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Mechanical to electrical energy conversion in a hybrid liquid-solid dielectric electrostatic generator

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The authors are studying the effect of the dielectric choice in electrostatic generators on the energy yield. Despite having high permittivities, solid dielectrics are shown to have a lower performance than is first apparent, due to the effect of the air gap. Liquid dielectrics are found to offer higher overall equivalent permittivities compared to solid dielectrics with air gaps but the conductivity of liquids limits their performance. Experimental work has been conducted using a hybrid generator which incorporates both solid and liquid layers. The solid polyvinylidene fluoride layer is used to limit the conduction between the plates and the liquid dielectric is withdrawn or injected for the necessary change in capacitance. The experimental work has demonstrated a number of design considerations for such generators and is ultimately used to show that energy conversion is possible using this electrostatic generator configuration. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3207834]

I. INTRODUCTION

This short paper shows progress made in understanding the characteristics of electrostatic (ES) generators and the requirements of the dielectric material for improved energy yields. There is increasing interest in using ES generators for energy scavenging applications as shown by Torres and Rincón-Mora,[1] Yen and Lang,[2] as well as Stark *et al.*[3] There has also been interest in combining ES generators with high voltage dc (HVDC) transmission in renewable power generation.[4]

However, to date, few commercial examples of ES generator have been produced: electromagnetic machines are generally considered advantageous due to the high energy density of the magnetic field compared to the ES field.[5] However, there are several advantages of the ES machine including; a simpler construction compared to an electromagnetic machine; the ability to generate pure dc; and in some cases increased overall efficiency[4] which may make the technology more commercially viable.

II. OPERATING PRINCIPLE OF THE ES MACHINE

The operating principle of the ES machine will now be described. The ES machine can be considered to be a variable capacitor. During energy conversion, mechanical work acts to change the generators capacitance between the maximum $C_{\max}$ and minimum $C_{\min}$. This ideally occurs in a four stage energy cycle as shown in Fig. 1.[6]

At stage (a) and at its maximum capacitance the generator is charged to

$$Q = C_{\max} V. \tag{1}$$

During stage (b), the energy conversion stage, there are two possible control strategies which allow electrical energy to be generated from the prime mover; these involve either constraining the charge within the generator or fixing the voltage across the generator plates.

In charge-constrained control, the generator's charge is fixed so that, according to Eq. (1), as the capacitance is decreased there is a resulting voltage rise. The cyclic energy yield E_{C-C} is calculated using Eq. (2) and the resulting voltage rise is given in Eq. (3) where V_{P-C} denotes the initial voltage

$$E_{C-C} = \frac{1}{2}(C_{\max} - C_{\min}) \cdot V_{P-C}^2, \tag{2}$$

$$V_{\text{final}} = \frac{C_{\max}}{C_{\min}} \cdot V_{P-C}. \tag{3}$$

In voltage-constrained control, the voltage is held constant as the capacitance is decreased, so the device charge must also fall according to Eq. (1). This decreasing charge manifests itself as a continuous current out of the generator. The cyclic energy yield E_{V-C} is given in Eq. (4) and the resulting current in Eq. (5).

$$E_{V-C} = \frac{1}{2}(C_{\max} - C_{\min}) \cdot V^2, \tag{4}$$

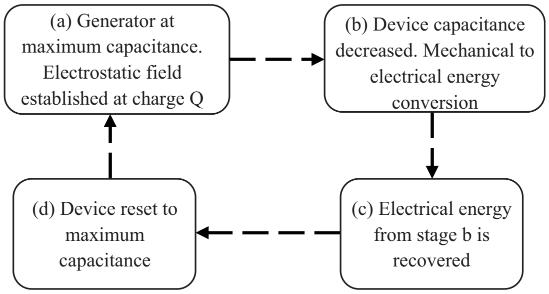

FIG. 1. Four stage energy cycle of ES generator.

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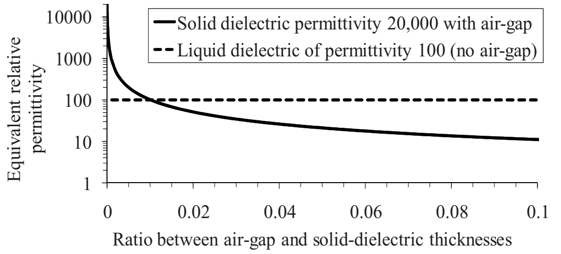

FIG. 2. Decreasing permittivity of dielectric made of a solid dielectric (of permittivity ε_s=20 000) and an air gap.

$$i(t) = V\frac{dC(t)}{dt}. \tag{5}$$

Note that when the voltage-constrained cycle is implemented with a constant rate of change of capacitance then an ideal ES generator can be configured to generate pure dc. This cannot be achieved with the charge-constrained cycle.

III. ACHIEVING VARIABLE CAPACITANCE

Consideration of the equation for the capacitance of a parallel plate capacitor, Eq. (6) reveals how the capacitance value may be varied

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d}. \tag{6}$$

There are three methods for achieving variable capacitance: changing the plate separation distance d; changing the dielectric between the plates ε_r; and changing the plate area A. All methods require relative motion between the plates and the dielectric material.

IV. USE OF LIQUID DIELECTRIC

In an ES generator, the highest energy yields are achieved by maximizing the device capacitance and thus the permittivity of the material between the plates. Solid dielectrics offer the highest relative permittivities [up to 20 000 (Ref. 7)]; however the requirement for an air gap for relative motion between plates and dielectric can be shown to reduce the strength of the field significantly.[8]

The equivalent relative permittivity for a parallel plate configuration is given in Eq. (7), where r_d is the total thickness of the air gap divided by the thickness of the solid dielectric and ε_s is the relative permittivity of the solid dielectric. This is also shown graphically in Fig. 2.

$$\varepsilon_r' = \left(\frac{r_d + 1}{r_d \varepsilon_s + 1}\right)\varepsilon_s. \tag{7}$$

Figure 2 shows that the equivalent relative permittivity of the solid-air dielectric arrangement is reduced from 20 000 to below 100 when the air gap is just 1% of the thickness of the solid.

Liquid dielectrics, which avoid the requirement for an air gap, can have a relative permittivity up to 100.[7] Despite having lower permittivities than solid dielectrics, liquid dielectrics can be considered to offer higher energy yields when the effect of even the smallest air gap is considered. This is a solution to improve the energy yields from ES devices.[8]

V. FINITE RESISTIVITY

The most important problem with using liquid dielectrics is that they have a significant conductivity which generally increases with the dielectric permittivity.[9] Examples given in Table I illustrate this. In most applications, this conductivity is regarded as small, however for ES generator applications it has the significant effect of causing the generator to discharge quickly and thus prevent energy conversion.

It has been found that when the cycle frequency is below 1 Hz, it is necessary to have a resistance between the plates above 10 GΩ in order to achieve net electrical energy production.[9] This means that that there is a requirement for an additional resistive layer for most liquid dielectric materials even with frequency increased to the kilohertz range. This shows that, the effect of self-discharging due to the finite resistance needs to be considered in the design of ES generators.

VI. EXPERIMENTAL DEMONSTRATION

To show that such a movable liquid dielectric ES generator is feasible, a simple experimental apparatus has been constructed in the laboratory. Using a servo motor mechanism, the prototype ES generator is pulled out of and lowered into a de-ionized water dielectric at a maximum frequency of 1 Hz, to achieve the desired variation of capacitance, as shown in Fig. 3.

The generator incorporates two aluminum plates separated by a total distance of 5 mm. One plate is encapsulated by a 1 mm thick polyvinylidene fluoride (PVDF) solid layer to increase the resistance between the plates and reduce the discharge rate of the generator across the dielectric (due to conductivity of the de-ionized water dielectric). This leaves 4 mm of de-ionized water between the exposed plate and the

TABLE I. Approximate permittivity and conductivity of various liquid dielectric types (Ref. 7).

Polarity	Example	Approximate permittivity	Conductivity when purified (Ω^{-1} m^{-1})
None	Transformer oil	2	10^{-14}
Mild	Aroclor in capacitors	6	$\leq 10^{-14}$
Strong (not associated)	Nitrobenzene	≥20	10^{-12}–10^{-10}
Strong (associated)	Water, ethanol	≥20	$\geq 10^{-8}$

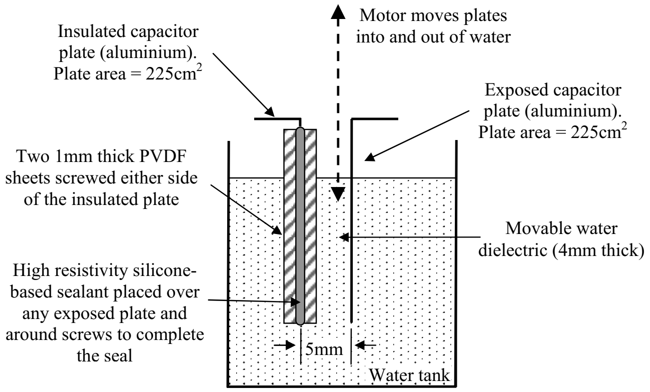

FIG. 3. Schematic of experimental apparatus.

encapsulated plate. PVDF has a permittivity of the same order as the water and so it has minimal impact on the capacitance value achieved.

Both the voltage-constrained and charge-constrained control strategies were considered for implementation into the apparatus. The theoretical current released during the voltage-constrained cycle was predicted using Eq. (5) and found to be extremely low, 4.53 μA even with 500 V applied for the maximum speed of reciprocating motion (47.1 cm/s, sinusoidal peak). This was not measurable by conventional instruments. Such a control strategy also requires more complex and automated external circuitry than the charge-constrained control strategy.

In this study, it was decided that designing such circuitry was unnecessary, since energy conversion may also be demonstrated using the charge-constrained cycle with a much simpler external circuit connected to the capacitor. Energy conversion would thus be demonstrated by an adequate voltage rise of the generator as the capacitor was partially withdrawn from the water.

VII. PREDICTED PERFORMANCE

During operational cycles, the experimental ES generator was operated between a measured maximum capacitance of 5.57 nF when the capacitor is completely immersed in the water dielectric and a minimum capacitance of 4.80 nF when the capacitor is partially withdrawn from the water. It was decided not to fully pull the capacitor out of the water in order to avoid any splashing effect which may result in unrepeatable results during experimentation. The capacitance value includes the stray capacitance of the control circuitry and instrumentation (measured at 3.40 nF). This additional stray capacitance, which does not change with the capacitor position, reduces the electrical energy harvested in a charge-constrained cycle adopted in the experiments. All capacitance values were carefully measured using a high-precision RLC (resistance-inductance-capacitance) impedance analyzer set at low frequency excitation with lead compensation.

Simulations predict that the charge-constrained cycle will give a final voltage of 285 V from a precharge voltage of 250 V and an energy yield of 20.9 μJ. These simulations account for the significant discharge of the ES generator capacitor through to the finite resistance of the dielectric and instrumentation (i.e., it not being possible to fully constrain the charge within the capacitor). Indeed due to the low capacitance of the generator, it was necessary to use a 10 GΩ resistance in series with the voltage probe to prevent the generator from discharging through this instrument. However further increase in the series insertion resistance with the voltage probe would result in significant loss of sensitivity in instrumentation.

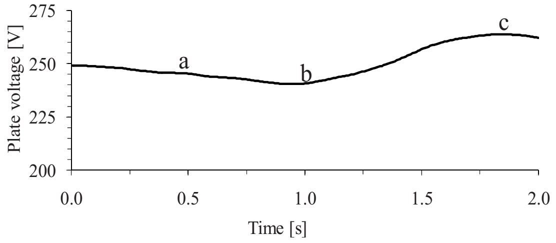

FIG. 4. Voltage-rise over charge-constrained cycle. (a) Discharge of generator over instrumentation. System at maximum capacitance $C_{\max}=5.57$ nF. (b) Start of energy conversion cycle, generator begins withdrawal from water and capacitance decreases. (c) End of energy conversion cycle, capacitance reduced to $C_{\min}=4.80$ nF.

VIII. DEMONSTRATION OF ENERGY CONVERSION

Figure 4 shows the measured voltage of the generator during a test cycle. This plotted voltage output has been scaled to reflect the potential divider created by the series insertion resistance and the impedance characteristic of the commercial voltage probe.

The capacitor was initially precharged to 250 V and started to discharge over the control circuitry and instrumentation from $t=0$ s when the precharging dc voltage source was disconnected. At about $t=1$ s, the capacitor began to be retracted from the de-ionized water and voltage started to rise, corresponding to the generator capacitance reducing.

As previously explained, due to the capacitance of the connected instrumentation and control circuitry (only the dc source was disconnected at t=0 s), the variation in total capacitance is from 5.57 to 4.80 nF. The experiment produced a voltage rise of 25 V and an energy yield of 8.12 μJ, subject to the accuracy of measuring the capacitance values,

$$\begin{aligned}\text{Energy yield} &= \left(\frac{1}{2}\times 4.80\ \text{nF}\times(265\ \text{V})^2\right)\\ &\quad -\left(\frac{1}{2}\times 5.57\ \text{nF}\times(240\ \text{V})^2\right)\\ &= 8.12\ \mu\text{J}. \end{aligned} \tag{8}$$

The measured voltage rise is significant and demonstrates that energy conversion is taking place within the generator; however, the net energy yield is not yet at generally useful levels within this experimental generator. Further work is required to:

- demonstrate methods of improving the energy yield,
- show that energy conversion is possible using the voltage-constrained cycle,
- design more effective electronic circuits: particularly

those to recover and reuse the precharge energy so that a full energy cycle can be implemented, and
- show that the findings are valid over a range of voltages.

IX. DESIGN CHALLENGES

The laboratory experiment has highlighted a number of important characteristics for control circuits used with practical ES generators. First, they must be of very high input resistance (10 GΩ in our experiment) to reduce the discharge rate from the generator. Second, any control circuitry that needs to be connected to the capacitor must be of a low capacitance to maximize the energy yield. The control circuit used in our experiment had an excessive capacitance of 3.40 nF: a capacitance in the order of picofarad is more suitable.

In the case of the experimental apparatus it was necessary to use a solid dielectric to insulate one of the plates and minimize conduction. This has been clearly demonstrated in this study. In liquid dielectrics of significant permittivities, a solution similar to this will need to be employed to allow the generator to hold charge for a significant amount of time. Using dielectrics of higher permittivity would offer an improved energy yield over that demonstrated by the experimental apparatus.

X. POTENTIAL OF THE HYBRID LIQUID-SOLID DIELECTRIC ES MACHINE

The potential of hybrid liquid-solid dielectric ES machines can be demonstrated by comparison to a conceptual vacuum insulated ES generator proposed by Philp.[5] His 7.3 MW HVDC generator requires an operating voltage of 200 kV! A generator of the configuration shown but with a hybrid liquid-solid dielectric arrangement would achieve an equivalent power level at an operating voltage of 17.3 kV.[9] For energy scavenging applications, the hybrid liquid-solid dielectric arrangement would reduce the device size due to the increased energy yield and would allow the ES generator to operate at a lower frequency, simplifying the gearing or gyrodynamic mechanisms that may be needed.

This study used a relatively large scale, low power density laboratory model. It is expected that the solution suggested to address the air gap and large self-discharging leakage current issues can also be applied to more compact variable capacitance ES generator designs. These would incorporate reduced separation distance between plates to increase the power density and increased surface areas to increase the energy yield. It is also likely that such a hybrid liquid-solid dielectric arrangement will be easier to implement from mechanical design point of view as compared to the purely solid dielectric alternative since the liquid may be simply pumped between the plates.

XI. CONCLUSIONS

It is believed that movable hybrid liquid-solid dielectric ES generators can offer improved energy yields over their purely solid dielectric counterparts with inevitable air gaps. This resolves the low equivalent permittivity issue and also prevents the problem of significant self discharging current through the liquid dielectric. The principle and some key characteristics of the proposed technology have been analyzed and demonstrated experimentally in the laboratory; however, improvements to the design through further studies are required to fully understand the benefits and limitations of this type of generator, as well as the design requirements. The demonstration of useful energy conversion depends on the accuracy of the capacitance measurement among other accuracy factors. It is hoped that the work, which clearly contrasts the conventional solid dielectric arrangement with a hybrid liquid-solid arrangement, can provide a basis for further studies in the future.

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