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Theoretical study of Dielectric Effect on Power in a Contact-Mode TENG

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ABSTRACT

We analytically calculated the instantaneous maximum power from contact-mode triboelectric nanogenerators (TENGs) to inspect parametric dependencies, especially resistance and permittivity on the system power. Here, a uniform movement of the upper electrode at a constant velocity is assumed. The numerical results show that the power associated with device performance can be optimized using a dielectric constant as a given material characteristic with the resistor.
Keywords : Power, Contact-Mode TENG, Dielectric Constant, Resistance.

I. INTRODUCTION

In triboelectric nanogenerators (TENGs) [1-4], several important parameters related to device performance are mostly open-circuit voltage (Voc), short-circuit current (Isc) and power. In particular, I (current) × V (voltage) type power takes into account both current and voltage information over time. Recently, as the power density of the contact-mode TENG is gradually increasing, it is used as power source for various application fields [5-8]. However, the theoretical analysis of power from the contact-mode TENG is still lacking [5-9]. There are parameters for the instantaneous maximum power of the TENG, such as the triboelectric charge density, the surface area, the speed of the top electrode, the vacuum permittivity, the resistance, the dielectric constant, the dielectric thickness and the maximum distance between the top electrode and the dielectric material. In particular, given the external resistance, research into the dielectric effects on TENG power is lacking. In general, the maximum power of the TENG is derived by optimizing the external resistance with a fixed dielectric constant of the triboelectric material. In this paper, the maximum power is discussed theoretically by optimizing the dielectric constant with a fixed external resistor oppositely.

II. RESULTS AND DISCUSSION

The maximum instantaneous power of contact -mode TENG as shown in Fig. 1 can be written as [10]

$$P_{max} = {I_{max}}^2 \cdot R = \frac{\sigma^2 \cdot S \cdot v}{\varepsilon_0} \cdot F^2 \cdot G^2(F.y) \quad \cdots\cdots\cdots (1)$$

$$\text{with } F = \frac{d_0}{\sqrt{R \cdot S \cdot \varepsilon_0 \cdot v}} = \frac{d_2}{\varepsilon_2 \sqrt{R \cdot S \cdot \varepsilon_0 \cdot v}} \quad \cdots\cdots\cdots (2)$$

$$y = \frac{\varepsilon_2 \cdot x_{max}}{d_2} \quad \cdots\cdots\cdots (3)$$

In the special case where the upper electrode moves with the constant v, the function G (F.y) can be described as follows.

$$G(F.y) = -1 + (1+y)e^{\left[-\frac{1}{2}F^2\cdot y(2+y)\right]\left[1-\sqrt{2}F\cdot Dawson\left(\frac{F}{\sqrt{2}}\right)\right]} + \left[\sqrt{2}F(1+y)\cdot Dawson\left(\frac{F}{\sqrt{2}}(1+y)\right)\right] \quad \cdots\cdots\cdots (4)$$

The Dawson's integral in Eq. (4) is defined as follows

$$\text{Dawson}(x) = e^{-x^2}\cdot\int_0^x e^{y^2}\cdot dy \quad \cdots\cdots\cdots (5)$$

The maclaurin series ($x \ll 1$) and the asymptotic series ($x \gg 1$) of the Dawson (x) are following

$$\text{Dawson}(x) \approx x - \frac{2}{3}x^3 + \theta(x^5) \qquad (x \ll 1)$$
$$\approx \frac{1}{2x} + \frac{1}{4x^3} + \theta\left(\frac{1}{x^5}\right) \qquad (x \gg 1) \quad \cdots\cdots\cdots (6)$$

If Eq (2) and Eq (3) are inserted into Eq (4), $G(F, y)$ can be rewritten as

$$\text{G}\left[\frac{d_2}{\varepsilon_2\sqrt{R\cdot S\cdot\varepsilon_0\cdot v}}, \frac{\varepsilon_2\cdot x_{max}}{d_2}\right] = \left(-1 + e^{-\frac{0.5d_2\cdot x_{max}\left(2+\frac{x_{max}\cdot\varepsilon_2}{d_2}\right)\left(1-\frac{\sqrt{2}d_2 Dawson\left[\frac{d_2}{\sqrt{2}\cdot\sqrt{R\cdot S\cdot v\cdot\varepsilon_0}\cdot\varepsilon_2}\right]}{\sqrt{R\cdot S\cdot v\cdot\varepsilon_0}\cdot\varepsilon_2}\right)}{R\cdot S\cdot v\cdot\varepsilon_0\cdot\varepsilon_2}}\right)\left(1+\frac{x_{max}\cdot\varepsilon_2}{d_2}\right) + (\sqrt{2}d_2(1 + \frac{x_{max}\cdot\varepsilon_2}{d_2})Dawson[\frac{d_2\left(1+\frac{x_{max}\cdot\varepsilon_2}{d_2}\right)}{\sqrt{2}\cdot\sqrt{R\cdot S\cdot v\cdot\varepsilon_0}\cdot\varepsilon_2}])/\sqrt{R\cdot S\cdot v\cdot\varepsilon_0}\cdot\varepsilon_2 \quad \cdots\cdots\cdots (7)$$

If Eq (7) is inserted into Eq (1), P_{max} can be restated as

$$P_{max} = \frac{d_2{}^2\sigma^2\left[-1 + e^{-\frac{0.5d_2\cdot x_{max}\left(2+\frac{x_{max}\cdot\varepsilon_2}{d_2}\right)\left(1-\frac{\sqrt{2}d_2 Dawson\left[\frac{d_2}{\sqrt{2}\cdot\sqrt{R\cdot S\cdot v\cdot\varepsilon_0}\cdot\varepsilon_2}\right]}{\sqrt{R\cdot S\cdot v\cdot\varepsilon_0}\cdot\varepsilon_2}\right)}{R\cdot S\cdot v\cdot\varepsilon_0\cdot\varepsilon_2}}\left(1+\frac{x_{max}\cdot\varepsilon_2}{d_2}\right) + \frac{\sqrt{2}d_2\left(1+\frac{x_{max}\cdot\varepsilon_2}{d_2}\right)Dawson\left[\frac{d_2\left(1+\frac{x_{max}\cdot\varepsilon_2}{d_2}\right)}{\sqrt{2}\cdot\sqrt{R\cdot S\cdot v\cdot\varepsilon_0}\cdot\varepsilon_2}\right]}{\sqrt{R\cdot S\cdot v\cdot\varepsilon_0}\cdot\varepsilon_2}\right]^2}{R\cdot\varepsilon_0{}^2\cdot\varepsilon_2{}^2} \quad \cdots (8)$$

The asymptotic behavior of the P_{max} in Eq (8) with $\varepsilon_2 \to \infty$ is

$$\lim_{\varepsilon_2\to\infty}[P_{max}] = \frac{e^{-x_{max}{}^2/R\cdot S\cdot v\cdot\varepsilon_0}\cdot x_{max}{}^2\cdot\sigma^2}{R\cdot\varepsilon_0^2} \quad \cdots\cdots\cdots (9)$$

The maximum output power of the contact-mode TENG consists of many parameters such as dielectric thickness, triboelectric charge density, maximum distance between the top electrode and the dielectric material, dielectric constant, resistance, surface area, speed of the top electrode and vacuum permittivity.

Numerically, given the resistance at constant v of the top electrode, some of the parameters are fixed as follows to see how the dielectric constant affects the output power of the TENG system. $d_2 = 125\ \mu m$, $S = 58.06\ cm^2\ (9\ inch^2)$, $\sigma = 10\ \mu C/m^2$, $x_{max} = 0.001\ m$, $v = 0.1\ m/s$, $\varepsilon_0 = 8.85\times 10^{-12}\ F/m$, and $R = 10^5, 10^7,$ and$10^9\ \Omega$

Firstly, for the case of $R = 10^5\ \Omega$, P_{max} can be written as follows.

$$P_{max} = \frac{0.199496\left[-1+e^{-\frac{121.635(2+8.\varepsilon_2)\left(1-\frac{7.79857 Dawson\left[\frac{3.89928}{\varepsilon_2}\right]}{\varepsilon_2}\right)}{\varepsilon_2}}(1+8.\varepsilon_2)+\frac{7.79857(1+8.\varepsilon_2)Dawson\left[\frac{3.89928(1+8.\varepsilon_2)}{\varepsilon_2}\right]}{\varepsilon_2}\right]^2}{{\varepsilon_2}^2} \cdots\cdots\cdots (10)$$

Secondly, for the case of $R = 10^7\ \Omega$, P_{max} can be

$$P_{max} = \frac{1}{{\varepsilon_2}^2}0.0000199496\left[-1+e^{-\frac{0.0121635(2+8.\varepsilon_2)\left(1-\frac{0.0779857 Dawson\left[\frac{0.0389928}{\varepsilon_2}\right]}{\varepsilon_2}\right)}{\varepsilon_2}}(1+8.\varepsilon_2) + \frac{1}{\varepsilon_2}0.0779857(1+8.\varepsilon_2)Dawson\left[\frac{0.0389928(1+8.\varepsilon_2)}{\varepsilon_2}\right]\right]^2 \cdots\cdots\cdots (11)$$

Thirdly, for the case of $R = 10^9\ \Omega$, P_{max} can be

$$P_{max} = \frac{1}{{\varepsilon_2}^2}0.0000199496\left[-1+e^{-\frac{0.0121635(2+8.\varepsilon_2)\left(1-\frac{0.0779857 Dawson\left[\frac{0.0389928}{\varepsilon_2}\right]}{\varepsilon_2}\right)}{\varepsilon_2}}(1+8.\varepsilon_2) + \frac{1}{\varepsilon_2}0.0779857(1+8.\varepsilon_2)Dawson\left[\frac{0.0389928(1+8.\varepsilon_2)}{\varepsilon_2}\right]\right]^2 \cdots\cdots\cdots (12)$$

Based on equations (10), (11), and (12), three plots are shown in Fig. 2 (a), (b) and (c), respectively. Figure 2 (a) shows the existence of an optimal dielectric constant for R = $10^5\ \Omega$ within the 2.5-2.7 interval. As the resistance increases to $10^7\ \Omega$, the optimum dielectric constant decreases within the range of 0.2-0.3 as shown in Fig. 2 (b). Finally, the dielectric constant asymptotically reaches some value as the resistance increases further to $10^9\ \Omega$. This means that as shown in Figure 2 (c), a large dielectric constant is more advantageous for improving maximum power. Otherwise, infinite power can be obtained if ε is zero.

III. CONCLUSION

To conclude, a mathematical model for maximum power is created in contact-mode TENG. The equations derived for the three cases of resistance (10^5, 10^7, and $10^9\ \Omega$) show that the pattern of maximum instantaneous power distribution is different with different optimum ranges of the dielectric constant. This can suggest guidelines for how to select the appropriate dielectric material in contact-mode TENG applications that provide resistance to improve the power of the system.

IV. ACKNOWLEDGMENTS

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VI. Figure Captions

Figure 1 : Schematic of metal-to-dielectric triboelectric nanogenerator

Figure 2: A plot of P_{max} $vs.$ ε for (a) $R = 10^5\ \Omega$, (b) $R = 10^7\ \Omega$, and (c) $R = 10^9\ \Omega$. (a) and (b) show optimum ε within a certain range.

Figure 1

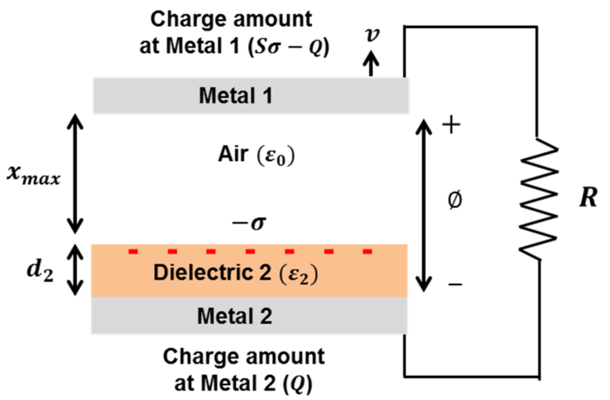

Figure 2