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Electric power generation using a parallel-plate capacitor

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Summary
In this study, we propose an efficient design for a portable energy generator using a parallel-plate capacitor. Analytical calculations show that if charge (Q) is kept constant and dielectric subsequently removed from the capacitor, then electrostatic energy increases by a factor of ε_r (permittivity). Initially, a priming charge must be loaded onto the capacitors that are subsequently disconnected from the voltage source. A significant mechanical nonlinear force is needed to remove the dielectric slab. In the proposed configuration, dielectric constitutes the rotor of generator and is located between two pairs of conducting disks, which constitute the stator. The rotor is divided into four dielectric sectors at 60° spacing whereas the stator is divided into six conducting sectors at 30° spacing. In each cycle, two dielectric slabs go inside the capacitor and two other come outside. This specific geometrical arrangement diminishes the extent of mechanical forces and helps to enhance the efficiency of generator significantly. Additionally, this work also relates to generating large amplitude of voltage that can be used as a high voltage source.

KEYWORDS
air gap, capacitor, dielectric, human motion, portable energy generator

1 | INTRODUCTION

Power storage capacity of a battery is a crucial factor for portable electronic devices, which affects the performance and cost of the device. At present, most portable scale electronic devices rely upon chemical cells of rechargeable or single-use type to store and deliver electrical power on demand. In the era of smartphones and other devices, portable energy generators are high on demand, and these demands support research in the area of energy generation methods,[1,2] as it is not always possible to find an available power outlet.

Previously, different types of energy generators covering a very broad range of applications is proposed and discussed.[2-10] Electrostatic generators have existed for a long time; the Van de Graaff generator[11] from the early 20th century is probably the most famous one. Variable capacitance–based energy generators are strong pillar of energy harvesting industry; some of the early examples of such generators are described by previous studies.[12-15] Here, the term variable capacitance is defined as the change in capacitance due to the application of an external force. There are several different methods to achieve variable capacitance for energy generation, for example, pressurized dielectric fluid, altering the permittivity of a dielectric material by external energies, displacement/separation of conductive plates, and displacement of dielectric slab.[16-19] Tashiro et al proposed a device for energy generation using variable capacitance with the aim to drive a cardiac pacemaker without a battery.[20] Interestingly, variable capacitance is also created by means of dielectric-modulating energies, eg, solar and electromagnetic radiations.[15,21] Capacitance changes also occur when solar radiation reacts with a radiation-sensitive material causing a modification of dielectric properties. In many cases, variable capacitance is produced by vertical or horizontal movement of capacitor plates (displacement/separation).[13,18,19,22] Ghezzo et al showed that two capacitors of varying capacitances can be created by introducing a third conducting plate between capacitor plates.[22] It was also reported that movement of dielectric plate near but outside the capacitor altered the capacitance substantially.[18,22]

As motion of conducting and dielectric plates is against the electrostatic force, mechanical force must be applied. The origin of force on partially inserted dielectric slab is nonuniform electric (fringing) field.[23-25] This force originates from interaction between free charges on capacitor plates and the polarization charge on the dielectric surface.[26] These mechanical forces can be driven by human or/and machine motion, eg, motor or slow-moving piston of a stirling engine. Interestingly, human muscle power is one potential source of energy that can be used to operate such generators.[5] Human motion–driven generators are more suitable for portable devices.[27] Previously, human motion was used to move conductors through a magnetic field in order to generate electricity.[28,29] Similarly, it can also be used for movement of dielectric slab in order to create variable capacitance.

In this work, we propose an efficient method for energy generation using parallel-plate capacitor. The principle of energy generation is explained using analytical calculations. The results obtained strongly support the idea of portable energy generator for smartphones and other similar devices.

Novelty statement

- The energy stored in capacitor enhances significantly when dielectric is removed from an isolated capacitor.
- A specific geometrical arrangement reduces the nonlinearity of mechanical forces, which helps to enhance the efficiency of generator significantly.
- This electrostatic generator is useful in supporting the power supply to portable electronic devices. This generator can also be used as a high voltage source.

2 | PRINCIPLE OF ENERGY GENERATION

A parallel-plate capacitor with dimensions of length a, width b, plates separation d, and permittivity of dielectric ε_r is shown in Figure 1. Effective capacitance of capacitor is given by

$$C_1 = \frac{\varepsilon_r \varepsilon_0 A}{d}, \tag{1}$$

where ε_0 is permittivity of free space and $A(=a \times b)$ is area of capacitor plates. In the absence of a dielectric, capacitance is expressed as

$$C_2 = \frac{\varepsilon_0 A}{d}. \tag{2}$$

For partially inserted dielectric slab, the magnitudes of capacitance, electrostatic energy, and force acting on the dielectric slab depend upon the position of the dielectric slab.[24] Let us consider the case that the charge (Q) on the capacitor plates is constant. The capacitor is charged to voltage V_c, and the voltage source is then disconnected. In this case, the electrostatic energy of the capacitor is expressed as

$$W_c = \frac{Q^2}{2C}. \tag{3}$$

If ε_r is sufficiently large and the dielectric is completely removed from the capacitor ($x = a$), then resultant

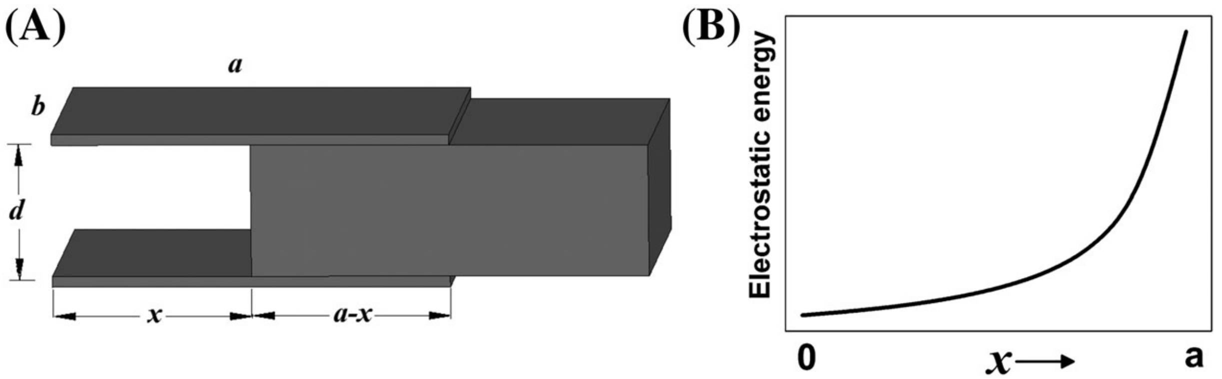

FIGURE 1 (A) A parallel-plate capacitor with partially inserted dielectric slab. (B) A graphical representation of electrostatic energy versus position of dielectric

capacitance decreases ($C_2 \ll C_1$), as a result the electrostatic energy increases significantly (Figure 1).

Let us understand the charging process of a capacitor. Figure 2 demonstrates the charging process of a capacitor from constant voltage source (V_s) through a resistor (r). As per Kirchhoff voltage law, Thevenin equivalent circuit is given by

$$r{\cdot}i(t) + V_C(t) - V_s = 0, \tag{4}$$

$$i(t) = \frac{dQ(t)}{dt} = C\frac{dV_C(t)}{dt}, \tag{5}$$

where C is the capacitance, $i(t)$ is the circuit current, and V_C is the capacitor voltage. By combining Equations 4 and 5, we arrive at

$$V_s = rC\frac{dV_C(t)}{dt} + V_C(t). \tag{6}$$

This is a first-order linear differential equation for V_C. Solution of this equation for a constant V_s is

$$V_C(t) = V_0e^{-\frac{t}{\tau}} + V_s\left(1 - e^{-\frac{t}{\tau}}\right) = V_s - (V_s - V_0)e^{-\frac{t}{\tau}}, \tag{7}$$
$$\lim_{t\to\infty} V_C(t) = V_s$$

where $\tau \equiv rC$ is the time constant and V_0 is the voltage of the capacitor at $t = 0$. Hence, the current in the circuit (Figure 2) is

$$i(t) = \frac{V_s - V_0}{r}e^{-\frac{t}{\tau}}. \tag{8}$$

The power generated by the voltage source is thus

$$p(t) = V_s{\cdot}i(t) = V_s\frac{V_s - V_0}{r}e^{-\frac{t}{\tau}}. \tag{9}$$

The total energy supply from the voltage source in order to completely charge the capacitor is

$$W_s = \int_0^\infty p(t)dt, \tag{10}$$

$$W_s = V_s\frac{V_s - V_0}{r}\int_0^\infty e^{-\frac{t}{\tau}}dt, \tag{11}$$

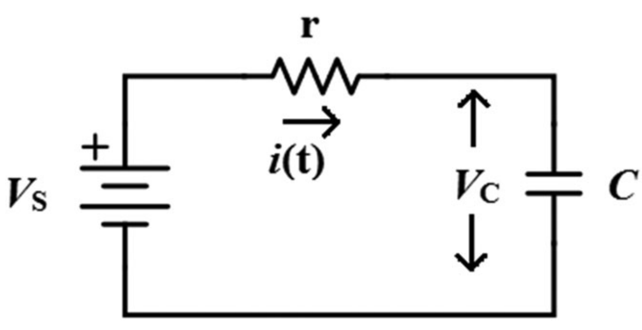

FIGURE 2 Diagram for charging process of capacitor

$$W_s = V_s(V_s - V_0)C = \left(V_s^2 - V_sV_0\right)C. \tag{12}$$

The power delivered to the capacitor is

$$\begin{aligned} p_c(t) &= V_c(t){\cdot}i(t) \\ &= \frac{V_S - V_0}{r}e^{-\frac{t}{\tau}}\left\{V_S - (V_S - V_0)e^{-\frac{t}{\tau}}\right\}. \end{aligned} \tag{13}$$

The energy stored in the capacitor is thus

$$\begin{aligned} W_c &= \int_0^\infty p_c(t)dt \\ &= \int_0^\infty \frac{V_S - V_0}{r}e^{-\frac{t}{\tau}}\left\{V_S - (V_S - V_0)e^{-\frac{t}{\tau}}\right\}dt \\ &= \frac{1}{2}\left(V_s^2 - V_0^2\right)C. \end{aligned} \tag{14}$$

If the charged capacitor is connected to a load, then the capacitor discharges the stored energy (W_c) to the load. As per Kirchhoff law, discharging process of a capacitor can be expressed as

$$V_c + V_R = 0, \tag{15}$$

where, as before, V_c is the voltage across the capacitor and V_R is the load voltage. Let us assume that the charge on capacitor is Q and is connected to the load with resistance R, then Equation 15 can be written as

$$\frac{Q}{C} - R\frac{dQ}{dt} = 0. \tag{16}$$

If initial charge is Q_0 (after charging), then it decreases as

$$Q(t) = Q_0e^{-t/\tau'}, \quad \tau' \equiv RC, \tag{17}$$

and the capacitor voltage changes as

$$V_c(t) = V_0e^{-t/\tau'}. \tag{18}$$

There are two situations that can be considered for any capacitor: (a) a system with constant charge and (b) a system with constant potential difference. The physical origin of the force acting on the dielectric slab is similar for both the cases.[24]

2.1 | Capacitor with constant potential difference

In this case, constant potential difference is maintained by means of an external energy source, ie, battery. If C_1 and C_2 are capacitances of capacitor with presence and absence of dielectric, respectively, then change in capacitor energy

$$\Delta W = \frac{1}{2}V^2(C_1 - C_2), \quad (19)$$

$$\Delta W = \frac{1}{2}V^2C_1\left(\frac{\varepsilon_r - 1}{\varepsilon_r}\right), \ (C_2 = C_1/\varepsilon_r). \quad (20)$$

For large values of ε_r,

$$\Delta W \approx \frac{1}{2}V^2C_1. \quad (21)$$

The above equation shows that the power generation is reasonable for this case as the electrostatic energy and charge are decreased when the dielectric is removed ($C_2 \ll C_1$). This energy is related to mechanical work done for insertion of the dielectric slab into the capacitor. No current flows during this process as the voltage is the same across the source and the capacitor. According to Roundy et al, energy generation is possible from capacitors with constant voltage but two separate voltage sources are needed.[30]

2.2 | Capacitor with constant charge

For this case, the constant charge is maintained by disconnecting the capacitor from the voltage source when $V_c \approx V_S$. If the dielectric is removed from the capacitor, then capacitance decreases and voltage rises sharply:

$$Q = V_1C_1, \quad (22)$$

$$V_2 = \frac{Q}{C_2} = \frac{V_1 \cdot C_1}{\left(\frac{C_1}{\varepsilon_r}\right)} = V_1\varepsilon_r, \quad (23)$$

$$W_2 = \frac{1}{2}{V_2}^2C_2, \quad (24)$$

$$W_2 = \frac{1}{2}(V_1\varepsilon_r)^2\frac{C_1}{\varepsilon_r} = W_1\varepsilon_r, \quad (25)$$

$$\Delta W = W_1(\varepsilon_r - 1) \approx W_1\varepsilon_r. \quad (26)$$

It is thus shown that the stored electrostatic energy becomes ε_r times as large as before. This energy enhancement is equal to the mechanical work done by external force. The above analysis shows that the energy generation is possible from capacitors with constant charge.

Meninger et al studied the merits of constant charge–vs constant voltage–based energy generation methods.[31] Here, we limit our discussion to energy generation from capacitors with constant charge.

3 | OPERATIONAL PRINCIPLE AND GEOMETRICAL ARRANGEMENT

Circuitry of such system involves rechargeable battery as voltage source, variable capacitor, physical device to supply mechanical energy, control circuit, and energy transfer elements. The main steps for energy generation are (a) charge priming, investing charge into a variable capacitor; (b) capacitance reducing, using an external force to decrease the capacitance; (c) charge liberating, the process of removing more energized charge from the capacitor at controlled voltage level that is higher than the priming voltage; and (d) charge collecting/reinvesting, using more energized charge as well as directing some part of collected charge to reuse as priming charge. The equivalent electrical circuit of the proposed device is shown in Figure 3; dotted portion represents the circuit diagram for charging process (equivalent to Figure 2). For ease of understanding, different elements of the generator are assigned by numbers. As a first step, variable capacitor (5) takes energy from voltage source (1) through resistor (3) and first diode (4). In order to maintain constant charge across capacitor plates, the capacitor is disconnected from the voltage source when the capacitor voltage (V_c) becomes equal to the source voltage (V_s). Now, external mechanical force is applied on the dielectric slab to push it outside the capacitor. The effective capacitance decreases with the movement of the dielectric, and the voltage across capacitor rises sharply. Figure 4A demonstrates the process of capacitance variation. In the absence of dielectric, the voltage across the capacitor increases by factor of ε_r. This voltage rise eventually turns on second diode (7) of Figure 3, resulting in the partial discharge of energy to storage devices through flyback circuit. This flyback circuit transfers the electric charge to the load (8) or other electrical energy storage means (9). Periodically, the flyback circuit sends some part of the harvested energy back to the voltage source (1) that again energizes variable capacitor (5). The first diode (4) turns on and the second diode (7) turns off for the second part of the operation, which allows charge injection from the voltage source (1) to capacitor (5). Figure 4B exhibits the equivalent circuit diagrams for functioning of both diodes. The function of the flyback circuit and role of the second diode (6) are discussed in detail by Yen and Lang.[32] Figure 5 shows the voltage and current characteristics across the variable capacitor as a function of time during

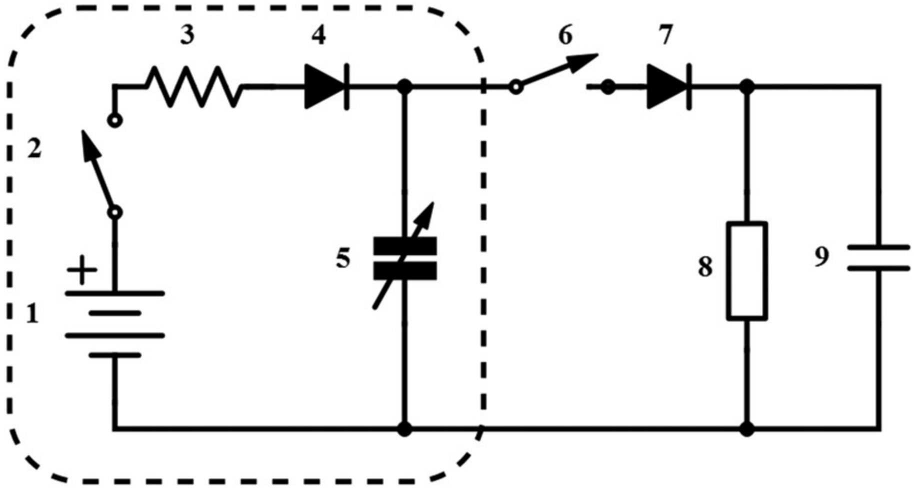

FIGURE 3 Generic model of electrostatic generator. Some of important elements are (1) voltage source, (2) switch-1, (3) resistor, (4) diode-1, (5) variable capacitor, (6) switch-2, (7) diode-2, (8) load and (9) storage capacitor

both charging and discharging processes. The capacitor voltage (V_c) reaches to the source voltage (V_s) when time changes from t_0 to t_1. Here, δt is time duration for dielectric slab's movement. Charge liberating process completes in time duration of $t_2 - (t_1 + \delta t)$.

One of the objectives of the present study is to provide a novel method that overcomes the limitations and disadvantages of prior arts. As we know that the field is the physical origin of force acting on the partially inserted dielectric slab in a capacitor.[24] The force on a dielectric slab at different positions (Figure 1) with respect to plates of an isolated and charged parallel-plate capacitor is expressed as[24]

$$F = \pm \frac{Q^2}{2C_2\left[1 + \frac{1-\varepsilon_r}{a}x\right]^2} \frac{\varepsilon_r - 1}{a}, \tag{27}$$

$$\frac{\partial F}{\partial x} = \mp \frac{Q^2}{C_2\left[1 + \frac{1-\varepsilon_r}{a}x\right]^3}\left(\frac{\varepsilon_r - 1}{a}\right)^2. \tag{28}$$

The magnitude of force changes with the position of the dielectric slab, and thus, the resultant force is not

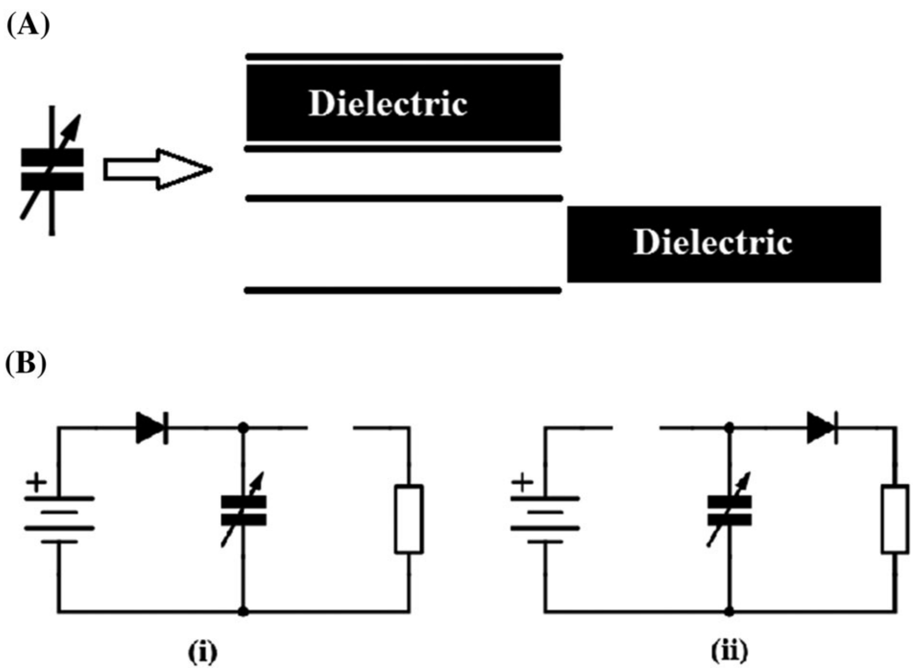

FIGURE 4 (A) Process for variable capacitance generation. (B) Equivalent circuit diagrams for different parts of the energy harvesting process

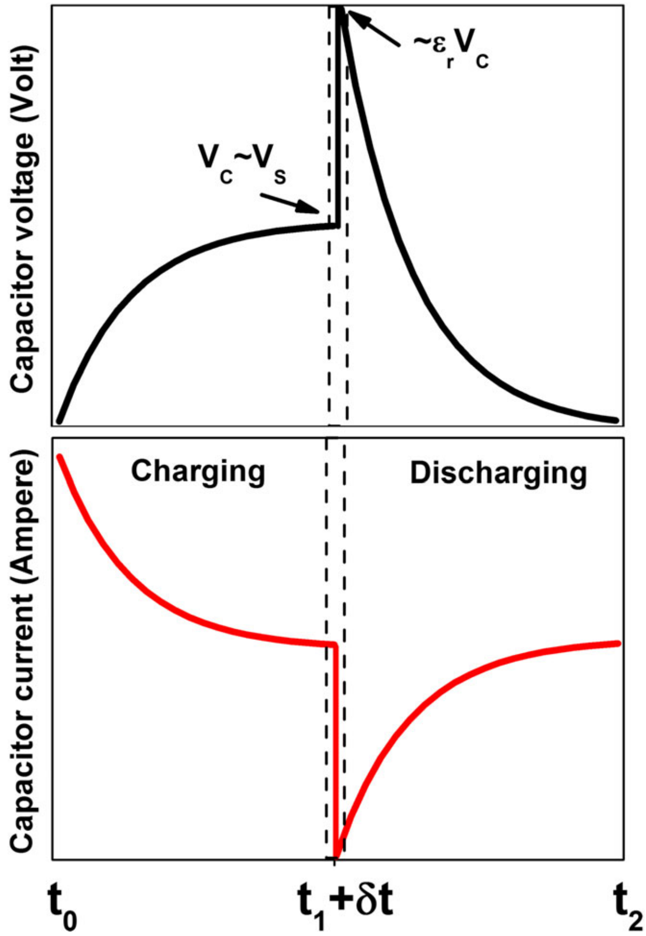

FIGURE 5 Time plot showing the voltage and current characteristics across the variable capacitor (5) during charging and discharging process [Colour figure can be viewed at wileyonlinelibrary.com]

uniform. Herewith, we propose a specific circular geometrical arrangement to decrease the force needed. We note here that the rotating machines that generate power electrostatically hold promise of high power to weight ratios and can be highly efficient easy to use and construct. Figure 6 demonstrates a geometrical setup for electrostatic generator, whose stator is a parallel-plate capacitor formed by two pairs of metal disks and whose rotor is a dielectric. Stator disks are divided into six sectors with 30° spacing while rotor disks are divided into four sectors with 60° spacing. It is important to note that both type of sectors (metal and dielectric) should have similar dimensions. Proposed geometrical arrangement consists of a total of six capacitors: two capacitors with dielectric and four capacitors without dielectric. Initially, all capacitors are charged, and the charging battery is then disconnected. Subsequently, the rotor disk rotates by means of external forces, ie, human muscle power or any other source.

In each cycle of rotation, two dielectric slabs go inside the capacitors and the other two come out from capacitors. The forces always act by pushing the dielectric into the region between the capacitor plates in order to reduce energy. Therefore, forces (F1 and F3) are in the positive direction with the movement of the rotor while forces (F2 and F4) are opposite to the movement. Resultant force can be expressed as

$$\vec{F}_r = \vec{F}_1 + \left(-\vec{F}_2\right) + \vec{F}_3 + \left(-\vec{F}_4\right), \tag{29}$$

$$\vec{F}_r \approx 0. \tag{30}$$

Magnitude of resultant force is very small for the proposed geometrical arrangement. Hence, it is easy to move the rotor disk using a human (eg, hand) without any other source. This specific arrangement is also helpful to enhance the efficiency of the generator. Before concluding this discussion, we want to emphasize the role of air gap between conducting and dielectric plates. It is important to note here that a small air gap should be maintained between both plates in order to avoid friction. Let us consider a small air gap between dielectric and capacitor plates (Figure 1). If thickness of dielectric slab is t and spacing between capacitor plates is d, then this configuration is equivalent to two capacitors connected in series, and equivalent capacitance can be expressed as

$$\frac{1}{C} = \frac{d-t}{\varepsilon_0 A} + \frac{t}{\varepsilon_0 \varepsilon_r A}, \tag{31}$$

$$C = \frac{\varepsilon_r \varepsilon_0 A}{\varepsilon_r (d-t) + t}. \tag{32}$$

The term ε_r comes at denominator in Equation 32, which partially cancels out the effect of large permittivity on capacitance. Hence, one should take utmost care to reduce the air gap; it will significantly affect the efficiency of the generator. To the best of our knowledge, there is no report dealing with the role of air gap in efficiency of electrostatic energy generator. We can rewrite Equation 32 as

$$C = \frac{\varepsilon_r \varepsilon_0 A}{d}\left[\frac{1}{1 + \left(\frac{\Delta}{d}\right)(\varepsilon_r - 1)}\right], \tag{33}$$

where $\Delta = d - t$. For maximum gain,

$$\left(\frac{\Delta}{d}\right)(\varepsilon_r - 1) \ll 1, \tag{34}$$

As $\varepsilon_r \gg 1$,

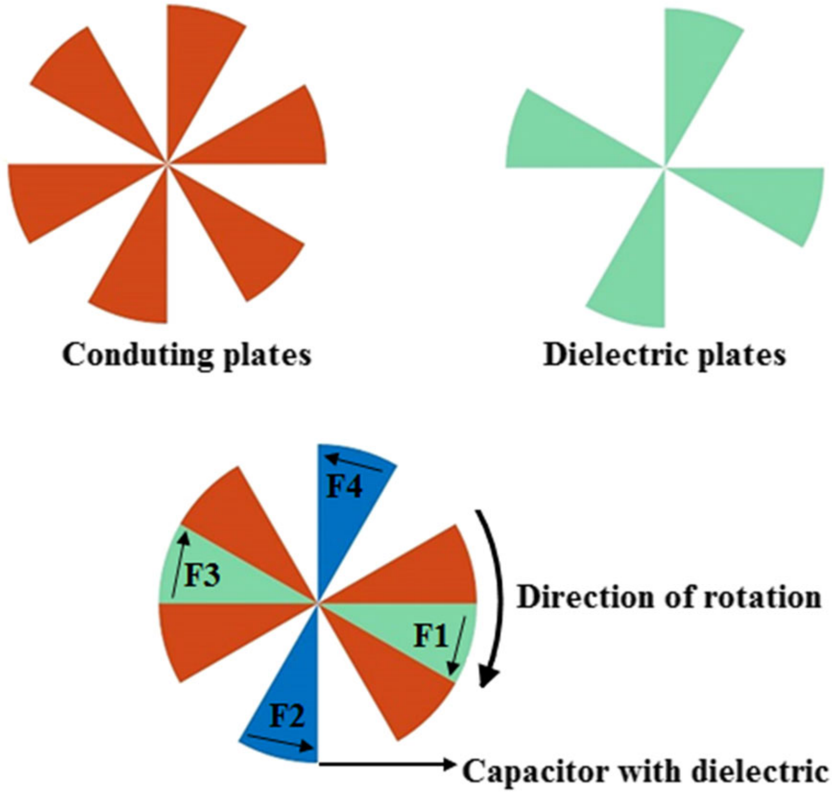

FIGURE 6 Proposed geometrical arrangement of electrostatic generator [Colour figure can be viewed at wileyonlinelibrary.com]

$$\Delta \ll \frac{d}{\varepsilon_r}. \tag{35}$$

This air gap can be replaced with dielectric fluids, although it will affect the efficiency of the generator. Additionally, breakdown field for dielectric fluids is also higher than that of air. In a recent work, Duranti et al[2] proposed a novel concept of dielectric fluid transducer, which is a variable capacitance electrostatic generator. Such transducers are able to convert mechanical energy into direct current electricity. Now we want to draw the attention of the readers toward the importance and the limitations of using high ε_r dielectric materials and air gap. Equation 32 can also be rewritten as

$$C = \frac{\varepsilon_0 A}{\Delta}\left[\frac{\varepsilon_r}{\varepsilon_r + \frac{t}{\Delta}}\right] = \frac{\varepsilon_0 A}{\Delta}\left[\frac{\varepsilon_r}{\varepsilon_r + \varepsilon_{r_m}}\right], \tag{36}$$

where $\varepsilon_{r_m} \equiv {}^{t}/_{\Delta}$ is geometrical factor. If $\varepsilon_r \gg \varepsilon_{r_m}$, then

$$C \approx \frac{\varepsilon_0 A}{\Delta}. \tag{37}$$

The above equation shows that extremely large values of ε_r do not increase the capacitance but in fact reduce it. If the dielectric material is selected in such a way that $\varepsilon_r \ll \varepsilon_{r_m}$, then Equation 36 can be expressed as

$$C \approx \frac{\varepsilon_0 A\ \varepsilon_r}{\Delta\ \varepsilon_{r_m}}. \tag{38}$$

In this regime, the capacitance and thus the energy generated by the generator increase with ε_r, as long as $\varepsilon_r \ll \varepsilon_{r_m}$, it is beneficial to choose a material with high ε_r. Thus, one should select both dielectric material and geometry of the capacitor correctly for efficient power generation.

Recently, it is claimed that a specific class of materials can provide a higher dielectric constant ($\sim 10^5$), herein called super dielectric materials (SDM).[33] Li et al[34] found that the Nb + In co-doped TiO_2 ceramics possessed considerable large dielectric permittivity ($\sim 10^5$) and attracted attention from the scientific community. Such dielectric materials can be a suitable candidate for variable capacitance–based electrostatic energy generators.

4 | CONCLUSION

In summary, we proposed an efficient and easy to use electrostatic energy generator based on a parallel-plate capacitor. Analytical calculations are performed in order to evaluate the amount of energy generated. For an isolated capacitor (charge is kept constant), the energy stored in the capacitor enhances significantly if the dielectric is removed from the capacitor. In other words, a charge is injected into the capacitor at maximum capacitance, and energy is used at the minimum capacitance. Specific geometrical arrangements for the capacitor and dielectric plates help to enhance the efficiency of the generator. It reduces the nonlinearity and magnitude of mechanical forces needed for the rotor's movement. The proposed generator is envisaged as being especially useful in supplying power to portable electronic devices (such as mobile phones) global positioning systems, and medical devices.

Experimental verification of the proposed design is under process and will be published later. Here, we also want to mention another aspect of this study. In the absence of dielectric, voltage across capacitor increases by factor of ε_r ($V_2 = \varepsilon_r \cdot V_1$). This large amplitude of voltage can be useful as high voltage source for radiation devices such as a gyrotron.[35]

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