Research Article

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The comparison of triboelectric power generated by electron-donating polymers KAPTON and PDMS in contact with PET polymer

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Abstract: The Triboelectric nanogenerators (TENGs) are Fabricated by contact between two surfaces of different materials and convert of electric loads between them. In such structures, the two contacting layers should be radically different in terms of their electric property so that one of the layers could induce positive electrical charge while the other induces a negative charge. The application of force on and friction between the two layers induce positive and negative charges. Through the electrodes in external load, the electrical charges flow as electric current. In the present study, TEGN structures fabricated of polyethylene terephthalate polymers (PET) act as electron acceptor while Polyamide (KAPTON) and polydimethylsiloxane (PDMS) act as electron donator. The resulting outputs are compared consequently. Considering the fact that the two materials are relatively identical in terms of electron donation as they are in contact with PET, the generators fabricated of KAPTON could generate 400% more power under identical conditions. Therefore, one may conclude that KAPTON could be more suitable for development of self-power system as they are more available and more environmentally compatible.

Keywords: electron donation; KAPTON; PDMS; PET; triboelectric.

Introduction

Ambient sources of mechanical energy such as body movement, fluid or wind flow and machine vibrations, have great potential to be exploited in order to power wearable, embedded, implanted and portable electronics and sensors (Crossley, Whiter, and Kar-Narayan 2014; Cook-Chennault, Thambi, and Sastry 2008; Jing and Kar-Narayan 2018). In this paper, the triboelectric nanogenerator is investigated which directly converts the mechanical energy of the environment into electrical energy and is used in low power consumers.

One of the materials that can be used in the structure of triboelectric nanogenerators is paper. Abundance, flexibility, lightness and compatibility with nature are the advantages of this material. Recently, cellulose-based papers have also been used as substrates for the production of a triboelectric nanogenerator (TENG), which converts mechanical energy into electrical energy by coupling triboelectricity and electrostatic induction, and as a low-cost energy generator. And a simple device is promising (Oh et al. 2019). Another form of triboelectric nanogenerators is their use as wearable structures (Liu et al. 2020). Using this technology, many groups have developed lots of wearable TENGs to harvest and convert human body motion energy into electricity, which makes the body motion energy a feasible and available power source for mobile and portable electronics. Because of fiber's merits of being small, lightweight, bendable, and washable property, the fiber-based wearable TENGs have been widely studied. Attractive applications of triboelectric nanogenerators include their use in charging and powering sensors and medical devices implantable in the body (Ryu et al. 2021). Using the movements and vibrations in the human body, the field of stable and continuous energy production using triboelectric nanogenerators can be used to feed nanosensors and other implantable devices in the human body. The development and emergence of new versions of the Internet, such as the 5G (5th-generation mobile networks) technology across the world, has increasingly focused on providing the energy needed for portable electronics instrument. Batteries as a mainstream power supply have drawbacks, such as a limited lifespan that requires frequent replacement or

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recharging. Volume and weight, hardness, biological incompatibility and environmental pollution are among the other drawbacks of batteries. Therefore, in order to meet the extraordinary requirements, ideal power supply units must have portable, stable, shrinkable, wearable and implantable characteristics, depending on the application. In this regard, nanogenerators can be developed as a sustainable solution (Shi et al. 2021). Other functions of triboelectric nanogenerators include cleaning and purifying the air of pollutants and pathogens that are the main cause of diseases such as asthma and pneumonia (Huo et al. 2021). The method is that by creating a strong electric field, they can damage the external structure of microbes and provide a basis for disinfection of the environment.

Triboelectric energy harvesters can be realized by combining pairs of dissimilar materials whereby charge is transferred between the surfaces due to contact and separation through relative mechanical motion (Fan, Tian, and Wang 2012a; Wang, Chen, and Lin 2015). Triboelectric charges are generated when surfaces of two materials with different surface potentials are brought into contact, with electrons injected at the interface from one material to another (Henniker 1962; Peng, Kang, and Snyder 2017; Wang, Chen, and Lin 2015). The flow direction of the electrons can be predicted by an empirically determined series called triboelectric series (Diaz and Felix-Navarro 2004; Henniker 1962), where materials at the tribo-negative end of the series are likely to accept electrons while those at the tribo-positive end are likely to donate electrons. Depending on the dielectric property of the materials, charges may remain on the surfaces when separated, thus uncompensated dipoles are generated. Triboelectric energy harvesters have been fabricated that take advantage of this contact electrification phenomenon which can then be harnessed to convert periodic mechanical motion into electricity via electrostatic induction. Polymers have featured prominently in triboelectric energy harvesters not only because several candidates in the triboelectric series are polymeric, but also due to their mechanical robustness, dielectric properties and ease of fabrication. Researchers have tried to improve the performance of triboelectric energy harvesters through different strategies, most common of which are surface roughness modification and surface charge distribution tuning. To increase roughness, nanopatterns, nanostructures, nanoparticles or NWs are incorporated into the surface to increase the contact surface area (Fan, Tian, and Wang 2012b; Lin et al. 2013; Wang, Lin, and Wang 2012; Zhu et al. 2012, 2013; Chen et al. 2013). On the other hand, to tune the surface charge density, charges could be directly injected onto the contact surface (Wang et al. 2014). Another idea is to correctly apply the triboelectric layers against each other. Some of the triboelectric materials lose their electron more easily than other materials, while some other materials in nature are more likely to electron capture than other materials. If layers are arranged in such a way that materials that absorb the electron are the most effective in their ability to produce the greatest output.

In the present paper, three types of polymers are used for fabricating these nanogenerators. Two types of polymers are identical electron donator and the remaining type of polymer is electron receiver. The objective of present study is to examine the type of electron-donating polymer in comparison with PET which makes a side of triboelectric nanogenerators in a dielectric-dielectric structure since it shows significant stability and desirable level of flexibility.

Theory and methods

The voltage between two electrodes is made up of two parts. The first part is due to polarized triboelectric loads that are represented by $V_{oc}(x)$. $V_{oc}(x)$ refers to voltage of the open circuit developed between the two electrodes as the air gap between two layers' changes. The second part of voltage is due to displaced Q loads that develops $-Q/C(x)$ voltage. In this case, $C(x)$ refers to the capacitance that varies in relation to the air gap between the two electrodes. Therefore, total voltage between the two electrodes is determined through the following expression (Hu et al. 2010):

$$V = -\frac{1}{C(x)}Q + V_{OC}(x) \tag{1}$$

Then, based on voltage of nanogenerator one could model triboelectric nanogenerator as a series connection of a voltage supply and an independent voltage supply (Figure 1).

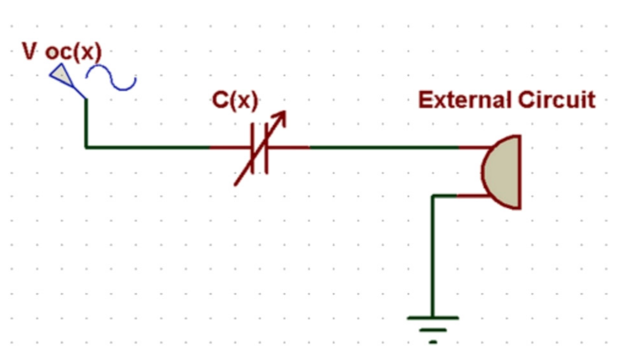

Figure 1: Equivalent triboelectric nanogenerator circuit modelled as series connection of capacitors and independent voltage source.

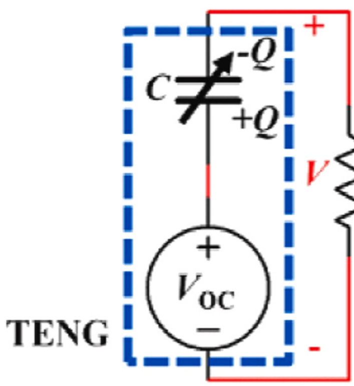

Figure 2: Equivalent electric circuit of triboelectric nanogenerator connected to resistive load (Zhang et al. 2004).

If one intends to model the behavior of nanogenerator when it is connected to resistive load, the equivalent circuit will be as shown in Figure 2.

After analysis of above-mentioned circuit model and in the case of drawing on Kirchhoff's law (Zhang et al. 2004), we have:

$$R\frac{dQ}{dt} = V = -\frac{1}{C}Q + V_{oc} \tag{2}$$

The above expression is a first- order differential equation which could be solved by boundary condition $Q(t = 0)$ (Chen et al. 2013). In order to solve the transient state equation, periodic boundary conditions should be used (i.e. $Q(t = 0) = Q(t = T) = 0$). If we solve the boundary conditions of the equation, the following expressions have obtained.

$$Q(t) = \frac{1}{R}\exp\left[-\frac{1}{R}\int_0^T \frac{1}{C(x(t))}dt\right] \times \int_0^T V_{oc}(x(t))\exp\left[\frac{1}{R}\int_0^T \frac{1}{C(x(t))}dt\right]dt \tag{3}$$

Therefore, the voltage and current of the triboelectric nanogenerator (considering an external resistive load) can be determined using the following equations:

$$I(t) = \frac{V_{oc}}{R} - \frac{1}{R^2C}\exp\left[-\frac{1}{R}\int_0^T \frac{1}{C(x(t))}dt\right] \times \int_0^T V_{oc}(x(t))\exp\left[\frac{1}{R}\int_0^T \frac{1}{C(x(t))}dt\right]dt \tag{4}$$

$$V(t) = V_{oc} - \frac{1}{RC}\exp\left[-\frac{1}{R}\int_0^T \frac{1}{C(x(t))}dt\right] \times \int_0^T V_{oc}(x(t))\exp\left[\frac{1}{R}\int_0^T \frac{1}{C(x(t))}dt\right]dt \tag{5}$$

Table 1: Specifications of materials used in the structure of the triboelectric nanogenerator (Ataei et al. 2017; Johnston et al. 2014; Lijima and Takahashi 1993).

	Materials		
Properties	**PDMS**	**KAPTON**	**PET**
Thickness	160 μm	55 nm	100 nm
Dielectric coefficient	2.3–2.8	3.4	3.7
Density	0.97 kg/m^3	1.42 g/cm^3	1.4–1.6 g/cm^3
Tensile strength	2.23 MPa	231 MPa	16 MPa

Experimental section

Three types of polymers with properties represented in Table 1 were used for fabricating TENG. A scheme of intended triboelectric nanogenerators structure is represented in Figure 3. The three nanogenerators were developed based on the structure to be consequently characterized. The specifications of fabricated nano-generators are as represented in Table 2.

In order to test the fabricated nanogenerators, a linear electric motor with low frequency range was developed. The linear motor should be able to apply a linear force on the nanogenerators if frequency and intensity of the force remains constant. In the structure of linear motor (Figure 4), the property of persistent displacement of magnet poles was used to develop a reciprocating motion. When AC input current is directly applied on a coil, the direction of flow in the coil always changes. The change of flow direction results in persistent change in direction of the magnetic field that the coil generates. Therefore, if another magnet is put close to the coil, expulsion and attraction forces may alternatively develop between the two magnets. In order to control the speed of movement, a potentiometer was placed

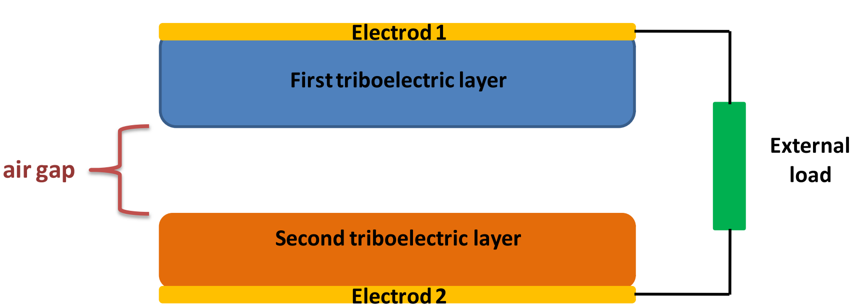

Figure 3: Scheme of TENG of dielectric-dielectric type.

Table 2: Dimensions and materials used in the structure of the triboelectric nanogenerator.

Material of Layer 1	Thickness of Layer 1 (μm)	Materials of Layer 2	Thickness of Layer 2 (μm)	Material of Electrode 1	Thickness of Electrode 1 (μm)	Material of Electrode 2	Thickness of Electrode 2 (μm)	Layers cross-section (cm^2)
PET	70	KAPTON PDMS	60	Al	120	Cu	200	3 × 4

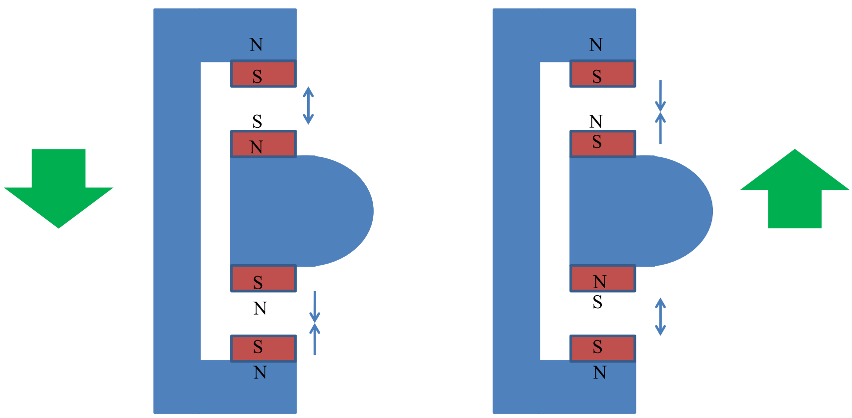

Figure 4: Structure of linear electric motor.

along the path of input current to the coil. As a result, change in resistance of potentiometer, the frequency of speed of impact on the nanogenerators will be controllable. The frequency range generated by linear motor ranges from 1 to 100 Hz and intensity of the force generated by the system is 20 mN.

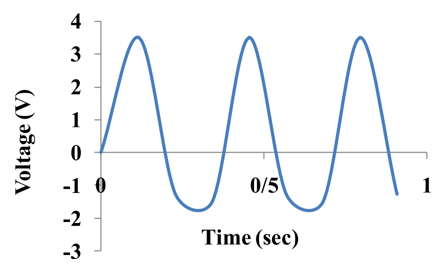

Figure 5: Transient voltage of PET-KAPTON.

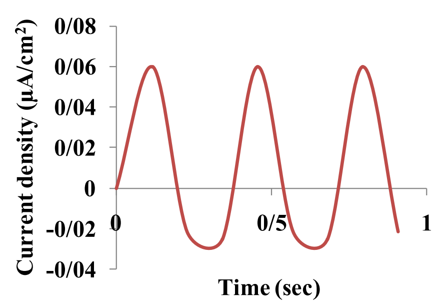

Figure 6: Transient current density for PET-KAPTON.

Results and discussion

The output current and voltage of representative TENGs were measured through alternative impacts of linear electric motor. In this case, a linear force with respective frequency and force of 3 Hz and 20 mN was applied on the fabricated nanogenerators and their specifications were measured. Figures 5 and 6 represent transient output voltage and current density respectively. It is observed that alternative output current and voltage is generated when force is in a reciprocating mode. In this case, sampling frequency of measurement system is less than the frequency of applied force. In addition, some of the peaks were removed. The PET-KAPTON nanogenerators with applied input is able to generate maximum voltage and current density of 3.5 V and 0.06 μA/cm^2 respectively. In the case of PDMS nanogenerators, the maximum voltage and current density are 1.5 V and 0.035 μA/cm^2 respectively (Figures 7 and 8).

In order to determine the output power, the effective values of outputs were measured too (Figures 9 and 10). The figures suggest that KAPTON-PET nanogenerator has higher effective voltage and current. In this regard,

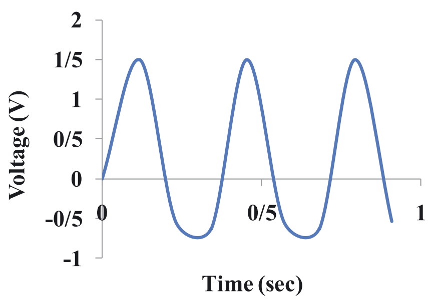

Figure 7: Transient voltage for PDMS-PET.

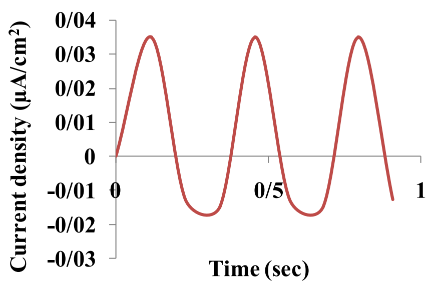

Figure 8: Transient current density for PDMS-PET.

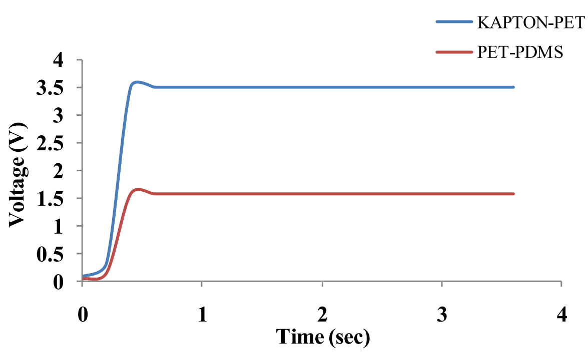

Figure 9: Effective voltage for representative TENGs.

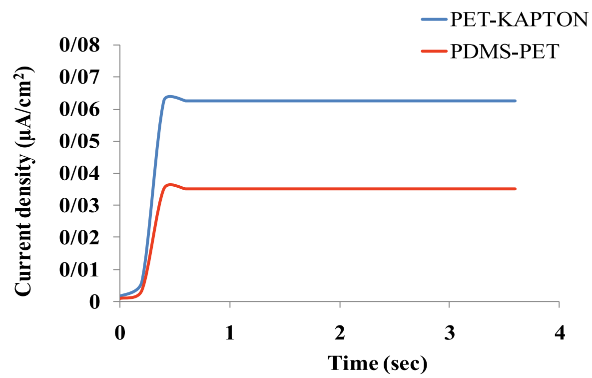

Figure 10: Effective current density of representative TENGs.

Table 3: Comparing output results of the PET-KAPTON and PET-PDMS triboelectric nanogenerators.

System outputs	PET-KAPTON	PET-PDMS
Voltage (V)	3.5	1.5
Current density (μA/cm^2)	0.035	0.06
Output power density (nW/cm^2)	122.5	90

the effective values of power density generated as outputs of the generators were 210 and 52.5 nW/cm^2 for PET-KAPTON and PDMS-PET nanogenerators respectively. These comparisons are presented in Table 3.

In the following, we plan to examine the effect of increasing the frequency of vibration on the triboelectric layers. As it is seen in Figures 11 and 12, increasing the frequency of vibrations on the triboelectric layers will amplified the response of the triboelectric nanogenerator. By increasing the frequency from 3 to 25 Hz voltages produced by the KAPTON-PET nanogenerator, it increase from 3.5 V to 6 peak-to-peak volts. Also, the voltage response of the PET-PDMS nanogenerator is increase from 1.5 to 3.5 peak-to-peak volts.

Based on the obtained results, one could observe that under identical conditions the contact between KAPTON-PET pair could generate the respective power than the contact between PDMS and PET. The standard tables for triboelectric series (Diaz and Felix-Navarro 2004; Henniker 1962), suggest that KAPTON is less different than PET in terms of electron donation and more similar to PDMS. However, the fabricated nanogenerator produces more total voltage.

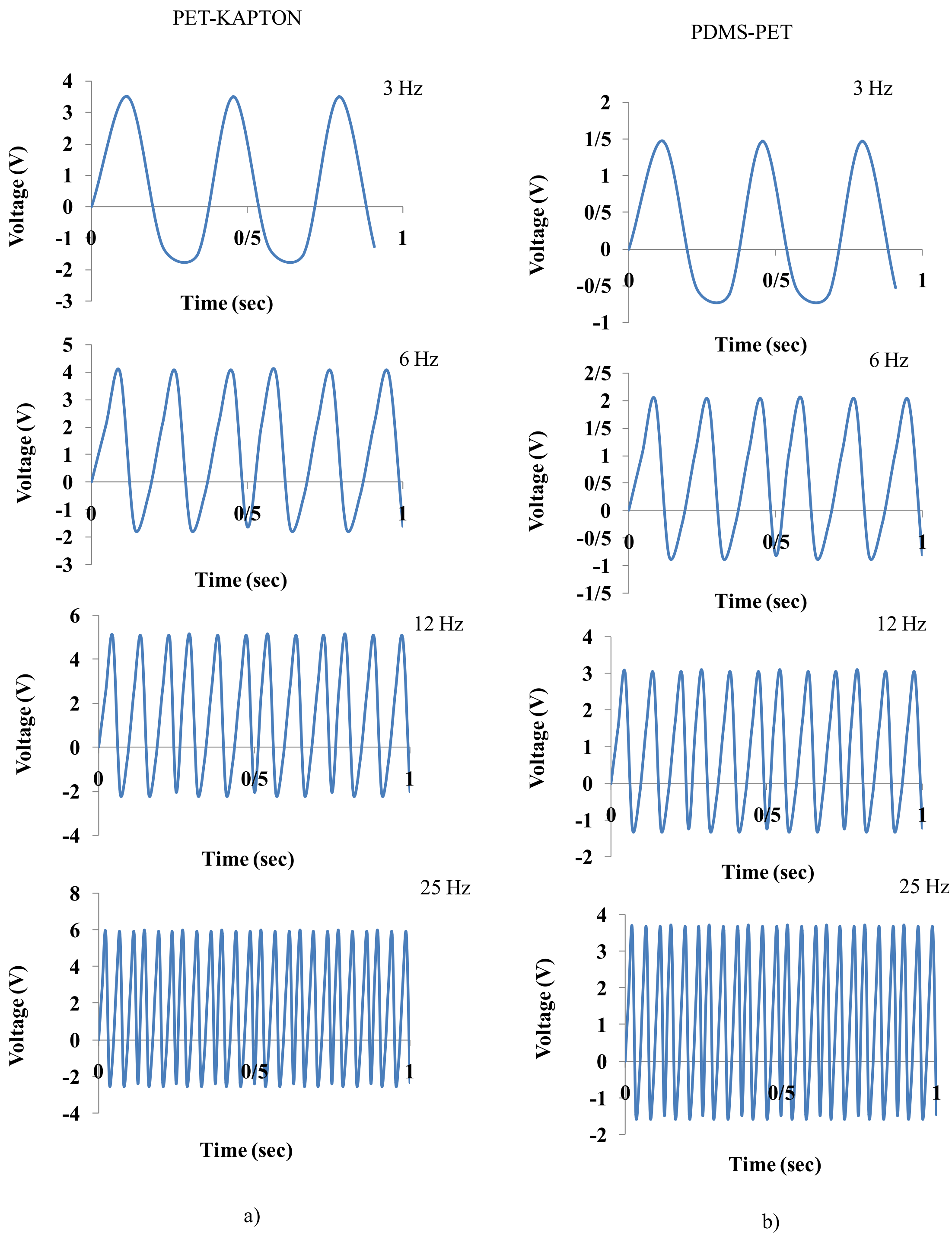

Figure 11: The effect of increasing the frequency on the response of the triboelctric nanogenerator under the frequency range 3, 6, 12, 25 Hz. a) Changes in voltage of KAPTON-PET nanogenerator, b) changes in voltage of PET-PDMS nanogenerator.

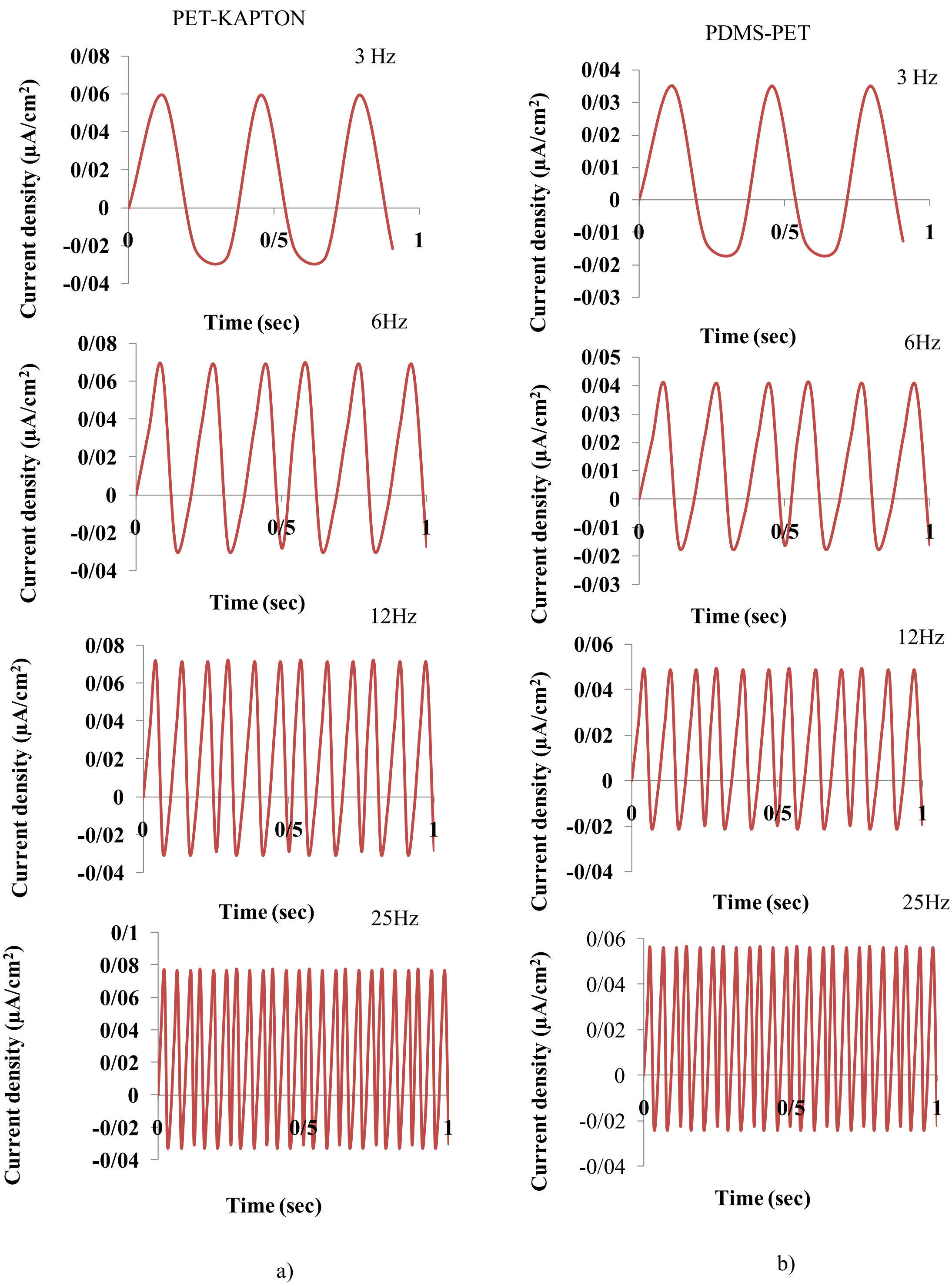

Figure 12: The effect of increasing the frequency on the response of the triboelctric nanogenerator under the frequency range 3, 6, 12, 25 Hz. a) Changes in current density of KAPTON-PET nanogenerator, b) changes in current density of PET-PDMS nanogenerator.

Conclusions

In the present paper, the powers generated by KAPTON, PDMS and PET polymers in the case of electrostatic induction of charge between them were analyzed experimentally. After applying linear force on fabricated triboelectric nanogenerators, outputs of nanogenerators were measured and levels of generated power were calculated. One could observe that KAPTON-PET pair could produce a definite output as it could generate respective voltage, current and effective power density of 3.5 V, 0.06 $\mu A/cm^2$ and of 210 nW/cm^2. In addition, the PDMS-PET pair generated the respective voltage, current and effective power density of 1.5 V, 0.035 $\mu A/cm^2$ and of 52.5 nW/cm^2. As a result, the nanogenerator fabricated of KAPTON-PET shows Quadrupole performance when compared with PDMS-PET. Considering the lack of change in directions of positive and negative charges induced in triboelectric nanogenerators, one may be able to develop generators of electric energy on wide and flexible surfaces by arranging the nanogenerators in series and parallel layout. In addition, environmental friendliness and availability of PET and KAPTON polymers enables one to use the nanogenerators fabricated of such materials in insoles of smart shoes, certain layers of carpet and other coverings so as to generate electric energy.

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