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Self-priming dielectric elastomer generators

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Abstract

Dielectric elastomer generators (DEG) in their present form are not suitable for autonomous power generation; they simply increase the amount of power that an electrical energy source can supply. They require a priming charge for each cycle, normally provided by an auxiliary power source but, due to charges being transferred to a load or depleted by system losses, the energy source will eventually need replacing. In this paper we present a self-priming DEG system that is capable of replenishing these charge losses from generated energy, meaning that the energy source no longer requires periodic replacement. We then experimentally demonstrate that this system not only can replenish charge losses, but also is capable of increasing the amount of charge in the system and the voltage across the capacitance storing the charge. For instance, the system was capable of gradually boosting its voltage from 10 V up to 3.25 kV. This is highly advantageous because it was also shown that the efficiency of DEG power generation increases monotonically with DEG voltage. Also, this system allows these higher voltages to be reached without the need for a high voltage transformer, reducing the system cost.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Dielectric elastomer generator(s) DEG are fabricated using highly flexible elastic dielectric materials sandwiched between flexible electrodes that convert mechanical work to electrical energy using a variable capacitance mechanism. An energy density of 400 mJ cm^{-3} and a specific energy density of 400 mJ g^{-1} have been reported for acrylic-based DEG [1]. Their energy density is an order of magnitude higher than conventional variable capacitor generators and comparable to conventional meso-scale electromagnetic generators [2].

DEG energy density is superior to that of conventional variable capacitor generators partly because dielectric elastomer materials are essentially incompressible. Any change in one dimension produces volume conserving changes in other dimensions, thus amplifying the effect of mechanical deformation on the electrostatic energy [3].

DEG show particular promise for harvesting energy from environmental sources such as ocean waves, wind, vibration of structures, and human movement. Their ability to harvest energy over a broad range of amplitudes and rates or frequencies, without severe reductions in the efficiency of their electrical system make DEG attractive [1]. This is because the energy generated is related to the stroke of the generator, which is therefore velocity independent. In the electromagnetic generator case, the energy generated is strongly related to the rate of motion.

A simple four step process for converting mechanical energy into electrical through a DEG is illustrated in figure 1. First, elastic strain energy is stored within the DEG by stretching it (1); the DEG is then primed, transferring electrical energy to it by charging it to a bias voltage (2); then the mechanical deformation is relaxed, increasing the DEG thickness and decreasing the electrode area whilst the amount of charge remains constant. This increases the potential energy per charge by packing like charges within each electrode more

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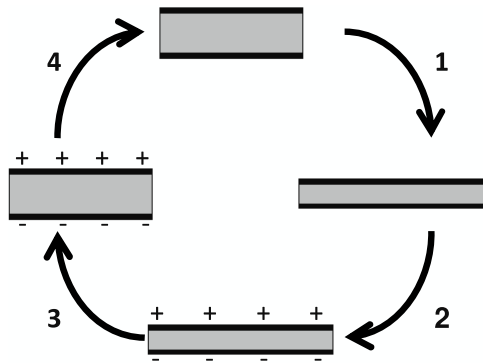


Figure 1. Schematic of the DEG states during a generation cycle. The grey area represents the dielectric and the black area represents the electrodes. The four steps in the cycle are (1) deform the DEG; (2) charge the DEG; (3) relax the deformation; (4) drain off the charges which are in a higher energy state.

densely and increasing the separation of opposing charges (3); in this higher energy form, the charge is drained from the DEG to its electrical load (4).

An energy reservoir such as a battery or capacitor bank is required to supply the bias voltage. Charge is lost from the system due to leakage. Also, an electrical load will consume charge. This means that unless extra charge is periodically added to the system, the amount of charge placed on the DEG will gradually drop.

A DEG will boost the energy that the reservoir’s charges supply to a load until the reservoir is depleted, at which point the system will stop generating power. Is there a way of converting some of the energy generated by the DEG into extra charge to replenish these losses? If we were able to produce a system where the charge reservoir was continually replenished, we would be able to scavenge energy from mechanical vibrations indefinitely. In this paper we present a self-priming DEG system that achieves this goal. It uses an inverse charge pump to convert some of the DEG voltage boost into charge, thus the system does not require periodic charge injections.

An example schematic of a self-priming DEG system is given in figure 2. The circuit consists of two capacitors and three high voltage diodes. This circuit controls the current in

the following manner: current flows from node A to node B when the DEG transfers generated energy to the self-priming circuit. When current flows in that direction, the capacitors are in series (energy is in a high voltage, low charge form) and the equivalent circuit is given in figure 2(c). The capacitors in the self-priming circuit toggle into a parallel state (see figure 2(d)) when the self-priming circuit primes the DEG. This shift between states allows the self-priming circuit to convert the generated energy to a higher charge form, replenishing charge lost from the system.

To allow current to flow between the DEG and self-priming circuit, the proportional change in voltage produced by the DEG needs to be higher than that across the capacitor bank when it toggles state. In the case above, if C1 is equal to C2, the voltage needs to double for the system to self-prime.

In this work an experimental analysis of a complete DEG system is carried out to demonstrate its ability to self-prime. Also, the energy output and efficiency of this system are measured and the factors that influence the system’s efficiency are discussed.

2. Methods

A diaphragm DEG (figure 3) was used in this study to demonstrate a self-priming circuit in a real system. The DEG consisted of a 3M VHB4905 acrylic membrane prestretched equibiaxially to nine times its original area and fixed to a Perspex™ annulus with an inner diameter of 110 mm. An inner Perspex™ hub of diameter 70 mm was adhered to the centre of the membrane. This hub was used for coupling the DEG to a mechanical load normal to its plane, deforming it as illustrated in figure 3(c). The electrodes were made by brushing Nyogel 756G carbon grease onto the membrane. The same DEG, which consisted of ~0.3 g of active acrylic membrane, was used in all experiments.

The test platform had both a mechanical and an electrical sub-system. The mechanical sub-system deformed the DEG, while measuring the amount of force applied and supplying displacement feedback. The electrical sub-system initially primed the DEG and then measured the voltage it delivered to a high impedance load. Both sub-systems were controlled by a single National Instruments LabVIEW (V7.1) program which

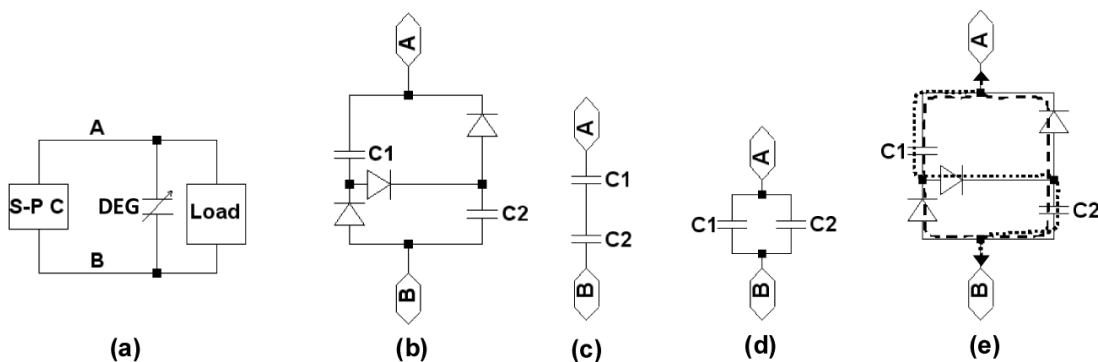


Figure 2. The self-priming circuit (S-P C) is connected in parallel with the DEG (a). A simple self-priming circuit is illustrated (b) along with its equivalent high voltage (c) and high charge (d) forms. With reference to (e), the circuit is in a high charge form when current flows along the dashed path and high voltage form when it follows the dotted path.

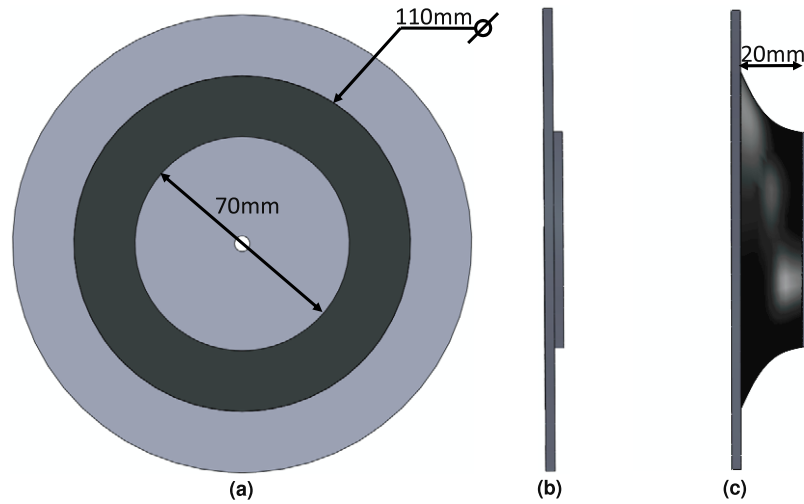


Figure 3. Schematic of our test DEG from a plan view (a), side view in a planar state (b), and side view when in the deformed state (c).

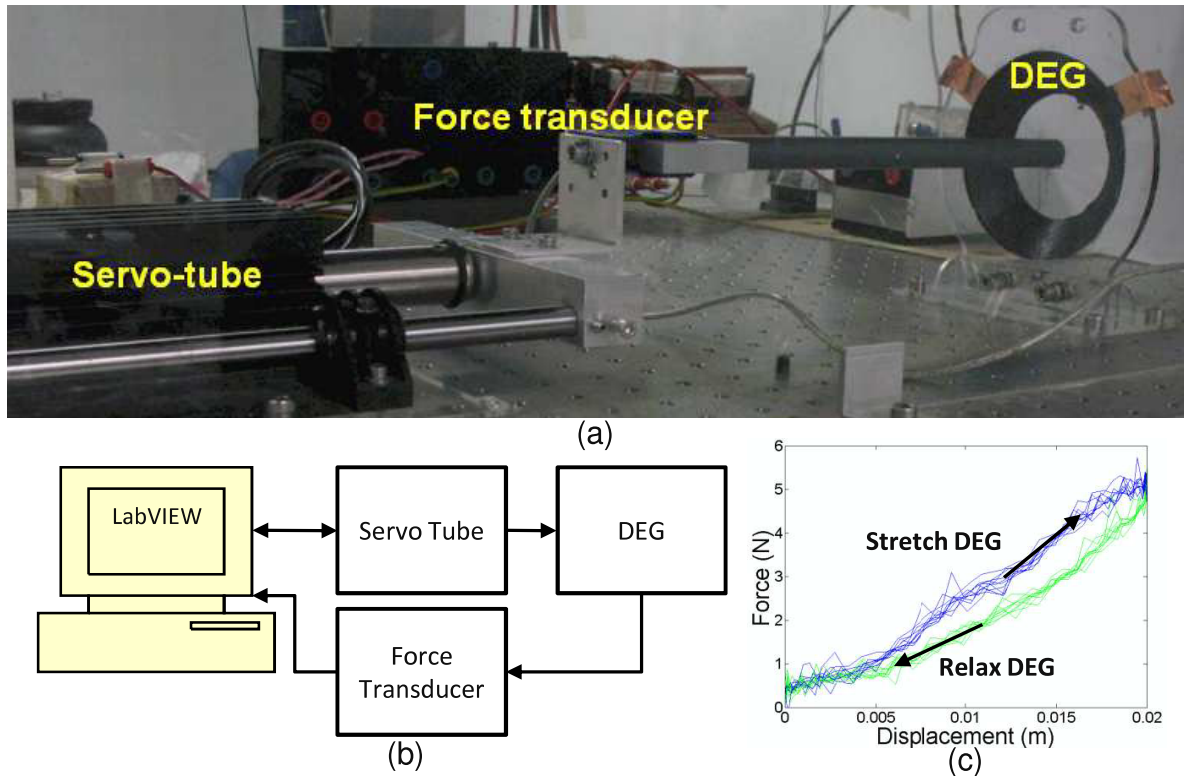


Figure 4. A photo (a) and schematic (b) of the mechanical system of our experimental platform and (c) example work curves used to calculate the mechanical work used by the DEG.

was also used to acquire the experimental data using a NI-6221 DAQ card at a sampling rate of 300 Hz. This data was used to measure the mechanical work delivered to the DEG and the electrical energy transferred to the load.

The mechanical system is shown figure 4. A Copley Controls STB2504S servo tube was used to deform the DEG between the two states shown in figures 3(b) and (c). The inner hub was sinusoidally cycled between the two states at frequencies of 2, 3, and 4 Hz. The force to deform the DEG was measured using an interface SM-50N load cell. The

mechanical work (W) delivered to the DEG was calculated using equations (1), where $F(t)$ and $u'(t)$ are the force exerted on the DEG and the velocity at which the inner hub was displaced. Since the DEG was cyclically loaded, this form of the work integral was used as it gives only the mechanical work used by the system (i.e. it excludes the work that was elastically restored). With reference to figure 4(c), our force displacement data for the DEG deformed at 2 Hz, this integral is the net mechanical work done, calculated as the difference in area under the curves for stretching and relaxing the DEG.

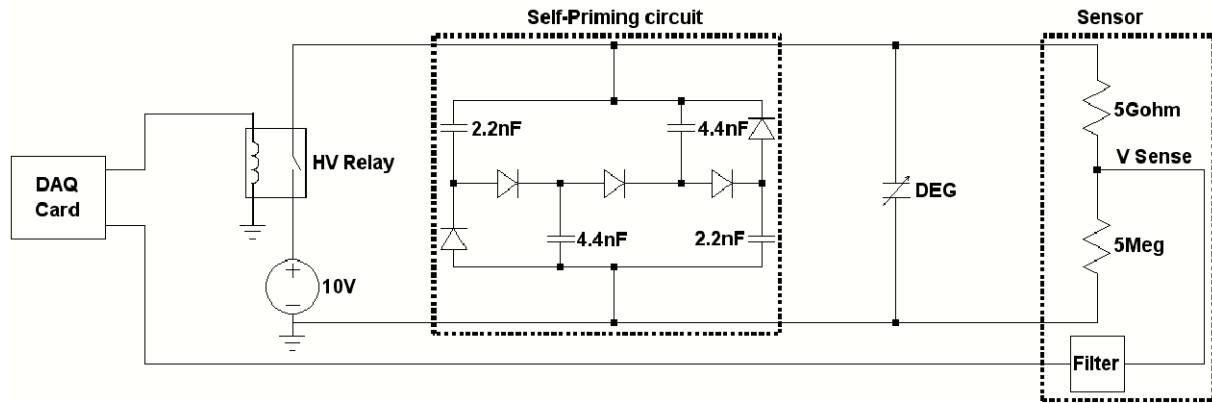


Figure 5. A schematic of the electrical system used in our experiments.

The trapezoid method was used to numerically evaluate this integral.

$$u' = \frac{u_{i+1} - u_i}{t_{i+1} - t_i} \quad W = \int_{T_0}^T F(t)u'(t) dt. \quad (1)$$

A schematic of the electrical system is given in figure 5. A Powertech MP-3087 power supply was used to prime the DEG to an initial voltage of 10 V. When the mechanical system was triggered, the DEG system was disconnected from the power supply using a dry reed relay (HV Relay), this ensured that the power supply did not top up the charge in the self-priming circuit, and isolated the power supply from high DEG voltages. The electrical output of the system was measured by placing a 5 G Ω high voltage sensor in parallel with the DEG. The energy delivered to this resistive load (U_{LOAD}) was calculated by integrating the power delivered to it. The trapezoid method was used to numerically evaluate the integral in equation (2), where $V(t)$ is the voltage across the sensor and R is its resistance. The change in stored energy during one cycle (ΔU_{STORE}) was calculated using equation (3), where C is the capacitance of the whole system when the DEG was in the planar state, and V_1 and V_2 are the voltage of the DEG system at the start and end of the cycle, respectively. The efficiency, η , of the DEG was then calculated using equation (4). The tests were analysed for DEG voltages up to 2 kV; higher voltages resulted in wrinkling of the DEG membrane, affecting rest capacitance and leading to error.

$$U_{LOAD} = \int_{T_0}^T \frac{V(t)^2}{R} dt \quad (2)$$

$$\Delta U_{STORE} = \frac{1}{2}C(V_2^2 - V_1^2) \quad (3)$$

$$\eta = \frac{U_{LOAD} + \Delta U_{STORE}}{W}. \quad (4)$$

An estimate of the electrical efficiency (η_{elect}) of the system that was operating at 2 Hz (i.e. with a purely elastic mechanical system) at a DEG voltage of 2 kV was calculated using equation (5). When the DEG voltage was at 10 V, mechanical to electrical energy conversion was very low. Therefore we assumed that the work used by the system at this priming voltage ($W_{10\text{ v}}$) was the same as that lost from the system through viscous losses for each cycle. It was then assumed

that the energy used by the electrical system itself at 2 kV was the mechanical work used at a DEG voltage of 2 kV ($W_{2\text{ kV}}$) minus the viscous losses ($W_{10\text{ v}}$).

$$\eta_{elect} = \frac{U_{LOAD_{2\text{ kV}}} + \Delta U_{STORE_{2\text{ kV}}}}{W_{2\text{ kV}} - W_{10\text{ v}}}. \quad (5)$$

A two-stage self-priming circuit was used, that is, the circuit toggled between two and three sets of capacitors in parallel. Since the capacitance of this system changed by a smaller amount than the circuit in figure 2, smaller DEG voltage swings were required. Schematics of the two-stage self-priming circuit are given in figure 6. This circuit toggles between equivalent capacitances of 6.6 nF (figure 6(b)) and 2.9 nF (figure 6(c)).

3. Results

When the DEG was deformed sinusoidally, the capacitive changes caused the voltage to decrease as the DEG was stretched and increase when the deformation was relaxed. When more power was generated than that transferred to the load, the charge stored in the self-priming circuit increased with each generation cycle, therefore the DEG voltage increased from one cycle to the next. Figure 7 shows the voltage output of a DEG operating in this ‘voltage-boost’ mode. After 236 cycles at 3 Hz, the DEG voltage was boosted from 10 to 3250 V, where the DEG failed due to dielectric breakdown.

The total energy ($U_{LOAD} + \Delta U_{STORE}$) generated, and the efficiency (η) per cycle at frequencies of 2, 3, and 4 Hz operating in voltage-boost mode are given in figures 8 and 9, respectively. These are plotted against the DEG voltage at the start of each cycle. The energy and efficiency increased as the voltage was boosted. The energy generated increased monotonically with frequency, whereas the efficiency decreased monotonically as frequency was increased. The peak in energy production per stroke was ~ 0.85 mJ at a DEG voltage of 2 kV and frequency of 4 Hz.

Comparisons of the work consumed at 2, 3 and 4 Hz at DEG voltages of 10 V and 2 kV are given in figure 10. The work increased with frequency. This figure also shows that the increase in frequency from 2 to 4 Hz had a much larger effect on the dissipated work than increasing the voltage from 10 V to 2 kV.

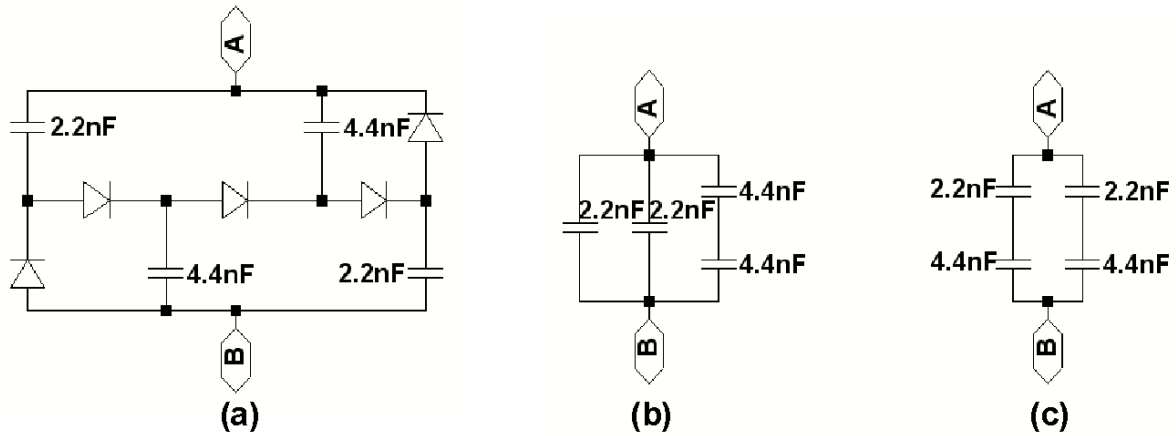


Figure 6. The two-stage self-priming circuit that was used (a) and its equivalent high charge (b) and high voltage (c) states.

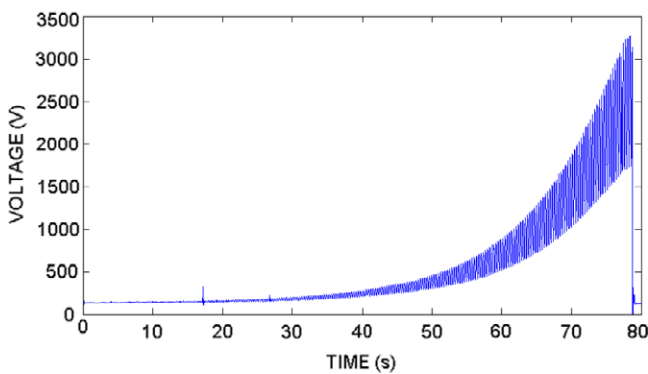


Figure 7. Voltage output versus time for a self-priming DEG operating in voltage-boost mode deformed at 3 Hz at 20 mm stroke.

4. Discussion

Pelrine *et al* and Jean-Mistral *et al* described experiments where DEG were connected to external power supplies to supply the bias voltage [1, 4]. The generator effectively increased the amount of power supplied to the load. To generate energy, these systems required energy input from the power supply during every cycle. The power supply would add substantial cost and mass to the DEG system.

Tashiro *et al* produced a variable gap parallel plate capacitive generator system where the bias was supplied by a

capacitor bank, when the variable capacitor generated power, charge was returned back to the capacitor bank [5]. Ihlefeld and Qu presented a DEG system using the same circuit [6]. Their circuit did not replenish charges lost from the system or delivered to the load, but some of the charges were recycled, increasing the time before the priming circuit needed to be recharged. Unlike these examples, the self-priming system presented here does not require recharging from an external source.

The self-priming circuit also presents an opportunity to produce DEG at very low cost. Expensive high voltage transformers are no longer required. The experimental results in figures 7–9 demonstrate the self-priming DEG system’s ability to boost its voltage from 10 V up to the kilovolt range. Figures 8 and 9 also demonstrate that high DEG voltages are desirable since both the efficiency and energy generated increase with DEG voltages.

The material used in this study, VHB4905, is highly viscous [1, 3, 7, 8]. As demonstrated in figure 10, the viscous losses from the mechanical system increased with frequency, resulting in a decline in efficiency. An increase in frequency has a larger effect on the work dissipated than an increase in the voltage; this indicates that the losses from the DEG are affected more by an inefficient mechanical system than by inefficient electromechanical coupling. Also, the generated electrical energy per cycle increased with frequency, this is because for the VHB4905 DEG, a significant amount of charge was leaking

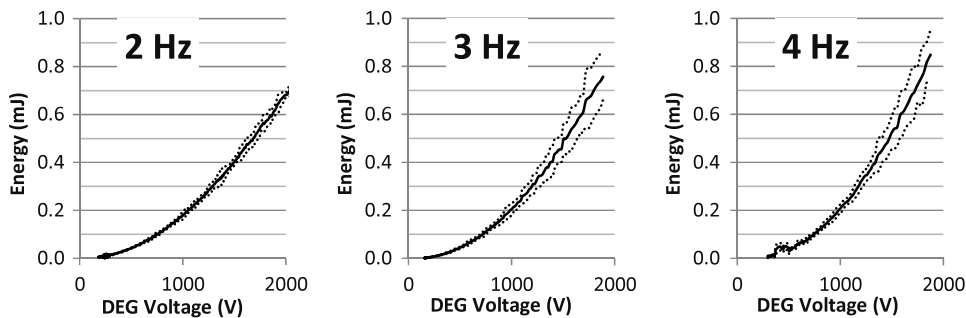


Figure 8. Generated electrical energy per cycle versus DEG voltage for deformations at 2, 3 and 4 Hz. The solid line illustrates the seven point moving average which is enveloped by plots of plus/minus one standard deviation (dotted lines).

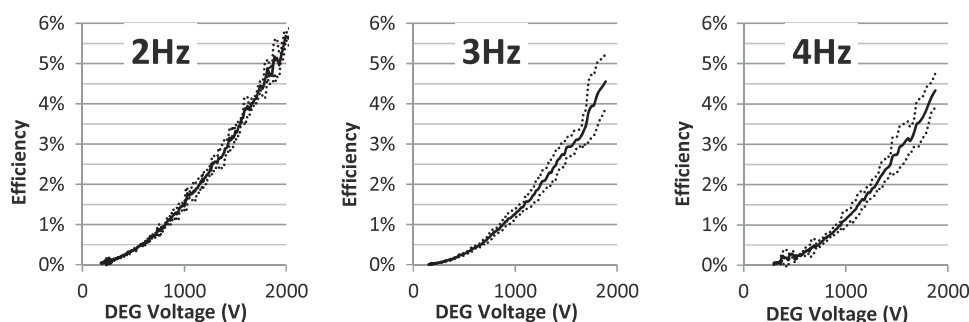


Figure 9. Efficiency versus DEG voltage for deformations at 2, 3 and 4 Hz. The solid line illustrates the seven point moving average which is enveloped by plots of plus/minus one standard deviation (dotted lines).

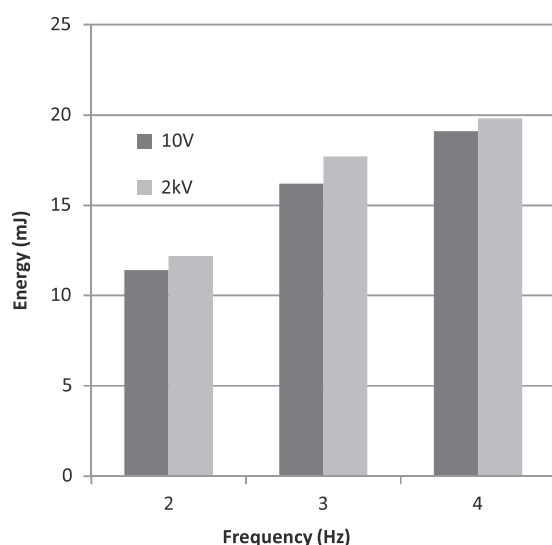


Figure 10. Work dissipated by DEG primed at 10 V and 2 kV deformed at 2, 3 and 4 Hz.

though the membrane [9]. When the frequency was increased, the power generated by the DEG became proportionally larger than that lost through leakage.

The maximum efficiency of our system was only 6.4%. Using equation (5), we estimate the system would have had an efficiency of 84% if there were no viscous losses from the mechanical system. Furthermore this figure could be improved if the system's electrical losses decreased. Three sources of electrical losses are the voltage drop across the diodes, resistance of the electrodes, and charge leakage through the membrane. The maximum forward voltage of the diodes is 3 V, so this is probably not a major source of losses. Given the high efficiency of the electrical system, the self-priming circuit design shows promise for creating efficient DEG if a less viscous, elastic material is chosen. Furthermore, if the material is not electrically lossy and low resistance electrodes are used, the efficiency of the electrical system can be further improved.

In this study, the largest amount of energy generated from a single stroke was 0.85 mJ. Since the active DEG membrane weighed 0.3 g, this corresponds to an energy density of 2.8 mJ g⁻¹. Pelrine *et al* reported a much higher experimental

energy density of 400 mJ g⁻¹ using a VHB4905/10 dielectric material, but their operating conditions were not specified [1]. Koh *et al* estimated the maximum achievable energy density to be approximately 2700 mJ g⁻¹ using a theoretical generation cycle bounded by DEG failure limits [10]. It should be noted that the work described in this paper was intended to demonstrate the charge boosting function of the self-priming circuit rather than the DEG itself, so the DEG was operated very conservatively. The maximum electric field was limited to 56 MV m⁻¹ and the maximum active area stretch to 1.6, while Koh *et al* used a maximum electric field of 300 MV m⁻¹ and an area stretch 25 for their model [10]. Substituting the operating conditions used in these experiments into the model developed by Koh *et al* yields a maximum theoretical energy density of approximately 110 mJ g⁻¹.

Is it possible to increase the energy density of a self-priming DEG system so that it is comparable to those reported elsewhere? There are a number of avenues for improvement. First, the DEG design could be considerably improved. The diaphragm DEG design used in this study has an inhomogeneous stretch field, so when the stretch limit is reached in the highest strain regions, much of the membrane is still in a significantly lower stretch state with a correspondingly low energy density. For instance, the maximum area stretch was 1.6, whereas the average area stretch was 1.4. Second, the self-priming circuit could be optimized. The number of stages in the self-priming circuit influences the amount of time that the charge on the DEG is held constant, also, the relative capacitance of the self-priming circuit influences how much charge flows to and from the DEG. Third, the load impedance could be matched to optimize power transfer. Last, we could increase the energy density by deforming the DEG at a higher frequency. As illustrated in figure 8, the energy per stroke increased with frequency. It should be noted that the energy densities quoted only refer to the active DEG membrane, and that self-priming circuits consisting of a small number of diodes and capacitors are highly miniaturizable DEG power electronics.

One limitation of the self-priming circuit is that it requires the DEG to produce a minimum voltage swing. To explain this, a schematic of the voltage waveform across a DEG in a self-priming system is given in figure 11. Iskandarani *et al* presented a similar analysis of an ideal DEG system that does not self-prime [11]. The four phases correspond to the

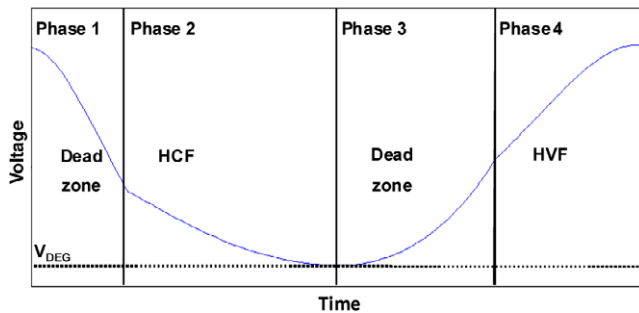


Figure 11. Schematic of self-priming DEG output waveform. Phase 1 and 3 are dead zones and current flows between the DEG and self-priming circuit in phases 2 and 4.

simplified steps given in figure 1. There is always charge on the DEG when the self-priming circuit is used. When the capacitance of the DEG increases it biases current to flow from the self-prime circuit to the DEG, the current flow is biased in the other direction when the capacitance decreases. However, no current will flow when it is biased to flow up a voltage gradient. With reference to figure 11, during phases 1 and 2, the self-priming circuit operates in the high charge form (HCF). During phases 3 and 4, the self-priming circuit is in the high voltage form (HVF). The four phases of the self-priming system are as follow:

- (1) The DEG is deformed so that its capacitance increases, but no charge is allowed to flow from the self-priming circuit to the DEG because $V_{\text{DEG}} > V_{\text{SP}}$.
- (2) The DEG continues to deform, but now $V_{\text{DEG}} < V_{\text{SP}}$, so current flows from the self-priming circuit to the DEG. This means that the drop in voltage with change in capacitance decreases.
- (3) The deformation of the DEG is relaxed so that its capacitance decreases, but no charge is allowed to flow from the DEG to the self-priming circuit because $V_{\text{DEG}} < V_{\text{SP}}$.
- (4) The relaxation of the DEG continues, but now $V_{\text{DEG}} > V_{\text{SP}}$, so current flows from the DEG to the self-priming circuit. This means that the increase in voltage with change in capacitance decreases.

In phases 1 and 3, we see that the system has ‘dead zones’ where no charge is transferred between the self-priming circuit and DEG until the voltage swing reaches a critical level. The required proportional voltage swing before current can flow is reduced if a smaller portion of the capacitor bank is transitioned (i.e. the self-priming circuit has a higher number of stages).

Power is transferred to the load throughout the generation cycle, even in the dead zones of the cycle. This means that when the mechanical deformations of the DEG are not large

enough to enable the system to self-prime, generated power can still be delivered to the load.

5. Conclusions

A DEG system was developed that was able to self-prime itself with additional charges to recover losses. When the power consumed by the electrical load was less than that produced by the DEG it was able to boost its voltage to a level where it was able to operate more efficiently.

The system was designed to demonstrate the feasibility of the self-priming system rather than for energy generation performance. Although the measured energy density and conversion efficiency were low, it is estimated that with a less viscoelastic DEG membrane material, efficiencies of up to 84% could be achieved when primed at 2 kV. This could be further improved by using lower resistance electrodes and a less lossy dielectric. Energy density could be considerably improved through further development of the DEG itself and its power electronics.

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