on it. The smallness of this number is indicative of low friction, resulting in less corrosion of the abrasive layer and low surface impact on the output.

**Discussion of results**

To study the effect of the number of rounds, other values including the thickness of the electrodes, the distance between the electrodes and the constant scanning frequency, considered to be 0.25 mm, 1.5 mm and 2 Hz, respectively, and different number of 4, 8, 16 and 20 rounds were investigated. In the following, current, voltage, and instantaneous and mean powers measured in constructed nanogenerator are shown based on the different numbers of rounds of electrodes. Figure 2 shows the instantaneous current measured in the nanogenerator with the number of rounds of the electrodes 4, 8, 16, and 20. Comparison of the obtained values suggests an increase trend in the instantaneous current by increasing the number of rounds of the spiral electrodes, which can be justified due to theoretical considerations and the increase of the surface of the overlapped abrasive layer and electrodes. Figure 3 illustrates the instantaneous voltage measured in the nanogenerator with the number of rounds of the electrodes 4, 8, 16, and 20. As can be seen, the instantaneous voltage measured with the number of rounds of the electrode 20 has the highest value and equal to 27.81 volts from peak to peak. In fact, when the number of rounds increases, the voltage also increases, which follows mathematical analysis and theoretical calculations, and it is due to an increase in the surface of the overlap of the electrodes and the triboelectric layer. Table 1 represents the comparison of the results of measuring the instantaneous current and voltage of a nanogenerator made with a different number of rounds. As can be seen, the built-in nanogenerator has a maximum voltage of 27.81 volts and a maximum current of 0.0696 μA for 20 rounds, and surveys on the number of circular electrodes’ rounds are indicative of increasing the voltage and current simultaneously with increasing the number of rounds. The number of rounds is proportional to the current and voltage and follows the mathematical analysis and theoretical calculations. In fact, the larger the area of the electrodes and the surface of the overlap, the higher current and voltage become.

Fig. 5(a) depicts the comparison of the average voltage measured for electrodes with different number of rounds, indicating a simultaneous increase in the voltage and current with increasing number of rounds. This trend of increasing the current and voltage seems obvious, due to the increase in the area of the electrodes and the surface of overlap. Fig. 5(b) shows the average voltage measured in built-in nanogenerator with a different number of electrode rounds. As can be seen, it increases with increasing number of voltage rounds, which was predictable according to the theoretical analysis. Here, by increasing the number of rounds from 4 to 20 rounds, the voltage rises from 0.9 to about 2 volts. Figure 5 (c) shows the FFT chart taken from the output of the nanogenerator made with the number of rounds of 20. As already mentioned and seen in the figure, the scanning frequency is approximately 2Hz. Fig. 5(d) shows the comparison of the instantaneous voltage measured with different number of electrode rounds. As it can be seen, by increasing the number of rounds, instantaneous voltage increases as well.

**4 – Conclusion**

In this paper, a triboelectric single-electrode spiral nanogenerator was designed and constructed in order to harvest mechanical and reciprocal mechanical energies. The specific feature of this nanogenerator is its independence on the path and direction of the motion of the layers on each other and its use in unpredictable and random motions, including shaking devices and random displacements such as the motion of waves. Because in most nanogenerator constructed with different technologies, the maximum power is obtained only in one path or a certain direction, as soon as the change occurs in the method or path of the predicted motion, the output power is strongly affected and decreases. Also, investigating the effect of the number of rounds of circular electrodes on it showed a simultaneous increase in the voltage and current with increasing number of rounds. The maximum achievable power from this nanogenerator obtained with 20 rounds, that with an electrode resistance of 8 ohms, the maximum measured power of this nanogenerator was 1.2 mW / m2.